WEEDS OF COTTON:
Characterization and Control

NUMBER TWO
THE COTTON FOUNDATION
REFERENCE BOOK SERIES



Edited by
Chester G. McWhorter
and
John R. Abernathy

WEEDS OF COTTON:
Characterization and Control

THE COTTON FOUNDATION

Reference Book Series

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The Foundation is pleased to publish **WEEDS OF COTTON: Characterization and Control,** the second in the series of cotton reference books. The first volume, **COTTON PHYSIOLOGY,** was published in 1986, and the third, **COTTON INSECTS AND MITES: Characterization and Management,** is planned for availability in 1993.

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WEEDS OF COTTON:
Characterization and Control

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Number Two
THE COTTON FOUNDATION
REFERENCE BOOK SERIES

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FOREWORD

Major weeds are highly competitive and may deprive crops, and even other weeds, of nutrients, water, light and space. In the case of cotton, uncontrolled weeds will impact both yield and quality adversely. Weeds can interfere with planting, efficient application of pesticides and irrigation water, boll opening and drying and harvesting. Weeds also may harbor or act as alternate hosts for cotton insect and disease pests. In addition, some weeds produce and and release inhibiting substances that adversely affect neighboring crop and weed plants.

Today, cotton is grown in an environment shared by some 30,000 or so species of weeds. Fortunately, in a given field or season, the number of troublesome species usually is limited to ten or less.

Weed control was not looked upon as a separate science until after the introduction of selective herbicides in the late 1940s and early 1950s. Prior to that time, weed research to develop new control methods was very limited and spread among several scientific disciplines.

Cotton was one of the first major crops for which producers recognized the need for, and importance of expanded research—both applied and basic—to develop new weed control technology. They recognized that one of the first needs was to have scientists trained in weed science and interested in using that training to develop the needed technology for cotton. In the 1950s and early 1960s, the Foundation for Cotton Research and Education (now The Cotton Foundation) funded several graduate assistantships in weed science. Two of the early recipients were Dr. John T. Holstun and Dr. Chester G. McWhorter. Dr. Holstun is deceased, but he made tremendous contributions during his shortened career.

Dr. McWhorter, a co-editor of this cotton reference book, still is making major contributions. He was president of the Weed Science Society of America 1983 and editor of the Society's 1987 monograph entitled *Methods of Herbicide Application*. Dr. McWhorter was recognized in 1989 by the U.S. Department of Agriculture as recipient of the ARS Distinguished Scientist of the Year Award.

The cotton industry played a significant role in early weed research in several other ways. During the 1960s, several state and federal pioneering weed research programs were funded in part by the Cotton Producers Institute, the forerunner to Cotton Incorporated. The cotton industry also played a major role in the successful efforts in the 1960s that provided federal funds to significantly increase weed research by both land grant institutions and USDA.

The cotton industry also played a role with regard to major contributions by the other co-editor of this book, Dr. John R. Abernathy. However, the relationship was more indirect. A short prelude is in order.

The High Plains of Texas often is referred to as the "biggest cotton field in the world." The 25 counties around Lubbock constitute the largest contiguous area of cotton production in the world.

A grant from the Cotton Producers Institute to Texas A&M University in the

1960s made it possible to establish the first full time weed research program for cotton in the Texas High Plains. After several years of productive research, the first scientist in that position moved on to university administrative work at College Station. Dr. Abernathy filled that position in 1973 and has made significant contributions to cotton weed management technology. In 1985, he became resident director of research at the Texas A&M Research and Extension Center at Lubbock. He also served as president of the Weed Science Society of America in 1991.

It is very appropriate that Drs. McWhorter and Abernathy served as co-editors of this book, **WEEDS OF COTTON: Characterization and Control.**

The National Cotton Council is pleased to have played a significant role in initiating The Cotton Foundation Reference Book Series. The first book in the series, *COTTON PHYSIOLOGY,* recently was reprinted for the second time. The three printings attest to the widespread interest in reference books on cotton. We believe the interest in **WEEDS OF COTTON: Characterization and Control,** the second in the series of books, will be as great.

As with the first book, the usefulness of **WEEDS OF COTTON: Characterization and Control** as a reference book will go beyond the traditional researcher, teacher and student. Private agricultural consultants and agricultural chemical industry representatives will find it to be a valuable source of information. Modern-day cotton producers also will find this book to be both interesting and useful. They are the ones who are not satisfied with just having technology to use. They want to know how it works and why. This helps them to refine and adapt new technology to their own specific conditions and situations. Innovative producers want to relate technology to economic returns and environmental concerns.

The National Cotton Council and The Cotton Foundation are indebted to the editors, Dr. Chester G. McWhorter and Dr. John R. Abernathy, and to the other 28 scientists who served as authors of the 15 chapters. These scientists have dedicated considerable time and effort in making this a book everyone can be proud of. A listing of all the contributors is shown on pages xxi through xxv.

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PREFACE

Weeds are familiar plants to most people; however, authorities in many disciplines have struggled for decades to develop an all-encompassing definition for these plants. Weed definition has never been a problem for the cotton farmer who classifies any plant in the field other than cotton as being a weed. From the time that cotton became a major crop in the United States in the late 1700s, the removal of weeds by hand represented more than 50 percent of the labor input required for production of the crop. Even as late as 1950 it was acknowledged that 50 to 60 percent of the total labor requirement in cotton production was for hand hoeing. The first attempts to use herbicides in the 1950s and early 60s were primarily to reduce the need for the large amounts of hand labor.

When farmers from other regions of the United States first visit the Cotton Belt, they observe that cotton producers may be overzealous in their attempt to control weeds as they appear to obtain near perfect weed control. Cotton yields are reduced from weed competition, especially competition during the first six weeks of the growing season, but producers are also concerned about losses in cotton lint quality because of weeds at harvest. The presence of weeds at harvest, especially grasses, will stain cotton lint and will cause trash from weeds to be mixed in lint, thus greatly reducing its value. This concern for high lint quality may cause cotton producers to seek a higher level of weed control than would be expected in other agronomic crops.

Until the mid 1900s the only form of weed control, other than hand hoeing, was with animal-drawn cultivators. It was not unusual for cotton to be cultivated weekly for the first 10 to 12 weeks of the growing season. Producers began shifting to tractor-mounted cultivators in the late 1930s and this shift was completed in the late 1940s when nearly all cultivation was with tractor-mounted cultivators. During this evolutionary period, producers made use of other mechanical means of control that included flame cultivators, rotary weeders, cross-cultivation and mechanical choppers. They also made extensive use of geese, especially to control grass species. These practices often helped reduce costs but even so, large quantities of hand labor still were needed to control weeds within the cotton drill.

Farmers were anxious to reduce the need for hand labor by using herbicides when they first were introduced in the early 1950s. Early cotton injury experiences caused many producers to be very cautious in their use of herbicides. It was not until the early 1960s that the use of herbicides showed rapid and consistent growth. Many highly selective herbicides were developed and marketed in the 1960s. By the mid 1970s, most of the cotton produced in the United States involved the use of one or more herbicides.

As the acreage treated with herbicides increased in the 1960s and 70s, ecological shifts occurred whereby weeds, such as prickly sida, that had been almost nonexistent in cotton fields became major weed problems. Perennials, such as

purple and yellow nutsedge, silverleaf nightshade and perennial vines, became much more troublesome because they did not have to compete with other weeds. These ecological shifts caused many researchers to devote more effort toward developing control technology for weeds that were not troublesome in the 1950s and also to develop predictive capability as to what new weeds may be troublesome in the future. Studies of this type are an important part of many research efforts in the United States at present. Accurate taxonomic identification of weeds also became more important.

Cotton farmers have been unique, as compared to the producers of other crops, in their desire to use innovative weed control technology. This was demonstrated not only by the early use of geese, flame cultivation, cross-cultivation and post-emergence-applied herbicidal naptha, but also by their early widespread use of herbicides applied in postemergence-directed sprays. Cotton producers adopted postemergence-directed application first and continue widespread use of this practice today.

Many highly selective herbicides have been introduced and marketed during the last three decades, but producers still do not have a herbicide for control of broadleaf weeds that can be applied as a broadcast over-the-top-spray as in other crops. This has forced cotton producers to continue to use postemergence-directed sprays to control broadleaf weeds that escape preemergence treatment. So many efficient herbicides were introduced in the 1960s that this decade has been referred to as the "golden decade" and the "fabulous 60s". At that time the "state-of-the-art" of weed control in cotton with herbicides was probably at a much more advanced stage than in other crops. Unfortunately, the introduction of new, highly selective herbicides for use in cotton decreased while those that became available for use in soybeans, corn and other crops increased dramatically. As a result, many of the herbicides introduced in the 1960s, such as trifluralin, fluometuron, DSMA/MSMA, linuron and paraquat, have continued to be valuable in cotton production into the 1990s.

In the 1950s and the 1960s, much of the research related to weed science in cotton production was devoted to the evalution of new herbicides and in the integration of these into existing weed control programs. The expanded use of herbicides in cotton production inthe 1960s and 70s led to expanded research on efficient application technology, the exact nature of weed interference, economic losses caused by different weeds, and on the residual effect caused by the use of herbicides. Expanded research also has been seen on the more basic aspects, such as the relationship of herbicide chemistry to mode of action and herbicide-soil-groundwater relationships as well as the more applied aspects, such as developing teamwork in weed management. These and other aspects are covered in this monograph and it is our intent that this publication provide a record on the state-of-the-art weed control technology in cotton to this point in history.

We express our appreciation to the many authors who contributed their time to make this publication possible. Hopefully, this book will not only serve as a background reference in the area of weed science in cotton, but it may also serve as the genesis for new ideas that lead to better weed management in this very important crop.

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Chapter 1

EVOLUTION OF WEED CONTROL IN COTTON

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Cotton, from the beginning of its production in colonial times to the present, is one of the culturally most complex crops grown in the United States. The physiology of the cotton plant and the historical importance both sociologically, economically and politically to the development of specific United States regions has to be understood as the importance of weeds and their control in this major United States crop is discussed. Due to its unique growth and development, the cotton plant is greatly influenced by weeds, resulting in a $300 million crop loss per year.

The purpose of this chapter is to provide a summary of the remaining chapters of this book and to list some of the important areas that need additional research. Leading scientists concerned with the control of weeds and cultural practices in cotton have provided detailed information about cotton production from a historical basis through the present with projections into the future. This is coupled with a parallel in the weed control practices. Questions such as why they occurred, how they developed, and what can be expected for the future will be examined.

From the beginning, cotton, which was used to provide domestic textile needs, developed into one of the four major agricultural commodities in the United States. Events in England dealing with the industrial revolution revolutionized mechanization of the textile processing industry and, thereby, generated a tremendous demand for cotton. In the United States vast areas of land, primarily in the southern part of the United States, were well suited for cotton production. However, cotton production did not gain economic significance until a major development occurred: Eli Whitney's cotton gin. For years after the Civil War, a gigantic cotton monoculture existed in the South, which was largely dependent on manual labor in an extensive form of agriculture.

For almost a hundred years cotton was grown without having a major insect

pest problem. In 1892 the cotton boll weevil invaded the United States and forced major changes in the cotton culture and greatly contributed to cotton acreage movement from the south and southeastern part of the United States towards the western areas. Technological innovations in the development of mechanical cotton harvesting and selective cotton herbicides allowed near complete mechanization of cotton culture.

The four major geographic areas of the United States in which cotton is produced vary considerably in their environmental and soil conditions. These four areas include: Southeast states of Alabama, Florida, Georgia, North Carolina and South Carolina; Mid-South states of Arkansas, Louisiana, Mississippi, Tennessee and Missouri; Southwest states including Texas, Oklahoma and New Mexico and the West including Arizona and California. Weed problems which occur in each of these geographic areas vary greatly due to the wide range of environmental, soil and cultural conditions.

As cotton production has evolved in the United States over the past 200 years, weed control technology has changed greatly. Up until the mid-1990s, cotton production and control of weeds involved a very intensive labor requirement both by humans and animals. Hand hoeing was the principal method of weed control and is still utilized today.

The first major advancement that changed weed control technology included mechanical technology which involved the row-crop tractor, the steel plow, and in-crop cultivation to mechanically till the crop and remove weeds. Many ingenious mechanical developments occurred during this era. Biological weed control was recognized during the mid-1940s with the use of geese in Mid-South and western states. Considerable effort is still being devoted to development of additional biological control mechanisms, mostly fungi. The development of the agricultural chemical industry began in the 1940s with initial development of herbicides. This initiated a dramatic new technology for weed control in cotton production in the United States which continues today as the major method of weed control. Hand hoeing as well as mechanical tillage for weed control continue to be utilized, but today these practices supplement the use of herbicides.

As weed science technology evolves and develops, scientists strive to understand more about how weeds interfere with cotton production through their competition for available resources including water, nutrients and light. The degree of competition is a function of the weed species composition of the population as well as the weed population density and duration. In addition, competition for these resources is regulated by their availability. The level of cultural and environmental conditions such as temperature, rainfall, cultural practices, row spacings and cotton cultivar influence competition. The consequence of competition, which is of major concern, is crop yield loss and lower lint quality, usually as a result of fewer, less mature bolls per plant in weed infested areas. Allelopathy is another component of interference which may also be important although limited evidence for this phenomenon can be documented in actual field production.

Allelopathy is the effect one plant has on other plants caused by chemical compounds given off by roots or decaying plant material. Production losses associated with weed interference may occur at harvest or with other management operations.

One of the major shortcomings of existing weed control technology is our inability to predict both cotton yield and quality losses from low populations of a few hundred to a few thousand weeds per acre for many individual weed species. Even more important, the effect of combinations of two, three, four or more species is unknown when they occur together in relatively low populations. In other words, what is the critical minimum of individual weeds or combinations of weeds that will permit us to say that neither yield nor lint quality will be affected by the presence of the weed or that weed seed production will be so low that the resulting weeds next year will not affect cost of production. This type of research is complex, time-consuming and costly. It is not likely that answers to these questions will be provided within the next decade even though this information is needed now to insure maximum profit in production.

Certainly the bottom line to any producer's interest is the cost associated with weeds and their control. It is an accepted fact that weeds indeed cause severe cotton losses and efforts have been made in recent times to document the actual losses by weeds in cotton. Losses have been as much as $300-500 million dollars a year in cotton production in the United States.

These economic considerations also have to include the cost of weed control programs associated with the cotton production. These costs have been documented in chapters within this book, specifically outlining the cost of various operations, herbicides used and the losses that are expected in cotton yield and quality. Weed scientists are providing actual loss figures per individual weed species. Weed science is a young discipline, and as scientists have time to develop the threshold levels of loss, then more precise weed control decisions can be made.

In order to utilize the most effective and most economical weed control practice, it is most critical that weeds are correctly identified in respective geographic areas. Included in this book is a taxonomic key and color photographs that can be used to identify many of the cotton weed pests in the United States. Weeds that were problems 20 years ago in many instances are not the weed problems that are of concern today. As better herbicides have been developed for specific weeds, new or different weeds have taken their place. It is a continuing battle for weed scientists to solve the new weed problems as they emerge. These changing weed populations may be influenced by many things including the continuous use of a respective herbicide, the continuous cotton monoculture, changing cultural practices, changing geographic areas, etc. Cotton producers know that if crop rotations and rotations of herbicides can be utilized in a farming program, the changing weed population can be minimized thus allowing better management of cotton production. However, as other cultural technologies evolve such

as conservation tillage, again, dramatic changes in weed populations occur. It is a never ending battle to continually understand the growth patterns, the physiology of the weeds and to find mechanisms to control weeds in cotton.

The use of some 60 herbicides and/or herbicide combinations currently provide the main attack on weeds in cotton production. The use of herbicides began primarily in the early 1950s with development of chemicals such as diuron (Karmex® and Diurex®). Today a very high percentage of all cotton is being treated with a preplant incorporated, preemergence, postemergence directed, postemergence spot-sprayed or a postemergence over-the-top herbicide application.

The use of herbicides to adequately control weeds in cotton was not an overnight success when usage began in the 1950s. Practically none of the producers were trained to apply herbicides correctly and most were afraid that "those chemicals" might injure their cotton. This initial reluctance was justified in 1952 and 1953 when thousands of acres of cotton were killed after dinoseb (Premerge®) was applied preemergence. It is almost certain that this unfortunate experience delayed widespread acceptance of herbicides by farmers for several years. Prior to 1960, less than 10 percent of the total cotton acreage received herbicide treatment, but then by the mid-1960s use increased at such an accelerated rate that by 1970 essentially most cotton acreage received some type of herbicide treatment. The impetus behind this rapidly expanded use was more selective and effective herbicides such as trifluralin (Treflan®) and DSMA/MSMA. Also, the mass exodus of farm workers, who had provided the hand labor for hoeing weeds in cotton, continued to move from rural to urban settings. These factors were combined with a new generation of farm managers who were better trained and realized the need to use new weed control technology. Many of these new managers were veterans of World War II who obtained their education on the GI Bill after the war, began farming with their parents, and then took over the family farming operation after a few years of experience. All of these factors combined in the 1960s to provide an unprecedented increased use of herbicides in cotton production.

The trends in use patterns are discussed for specific cotton herbicides over time. The amount of herbicide use in cotton probably will remain constant over the next decade although there are significant new herbicides being developed that could find their niches in today's cotton market. Without the availability of current herbicides, it would not be unusual for hand labor weed control costs to run as high as $300 per acre. Obviously this would be prohibitive in terms of cotton production. The herbicides used in United States cotton production are primarily applied by farmers themselves, although the use of custom application has increased considerably in recent years. In some parts of the West more custom application is done than in areas of the Southeast and Mid-South.

As respective herbicides are used in cotton, a need exists to understand many things about them, including why and how they work or may not work in certain

instances. This permits us to use herbicides more efficiently. This book spends considerable time on respective families of herbicide chemistry used in cotton production. The actual chemistry of each one of these herbicides plays a major role in its performance, persistence and activity in the soil, activity in plants, ability to penetrate or translocate in a plant and ability to control a specific weed species.

Linked with understanding the chemistry of respective herbicide families is the knowledge of their respective mode of action on specific weeds and on the cotton plant. An understanding of the herbicide mode of action is not only needed to aid in control of specific weeds but also to help design better, more specific herbicides for future use. There is no general mode of action of all cotton herbicides; each family of chemicals reacts differently. A herbicide may be targeting the germination process of the seed, or the root growth and development, or they may act by needing sunlight or the process of photosynthesis to be active. New herbicides being developed are even more specific in their mode of action—even down to a specific enzymatic reaction within the plant being sensitive to the herbicide.

Because a great percentage of cotton herbicides are soil applied with mechanical incorporation prior to planting or to the soil surface after planting, it is critical to have an understanding of the influence of soil on performance of respective herbicides. With cotton being planted across a large geographic area in the United States, many different types of soils are involved, from very sandy to clay, from essentially no organic matter ranging up to three percent. The percentage of sand, silt, clay and organic matter plays a critical role in soil applied herbicide performance. These factors influence the ability of the weed to absorb the herbicide from the soil as well as influence the length of time in which the herbicide remains in the soil before it is degradated. These factors also play a major role in determining the use rates of most herbicides.

Coupled with the actual soil properties, an understanding of how water in the soil and air affects herbicide performance is essential. Other things such as the volatility of the chemical, and whether it is subject to sunlight degradation are of vital importance to herbicidal activity. For instance, the dinitroaniline herbicide trifluralin (Treflan®) will not perform in most areas of the United States if it is simply sprayed and left undisturbed on the soil surface. It must be mechanically incorporated because of its high inherent volatility. When trifluralin (Treflan®) is trapped in the soil and protected against sunlight degradation, it becomes a vital herbicide. Without that simple mechanical incorporation, it would never have been a commercial herbicide. Factors such as the pH of the soil may also play a major role in herbicide performance. All of these factors and their interactions with herbicides are discussed in detail.

Another critical consideration in herbicide performance is application technology. A very interesting chapter on application technology is included which describes sprayer calibration, nozzles, pump types, and the mechanisms of

herbicides application from a historical basis through present time and with projections into the future. Today as only ounces per acre of a herbicide are applied, application technology must be very precise. Significant advances have been made in this technology in recent years, but as conscientious farmers and scientists we must do a better job of accurately applying herbicides to the desired target.

As environmental constraints on application of chemicals become stricter, it is imperative that a better job of calibration and application be done. This chapter points out the interesting ingenuity of both farmers and scientists in their quest for ways of applying herbicides. When Roundup® (glyphosate) was developed, it was phytotoxic to cotton and too expensive when applied broadcast on a per acre basis. New ways were devised to apply the herbicide using recycling sprayers, wiper devices and spot sprayers which allowed selectivity and economic application of this herbicide on millions of acres of land. The ingenuity of applying chemicals is a very interesting psychological development in agriculture.

Even though a number of innovative herbicide application techniques have been developed for use in cotton, the technology of herbicide application was developed with little financial or moral support from industry, government, or academia. For example, in 1982, there were only 2.5 scientific years being devoted in agricultural engineering to weed science research in the United States and only a smaller portion of this would have been devoted to cotton. A number of recent conferences on pesticide application have acknowledged the need for greatly expanded research on application technology and have defined several steps that need to be taken to accomplish this, including: (a) defining obstacles that inhibit the development of improved application technology; (b) establishing research priorities that will respond to current problems; (c) developing plans for the establishment and funding of research centers of excellence; and (d) examining mechanisms for fostering interdisciplinary research activities within and between industry, government and academia.

The use of herbicides may cause problems from a crop injury standpoint. One of the chapters discusses in detail the respective injury problems associated from the different families of herbicides that are used in cotton and also describes some of the residual or carryover effects of herbicides from preceding crops as they might affect cotton production. In many cotton production areas, herbicides are used in other crops or pastures that are inherently very phytotoxic to cotton. The physical and/or volatility drift problems onto adjacent cotton fields have caused serious problems in the past. A discussion about these types of injury problems and symptoms is also included. This chapter also points out the need for a greater understanding of how herbicides behave from their chemistry standpoint, from their persistence in the soil and from their physiology and mode of actions. We must be able to insure that a cotton plant will not be injured when we use a chemical for the control of weeds within the crop or on adjacent areas.

Who develops new herbicides and identifies their potential use in cotton?

There are several groups of people that need to be identified as the key players in bringing forth weed control technology that is utilized today. The agricultural chemical industry has seen the need from an economic standpoint to develop and produce herbicides that will fit into the cotton market in the United States and around the world. They play a major role in bearing the cost of development of these chemicals as well as maintaining large research forces in laboratories and in field locations across the United States. Their marketing divisions deliver these products and provide technical assistance to the farmers.

Working with industry are two research groups: the USDA, ARS and state agricultural experiment stations and universities. These organizations conduct many research experiments in specific geographic locations throughout the United States each year. Their understanding of local areas can add valuable expertise as they work with industry to develop the herbicides that are needed for a geographic region. The extension service in each state has had and continues to play a vital role in the development and recommendations of herbicides. Agricultural consultants which bridge the gap between research and extension and the individual growers are emerging as important players in this team effort. Certainly, the farmer is the primary individual in this circle. By taking the herbicide and utilizing the best expertise and technology that other groups have developed, he can improve the profitability of his own farming operation.

Today we have other groups that serve as integral components of the weed control process; regulatory agencies of the Environmental Protection Agency and state regulatory groups. Many challenges in the regulation of herbicides and other agricultural chemicals will face us. But working hand-in-hand with these people and by providing the essential expertise, we can make this process successful. The development of herbicides has certainly been a teamwork effort, however, it is one that is not well understood by many people. Credit must be given to all facets of the industry for doing a magnificent job in the development of excellent herbicides for use in United States cotton production.

In looking to the future of weed control in cotton, we must consider evolving new cultural technology such as conservation tillage or limited tillage. In many parts of the Cotton Belt, research is underway that will provide the knowledge to produce cotton with little or no tillage. In order to make this technology work, effective economical weed control is absolutely essential.

Conservation tillage practices are being encouraged in many areas due to provisions of the 1985 and 1990 Farm Bills such as conservation compliance issues which will demand that farmers produce crops in a conservation tillage manner on erodible soils. As experience is gained in this technology, it is known that the weed populations change dramatically, and previously latent weeds become problems. There are excellent opportunities for the development of new herbicides and cultural technology for conservation tillage.

The future brings much optimism both in conventional and reduced tillage systems of cotton production. The future of weed control technology whether it

is herbicidal, biological, mechanical, or some other mechanism that we don't understand at this time is very exciting. We know that the agricultural industry continues to develop many new experimental compounds that have potential for use in cotton. An example today is a new herbicide that will control cocklebur when applied postemergence over the top of cotton. The possibility of genetic manipulation of a cotton plant to provide resistance to either existing or new herbicides is very exciting. The possibility of biological control mechanisms that are emerging which can perhaps control very specific weed pests without the use of chemicals is also very exciting from an environmental standpoint. Indeed, we are facing increasing levels of regulation from the Environmental Protection Agency and from laws such as the Endangered Species Act. As a group of farmers, scientists and industry personnel, efforts must be coordinated to develop better methods of weed control in the future which will allow us to protect our environment and the individual user, while doing the very best job possible in controlling weeds.

Major advances in weed control technology during the past 40 years have provided many successful weed control options for United States production. It must be recognized that continued weed control research in high priority areas is essential. Through several surveys the following priority weed research areas have been identified:

1. Develop better herbicides and biological weed control mechanisms for current and evolving cotton production systems.
2. Identify, understand and develop naturally occurring allelopathic compounds.
3. Develop new and improved herbicide application technology.
4. Understand and manage environmental aspects such as surface and groundwater contaminants.
5. Develop weed/cotton competition and interference data.
6. Develop cotton herbicide resistance through genetics, biotechnology and chemical antidotes.
7. Develop models which describe weed growth and development and herbicide mobility and persistence.
8. Develop technology to regulate weed seed germination.
9. Develop formulation technology to control mobility of herbicides in soils.

As editors of this book, Weeds of Cotton, we hope that you find the remaining chapters extremely helpful in providing technology at whatever your level of use. The authors have done an outstanding job of presenting existing technology from a historical perspective through the future that could be used in the cotton industry in the United States.

Chapter 2

TRENDS IN COTTON PRODUCTION: HISTORY, CULTURE, MECHANIZATION AND ECONOMICS

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INTRODUCTION

Cotton has played an important role in the United States economy for almost 200 years. From the beginning, cotton has been a major cash crop and a significant source of foreign exchange. The invention of the cotton gin encouraged expansion of production and exports of lint to textile mills in England. The development of cotton textile manufacturing in the United States ushered in the industrial revolution and dominated the New England economic scene for many years.

Production regions gradually shifted from east to west, and manufacturing moved from the northeast to the southeast. Cotton, however, remains an economic mainstay crop across the Cotton Belt, where it is produced on farms from Virginia to California. The cotton marketing system moves a large part of the crop long distances to the domestic mills and to ports for export.

The lint is processed into yarns, woven goods and other textile products which are shipped from mills either to manufacturers of cotton apparel and household articles located largely in the industrial northeastern and mid-atlantic states or to foreign manufacturers. Finished cotton items are packaged, stored, and shipped through wholesalers to retail outlets in all cities in the United States and to some foreign outlets. Investments in real estate; processing, marketing and transpor-

tation facilities; textile and apparel manufacturing plants; and wholesaling and retailing establishments total billions of dollars.

The industry remains dynamic as continued improvements in technology impacts production units, the market infrastructure, textile equipment, and the market-related services. This makes the cotton industry ever-changing in character.

ORIGIN OF COTTON

Cotton is used in reference to the species of *Gossypium* that produce spinnable fibers (lint) on the seedcoat. The genus *Gossypium* is relatively large, with 39 reported species, and is very diverse (Fryxell, 1984). Today, only four species of *Gossypium* are used in commercial cotton production; two (*Gossypium arboreum* and *Gossypium herbaceium*) are diploids (n = 13) of Middle East or Old World origin and two (*Gossypium barbadense* and *Gossypium hirsutum*) are tetraploids (n = 26) that evolved in the New World.

When and where cotton was first used by man as a raw material for textiles is unknown. Archaeological and historical evidence clearly show that the use of cotton predates recorded history by several centuries (Lewis and Richmond, 1968). Cotton fabrics dating to 3000 B.C. have been found in excavations at Mohenjo-daro in the Indu River Valley in northwestern India (Gulati and Turner, 1928). In the New World, cotton specimens dating to 2500 B.C. were found in the Ancon-Chillon district of Peru (Stephens and Moseley, 1974).

In the Americas, it appears that *Gossypium barbadense* evolved as a wild species in South America and was in fact domesticated in Peru (Lee, 1984). *Gossypium hirsutum* occurs in the wild in Central America, northern South America and in the West Indies. No form of *Gossypium hirsutum* has a history of growing wild as a perennial plant in what is today the continental United States.

Available evidence suggests that Old World cottons were domesticated and cultivated to serve the needs of the ancients in well established, sophisticated agricultural societies that already had the technology for spinning and weaving other fibers (Hutchinson *et al.*, 1947; Lee, 1984). In the Americas, cotton cultivation more than likely evolved from the "dump heap" type agriculture described by Anderson (1954). In such a system, seed and fiber were collected from wild plants by the indigenous people and carried to their dwellings. Later, the discarded seeds provided a convenient source of cotton, and the proximity encouraged cultivation and perhaps selection for plants that produced more lint on the seed, larger bolls, etc. (Lee, 1984).

Botanically, cotton is a perennial of tropical and semi-tropical origins. Through natural crossing and by selection, agronomically acceptable types have evolved which can be grown as day-neutral annuals in temperate zones. In the United States, some cotton is grown close to latitude 37° N; in the Soviet Union, most of the cotton is grown between latitudes 37° N and 42° N; and in northeast China,

some cotton is grown north of latitude 40° N. Although cotton is grown commercially in areas with as few as 180 frost-free days (Niles and Feaster, 1984), the major production regions typically have about 200 days between killing frosts and a minimum average summer temperature of 77F (25C) (Starbird *et al.*, 1987). The crop requires more than 160 days when minimum temperatures are above 60F (15C) (Waddle, 1984).

The wild species of *Gossypium* occur in relatively arid parts of the tropics and subtropics (Fryxell, 1979; Fryxell, 1986). For commercial production, however, an acceptable cotton crop requires at least 20 inches (50 cm) of water during the growing season (Waddle, 1984). In the United States, cotton is usually irrigated when annual rainfall is less than 16 inches (40 cm). Supplementary irrigation is frequently used in the 16- to 35-inch (40 to 88 cm) rainfall zone, whereas most of the cotton produced in higher rainfall areas is typically not irrigated. Cotton is adapted for production on a wide range of soil types as long as inherent or supplemental fertility is adequate to sustain desired yield levels and the soil's physical condition allows adequate drainage and root penetration.

COTTON IN THE NEW WORLD

In 1492, when Columbus landed in the New World, he found fabrics that were woven from cotton produced by the native population. The Europeans that followed Columbus found not only cotton culture but also highly skilled spinning and weaving capabilities among the native population in the West Indies, Mexico and Peru (Brooks, 1911). The people were using cotton bedding, clothes, armor, awnings, carpets and tapestries. Cotton was an important item of trade in the Aztec, Maya and Inca civilizations and great quantities were seen in the market places by explorers from Spain (Lewis and Richmond, 1968).

Cotton culture and the use of cotton textiles apparently extended north of the Mexican border into New Mexico, Southern Colorado and Utah in prehistoric times (Kent, 1957). During the Spanish colonial period, however, cotton was found growing only as far north as the modern town of Espanola in the West Indies, the Hopi Indian Country in the Gila River Valley in Arizona, and along the San Pedro and Santa Cruz Rivers in South America. No native cottons were found in the southeastern and mid-south sections of the United States (Lewis and Richmond, 1968), and there is no evidence of the presence of cotton in these areas until after 1600.

COTTON CULTURE AND PRODUCTION IN THE UNITED STATES

COLONIAL PERIOD

> "Plant your cotton when the leaf upon the oak is as big as a Squirrel's ear." (Lyman, 1866)

The first attempts by English colonists to produce cotton in the United States were made in the early 1600s at Jamestown. Settlers were provided seed to determine if the crop could be grown in the newly established colony. Some years before Jamestown was settled, England had acquired the technology to weave cotton-wool blends (Brooks, 1911) and needed a steady supply of cotton at a controllable price to support its textile manufacturing industry.

The first cottons used by the colonists were types of *Gossypium hirsutum*, probably from the Levant region (Brown and Ware, 1958; Niles and Fester, 1984). Quite possibly, these importations were returned New World stocks that had been carried to the Old World by early explorers. Eventually, settlers, traders, travelers and governmental officials brought cottonseed to the United States from Italy , the West Indies, the Caribbean, Egypt, Siam, India and other tropical and semi-tropical climates. Cultivars that were photoperiodic were quickly eliminated because they produced no seed. The stocks that proved to be best adapted to the upland sites were subsequently called upland cottons and were cultivars of *Gossypium hirsutum* (Brown and Ware, 1958). A few Asiatic cultivars were introduced and temporarily established but did not compete in production and quality with the *Gossypium hirsutum* and were soon discarded. Thus, in this early period, stringent selection pressures were applied for plants with a day-neutral habit which facilitated the establishment of near-annual forms that exhibited desired yield and fiber characteristics.

Brooks (1911) describes the cottons that survived in the South Atlantic states as "...a different species...unlike the cotton of the tropics...(with) lint not so fine as that of India...a smaller plant...that requires replanting every year.... But the most difficult thing about this hybrid plant is in the separation of the seed from the lint.... it (lint) adheres so closely to the seed that it cannot be shaken off, whipped off or rolled off, and it is with much difficulty that it can be picked off."

Domestic manufacturing of cotton goods was discouraged and even forbidden to the colonists. Nevertheless, settlers coming from England brought with them knowledge of spinning and weaving, and soon small "cotton patches" were established to supply cotton for domestic needs such as clothing, bedding and home furnishings. Cotton was cultivated, mainly in garden plots, with some success as far north as Delaware, New Jersey, Pennsylvania and Maryland. The more serious efforts to produce cotton occurred in Virginia, the Carolinas and Georgia, but even here plantings rarely exceeded one-to-five acres. Cotton pro-

duction in Colonial America was not profitable except for home use. Tobacco, indigo and rice developed into the primary cash crops for the early English settlers, and receipts from these crops were used in part to purchase textile products from abroad that could not be manufactured in the colonies.

THE 1775-1792 PERIOD

The lackadaisical attitude of the English colonists to cotton production and manufacturing of textile goods was brought to an abrupt halt when the availability of textiles was curtailed by the Revolutionary War. By the standards of those days, cotton acreage was rapidly expanded to meet domestic fiber needs. However, the production of cloth was severely restricted by the lack of efficient systems to separate the lint from the seed and to process the fiber into cloth.

The immediate effects of the British textile embargo were to stimulate home manufacture of textiles. Large quantities of homespun cloth were produced on home-spinning frames and looms, and a "factory" was built in Philadelphia for cording and spinning cotton. Societies were formed to check on importation of clothes from abroad and to encourage manufacture and use of American goods (Brooks, 1911), much like the modern day "Grown and Made in the USA" movement.

A series of inventions—beginning with the development of the fly shuttle by John Kay in 1738—propelled British textile manufacturing from a fragmented, home-based, labor intensive industry to a concentrated, highly mechanized factory system (Anderson, 1976; Baines, 1845; Lee, 1984; Dodge, 1984). The fly shuttle was followed by James Hargreaves "spinning jenny" in the 1760s. Also during this period, Richard Arkwright directed the development of a successful spinning frame that employed roller drafting and the flyer bobbin principle and which was adapted to water power. In the mid-1770s, Samuel Crampton developed the "spinning mule" which combined the spinning jenny and the spinning frame and, in time, replaced both machines (Catling, 1970).

The perfection of the steam engine by James Watt in 1790 provided a power source for the mechanization of the spinning mules and spinning frames. Around 1792, steam was used to power the loom developed by Edmund Cartwright. The first mills appeared in England in the 1740s. By the 1780s England had 120 mills and several more had been built in other countries. As the 19th century began, powered mules and spinning frames as well as powered, all-metal looms were the standard tools of the rapidly expanding textile industry in England.

Once the War of Independence had been won, the newly formed United States strove for unification under the Constitution and for self-sufficiency in both agriculture and manufacturing. Political matters such as states rights, slavery and protective tariffs had not as yet become regionalized issues. The demand for cotton and cotton textiles triggered by the Industrial Revolution seemed boundless. England's burgeoning textile industry required substantially more raw cot-

ton than could be provided by the production regions of India, the Mediterranean areas, the West Indies and the countries of South America.

American planters in the southern states desperately needed a cash crop and were eager to supply the English cotton market. Production expanded from the coastal areas into the interior regions of the Carolinas and Georgia. Following the French and Indian Wars in early 1760s, the Pennsylvania Dutch, Tidewater people and European immigrants moved into up-country regions. Cotton culture expanded with the spread of the population (Niles and Feaster, 1984).

As noted previously, the upland types of *Gossypium hirsutum* became the predominant cotton grown in the colonies. Two principal types, described as naked black seeded and fuzzy green seeded, gained initial acceptance but the latter became dominant by the late 1700s. Demand for cotton stimulated a search for better adapted, more productive cottons. New sources of seed were frequently tested, and many planters experimented with intra-cultivar selections. A Danish West Indies planter named Von Rohr was commissioned by his government during the 1780s to collect and study cottons obtained from the known production regions of the world. He established the first extensive collection of living material of *Gossypium* in St. Croix and attempted to characterize these plants according to characteristics having agricultural importance (Fryxell, 1979). Rohr also was among the first to begin technical cotton breeding in the New World. In his writings, Rohr reportedly discusses methods he used in selection and hybridization of cotton (Brown, 1927; Watt, 1907). In all likelihood, seed from some of his specimens were eventually carried to the United States.

About 1785, Sea Island cotton, *Gossypium barbadense*, was introduced and soon gained limited acceptance along the coastal areas and islands off the coasts of the Carolinas and Georgia. The Sea Island or "lowland" type had two distinct advantages over the upland types: (a) it produced a superior quality fiber, and (b) the lint could be separated from the seed with roller gins. Its disadvantages were that it failed to mature in inland locations, and its yield potential was well below that of the upland cottons.

The Industrial Revolution was also making its presence felt in America. Whereas an agricultural economy prevailed in the South, the North was developing numerous industrial and trade enterprises. Like the rest of the world, America hungered for the technology to develop its own textile industry. England had the necessary technology but forbade its export. In order to preserve exports of cotton textiles and hopefully keep the United States an agricultural economy, English manufacturers made every effort to keep cotton-mill machinery out of the United States. Although the Revolution had stimulated American household manufacturing of textiles, soon afterwards, British goods were again imported in large quantities (Cohn, 1956).

To establish a mercantile industry, various incentives were offered by American entrepreneurs to inventors and other enterprising individuals to develop the high capacity spinning and weaving equipment needed for a factory system

(Brooks, 1911). In 1789, Samuel Slater, an English cotton-mill mechanic, immigrated to America. With financial backing from two American businessmen, Slater reproduced from memory some of England's most efficient mill machines. Then, he supervised the construction and operation of America's first cotton mills, including the Old Slater Mill which was built in 1793 and still stands in Pawtucket, Rhode Island.

The southernmost states had the soil resources, climate and labor force to grow cotton on millions of idle acres. The agrarian South desperately needed a cash crop and an apparently insatiable market existed for raw cotton abroad. Also, the prospects for a domestic textile industry, centered around the evolving factory system, further stimulated demand for cotton.

Yet, before southern planters could take advantage of these ready markets, the problem of separating the lint from the seed of the green-seeded cottons had to be solved.

1793—THE COTTON GIN

> "After their day's work the good man and his wife and children sitting around the open fireplace...would bring the basket out from under the bed and pick seed until bedtime. Usually a shoe full of lint was a good night's work for any one person. So tedious was the process that it took one man a whole day to pick one pound of lint. ...it would take such a man nearly two years to pick enough lint to make a bale of cotton" (Brooks, 1911).

Before cotton fibers can be used in textile manufacturing, they must be removed from the seed either by hand or by machine. The first recorded machine designed to separate the lint from the seed was a crude version of the modern roller gin. The "churka" gin was first used in India many centuries ago. This type of gin only works with long staple, smooth seeded cottons such as Sea Island, Egyptian or Pima. The output of these manually operated machines was about five pounds of lint per day. According to Brown (1927), attempts were made by Krebs of Mississippi in 1772, Burden of South Carolina in 1777 and Eve of Georgia in 1790 to improve the roller gin and perhaps to even enable it to gin green-seeded cotton; none proved successful.

In 1793, Eli Whitney, a native of Westboro, Massachusetts and newly graduated from Yale, accepted a teaching position in South Carolina. A mis-communication regarding the availability of the position he sought and a chance encounter with the widow of General Nathanial Green introduced young Whitney to plantation life in Georgia, cotton production, the economic plight of the southern farmer and the need for a machine capable of processing upland cotton. Whitney received a patent on a machine to gin cotton on March 14, 1794 (Tompkins, 1901).

Whitney's gin used metal spikes driven into a wooden cylinder in concentric

rows to remove cotton fiber from the seed. It was a batch-type process. To operate the gin, a few handfuls of seedcotton were placed in the gin and the cylinder was turned by hand until the fibers were removed from the seed and brushed into a pile behind the machine. The gin was then stopped, the seeds were removed, and the process repeated. Whitney's invention, and the many copies that followed, proceeded almost directly from conception to execution. Within a year, gins were being manufactured and stationed in key production areas.

Henry Ogden Holmes, a plantation blacksmith from South Carolina, invented and received a patent on May 12, 1796, for an improved gin very similar in principle to modern gins. The Holmes gin used metal saws positioned on a shaft rather than spikes in a wooden cylinder. His machine allowed the cleaned seeds to fall out the bottom, making ginning a continuous, rather than a batch process. Whitney soon recognized the value of Holmes' improvements and incorporated the saw teeth in his machines (Bennett, 1961).

THE 1794-1860 PERIOD

> "... and the trespass of a little worm upon it's (cotton's) green leaf is more to England than the advance of the Russian army on her Asian outposts...." Henry W. Grady (Brooks, 1911)

The development of the cotton gin resulted in an immediate, dramatic increase in cotton production in the United States as shown in Table 1 and in the production summary for the cotton producing states provided in Table 2.

In the 40 years following the invention of the cotton gin, production more than doubled during each succeeding decade (Table 2). Also, in 1791, there were five southern states and only two produced enough cotton to warrant mention in production reports of the day. By 1822, Missouri, Louisiana, Mississippi and Alabama joined the Union and quickly became major cotton producing states. The annexation of Arkansas in 1836, and Texas and Florida in 1845 led to additional acreage expansion, and, by the outbreak of the Civil War, the "cottonbelt" states were producing about four million bales annually—more than half the world supply of cotton (Brown, 1927).

During this period, exports and domestic consumption were keeping pace with production increases. In 1790, only 279 bales were exported; in 1800, 31,822; in 1820, 249,787; in 1840, 1,060,408 and in 1859, 3,535,373 bales, Table 1 (Brown, 1927). The great majority of this cotton was being shipped to England, although France and other European nations imported substantial quantities as well. The value of cotton exports reached $191.8 million in 1860 (Cohn, 1956).

In the United States, the first cotton mill was built in Beverly, Massachusetts in 1787. Thereafter, the number of mills constructed, mainly in the New England states, increased steadily. The War of 1812 gave added impetus to domestic manufacturing—and textile mill construction—because United States citizens were again unable to import needed goods from Great Britain.

Table 1. U.S. Cotton: acreage, yield, production, imports, domestic use, exports, carryover and price, 1790-1989.

Year	Planted acres	Harvested acres	Yield per acre	Supply			Total supply	Demand		Total use	Ending carryover	Season average price
				Beginning carryover	Production	Imports		Mill consumption	Exports			
	(1000 acres)		(lb/acre)					(1000 bales)				
1790					3	1		11		11		26.00
1791					4	1				0		29.00
1792					6	6			1	1		32.00
1793					10	5			4	4		33.00
1794					11	9			9	9		36.50
1795					17	9			12	12		36.50
1796					21	7			8	8		34.00
1797					23	8			19	19		39.00
1798					31	8			19	19		44.00
1799					42	9		17	36	53		28.00
1800					73	9		19	32	51		44.00
1801					100				48	48		19.00
1802					115	1			75	75		19.00
1803					126				70	70		20.00
1804					136			23	77	100		23.00
1805					146	1			71	71		22.00
1806					167	1			128	128		21.50
1807					167	6			21	21		19.00
1808					157	2			102	102		16.00
1809					172	1		33	187	220		16.00
1810					178			36	124	160		15.50
1811					167	1			58	58		10.60
1812					157	3			38	38		12.50
1813					157				35	35		15.50
1814					146			52	166	218		21.00
1815					209	2			164	164		29.00
1816					259	3			171	171		27.10
1817					272	4			185	185		31.00
1818					262	5			176	176		24.70
1819					349				256	256		16.50
1820					335			100	250	350		14.90
1821					377				289	289		14.70
1822					439				347	347		11.20
1823					387	1			287	287		14.70
1824					450				353	353		17.90
1825					533				409	409		13.40
1826					732			104	589	693		10.20
1827					565	1		85	421	506		10.30
1828					680			85	530	615		9.90
1829					764			90	597	687		9.70
1830					732			130	554	684		10.10
1831					805			131	644	775		9.10
1832					816			142	649	791		11.40
1833					931			149	769	918		13.10
1834					962	2		167	775	942		16.30
1835					1,062			185	847	1,032		16.70
1836					1,129	1		176	888	1,064		14.40
1837					1,428			195	1,192	1,387		10.00
1838					1,093			222	827	1,049		13.20
1839					1,654			237	1,488	1,725		9.40
1840					1,348	1		245	1,060	1,305		9.60
1841					1,398			222	1,169	1,391		8.10
1842					2,035	2		278	1,585	1,863		7.20
1843					1,750	1		299	1,327	1,626		7.80
1844					2,079	1		338	1,746	2,084		5.90
1845					1,806			363	1,095	1,458		7.80

Table 1. Continued

Year	Planted acres	Harvested acres	Yield per acre	Supply			Total supply	Demand		Total use	Ending carryover	Season average price
				Beginning carryover	Production	Imports		Mill consumption	Exports			
	(1000 acres)		(lb/acre)					(1000 bales)				
1846					1,604			386	1,054	1,440		10.90
1847					2,128	1		537	1,629	2,166		8.50
1848					2,615			586	2,053	2,639		7.20
1849					1,975			576	1,271	1,847		12.00
1850					2,136			423	1,854	2,277		12.60
1851					2,799	1		617	2,186	2,803		9.30
1852					3,130	1		736	2,223	2,959		11.00
1853					2,766	1		663	1,976	2,639		11.00
1854					2,708	4		642	2,017	2,659		10.30
1855					3,221	2		731	2,703	3,434		10.30
1856					2,874	2		762	2,097	2,859		13.20
1857					3,012			551	2,237	2,788		12.50
1858					3,758			867	2,773	3,640		12.10
1859					4,310			845	3,535	4,380		11.30
1860					3,841			842	615	1,457		12.30
1861					4,491	62		369	10	379		28.20
1862					1,597	68		287	23	310		65.20
1863					449	52		220	24	244		91.20
1864					299	69		344	18	362		95.40
1865					2,094	10		615	1,301	1,916		44.30
1866		7,666	122		2,097	1		715	1,323	2,038		32.20
1867		7,864	143		2,520	0		844	1,511	2,355		24.50
1868		6,973	151		2,366	2		860	1,288	2,148		28.60
1869		7,751	155		3,011	3		797	1,980	2,777		25.30
1870		9,238	208		4,352	2		1,027	2,894	3,921		17.00
1871		8,285	159		2,974	6		1,147	1,851	2,998		21.90
1872		9,580	182		3,933	10		1,116	2,437	3,553		20.20
1873		10,998	168		4,168	4		1,213	2,706	3,919		17.30
1874		10,753	157		3,836	4		1,098	2,523	3,621		15.70
1875		11,348	181		4,631	4		1,256	3,003	4,259		13.10
1876		11,747	168		4,474	5		1,314	2,869	4,183		9.71
1877		12,606	170		4,773	5		1,459	3,198	4,657		8.53
1878		13,539	168		5,074	5		1,457	3,265	4,722		8.16
1879		14,474	181		5,756	8		1,501	3,711	5,212		10.28
1880		15,921	191		6,606	5		1,866	4,409	6,275		9.83
1881		16,483	149		5,456	3		1,849	3,430	5,279		10.66
1882		15,638	209		6,949	5		2,038	4,582	6,620		9.12
1883		16,295	162		5,713	11		1,814	3,745	5,559		9.13
1884		16,849	155		5,682	7		1,687	3,740	5,427		9.19
1885		17,922	170		6,576	8		2,095	4,193	6,288		8.39
1886		18,370	164		6,505	8		2,050	4,274	6,324		8.06
1887		18,793	175		7,047	12		2,205	4,557	6,762		8.55
1888		19,520	170		6,938	15		2,309	4,720	7,029		8.50
1889		20,191	177		7,473	18		2,518	4,934	7,452		8.55
1890		20,937	196		8,653	46		2,604	5,859	8,463		8.59
1891		21,503	199		9,035	64		2,847	5,888	8,735		7.24
1892		18,869	169		6,700	86		2,416	4,456	6,872		8.34
1893		20,256	175		7,493	59		2,300	5,309	7,609		7.00
1894		21,886	219		9,901	99		2,984	7,010	9,994		4.59
1895		19,839	172		7,162	112		2,500	4,710	7,210		7.62
1896		23,230	175		8,533	115		2,841	6,172	9,013		6.66
1897		25,131	209		10,899	106		3,472	7,757	11,229		6.68
1898		24,715	223		11,278	106		3,672	7,662	11,334		5.73
1899		24,163	185		9,346	140		3,687	6,228	9,915		6.98
1900		24,886	195		10,124	109		3,604	6,800	10,404		9.15
1901		27,050	168		9,508	202		4,080	6,949	11,029		7.03
1902		27,561	185		10,630	151		4,187	7,084	11,271		7.60

Table 1. Continued

Year	Planted acres	Harvested acres	Yield per acre	Supply: Beginning carryover	Supply: Production	Supply: Imports	Total supply	Demand: Mill consumption	Demand: Exports	Total use	Ending carryover	Season average price
	(1000 acres)		(lb/acre)					(1000 bales)				
1903		27,762	170		9,851	103		3,981	6,207	10,188		10.49
1904		30,077	214		13,438	129		4,523	8,908	13,431		8.98
1905		27,753	182		10,576	144		4,877	7,118	11,995		10.78
1906		31,404	202	1,935	13,274	227		4,974	8,943	13,917	1,349	9.58
1907		30,729	173	1,349	11,106	153		4,493	7,666	12,159	1,515	10.36
1908		31,091	204	1,515	13,241	181		5,092	8,955	14,047	1,236	9.01
1909	31,744	30,555	157	1,236	10,005	170		4,622	6,353	10,975	1,484	13,60
1910	32,480	31,508	176	1,484	11,609	245		4,498	8,027	12,525	1,040	13.95
1911	35,634	34,916	215	1,040	15,694	233		5,129	11,116	16,245	1,375	9,60
1912	33,199	32,557	201	1,375	13,703	249		5,483	9,146	14,629	1,777	11.49
1913	35,721	35,206	192	1,777	14,153	273		5,626	9,508	15,134	1,648	12.51
1914	36,197	35,615	216	1,511	16,112	261	15,775	5,597	8,702	14,299	1,366	7.36
1915	30,544	29,951	179	1,366	11,172	382	17,654	6,398	6,113	12,511	3,936	11.22
1916	33,977	33,071	166	3,936	11,448	438	15,442	6,789	5,525	11,923	3,140	17.33
1917	33,064	32,245	167	3,140	11,284	292	14,796	6,566	4,402	11,191	2,720	27.12
1918	36,123	35,038	164	2,720	12,018	221	14,189	5,766	5,774	12,340	3,450	28.92
1919	34,573	32,906	166	3,450	11,411	202	15,558	6,420	6,707	12,473	4,287	35.41
1920	35,872	34,408	187	4,287	13,429	700	16,313	4,893	5,973	12,393	3,563	15.92
1921	29,716	28,678	133	3,563	7,945	226	17,060	5,910	6,348	11,241	6,534	17.01
1922	32,176	31,361	149	6,534	9,755	363	14,875	6,666	5,007	10,917	2,832	22.87
1923	37,000	35,550	136	2,832	10,140	470	13,031	5,681	5,815	12,481	2,325	28.69
1924	40,690	39,501	165	2,325	13,630	292	12,788	6,193	8,240	13,921	1,556	22.91
1925	45,968	44,386	174	1,556	16,105	313	15,508	6,456	8,267	14,460	1,610	19.59
1926	45,839	44,608	193	1,610	17,798	326	18,059	7,190	11,299	17,775	3,543	12.47
1927	39,471	38,342	162	3,543	12,956	401	12,699	6,834	7,857	15,047	3,762	20.19
1928	43,737	42,434	163	3,762	14,477	338	16,883	7,091	8,419	15,253	2,536	17.99
1929	44,448	43,232	164	2,536	14,825	458	17,291	6,106	7,035	14,126	2,312	16.79
1930	43,329	42,444	157	2,312	13,932	378	17,238	5,263	7,133	13,239	4,530	9.46
1931	39,110	38,704	212	4,530	17,097	108	18,394	4,866	9,193	14,456	6,370	5.66
1932	36,494	35,891	174	6,370	13,003	132	23,131	6,137	8,895	13,761	9,678	6.52
1933	40,248	29,383	213	9,678	13,047	130	22,518	5,700	7,964	14,101	8,165	10.17
1934	27,860	26,866	172	8,165	9,636	148	20,977	5,361	5,037	10,737	7,744	12.36
1935	27,888	27,335	186	7,744	10,638	107	17,323	6,351	6,627	11,628	7,208	11.09
1936	30,932	30,054	198	7,208	12,407	155	17,783	7,950	5,689	12,040	5,409	12.30
1937	34,090	33,623	270	4,499	18,946	159	22,924	5,748	5,976	11,724	11,533	8.70
1938	25,018	24,248	236	11,533	11,943	150	23,268	6,858	3,512	10,370	13,033	8.70
1939	24,683	23,805	238	13,033	11,817	168	24,568	7,784	6,501	14,285	10,564	9.90
1940	24,871	23,861	253	10,564	12,566	193	23,020	9,722	1,174	10,896	12,203	10.80
1941	23,130	22,236	232	22,167	10,744	274	22,959	11,170	1,162	12,332	10,640	17.90
1942	23,302	22,602	272	22,585	12,817	178	23,305	11,100	1,498	12,598	10,657	19.20
1943	21,900	21,610	254	23,570	11,427	135	21,856	9,943	1,146	11,089	10,744	19.60
1944	19,990	19,617	299	25,404	12,230	193	22,858	9,568	1,909	11,477	11,164	20.60
1945	17,588	17,029	253	26,598	9,015	349	20,359	9,163	3,678	12,841	7,326	24.40
1946	18,251	17,584	235	23,041	8,640	284	16,170	10,025	3,656	13,681	2,530	33.30
1947	21,611	21,330	266	17,097	11,860	244	14,416	9,354	2,025	11,379	3,080	32.40
1948	23,264	22,911	311	14,500	14,877	173	17,892	7,795	4,961	12,756	5,287	30.00
1949	27,719	27,439	284	14,600	16,128	254	21,453	8,851	6,004	14,855	6,846	30.30
1950	18,866	17,843	269	6,846	10,014	189	16,914	10,509	4,280	14,789	2,278	41.40
1951	29,353	26,949	269	2,278	15,149	79	17,419	9,196	5,711	14,907	2,789	38.40
1952	28,065	25,921	280	2,789	15,139	195	18,149	9,461	3,181	12,642	5,605	32.50
1953	26,872	24,341	324	5,605	16,438	145	22,149	8,576	3,914	12,490	9,728	32.00
1954	20,052	19,251	341	9,728	13,673	150	23,465	8,841	3,585	12,426	11,205	32.00
1955	17,991	16,928	417	11,205	14,698	137	26,022	9,210	2,320	11,530	14,529	32.10
1956	17,077	15,615	409	14,529	13,290	137	27,986	8,608	7,917	16,525	11,323	30.00
1957	14,310	13,558	388	11,323	10,948	141	22,572	7,999	5,959	13,958	8,737	30.50
1958	12,379	11,849	466	8,737	11,495	137	20,409	8,703	2,895	11,598	8,885	30.80
1959	15,833	15,117	461	8,885	14,527	136	23,628	9,017	7,391	16,408	7,560	28.60

Table 1. Continued

Year	Planted acres	Harvested acres	Yield per acre	Supply: Beginning carryover	Supply: Production	Supply: Imports	Total supply	Demand: Mill consumption	Demand: Exports	Total use	Ending carryover	Season average price
	(1000 acres)		(lb/acre)					(1000 bales)				
1960	16,080	15,309	446	7,501	14,237	129	21,557	8,353	6,857	15,210	7,056	31.50
1961	16,588	15,634	438	7,056	14,283	153	21,206	9,017	5,056	14,073	7,699	34.30
1962	16,293	15,569	457	7,699	14,827	137	22,374	8,484	3,429	11,913	11,136	33.20
1963	14,843	14,212	517	1,136	15,294	135	26,114	8,696	5,775	14,471	12,351	33.60
1964	14,835	14,057	517	2,351	15,145	118	27,151	9,261	4,195	13,456	14,249	31.00
1965	14,152	13,615	527	4,249	14,938	118	28,873	9,596	3,035	12,631	17,028	29.30
1966	10,349	9,552	480	7,028	9,557	105	26,246	9,574	4,832	14,406	12,344	21.70
1967	9,448	7,997	447	2,344	7,443	149	19,513	9,077	4,361	13,438	6,584	26.70
1968	10,912	10,160	516	6,584	10,926	168	17,263	8,332	2,825	11,157	6,544	23.10
1969	11,882	11,055	434	6,544	9,990	52	16,320	8,114	2,878	10,992	5,843	22.00
1970	11,945	11,155	438	5,843	10,192	37	15,873	8,204	3,897	12,101	4,203	22.90
1971	12,355	11,471	438	4,203	10,477	72	14,555	8,259	3,385	11,644	3,258	28.20
1972	14,001	12,984	507	3,258	13,704	34	16,183	7,769	5,305	13,074	4,221	27.30
1973	12,480	11,970	520	4,221	12,974	48	17,176	7,472	6,123	13,595	3,808	44.60
1974	13,679	12,547	441	3,808	11,540	34	15,227	5,860	3,926	9,786	5,708	42.90
1975	9,478	8,796	453	5,708	8,302	92	13,932	7,250	3,311	10,561	3,681	51.30
1976	11,636	10,914	465	3,681	10,581	38	14,151	6,674	4,784	11,458	2,928	64.10
1977	13,680	13,275	520	2,928	14,389	5	17,157	6,483	5,484	11,967	5,347	52.30
1978	13,375	12,400	420	5,347	10,856	4	16,042	6,352	6,180	12,532	3,958	58.40
1979	13,978	12,831	547	3,958	14,629	5	18,438	6,506	9,229	15,735	3,000	62.50
1980	14,543	13,215	404	3,000	11,122	27	14,149	5,891	5,926	11,817	2,668	74.70
1981	14,330	13,841	542	2,668	15,646	26	18,340	5,264	6,567	11,831	6,632	54.30
1982	11,345	9,734	590	6,632	11,963	20	18,615	5,512	5,207	10,719	7,937	59.40
1983	7,926	7,348	508	7,937	7,771	12	15,721	5,928	6,786	12,714	2,775	66.40
1984	11,145	10,379	600	2,775	12,982	24	15,781	5,540	6,215	11,755	4,102	57.80
1985	10,685	10,229	630	4,102	13,432	33	17,567	6,399	1,960	8,359	9,348	56.30
1986	10,045	8,468	552	9,348	9,731	3	19,082	7,452	6,684	14,136	5,026	52.40
1987	10,379	10,030	706	5,026	14,760	2	19,788	7,617	6,582	14,199	5,771	64.30
1988	12,515	11,948	619	5,771	15,411	5	21,187	7,782	6,148	13,930	7,092	56.60
1989	10,587	9,538	614	7,092	12,196	1	19,289	8,750	7,800	16,550	2,990	65.60

SOURCES: Various issues of agricultural statistics, Cotton and Wool Situation and Outlook, and Statistics on Cotton and Related Data, USDA.

Improvements in mill technology were being made in the United States. In 1828, John Thorp patented the basic elements of ring spinning (Lee, 1984). By 1840, there were approximately 850 mills in the United States that processed over 225,000 bales annually; in 1860, 1090 mills used some 840,000 bales of United States grown cotton (Brown, 1927). Cotton had become the primary cash crop of the South. Cotton textile manufacturing had become an important industry for the North and cotton lint a major agricultural export commodity for the United States.

Rapid expansion of cotton production in the southern states is attributable to four major factors: (a) environmental conditions suited for growth of the crop, (b) availability of a large, relatively unskilled labor force, (c) accessibility to large acreages of idle land suitable for cotton production, and (d) most importantly, strong markets for cotton. Extensive sections of Virginia, North Carolina, South Carolina, Georgia, Florida, Mississippi, Alabama, Louisiana, Texas, Arkansas, Tennessee and Missouri were suited for cotton production. In the pre-Civil War

Table 2. United States Cotton production by state during the 1791 to 1834 period (Brooks, 1911; Goulding and Dustan, 1919).

State	Year				
	1791	1801	1811	1821	1834
	lbs lint produced (x 10^6)				
South Carolina	1.5	20	40	50	65.5
Georgia	.5	10	20	45	75
Virginia		5	8	12	10
North Carolina		4	7	10	9.5
Tennessee		1	3	20	45
Louisiana			2	10	62
Mississippi				10	85
Alabama				20	85
TOTAL	2	40	80	177	437

period, cotton acreage expanded as far north as latitude 37° N and as far west as the 30- to 35-inch (80 to 90 cm) annual rainfall belt in Texas. Initially, cotton was grown mostly in the alluvial valleys and bottom lands adjacent to natural waterways; as the demand for land increased, production was expanded into the vast, unused, acreages of "hilly lands" and prairies.

Through the ages, cotton culture has been a labor intensive enterprise. The rapid advancement of cotton across the South was a prodigous, remarkable achievement because of the immense amount of hand labor that was required. Land had to be cleared with muscle, fire and axe. First, thousands and later millions of acres had to be hand-planted, hand-weeded, hand-thinned and hand-harvested. Much of this great expansion was accomplished with black slave labor.

Slaves were introduced into colonial America during the 1600s and used mainly in agricultural endeavors because of language barriers and a lack of technical skills needed in industrial work. In the late 1700s, slavery fell into disrepute, and all states agreed to legally abolish the practice by 1808. However, the tremendous increase in cotton acreage following the invention of the gin produced a simultaneous demand for a large number of unskilled laborers. To southern plantation owners, expansion of the slave population seemed to be the logical solution to the problem. In reality, less than 25 percent of the southern population that were engaged in agriculture owned slaves but the slave owners were also the large land holders and thus set the pattern for both cotton culture and the social structure in the South (Cohn, 1956).

The consequence was the development of a gigantic cotton monoculture which required much manual labor and employed few tools and machines. Since

land was readily available, there was no immediate need for practices that would conserve soil resources and maintain their productivity. An extensive, rather than intensive, agricultural system developed. As production began to decline, old fields were abandoned and new ones were put to the plow. On the larger plantations, it was not uncommon for a portion of the labor force to be permanently assigned to clearing land for the establishment of new cotton fields (Cohn, 1956).

As cotton production expanded in response to increasing demand in the United States and abroad, a cotton marketing system was developed to serve the needs of the textile manufacturers and to bring together the broad sources of supply across the South. For the first time, efforts were made to standardize bale weights and the quality measurements of cotton lint. Where cotton had been handled by general traders and merchants, specialists in cotton buying and shipping appeared. These middlemen began to surface between the grower, the shipper, the importer, and the dealer selling to the spinners (Lee, 1928). Spinners began to employ the services of middlemen to keep them informed as to the qualities of cotton available, its location, its price, and, if possible, the mill requirements.

The unity among the states, that had been a strong factor in the formation and establishment of the new nation, encountered its first sectional rift over the slavery issue. By law, slavery was to have been abolished in 1808, but the South chose not to honor this legislation. After the War of 1812, the British exported huge quantities of low-cost textiles into the United States hoping to stifle its developing textile industry. The industrial North retaliated by successfully lobbying for tariffs on textile imports; the Europeans countered with stiff tariffs on imports of raw cotton from the United States. The tariffs effectively protected the industrial North, but the South suffered economically because of the poor trade relations with European buyers of raw cotton which resulted. Slavery, states rights and tariffs now became a sectional issue between the northern and southern states which divided the nation and, in 1861, plunged it into war.

THE 1862-1892 PERIOD

> "No, you dare not make war on cotton. No power on earth dare make war on cotton. Cotton is King!"
>
> Senator James A. Hammond
> Address to United States Senate
> March 4, 1859

During the Civil War, the South attempted to force the European powers to recognize the Confederacy by withholding cotton from domestic and export markets. In 1859, the South produced 3.8 million bales of cotton, exported 3.5 million bales and sold the remainder to domestic mills. By 1864, cotton production was less than 0.3 million bales and exports were only 18,000 bales (Brown,

1927; Lewis and Richmond, 1968). The cotton embargo severely affected the textile industries of England and France but failed to win their support for the Southern cause. The European countries, especially England, attempted to relieve the raw cotton shortages by developing and extending cotton production in their tropical possessions (Cohn, 1956; Bigwood, 1919). Although such efforts had little impact on cotton supplies, attempts by Great Britian to free itself of the strong dependence on American cotton continued into the 20th century (Bigwood, 1919).

The textile industry of the North was also affected by the War but not as severely as that of Europe. Like Europe, the North built large inventories of cotton prior to the hostilities, managed to maintain a clandestine cotton trade with the South during the war years and imported some of its cotton. Domestic consumption nevertheless fell from 0.84 million bales in 1859 to approximately 0.3 million bales annually during the War (Brown, 1927).

The South was economically and socially divided by the War and desperately in need of internal improvement following its aftermath. To attain self-sufficiency, the South again turned to cotton and within ten years, production and exports exceeded pre-war levels (Table 1). Great changes, however, had occurred. The plantation system was greatly weakened. Large land holdings were divided and the average farm size fell from 401 acres before the War to 229 acres in 1870 (Cohn, 1956). Small farmers, encouraged by relatively cheap land prices and readily availabile credit, began to buy up portions of the old plantations and to plant cotton.

The labor force also underwent a drastic change. Many former slaves and impoverished whites left the South after the War. Those that remained disliked working for wages but were willing to enter into share-cropping agreements (Brooks, 1911; Cohn, 1956). Prior to 1860, the ratio of whites to blacks engaged in cotton culture was 1 to 8, in 1875 it was 2 to 3.

For the first time, real interest developed in labor-saving machinery and better production practices that could be applied to cotton culture. With the break-up of the plantation system and the slave labor force, cotton culture began a gradual transition from extensive to intensive agriculture. Little fertilizer was used prior to 1860 (White, 1896), but, in the states east of the Mississippi usage increased dramatically after the War. Increased fertilizer use, mainly phosphorus and potash, contributed to the maintenance of cotton yields in the Old South, at least temporarily.

Variety development and selection also began to receive more attention as production expanded and growers noticed differences in the performance of varieties available to them (Brown and Ware, 1958; Lewis and Richmond, 1968; Niles and Feaster, 1984). As certain varieties became more popular, seed businesses developed. Although the developers of these varieties seldom had any technical training, most were inherently good observers and through mass selection were able to develop agronomically acceptable types that represented im-

provements over the parent stocks. In 1895, Tracy (1896) listed 118 varieties that had been used in commercial production since the late 1800s. The life of a cotton variety in those days tended to be brief. Tracy (1896) noted that of the 58 varieties named in census reports in 1880, only 6 were still in use by 1895.

Perhaps the greatest post-war change occurred on the economic fronts. The practice of extending credit to large cotton growers greatly influenced marketing arrangements. The big trading companies, organized in previous centuries, served as large supply stores for accumulating raw materials for export and storing finished goods for sale. These places were known as "factories" and the persons in charge as "factors." These companies supported the plantations by supplying raw materials. In return, the plantation planters were extended credit to produce cotton.

In time, the big factories broke up, and the persons operating as factors became independent and began operations of their own. The factors made connections with supply houses in England and furnished credit to planters (Bruchey, 1967). The factors followed seaport and river towns providing necessary supplies and a contact for selling cotton. In profitable years, planters expanded by using credit furnished by the factors. The factors accepted mortgages on the crop as security. As part of the contract, factors had the right to sell the planters' cotton and to charge a commission (Cox, 1953). When railroads were built, the factorage system spread to the smaller general stores. These stores furnished supplies on credit for mortgages on crops, tools and livestock. In turn, they generally sold the farmers' cotton at harvest for the existing market price. Thus, the cotton farmers were at the mercy of the creditors and stood all the risk of the market.

To expedite and efficiently market cotton in the United States and abroad, a recognized system for describing quality was essential. In the early 1800s, American cotton was known as New Orleans, Upland and Sea Island. Later terms such as Ordinary, Choice and Fair began to appear. In 1843, Middling Uplands or Middling Orleans was used and in 1853, in New York, brokers formed an association and adopted a set of standards. The recognized standard descriptions made possible the sale of cotton without buyers seeing the cotton.

The development of a cotton futures market was perhaps the greatest step in the evolution of the present system of cotton marketing. It revolutionized cotton marketing because cotton could be bought and sold in transit. Mills could make forward orders based on agreements with merchants for forward deliveries (Hoffman, 1932). Futures developed because of the extreme price fluctuations, industry growth, standardization of cotton classification and the development of the Atlantic Cable in 1866 which made immediate communication with Europe possible.

With the development and use of cotton futures markets, the market became distinctly worldwide. Hedging purchases for future delivery by merchants opened the cash market up to all the cotton produced during the harvest season. This made it possible to have large centralized markets that integrated the spin-

ners, futures and local markets. The futures markets furnished a system of price insurance for all segments of the cotton industry.

With the post-war recovery in the textile industry and the improvements in marketing of cotton, the South was once again locked into a one-crop economy and to the factorage system of financing. To survive, the cotton producers had to expand acreage and production which led to lower prices. Cotton prices fell from 43.2 cents per pound in 1865 to 13.0 cents in 1875 and 9.4 cents in 1885; in 1865, the South produced 2.1 million bales, 4.3 million in 1875 and 6.3 million in 1885, (Table 1).

Despite these hurdles, the South, and cotton, was gradually gaining self-sufficiency. The development of the railroad system greatly facilitated the movement of goods and people and reduced the strong dependence on natural waterways as the principal means of transportation. By 1890, the railroad mileage in the South was more than twice what it had been in 1860 (Todd, 1950).

On May 15, 1862, Congress established the Department of Agriculture and in 1889 made it an executive agency. Although poorly funded and sparsely staffed, the Department was mandated to conduct agricultural and marketing research, some of which dealt with cotton production. The Morrill Act of 1862 provided for the establishment of agricultural colleges in the States and the Hatch Act of 1887 provided financial aid for the development of the state agricultural experiment stations. Serious scientific explorations of cotton production technology began to occur as the colleges and experiment stations were established in the South.

THE 1892-1935 PERIOD

> "The other difficulties of seasons, boll-worms and cotton caterpillars are natural, and not therefore entirely within the control of the planter; yet, we may reasonably hope that Providence will in the future dispose of them as in former years." (Cloud, 1866)

The somewhat nonchalant attitude of Dr. Cloud and other planters toward insects was partially justified in that up to 1892, cotton was produced in the United States without a major, annually recurring insect problem (Walker, 1984; Brown, 1927; Newsom and Brazzel, 1968). Prior to 1892, bollworms (*Heliothis* spp.) and cotton leafworms (*Alabama argillacea*) occasionally caused serious damage to cotton, usually late in the season (Comstock, 1879). Growers countered the problem mainly by timely planting and, to a lesser extent, selection of earlier maturing varieties and other cultural practices (Lyman, 1866; Brown, 1927). Some planters also experimented with biological and chemical (mainly arsenical) control agents (Comstock, 1879).

In 1892, however, the situation was drastically altered when the boll weevil (*Anthonomus grandis*, Boh.) crossed from Mexico into Texas and rapidly spread northward and eastward into the heart of the Cotton Belt. The boll weevil, appar-

ently an ancient pest of cotton in its centers of origin in Central and South America, was, for many decades, ecologically isolated from the vast cotton production regions of the southern United States. Unlike other cotton insects which have one or more alternate hosts and may be held in check by predators or migrate into fields late in the season, the boll weevil is a one-host pest with few natural enemies that attacks the crop annually. It reproduces in geometrical proportions throughout the protracted fruiting cycle of cotton.

The boll weevil did considerable damage in Texas in 1894, entered Louisiana in 1903, Mississippi in 1907, Alabama in 1909 and completed its track to the Atlantic in the 1920s. Production losses associated with boll weevil infestations ranged from 25 to 50 percent (Parencia, 1978).

Newsome and Brazzel (1968) divided the time after boll weevil establishment into four periods, including: (a) before general use of insecticides, 1908-1923; and (b) widespread use of calcium arsenate, 1924-1945. During the first period, extensive efforts were made to develop cultural controls for the boll weevil. For the first time, modern plant breeding techniques were applied to cotton, mainly at recently established state and federal research facilities (Brown and Ware, 1958). The boll weevil forced producers and breeders to abandon the vigorous, late maturing upland cotton with relatively long fibers and to develop early maturing but shorter stapled cottons (Bennett, 1908; Niles and Feaster, 1984; Lewis and Richmond, 1968; Ware, 1951). Rapid adoption of the new varieties and cultural practices such as reduced row widths (Niles *et al.*, 1978) enabled producers to minimize boll weevil damage and maintain economically acceptable production levels.

The preference of the weevil for the high-rainfall regions of the Cotton Belt with long frost-free periods and abundant overwintering habitat was quickly recognized (Walker, 1984). As a result, cotton acreage began to decline in the 50+ inch (100+ cm) rainfall zones of the deep South and increase in the 20- to 30-inch (50 to 75 cm) zones, mainly in Texas and Oklahoma and in the northern reaches of the cotton producing states where cold winters and limited overwintering habitat restricted winter survival. With the development of irrigation, cotton production also gradually extended westward, away from the boll weevil, into New Mexico, Arizona and California (Todd, 1950).

The potential advantages of early crop termination and stalk destruction were recognized early on, but the practice was impractical because of the extended period required to harvest the crop by hand. An alternate solution was to control the weevil with insecticides. Numerous compounds were tested, and it was established that calcium arsenate would effectively control this pest. However, growers and entomologists soon learned that repeated applications of this insecticide often resulted in uncontrollable outbreaks of secondary pests such as the bollworm and aphids (Walker, 1984).

Consequently, cultural practices for control of the boll weevil remained in vogue and their application was introduced to growers through on-farm demon-

strations such as those conducted by Seaman E. Knapp in Texas in 1903. Dr. Knapp's activities proved to be highly successful and contributed significantly to the introduction and passage of the Smith-Lever Act in 1914 which provided for the establishment of the state agricultural extension services.

The boll weevil did not cause the demise of the cotton industry as many predicted. Instead, acreage actually expanded from 20.2 million acres in 1892 to an all time high of 44.6 million acres in 1926 (Table 1, Figure 1). In the decade of 1910-19, the U.S. cotton crop accounted for nearly 60 percent of the total world production (Murray, 1950). Despite the presence of the weevil, yield levels increased from an average of 177 pounds per acre for the 1874-1894 period to 191 pounds for the 1895-1915 period (Brown, 1927). The improvement in yield may be construed as a tribute to the early plant breeders in that their "new" earlier maturing varieties were being grown not only in the traditional rainbelt regions but also in areas with drier climates and shorter growing seasons.

Insects were not the only pest problems attracting the attention of plant breeders. Diseases had been present in cotton growing areas of the U.S. since the very early periods of cotton culture but generally did not cause extensive damage until the change from an extensive to an intensive form of cotton culture (Presely and Bird, 1968). Serious attention began to be directed at plant pathogens in the late 1800s when Pammel (1888) reported that a fungus, *Phymatotrichum*, caused cotton root rot and Atkinson (1892) described bacterial blight (*Xanthomonas malvacearum*), fusarium wilt (*Fusarium oxysporium*), boll rots (several bacteria and fungi spp.), and root-knot nematode (*Meloidogyne incognita*) damage in Alabama. Fusarium wilt had become firmly entrenched in the areas of the Southeast where Sea Island cotton had been grown for many years. Mr. E. L. Rivers, a cotton producer, developed a variety resistant to the disease with the aid of USDA researchers (Presely and Bird, 1968). A few years later, one of these scientists, W. A. Orton, developed and released several upland varieties with resistance to this disease (Orton, 1908).

Prior to 1900, cotton breeding efforts were based on selection and the plant-to-row breeding method. After the rediscovery of Mendel's papers on genetics and the publication of Johannsen's pure line theory around 1900, hybridization began to be used as a technique to transfer desirable traits such as earliness, disease resistance and fiber quality (Lewis and Richmond, 1968; Niles and Feaster, 1984). Fiber improvement warranted immediate attention because the introduction of earliness resulted in shorter stapled cottons which were being penalized in the market place (Kerr, 1951).

As cotton production shifted westward into regions that were drier but with longer growing seasons, extra long staple (ELS) cottons, *Gossypium barbadense*, were introduced into Arizona and California. From introductions of cotton from Egypt, breeders made selections which resulted in the development of agronomically acceptable varieties for the West (Lewis and Richmond, 1968).

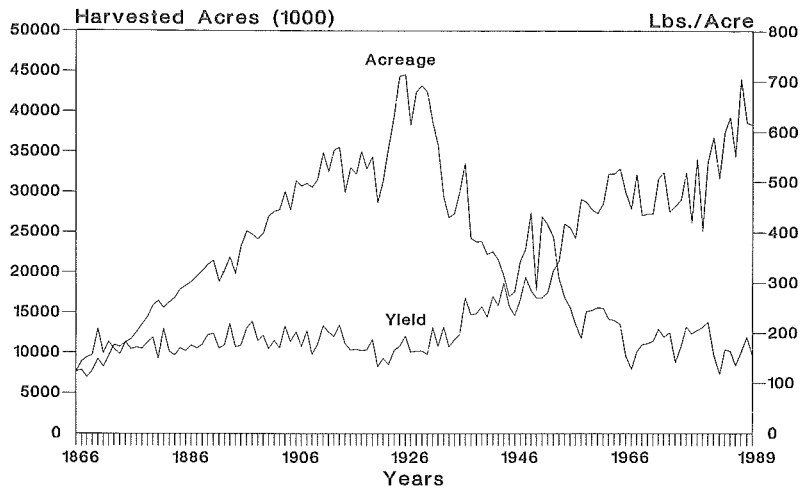


Figure 1. U.S. Cotton Acreage and Yield, 1866-1989.

The United States acreage of ELS cotton reached 240,000 acres in 1920 but declined to less than 40,000 in the 1930s (Starbird *et al.,* 1987).

During the 19th and early 20th centuries, numerous studies were conducted to ascertain the importance of various fertilizer elements in cotton production (Brown, 1927; Tucker and Tucker, 1967; Jones and Bardsley, 1968; Kamprath and Welch, 1968; Hinkle and Brown, 1968). Whereas little fertilizer was used on cotton prior to the Civil War, over 14 million of the 38.3 million acres planted in 1923 were treated with manure or some form of commercial fertilizer (Brown, 1927). Most of the fertilizer used during this period was confined to the traditional cotton production areas of the deep South where annual rainfall was typically in excess of 50 inches (125 cm) annually.

Production techniques remained relatively static until about 1930. Planting and cultivation continued to be done with animal drawn equipment, and weed control and thinning were accomplished manually with the hoe. As labor became scarcer and more expensive, greater emphasis was placed on mechanization and the use of equipment in stand establishment and crop maintenance.

The structure of the cotton marketing system continually changed to meet supply and demand conditions. This system is made up of farmers, warehousemen, merchants, manufacturers, converters, wholesalers, and retailers that perform the necessary functions to make cotton goods available to consumers. Hedging price risk on futures contracts made it possible for the development of large cotton merchandising firms. These firms accumulated cotton from growers through local cotton buyers and classed it into even-running lots for sale to mills.

The system of local buyers scattered over the cotton production areas was effective but resulted in fairly restricted, and widely fluctuating, markets for growers.

Because of the worldwide market and wide range in quality, a standardization of price determining factors was needed. Early cotton grading began in Liverpool in 1800. After World War I, the United States began to set up cotton standards that were to be recognized around the world. The methods of selling cotton used to reflect quality were as follows: (a) by actual sample of cotton lint from the bale; (b) on type by a group of samples representing grade, staple, and character without reference to individual bales; and (c) on description that was equal to a certain grade and staple.

The instability of cotton prices and markets in the United States was due to the long standing difficulties in matching supply and demand. Cotton production had increased from about 2 million bales in 1866 (McArthur, 1980) to nearly 18 million bales in 1926. During the same period, harvested acres increased from 7.7 million in 1866 to an all-time high of 44.6 million in 1926 (Table 1.) Throughout the period, however, cotton yields averaged about 190 pounds per harvested acre and rarely exceeded 200 pounds per acre (Miller, 1977). For cotton production to remain profitable, improvements in production technology were needed.

THE 1936-1965 PERIOD

> "Cotton is a very jealous plant and will not struggle with weeds or grass for a division of the fertilizing properties of the soil. It will not grow unless kept very clean and the full energy of the soil is kept concentrated on it alone." (Lyman, 1866)

Beginning in the mid-1930s, yields began to increase and acreages to decline (Figure 1 and Table 1). There were a number of economic and agronomic reasons for these changes. Government farm programs that spanned the 1933-65 period usually included acreage allotments, marketing quotas and parity price supports (Starbird *et al.*, 1987). The troubled economic times associated with the Great Depression set the cotton industry back substantially. The economic crisis was very severe across the farm sector, especially after World War I. The Agricultural Marketing Act of 1929 was enacted to make loans to marketing cooperatives for the purchase and storage of surplus commodities including cotton (Starbird *et al.*, 1984). Because of declining demand and lack of production controls, the Federal Farm Board, created by the 1929 Act, failed to stabilize prices or increase farm income.

The Agricultural Adjustment Act of 1933 followed and was aimed at controlling production and increasing prices (Bowers, 1984). This was the first federal farm program to affect cotton. Since then, cotton programs have contained many of the features of this first program. These included payments for voluntary acreage reduction, payments to increase farm income, price support loans and allotments to use in determining farm payments. Providing payments, even

though no cotton was planted, was a form of disaster protection. There also were rules as to what crops could be planted on acreage taken out of cotton.

Through such programs, marginal acreages were diverted to alternate crops or to soil-conserving crops such as grasses and legumes. By the 1960s, cotton had largely moved out of the hilly areas of the Cotton Belt states to the deeper, more fertile, relatively level soil resource areas that are not only more productive but better suited for farming with large equipment (McArthur *et al.*, 1980). Fertilizer use increased dramatically, especially after World War II, when a scientific basis for determining fertilizer use in specific areas or on given soils began to be established and appropriate commercial fertilizers were formulated to accommodate such recommendations.

As agriculture became more mechanized, tremendous strides were made in the development of equipment for production of cotton. Planters, cultivators, fertilizer and chemical applicators, mechanical cotton choppers, flame cultivators, stalk cutters, shredders, disks, listers, moldboard plows and chisels were just some of the tools developed or improved and enlarged as cotton producers changed from animal power to row-crop tractors (Smith, 1950). Improved equipment and tractor power provided the means for performing cultural operations in a timely manner, for correcting soil physical problems such as hardpans with deeper tillage than heretofore possible and for utilizing newly developed chemical pest control agents.

Cotton mechanization during this period had major impacts on two production components—weed control and harvesting, both of which required extensive hand labor. Progress in mechanization needed to be parallel in these two production sectors, as seasonal labor to perform only one of these labor intensive operations simply could not be kept available. The dual switch from hand-labor to chemical weed control and from hand to mechanical harvesting freed a significant percentage of the population in cotton producing areas from a life of very hard labor but it also created new sociological and economic problems for farm workers.

The general design of the mechanical cotton picker, which became the industry standard, was developed prior to World War II and production models started penetrating the industry in the late 1940s. Stripper harvesters were developed almost concurrently. Strippers are much simpler and cheaper to operate, but gather more foreign material along with the cotton. As a result, stripped cotton requires more cleaning machinery at the gin. Strippers were developed in Texas and are used predominantly in the Texas-Oklahoma production region.

In 1947, 98 percent of the United States cotton crop was hand-picked or hand-snapped (Fortenberry, 1956), whereas in 1957 only 68 percent of the crop was hand-harvested. Thus, machine-harvesting had increased from 2 to 32 percent in 10 years—an average of 3 percent per year (Table 3). The change to mechanical harvesting accelerated rapidly beyond this point and by 1962, 70 percent of the United States cotton crop was machine-harvested—an average increase of 7.5

Table 3. The percentages of United States cotton harvested by hand and by machine from 1947 to 1970.

	Harvest method						
	Hand			Machine			
Crop	Picked	Snapped	Total	Picked	Stripped	Scrapped	Total
	(Percent)						
1947	77	21	98	—	—	—	2
1948	—	—	—	—	—	—	—
1949	68	26	94	—	—	—	6
1950	71	21	92	—	—	—	8
1951	61	24	85	—	—	—	15
1952	63	19	82	—	—	—	18
1953	—	—	—	—	—	—	—
1954	54	24	78	—	—	—	22
1955	54	23	77	17	6	0	23
1956	53	20	73	20	7	0	27
1957	44	24	68	19	13	0	32
1958	44	22	66	21	13	0	34
1959	39	18	57	31	12	0	43
1960	33	16	49	36	15	0	51
1961	27	14	41	39	19	1	59
1962	20	10	30	48	20	2	70
1963	21	7	28	51	20	1	72
1964	16	6	22	58	19	1	78
1965	11	4	15	60	24	1	85
1966	8	3	11	61	27	1	89
1967	5	1	6	67	26	1	94
1968	3	1	4	68	27	1	96
1969	3	1	4	71	24	1	96
1970	2	0	2	71	26	1	98

Source: Ghetti and Looney, 1982.

percent per year. This trend continued until 1970 when 98 percent of the crop was machine harvested (Ghetti and Looney, 1982). Currently, a hand-harvested bale of cotton is very rare in the United States.

Mechanically harvested seedcotton which contained more foreign material, created a need for more cleaning at the gin in order to deliver satisfactory fiber to textile mills. To remove as much of this foreign material as practical, seedcotton

cleaners (including incline cleaners, impact cleaners, stick machines and bur machines) and lint cleaners were developed. Because cotton (either seedcotton or lint) cleans much easier when it is dry, more seedcotton drying equipment was also needed in gins. In response to mechanical harvesting, gins quickly installed additional drying and cleaning equipment in the late 1950s. By 1960, 93 percent of the gins operating in the United States had some seedcotton drying equipment; of this total, 40 percent had two stages, and 6 percent had three stages. At that time, 85 percent of the gins had some type of lint cleaning; of these, 38 percent had two stages, and 4 percent had three stages.

A strong factor contributing to the yield improvements of this period was the development of chemicals that effectively controlled many weed, insect and disease pests and which conditioned the crop for timely harvest with mechanical harvesters. Mechanical devices such as cultivators, rotary weeders, flame cultivators and even mechanical choppers were helpful in eliminating many weeds but did not provide adequate control of weeds within the cotton drill (Brown and Ware, 1958; Christidi and Harrison, 1951). Selective herbicides began to appear in the late 1940s and early 1950s (Ridgeway *et al.*, 1984; Ennis, 1962, McWhorter and Holstun, 1966; Holstun and Wooten, 1968). Herbicide usage in cotton began to gain some farm acceptance in the 1950s and by the 1960s constituted the primary means of weed control.

Prior to World War II, the boll weevil remained a nemesis to cotton. Calcium arsenate effectively controlled the boll weevil but triggered secondary outbreaks of *Heliothis* spp. and cotton aphids (*Aphis gossypii*). After World War II, the chlorinated hydrocarbon insecticides provided cost-effective control of not only the boll weevil but the secondary pests as well (Walker, 1984; Newsom and Brazzel, 1964; Ridgeway *et al.*, 1984). By the mid-1960s, the organophosphate and carbamate classes of insecticides were also available and widely used. For a time, the cultural management techniques for suppression of the boll weevil and other insect pests were totally or partially ignored because the new insecticides seemed to provide a total solution to cotton insect problems.

By the mid- to late-1950s, however, failures of the synthetic organic insecticides to control all insects were noted and environmental concerns began to develop about the increasing use of pesticides. The development of resistance, elevation of secondary insects to major pest status and rising costs of chemical control measures called for a re-examination of insect control strategies. For the time being, however, growers were strongly dependent on available insecticides to deal with their ever increasing cotton insect problems.

The need to obtain timely uniform stands of cotton and protect seedlings from various pathogens prompted the development and widespread use of fungicides (Presley and Bird, 1968). Organic and inorganic fungicides were used as seed, hopperbox and/or in-furrow treatments to provide control of seedling diseases. Fumigants were used to control nematodes. To a large extent, however, growers

were relying on plant breeders to develop cultivars with genetic resistance to the major disease pests (Bird, 1980).

The advent of mechanical harvesters developed a need for preparation of the cotton plant for harvest. The efficiency of the picker is dependent on removing much of the foliage and reducing the moisture of the remaining leaves prior to harvest. For stripper harvesting, the principle requirement is complete desiccation of foliage and stems before harvest.

Chemical defoliation of cotton was discovered in South Carolina in 1938 and gained rapid acceptance as machine pickers became available (Smith, 1950b; Cathey, 1986; Walhood and Addicott, 1968). Likewise, the desiccants, primarily arsenic acid, gained rapid acceptance as stripper harvesters were introduced into the Southwest.

Plant breeders made significant improvements in: (a) plant conformation to accommodate machine harvesting, (b) enhanced earliness in both the upland and ELS cottons, (c) improved fiber properties (mainly length), (d) pest resistance and (e) environmental stress tolerance (Niles and Feaster, 1984; Lewis and Richmond, 1968). During this period, a strong cotton planting seed industry developed to complement public and private breeding efforts. Private companies produced, harvested and processed proprietary, and in some instances, state released varieties for sale to producers. By the mid 1960s, most of the commercially processed planting seed were flame or acid delinted and treated with fungicides.

Most states instituted seed certification programs to ensure genetic purity and, in some cases, quality standards of the planting seed sold to producers. Laboratory tests were developed to ascertain the viability and vigor of cottonseed (Baskin *et al.*, 1986; Delouche, 1986; Cherry and Leffler, 1984), and public and private laboratories provided seed testing services to seedsmen and producers. The Association of Official Seed Analysts was formed to standardize seed testing procedures for several crops, including cotton.

THE 1966-1986 PERIOD

From 1966 through 1980, the acreage of cotton harvested in the United States fluctuated greatly but showed no clear trends (Figure 1, Table 1). Lint yields during this period, however, actually declined by about 0.8 pounds per acre per year (Meredith, 1982). In some production regions such as the Texas High Plains, even sharper declines were noted (Neal and Ethridge, 1984). From studies conducted to assess the reasons for the yield decline, it was generally concluded that the factors responsible varied from region to region (Brown, 1977; Neal and Ethridge, 1984; Meredith, 1982; Meredith, 1987; Neal *et al.*, 1984) and were closely linked to economic considerations. For example, in the Delta states, the decline appeared to be associated with insect control, especially of early-season pests (Meredith, 1987); whereas, on the Texas High Plains, declining yields appear to be more a function of reduced irrigation and fertilizer usage (Neal and

Ethridge, 1986; Wanjura and Barker, 1986). The cost-price squeeze that began in the 1970s forced many producers to reduce input costs which in turn had a negative impact on yields (Starbird *et al.*, 1987). Some improvements in yields were noted during the 1981-85 period and are attributed to more widespread usage of new technology, better management and the shift to more irrigated production.

Rather impressive improvements have been made in the culture, mechanization and marketing of cotton during the last two decades. Starbird *et al.* (1987) recently reviewed the production practices currently in use in the various sections of the Cotton Belt. Widespread mechanization has reduced dependence on hand labor, improved timeliness of all operations from land preparation through harvest and contributed to the increasing size of modern-day farms. Currently used herbicides are highly selective for cotton and control a broad spectrum of grassy and broadleaf weeds. These have largely replaced hand hoeing as the primary method of weed control. In 1976, approximately 18.3 million pounds of herbicides were used on cotton. The average cost of these chemicals was $10.33 per acre. Achieving equivalent levels of weed control by hand hoeing and additional tillage would have cost $29.39 per acre (Abernathy, 1981).

Integrated pest management (IPM) was introduced in the early-1970s as a means of dealing with insect resistance to certain insecticides and the steadily increasing costs of chemical control measures. The IPM approach utilizes both old and newly developed classes of insecticides in combination with cultural practices to provide cost effective control measures for insect pests.

Fertilizers have become primary production inputs in most production regions and soil testing is widely used to establish fertilizer requirements on a field-by-field basis. In the 1970s, plant growth regulators were introduced for controlling plant size, enhancing earliness and hastening boll-opening (Walter *et al.*, 1980; Cathy *et al.*, 1982; Cathey and Thomas, 1986). Parvin *et al.* (1987), Ray and Minton (1973) and others have shown that the yield and value of cotton deteriorates rapidly if harvest is not initiated when the crop is ready. A strategy has evolved in recent years to control plant size, advance maturity, terminate fruiting, induce senescence and/or open bolls with plant growth regulators and to defoliate or desiccate the crop with harvest-aid chemicals to prepare it for timely harvest (Cathey, 1986; Colwick *et al.*, 1984). Such practices are also important in the management of the boll weevil, pink bollworms and other cotton pests.

Improvements in varieties are continually being made by public and private breeders in response to changing cultural practices, pest pressures and mill needs (Niles and Feaster, 1984; Bridge and McDonald, 1987; Gannaway and Dever, 1986). The yielding ability of cotton has been steadily enhanced through genetic improvement. Miller (1977) estimated that the varieties grown in the mid-1970s had the genetic potential to yield 2 to 17 percent more than varieties grown in 1965. Bridge and Meredith (1983) compared the performance of obsolete and current varieties in Mississippi and found that for the 1910 to 1979 period, yields

increased at the rate of 7.7 pounds per acre (8.6 kg/ha) per year as a result of genetic improvement.

Much of the genetic improvement in yield is attributed to the ability of modern cultivars to partition more dry matter into reproductive structures (Wells and Meredith, 1984). As a result, the newer varieties tend to be shorter, more compact and earlier maturing as well as more productive. The widespread acceptance of these varieties, especially in the Mid-South and Southwest, and the adoption of better management practices has tended to decrease the number of days required to produce the crop. Within the last 20 years or so, the length of the planting to harvest period has decreased by 1.18 days per year in Stoneville, Mississippi; 1.33 days in College Station, Texas; and 2.43 days in Florence, South Carolina (Bridge and McDonald, 1987). The increasing acceptance of narrow-row culture is expected to create a need for additional cultivars which are early maturing, develop compact plants with short fruiting limbs and produce fiber that more precisely meets the needs of yarn and fabric manufacturers.

With an increase in the size of individual farming operations, higher costs of inputs and narrower profit margins, management becomes critical. Modern digital computers have made it possible to develop crop simulation models with application in research management, plant breeding, yield forecasting, and pest control as well as in crop management (Baker, 1980). GOSSYM-COMAX, a crop simulation model and expert system, was made available for on-farm use in the 1980s (Creech, 1986; Mullendore, 1986) and is designed to aid in cotton management by predicting growth events and by assessing the need for nitrogen and water inputs to achieve desired yield levels. Currently, several other cotton simulation models are also under development (Wade, 1987).

The development of the modular system for handling seedcotton from the field to the gin was one of the most significant engineering accomplishments in the history of the cotton industry, rivaled only by the invention of the gin and the mechanical harvesters. Modular systems were first used commercially in 1974 when two percent of the crop was moduled. Since 1980, 32 to 42 percent of the crops have been moduled. The modular system is a transportation and storage system, but its economic advantages come primarily from storage components (Willcutt and Mayfield, 1985). The system includes a builder which receives seedcotton from the harvester and compacts it into a free standing module in the field. A transporter picks modules off the ground and moves them from the field to the gin. The modules are then fed into the gin with either an automatic module feeder or with a conventional suction system. With the modular system, ginning capacity no longer has to equal harvesting capacity. The net effect is that gins can be operated more hours per year, improving their utilization efficiency and reducing ginning costs.

The universal density (UD) gin press was also a significant development during this period. The cotton industry began an organized program to adopt the universal density bale as an industry standard in 1970. Prior to the UD gin press,

most bales were compressed at the gin to a low density, then recompressed at a central facility to either standard density or high density. This non-uniformity created handling and transportation problems and added unnecessary re-compression and handling costs. By 1985, approximately 65 percent of the crop was packaged to its final density by UD gin presses.

The high volume instrument (HVI) system of classing cotton was introduced to the industry in the early-1980s. This system generally evolved from laboratory equipment and methodology that had been used for several years. The current cotton classification system typically uses a combination of manual and machine quality evaluations. The grade is determined by a classer, and the micronaire, length, and strength by machine. Over the last few years, 30 to 40 percent of the crop has been classed on HVI.

Other significant developments during this period focused on increased size and capacity of farm machinery. One and two-row cotton pickers were replaced with two- and four-row models. Improvements were also made in harvester operation, efficiency and maintenance. Gins have increased in size and complexity. The average annual volume per gin increased from approximately 3,000 bales in 1965 to approximately 7,300 bales in 1985, while the number of active gins decreased from 4,870 to 1,772. Individual gin machinery became larger with more capacity, safer, more reliable and more automated.

Government programs continued to play a major role in attempts to adjust supply to demand and prop farm income up during periods of very low prices. The Food and Agriculture Act of 1965 attempted to do just that. This Act was somewhat market-oriented in that it supported cotton at 90 percent of estimated world price levels. The Agricultural Act of 1970 set up a voluntary program for cotton as marketing quotas were suspended for three years. It also put a $50,000 annual limit on direct government payments to producers of upland cotton, wheat and feed grains.

By 1973, the worldwide demand for American farm products surged due to world crop shortages, devaluation of the dollar and economic growth worldwide. The agricultural environment progressed from chronic surpluses and low producer income problems to a situation where the government could reduce its regulatory role as well as the cost of farm programs. A new target price concept was introduced in the 1973 Act. If market prices received were under target price levels, then a payment for the difference was made to the producer to support farm incomes. The 1973 Act also introduced disaster payments. Cotton producers, who were prevented from planting or who suffered low yields due to a natural disaster, received a payment based on a percentage of the target price level. Disaster payments were made for each of the 1974 to 1982 crop years. A price and income safety net for growers that would not disrupt market prices was the major objective of the 1973 and 1977 Acts.

The Agriculture and Food Act of 1981 extended cotton provisions of the 1977 Act. Disaster payments were to be phased out and replaced with all-risk Federal

Crop Insurance Corporation (FCIC) insurance. The Food Security Act of 1985 was designed to make agricultural commodities more competitive in the world market. The cotton program's objectives were to protect farm income and to lower carryover stocks to workable levels through the use of a marketing loan and a competitive price. In effect, the marketing loan assured that United States cotton would be competitively priced with foreign growths.

The productivity of American cotton growers has generally outstripped growth in demand for cotton. Farmers have worked to increase their efficiency to escape the squeeze between rising production costs and the slow advance in prices paid for their commodities (Anderson, 1972). The result has been basic changes in the structure of the cotton industry—a decline in number of cotton farmers and a continuation of improvements in production techniques. These changes have cut not only the number of acres required for production of cotton but also the labor required.

As the productivity of growers increased, development of new synthetic fibers and changes in consumer preferences reduced the demand for cotton. Particularly significant was the growth in domestic use of synthetic fibers, which invaded many traditional cotton markets (National Advisory Commission on Food and Fiber, 1967). Total United States fiber consumption, including the raw fiber equivalent of textile imports, rose from about 4.7 billion pounds during 1940 to about 12.5 billion pounds in 1978 (Starbird *et al.*, 1987). Population growth, rapidly rising real incomes, changing lifestyles, the invention of new textile products and decreases in real fiber prices contributed to the increase in fiber consumption. Per capita fiber use rose from about 34 pounds in 1949 to about 56 pounds in 1978. But, total and per capita fiber consumption fell during 1979-82 to 10.5 billion pounds and 45 pounds, but then increased to about 13.5 billion pounds and 57 pounds in 1985.

However, despite the increased fiber consumption, domestic use of cotton declined from a post-war peak of 10.5 million bales in 1950 to 5.3 million bales in 1981, before rebounding to 8.8 million bales in 1989, Table 1. Cotton use per capita was 21.6 pounds in 1988, compared with 25.2 pounds in 1966. Loss of cotton's market share was due mainly to polyester and nylon. Cotton accounted for 81 percent of total United States fiber consumption in 1940, 53 percent in 1966, and about 32 percent in 1988 (Sandford, 1990).

Cotton consumption has been reduced by both competition with man-made fibers and by growth in the cotton textile trade deficit. Following the 1950s, cotton lost market share to polyester and nylon because of their easier care, durability, and the desirable spinning characteristics of synthetic fiber. Also, man-made fiber prices are more stable than cotton prices. Because of the adversities of weather and response to big changes in price levels, cotton production is erratic from year-to-year. The uncertainty of cotton prices, combined with polyester's stable price advantage, contributed to loss of market share of cotton. Unlike the cotton industry with its many producers selling through a series of market chan-

nels, the synthetic fiber industry was made up of a small number of large manufacturers, and was able to gear its production to its market thereby becoming a highly efficient competitor. Cotton's major advantages over man-made fibers are its absorbency, softness and breathability. Although foreign use of cotton has tripled since World War II, domestic use has shown little change.

To support farm income in a rapidly changing market situation, the government has tried through various farm programs for more than half a century to cope with the problem of overcapacity. Only since the mid-sixties has the cotton industry given more attention to expanding consumer demand for cotton. Programs began reflecting a newfound emphasis on efforts to counter the steady decline in demand for cotton by improving its competitive position. The most direct government effort to influence demand came with the Cotton Research and Promotion Act of 1966. This legislation established a program of self-help in the expansion of cotton markets. New programs were designed to allow the price of cotton to seek competitive levels at home and abroad.

THE FUTURE FOR COTTON

The immediate future for the United States cotton industry appears bright. On the demand side, consumers around the world are favoring cotton goods. World cotton consumption has increased in excess of 20 million bales during the last decade. The United States textile industry is making strides in upgrading the quality of cotton garments and in the production efficiency of manufacturing cotton textiles. This makes for a more competitive industry in the international market as well as in the United States with textile imports. Growers are also producing a higher quality fiber in response to the needs of their textile mill customers and the development of a HVI cotton testing system which provide a means for rapidly measuring fiber parameters such as length, strength, color and elongation. As a result, cotton is now more competitive with synthetic fibers.

On the supply side, based on the productivity of American cotton growers, United States cotton can compete at international market price levels. However, given this country's tremendous production potential, acreage reduction programs will continue to be needed to help balance supply with demand, and maintain stocks at desired levels.

Biotechnology is likely to have a major impact on cotton culture in the coming decades. Recombinant DNA technology and tissue and cell culture coupled with traditional breeding programs may markedly reduce the time required to generate new varieties. Genetic resistance to insects and diseases, earliness, enhanced tolerance to specific herbicides and environmental stresses, improvements in fiber properties and in seed quality are among the traits that will continue to be stressed in variety development programs. The use of crop simulation models and expert systems as crop management aids is expected to increase as these models are refined and producers become more acquainted with their capabili-

ties. Growers are also likely to make greater use of telecommunication networks which continuously update marketing and production information.

The advantages of narrow-row culture in which plant populations are optimized to make the best use of light, water and nutrients are already apparent to growers and widespread adoption of this practice is likely within the next decade. Conservation tillage systems offer a means for reducing production costs, affording crop protection from environmental hazards and meeting governmental erosion control guidelines. The use of supplemental irrigation in the rainbelt states is likely to increase as growers strive to minimize stress conditions that negatively impact yields. Synthetic plant growth regulators have great potential for modifying plant growth, water use characteristics and susceptibility to pests. The protection against pests that is now offered by chemicals will need to be complemented with new chemistry, as well as with genetic, biological and management approaches.

Industry trends in developing machinery to meet the ever-changing needs of cotton producers will continue at an accelerated pace. Equipment developed for conventional and conservation tillage systems will tend to combine tillage operations to reduce the number of trips through the field. In irrigated areas, greater use will be made of the drip systems and multifunction sprinkler systems which not only deliver water with minimal evaporation and runoff losses but will also precisely place fertilizers and pesticides. In time, the multi-function sprinkler systems may even replace some traditional tractor operations.

A complete instrument system of evaluating the quality of cotton must be developed and adopted by all segments of the industry from the producer to the textile manufacturer. This change will force the marketing system to put fair premiums on the fiber quality factors that are required by textile manufacturers. The premiums should make it profitable for producers to deliver the fiber quality which the textile manufacturer needs.

SUMMARY

From a humble beginning as a garden crop used to provide for domestic textile needs, cotton developed into a major agricultural commodity in the United States. The industrial revolution in England resulted in the mechanization of textile processing and generated a tremendous demand for cotton. Vast areas of the southern United States were suited for cotton production, but the crop did not attain economic significance until the invention of the cotton saw gin. Until well after the Civil War, a gigantic cotton monoculture existed in the South which was largely dependent on manual labor and an extensive, rather than intensive form of agriculture.

For nearly 100 years, cotton was grown without interference from a major, annually recurring insect pest. In 1892, the invasion of the boll weevil forced major changes in cotton culture and greatly contributed to the westward move-

ment of the crop. Technological breakthroughs in the development of mechanical cotton harvestors and selective cotton herbicides allowed near complete mechanization of cotton culture.

As the productivity of cotton producers increased, development of synthetic fibers and changes in consumer preferences reduced the demand for cotton both domestically and abroad. Since the mid 1960s, the cotton industry has provided attention to both increasing production efficiency and improving its competitive position relative to manmade fibers. Despite continued challenges, the immediate outlook for the United States cotton industry appears bright. The challenge of the future will be to combine technology, management and natural resources into a system that produces high quality cotton textiles at a cost competitive with synthetics and foreign cotton products.

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Chapter 3

TRENDS IN WEED CONTROL METHODS

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INTRODUCTION

Weeds are a major problem in the production of cotton (*Gossypium hirsutum* L.). Their control requires considerable crop managerial skills and represents major expenditures in the production of the crop. It is not surprising that weeds are such a significant problem in the production of cotton. First, cotton emerges and grows slowly during the first few weeks after planting, particularly during cool weather or under other adverse growing conditions. There are numerous insects and diseases of cotton that may also inhibit its competitiveness with weeds during the early growth period. It is only after the cotton plant has become well established and soil temperature is greater than 75F (24C) that the plant becomes competitive. During this entire early period of establishment, usually the first 9 to 10 weeks after planting, control of weeds is a necessity for orderly development of cotton (Buchanan and Burns, 1970).

Weeds are those plants that seriously interfere with other plants that humans grow for food, feed, fiber or for asthetic reasons (lawns, flowers, etc.). Only a very few—probably less than 30,000 of the more than 300,000 species of plants found throughout the world—are weeds in any crop. Indeed, Holm *et al.* (1977) suggest that probably no more than 200 species account for approximately 95 percent of the weed problems in food and fiber production.

While there are few definitive data regarding the specific weeds of cotton, over 100 plant species are considered troublesome in cotton (Holm *et al.*, 1977). Several weed species are serious pests in cotton in different countries around the world. These include species in the genera *Portulaca*, *Cynodon*, *Cyperus*, *Eleusine*, *Sorghum*, *Echinochloa* and *Dactyloctenium*.

Observations by cotton weed scientists and reported by Whitwell *et al.* (1981) indicate over 30 genera of plants include important species of weeds in United States cotton. These include both annual and perennial as well as grass, sedge, and broadleaf species of plants. In 1980 it was estimated by these scientists that approximately 8.7 million acres of United States cotton was infected with pig-

weed (*Amaranthus* spp.); 4.0 million acres with sorghum (*Sorghum* spp.); 3.5 million acres with thistle (*Salsola* spp.); 3.0 million acres with nightshade (*Solanum* spp.); and 1.9 million acres with morningglory (*Ipomoea* spp.). There were some changes in the 1986 estimates where infestation was estimated as 4.9 million acres with *Amaranthus* spp.; 3.5 million acres with *Sorghum* spp; 3.9 million acres with *Proboscidea* spp.; 2.9 million acres with *Solanum* spp; and 2.4 million acres with *Ipomoea* spp. (Patterson and Monks, 1986). Estimated reduction in percentage of cotton yields in 1986 was as high as 8.0 percent for nutsedge (*Cyperus* spp.); 7.6 percent for *Sorghum* spp.; 7.8 percent for *Amaranthus*; 12.0 percent for cocklebur (*Xanthium* spp.); and 18.4 percent for *Ipomoea* spp. The widely divergent population of weeds that affect cotton ensures continuous competition pressure to the cotton crop.

The specific nature of the cotton plant and its culture have influenced the evolution of weed control procedures. In much of the United States, cotton is planted during the early spring when soil temperatures are too low for optimum growth (Buchanan, 1981). Unfortunately, there are many weed species that germinate and thrive under such conditions that are unfavorable for cotton. Casual observations in the spring reveal that many species in the genera *Cassia*, *Cyperus*, *Ipomoea* and *Xanthium* germinate and initiate growth at temperatures that are too cold for cotton.

Another complicating factor is that cotton is often produced continuously on the same land, resulting in an intensification in the populations of certain species of weeds, particularly perennials. Weeds in the genera *Cynodon*, *Sorghum*, *Cyperus* and *Solanum* are among those that increase rapidly in continuous cotton. Less common, but occasionally serious weeds that often increase dramatically in continuous cotton include trumpet creeper (*Campsis radicans* L.), and passion flower (*Passiflora incarnata* L.). The result is usually an increase in weed species that are more difficult to control with the procedures available and suitable for the crop.

METHODS OF WEED CONTROL

Methods of controlling weeds in cotton include five general categories: cultural, mechanical, biological, radiant energy or flaming and chemical. The development of these methods of managing weeds has evolved slowly and illustrates the changes that have occurred in agriculture. If there is to be an understanding of trends in weed control in cotton, the nature of the methods available for controlling weeds must be appreciated from a historical perspective.

CULTURAL METHODS

The importance of cultural methods of controlling weeds is often overlooked. This method of weed management is simply the direction of all production practices towards the creation of the most favorable environment for the cotton plant

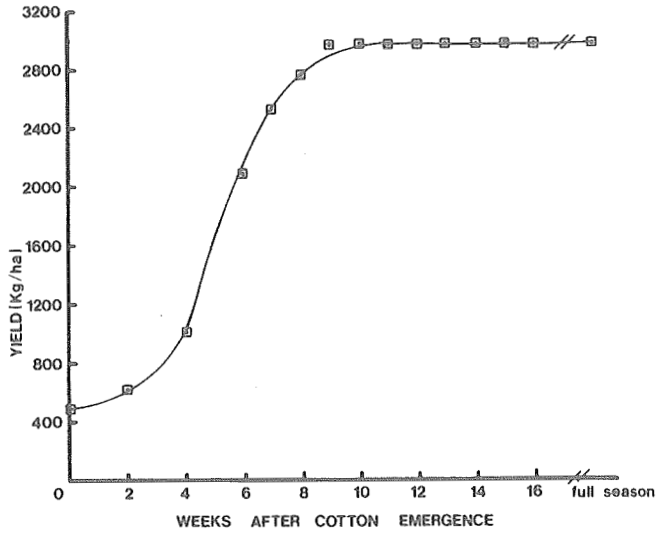
and, at the same time, the least favorable environment for weeds. Unfortunately, this often results in the creation of conditions just as suitable for certain weed species as they are for cotton growth.

Management decisions such as selection of variety, seedbed preparation, time of planting, use of clean seed, soil fertility and pH, planting pattern and moisture can be manipulated so that the cotton is favored to the detriment of the weed flora. Control of limited populations of recently introduced weed species in the "skip" of skip-row cotton, in row-ends, and in turn-rows is an important component of cultural weed control. Rotation with other crops, particularly with crops that permit widely differing weed control procedures and practices, aids in long-term weed management (McWhorter and Hartwig, 1965). Finally, use of fallow or cover crops is an integral part of the cultural approach to weed control.

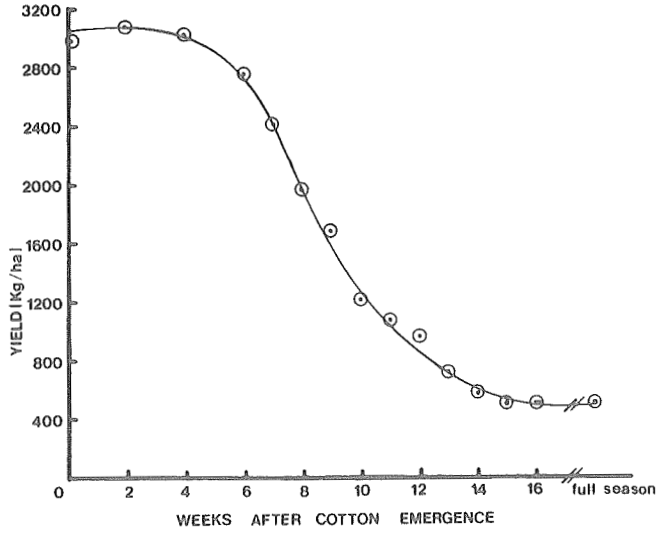
An extensive series of experiments conducted over several years confirm that if cotton is kept free of weeds for 8 to 10 weeks after planting, it is sufficiently competitive to suppress further weed growth (Figure 1). This is contingent upon a good, uniform stand of cotton under acceptable growing conditions and a mixed population of annual grass and broadleaf weeds. On the other hand, cotton yields may be reduced if weeds are allowed to compete for as little as five weeks after cotton emergence even though cotton is maintained free of weeds for the remainder of the season.

Cotton planted in 21-inch row spacing required a shorter weedfree maintenance period before becoming competitive with weed flora than did cotton planted in more conventional (42-inch) row spacing (Rogers *et al.*, 1976). In further studies, it was noted that nitrogen application up to 90 pounds per acre did not alter this competitive relationship (Buchanan and McLaughlin, 1975). As one would expect, these relationships may be altered when competing with a single species. It was noted that cotton has a substantially shorter weed-free requirement when competing with prickly sida (*Sida spinosa* L.) as compared to competing with a mixed population of annual grass and broadleaf weeds (Buchanan *et al.*, 1977).

Crop rotation, along with associated weed control programs, can, and often does, have a dramatic impact on specific weed problems. Frans (1969) noted increases in *Cyperus*, *Sida*, *Xanthium*, *Cassia*, *Sorghum* and *Ipomoea* spp. in cotton in a survey conducted in 1969. Increasingly widespread use of trifluralin (Treflan®) has been credited, to a great extent, for increases in weeds of these particular genera. On the other hand, Dowler and Hauser (1974) reported that three years' application with fluometuron (Cotoran®, Lanex®) decreased the population of several broadleaf species with an accompanying increase in populations of yellow nutsedge (*Cyperus esculentus* L.) and several annual grass weed species. Dowler *et al.* (1974) noted that several cropping sequences involving intensive cultural or herbicidal weed control programs drastically reduced weed populations. They further reported that none of the treatments altered the composition of the weed populations. Higher populations of weeds were generally



A



B

Figure 1. Yield of seed cotton as affected by periods of weed-free maintenance or weed competition. Data are averages of three experiments at two different locations: (a) Weeks of weed-free maintenance, (b) Weeks of weed competition. (From Buchanan and Burns, 1970.)

associated with corn rather than with cotton, peanuts (*Arachis hypogaea* L.), or soybeans (*Glycine max* L.).

Just as crop plants respond differently to soil pH and fertility, weeds are greatly influenced by these growth factors. Indeed, experiments have shown soil pH and fertility to be involved in causing shifts or changes in weed populations in cotton fields (Buchanan *et al.*, 1975; Hoveland *et al.*, 1976).

Cultural weed control procedures are characterized by modest or no additional production cost, while they favor growth of cotton. Also, there is no problem from herbicide residues or adverse growth effects on the cotton. Such procedures do, however, require a high level of managerial skills to implement effectively. Cultural means of controlling weeds in cotton only enhance primary control methods such as use of chemical or mechanical means. Used in conjunction with chemicals and/or mechanical means, cultural approaches become exceedingly powerful measures of dealing with weed populations.

MECHANICAL METHODS

Control of weeds using various types of mechanical devices dates to man's earliest excursions into agriculture. One can visualize the use of simple hand tools to uproot weeds growing in close proximity to the crop. Use of such tools along with animal powered cultivators comprised the cotton farmer's total arsenal of weapons in his war on weeds around the turn of the century. Cates (1917) gives a colorful description of cotton weed control in the early 1900s in Texas using "buzzard wing" sweeps. He pointed out that the first such cultivation usually occurs only ten days to two weeks after planting with each crop receiving four to five cultivations. He further noted that additional cultivations—up to six or seven—often resulted in greater yields. In the more humid Southeast, as many as ten cultivations in one crop were not uncommon. It is interesting to note that *Amaranthus*, *Panicum*, *Ipomoea* and *Sorghum* spp. were serious weeds then, and are still major problems today.

Hand-hoeing has been an integral part of cotton weed control, especially prior to the introduction of herbicides (Figure 2). The first hoeing, usually referred to as "chopping", is accomplished immediately after the first cultivation. Both grass and broadleaf weeds, along with excessive cotton plants, are removed in this process. Brown (1927) pointed out in his book that, "hoeing is expensive tillage, but apparently there is no way to avoid it."

Prior to the introduction of herbicides, hand-hoeing accounted for well over half of the total labor requirement in the production of cotton. However, as use of herbicides became more widespread in the 1950s and early 1960s, hand-hoeing became more of a secondary or supplementary means of controlling weeds. While hand-hoeing is still employed occasionally to remove low levels of infestation of weeds that escaped primary control measures, it is not envisioned that use of this procedure will be an integral component of cotton weed control programs in the future.



Figure 2. Removal of weeds by hand-hoeing. This is a highly effective but costly means of controlling weeds in cotton and was used extensively prior to the introduction of herbicides. It is still occasionally economically feasible to remove modest populations of weeds in this manner.

During the late 1930s and 1940s, animal power gave way to tractor power. Accompanying this transition was the improvement in conventional cultivators, emergence of rotary weeders (Holstun, 1963), mechanical choppers, and the concept of crossplowing (Brown and Ware, 1958). Each of these devices or concepts was designed to cover, uproot, or cut the weed seedling immediately below the soil surface.[1] Weeds are more successfully controlled with such devices when weeds are relatively small and especially if there is a crust on the soil surface. Weeds are killed by desiccation in the dry soil or by covering them with soil. While this is usually successful with annual weeds, it is far less effective with perennials.

Sweep cultivators are highly effective in controlling weeds growing between the drill-rows, but generally less effective in controlling weeds in the drill-row (Ennis *et al.*, 1963). Indeed, effectively controlling weeds in the drill row is the primary concern. During the period after the introduction of tractor power (late 1930s), and before the introduction of herbicides (1950s), numerous rather ingenious mechanical devices were developed and used for weed control in cotton (Figure 3). While all of these devices were effective to some degree, they were effective only when weeds were relatively small and when used under ideal mois-

[1]Weed control equipment and methods for mechanized cotton production. South. Coop. Serv. Bull. 71 (1960). 48 pp.

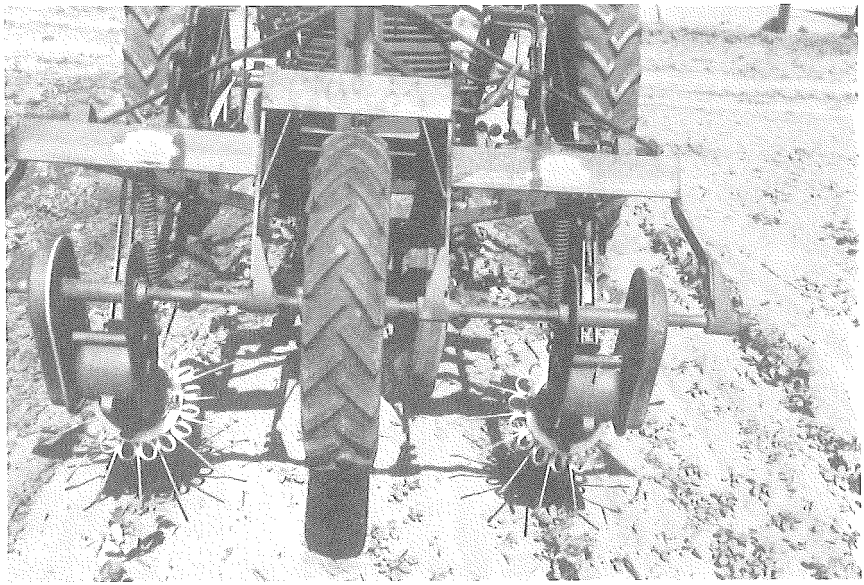


Figure 3. Many tools have been developed over the years for controlling weeds in cotton. Pictured above is a Dixie weeder showing a type of technology that was emerging for weed control and thinning cotton utilizing mechanical devices in semiarid climates of the cotton growing areas. (Photo courtesy Texas Agricultural Experiment Station.)

ture conditions. Of course, since they did not provide any residual control, a new crop of weeds would occur following the next shower.

The concept of cross-cultivation emerged during this period (Figure 4). This procedure can be highly effective in controlling weeds where topography precludes erosion problems. Obviously, good stands of cotton at relatively high seeding rates are required for cross-cultivation to be successful. Usually the first cultivation is in the direction of the row, with subsequent cultivations at 90 degree angles to the direction of the row (Holstun and Wooten, 1968). Subsequent cultivations alternate in direction. Cross-cultivation reduces the amount of handhoeing required by as much as 60 percent under certain conditions (Holstun *et al.*, 1960).

While the effectiveness of mechanical cultivation in controlling weeds is unquestioned, other benefits to cotton from cultivation have been highly controversial. To clarify the total benefits accruing from cultivation of cotton, an extensive series of experiments was conducted at two locations over several years in Alabama (Buchanan and Hiltbold, 1977). Results from these experiments showed that the only benefit cotton received from cultivations was from control of weeds. These findings occurred when cotton was planted in a well-prepared seedbed.



Figure 4. Cross-cultivation was used extensively in much of the Mid-South during the late 1940s and throughout the 1950s. A relatively dense, uniform stand of cotton was required to effectively utilize this method of weed control. (Photo courtesy Delta Branch Experiment Station.)

Throughout history, mechanical control of weeds has depended upon human effort, and either animal power or the internal combustion engine. For most of that history, man, and later his animals, were the crucial elements of successful weed control programs. The introduction of the tractor as a power source added a versatile dimension to mechanical control but failed to completely solve the weed problem in cotton.

Mechanical control of weeds is easily implemented and is usually economical, with no possibility of residual chemical problems. Disadvantages are its lack of sustained control with rain resetting or transplanting weeds; the difficulty of controlling weeds growing directly in the drill-row; and its promotion of soil erosion under some conditions. It should be noted, however, that tillage is effective in reducing wind erosion under some conditions. The necessity for the termination of mechanical cultivation with tractors after cotton reaches a certain size is obvious.

BIOLOGICAL METHODS

The concept of biological methods of controlling weeds in cotton has received significant interest over the past several decades. There has been considerable diversity of biological agents employed for weed control, including geese, insects, pathogens, and even nematodes (McWhorter and Chandler, 1982).

To date there have been only a few real successes in controlling specific weeds in agronomic crops, particularly cotton, with biological agents. There have, however, been several rather innovative approaches to employing biological agents. For example, geese will eat seedlings of *Cyperus* spp., *Digitaria* spp., *Sorghum* spp., *Cynodon* spp., and other common weed species, but they will not eat many other weed species often found in cotton (Johnson, 1960; Miller *et al.*, 1962; Mayton *et al.*, 1945). Geese have been used fairly extensively in the Mid-South and Far-West for weed control. Geese require high levels of management for effective utilization as weed control agents. They must be provided supplemental feedings as necessary and clean drinking water at all times (Miller *et al.*, 1962). Geese must be protected from predators such as dogs. Under conditions of extremely high temperature, they must be protected by providing some means of shade. A major problem which enhances the required management is their susceptibility to certain insecticides. Because of this, geese must be relocated prior to insecticide application. Also, it has been shown that while geese would not eat young glanded cotton seedlings they would eat the seedlings of glandless strains.

It was estimated in a California study that it cost $13 per acre to use geese for controlling weeds in cotton. This included the cost of the geese, necessary fencing, supplemental feeding, water and labor. While this was a very reasonable cost, due to the availability of more selective herbicides during the late 1960s, the use of geese for weed control in cotton has decreased in popularity (Danielson *et al.*, 1972; Kempen, 1987).

Silverleaf nightshade (*Solanum elaeagnifolium Cav.*) is an economically important weed in cotton in the southwestern United States. It is naturally parasitized by the parasitic nematode *Orrina phyllobia* (Thorne, Brzeski) (Orr *et al.*, 1975 a, b). Invasion of this host-specific, leaf-feeding nematode either severely stunts or kills the nightshade plant. Unfortunately, this has not resulted in satisfactory control of this weed on a widespread basis. On the other hand, effective control of northern jointvetch (*Aeschynomene virginica L. (B.S.P.)* in rice (*Oryza sativa* L.) and soybeans with the fungus *Colletotrichum gloeosporioides (Penz.)* Sacc. f. sp. *aeschynomenes* is an encouraging indication that biological agents will be developed for major weeds of cotton (Smith *et al.*, 1973; Templeton, 1982). This concept has been referred to as the "mycoherbicide" approach to weed control (Templeton, 1986).

Further support is provided by the more recent successful results of the effectiveness of the fungus *Alternaria cassiae* (Jurair and Kahn) in control of sicklepod (*Cassia obtusifolia*), a major weed problem in cotton in the southeastern United States (Charudattan *et al.*, 1986). These results were based on an extensive series of experiments across much of the South. Probably the most exciting development in the biological control area has been the effectiveness of rust (*Puccinia canaliculata* (Schw.) Lagerh.) (Callaway *et al.*, 1987; Phatak *et al.*, 1983) for control of yellow nutsedge, which is not only a serious weed in cotton, but is among the most devastating weeds in the world (Holm *et al.*, 1977).

Effective use of some biological agents to control weeds provides a remarkably high degree of selectivity at a modest cost. Unfortunately, the cost of development of such agents is often exceedingly high, and for many species of weeds there are few, if any, pathogens or other biotic agents that can be successfully used for weeding cotton. The major drawback, however, is that most cotton fields are infested with several widely differing weed species. Consequently, multiple pathogens or additional weed control measures would be required for effective control.

RADIANT AND UHF ELECTROMAGNETIC ENERGY

Flame for control of undesired vegetation has been used for hundreds of years. The "slash and burn" agriculture that exists, even today, in some parts of the world employs this method. Much of the eastern part of this country was originally cleared by fire.

The use of flame cultivation as early as 1947 was revealed in an unpublished Texas survey (Table 1). However, the first recommendation of flame as a means of controlling weeds occurred in 1959 (Miller *et al.*, 1962; Holstun *et al.*, 1960).

The emergence of flame cultivation was stimulated by development of the flame burner. Inexpensive natural gas, usually butane or propane, that was both cheap and abundant in the 1950s, was the crucial ingredient that stimulated the interest in flame weed control (Figure 5). Early in the development of the concept



Figure 5. An early model of a flame cultivator used to control weeds and cotton. (Photo courtesy Delta Branch Experiment Station.)

Table 1. Flame cultivator used in Texas from 1960 to 1973.[1]

Year	Flame cultivators in use
1960	0
1961	0
1962	3,375
1963	2,164
1964	2,181
1965	3,876
1966	1,502
1967	1,461
1968	762
1969	490
1970	376
1971	282
1972	282
1973	170

[1]Data compiled from county agent annual reports by Cotton Specialist Fred C. Elliott, Texas Agricultural Extension Service, Texas A&M University, College Station, Texas.

of flame cultivation, it was realized that the crop plant must have a relatively tough bark for successful employment of this procedure. Cotton, of course, met this requirement. Use of flame was usually not employed until cotton stems were about 3/16-inch in diameter at ground level and plants were about 8 inches tall. Employed under these conditions and directed under the cotton plant, flame cultivation did not reduce the yield of cotton.

During the 1950s with readily available and inexpensive natural gases, the total cost of flame cultivation was only about $1.30 per acre. It was not unusual to use five to seven flame cultivations in a single season (Miller *et al.*, 1962).

Flame is effective on a wide range of weed species, particularly when weeds are small (less that two inches tall), and flame is used repeatedly over the season (Holstun *et al.*, 1960). Flame is relatively ineffective after broadleaf weeds are four to five inches tall. Improvements in flame cultivators increased the effectiveness of this means of controlling weeds (Figure 6).

From its inception, flame cultivation was considered to be supplementary to other methods of control. It is generally far less effective when employed as the primary means of weed control. Since there is no residual control associated with flaming, repeated treatments are necessary.

Flame cultivation has an advantage in that it can be employed when soils are wet, does not disturb the soil, and leaves no chemical residue. Even so, this technique is rarely used today. The emergence of effective herbicides and the

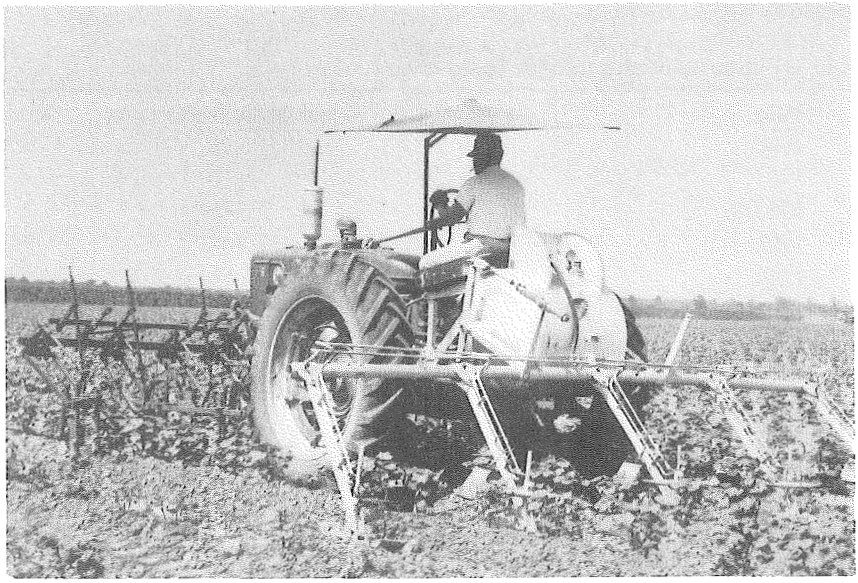


Figure 6. A later model of a flame cultivator used for flaming cotton. Note the simplicity and evolution of this piece of equipment as compared to that shown in Figure 5. (Photo courtesy Delta Branch Experiment Station.)

escalating price of natural gases are primarily responsible for the loss of interest in flame cultivation, and it is quite unlikely that this will be a viable component of weed management systems in cotton in the future.

Use of ultra-high frequency electromagnetic energy as a weed control method received some interest in the early 1970s (Davis *et al.*, 1971, 1973). Investigation showed that *Amaranthus* spp., a major weed of cotton, could be controlled under field conditions with exposure to 360J/cm^2 (Menges and Wayland, 1974). Because of excessive cost of energy generation and other technical difficulties, this method has not evolved beyond the novelty stage.

CHEMICAL METHODS

The emergence of safe, effective, and relatively inexpensive agricultural chemicals, particularly herbicides, remains one of the most significant agricultural developments in the entire history of agriculture. It is difficult to imagine that the era of highly effective, selective herbicides is only as recent as the end of World War II.

Cotton farmers, along with peanut farmers and a few others, were early adopters of the emerging technology of chemical weed control. The increasing scarcity and high cost of hand labor and the necessity for a clean field to ensure acceptable yields and market quality contributed to the rapid acceptance of the chemical method of controlling weeds in cotton. The relatively long (nine to ten

weeks) period that weeds must be controlled before cotton becomes competitive further increased the grower's interest in methods of controlling weeds that had residual effects.

In addition to the above factors, farmers were attracted to chemicals and other new methods for controlling weeds in cotton for the simple reason that existing methods were not fully satisfactory. While the problems with labor were extremely difficult to manage, probably the most important factor in the rapid acceptance of the chemical method of controlling weeds was that herbicides were effective and highly versatile with regard to placement, method and time of application.

In the basic agronomy textbook, Principles of Field Crop Production (Martin and Leonard, 1949 edition), not a single mention is made of herbicides. Indeed, only a brief section is devoted to the control of weeds in cotton.

Special non-fortified (phytotoxic) oils were among the first chemicals used for weed control in cotton in the early 1950s (Table 2). Effective and inexpensive petroleum products made the phytotoxic oils a cost effective means of controlling weeds for a number of years.

Petroleum fractions, commonly referred to as naphthas, with a boiling range of 302F (150C) to 392F (200C) containing 18 to 25 percent aromatic compounds are the most satisfactory herbicidal oils for controlling weeds in cotton (Colwick, 1960). The herbicidal naphthas were among the first chemicals available for post-emergence weed control in cotton (Talley, 1950). Used properly under appropriate conditions, they were highly effective in controlling a wide range of weed species, especially young grasses and broadleaf weeds (Holstun and McWhorter, 1965).

The herbicidal naphthas were also great educational tools. Because they were highly phytotoxic to cotton foliage, farmers learned the necessity of careful application techniques. Successful use required properly designed and adjusted application equipment and a good, debris-free seedbed (Figure 7). There are also certain environmental conditions required for successful use. Grower experience with the herbicidal naphthas paved the way for successful use of the new generation of herbicides soon to follow.

An interesting and very important part of the development of herbicides for weed control in cotton was provided by the introduction of the dinitro compounds. Davis (1964) noted "The spectacular rise and fall of interest in the dinitro-[2]compounds between 1950 and 1956 represents one of the most valuable lessons that we have learned in weed research in the past 15 years." Various amine salts of dinoseb (Premerge®) applied preemergence had shown generally favorable results for selective weed control in cotton prior to 1952 (Cowart *et al.*, 1950; Harris *et al.*, 1950). Although there had been some scattered evidence of a potential hazard to cotton from dinoseb, considerable acreage was treated in

[2]The most common material in this general group is dinoseb (4,6-dinitro-o-*sec* butylphenol) usually formulated as an amine salt.

Table 2. Herbicides used in cotton in the United States.

Common name	Trade name	Year of introduction
dinoseb	Premerge 3®	1947
herbicinal	Naphthas	1952
chlorphopham	Chloro IPC®	1950
dalapon	Dowpon®	1953
diuron	Karmex®	1954
DCPA	Dacthal®	1956
EPTC	Eptam®	1961
DSMA	(several)	1963
MSMA	(several)	1963
trifluralin	Treflan®	1963
norea	Herban®	1963
monuron	Telvar®	1963
dicryl	Dicryl®	1963
sodium chlorate	(several)	1966
nitralin	Planavin®	1968
linuron	Lorox®	1962
fluometuron	Cotoran®	1964
prometryn	Caparol®	1964
bensulide	Prefar®	1968
paraquat	Paraquat CL	1965
alachlor	Lasso®	1969
dipropetryn	Sancap®	1973
profluralin	Tolban®	1975
dinitramine	Cobex®	1971
norflurazon	Zorial®	1975
fluchloralin	Basalin®	1976
pendimethalin	Prowl®	1976
oryzalin	Surflan®	1976
methazole	Probe®	1976
perfluidone	Destun®	1979
cyanazine	Bladex®	1972
glyphosate	Roundup®	1974
sethoxydim	Poast®	1982
fluazifop	Fusilade®	1982
metolachlor	Dual®	1984
oxfluorfen	Goal®	1984

(Chandler, 1984; Herbicide Handbook, Weed Sci. Soc. Amer. (1974), 430 pp.; Herbicide Handbook, Weed Sci. Soc. Amer. (1979), 479 pp.)

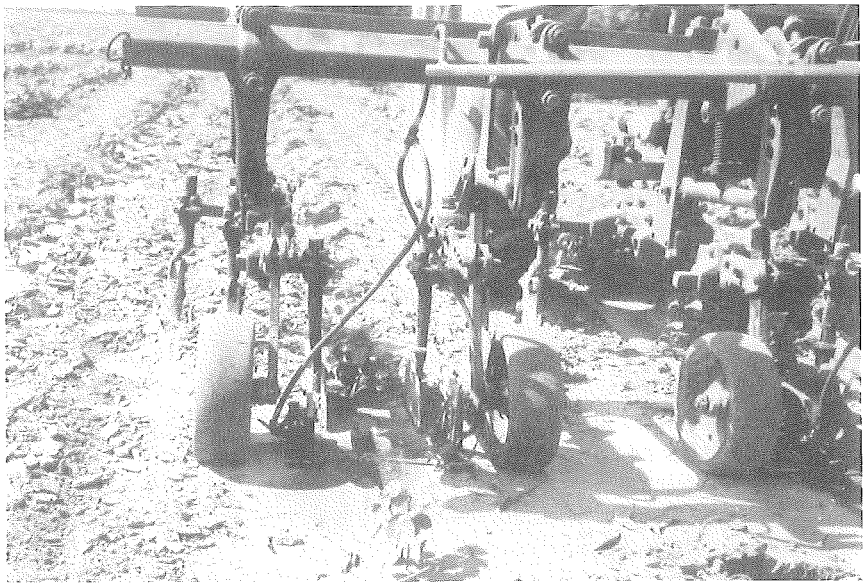


Figure 7. Pictured here is a typical device used for applying herbicidal naphthas to cotton. A relatively smooth debris-free seedbed was an absolute must to effectively utilize this technique for controlling weeds in cotton. (Photo courtesy Delta Branch Experiment Station.)

1952. Unfortunately, several hundred acres of cotton were either killed or severely injured. An intense scientific investigation quickly followed leading to the conclusion that soil type, rainfall, soil pH, and temperature influence the phytotoxicity of dinoseb to cotton (Davis, 1956; Davis and Davis, 1954; Davis *et al.*, 1954; Barrons *et al.*, 1953). Further investigation showed the importance of phytotoxicity of these compounds through vapor action (Hollingsworth and Ennis, 1953) and that cotton is not much more tolerant to dinoseb than are the weeds it is intended to control (Davis, 1964).

While the above incident was quite unfortunate for the cotton farmers and others, it did provide a very real learning experience and valuable lesson that ultimately was helpful in the future development of herbicides for weed control in cotton. It clearly pointed out the potential pitfalls associated with this new weed control technology and revealed the latent need for better and more effective means of controlling weeds in cotton.

The search for more selective herbicides for weed control in cotton continued through the 1950s. Chlorpropham (Chloro IPC®) was introduced about the same time as dinoseb, and monuron (Telvar®) and diuron (Karmex®) somewhat later. These were far more selective herbicides for cotton than was dinoseb, although monuron was occasionally phytotoxic. Each of these herbicides is applied preemergence. Dalapon (Dowpon®), which was introduced during the 1950s, exhib-

ited excellent postemergence activity against johnsongrass, a potentially troublesome perennial grass in cotton. Dalapon proved to be too phytotoxic to apply as an overall spray to cotton, but worked quite nicely when used as a spot-directed treatment (Swezey and Fisher, 1955; Watson, 1955).

Development of selective herbicides continued slowly but steadily throughout the 1950s. However, even by 1963, most cotton producing states recommended only three herbicides—diuron, chlorpropham and dalapon—along with herbicidal naphthas for weed control in cotton (Standifer, 1964).

A number of new herbicides were introduced during the 1960s. The importance of some of these herbicides was exceedingly far-reaching and impacted dramatically on cotton production in the United States.

The introduction and rapid acceptance of trifluralin (Treflan®), a dinitroaniline, added a new herbicide to the cotton farmer's arsenal of weed control agents and also ushered in the new concept of soil incorporation of herbicides. The farmers have employed numerous types of devices to incorporate herbicides into the soil (Figure 8); however, the conventional disk harrow remains the most commonly used device for this purpose (Figure 9).

Trifluralin was followed later in the 1960s by nitralin (Planavin®), another dinitroaniline herbicide that required soil incorporation. This herbicide remained on the market for only a few years.

The severe problem of nutsedge stimulated interest in the thiocarbamates. Use of EPTC (Eptam®), a thiocarbamate, as an injected treatment was developed and used for a few years (Wooten *et al.*, 1966; Holstun *et al.*, 1963). Short residual and the narrow margin of safety contributed to the loss of interest in this weed control treatment for cotton.

While the herbicidal naphthas were used widely during the 1960s, there was still interest in more selective postemergence herbicides. The organic arsenicals, DSMA and MSMA, met this requirement and have been widely used since, often in combination with other herbicides which have residual activity. The excellent activity of the arsenicals, particularly MSMA, on annual grasses and substantial activity on nutsedge (*Cyperus* spp.) and *Sorghum* spp. has resulted in extensive use of these herbicides. These herbicides along with the introduction of paraquat (Gramoxone®) continued to stimulate interest in equipment to apply herbicides as directed sprays. Numerous designs have been conceived and pieces of equipment have been developed for applying herbicides in this manner (Figure 10).

A number of other herbicides, some of which are still in use today, were also introduced during the 1960s. Fluometuron (Cotoran®, Lanex®), introduced during the 1960s, has proven to be one of the most successful preemergence applied herbicides yet for weed control in cotton. Several other herbicides introduced and used during the 1960s have either been discontinued or used very little during recent years. These include norea (Herban®) and dicryl (Dicryl®).

There were few truly major developments in herbicides for cotton weed control during the 1970s. Several dinitroanilines, including pendimethalin (Prowl®),

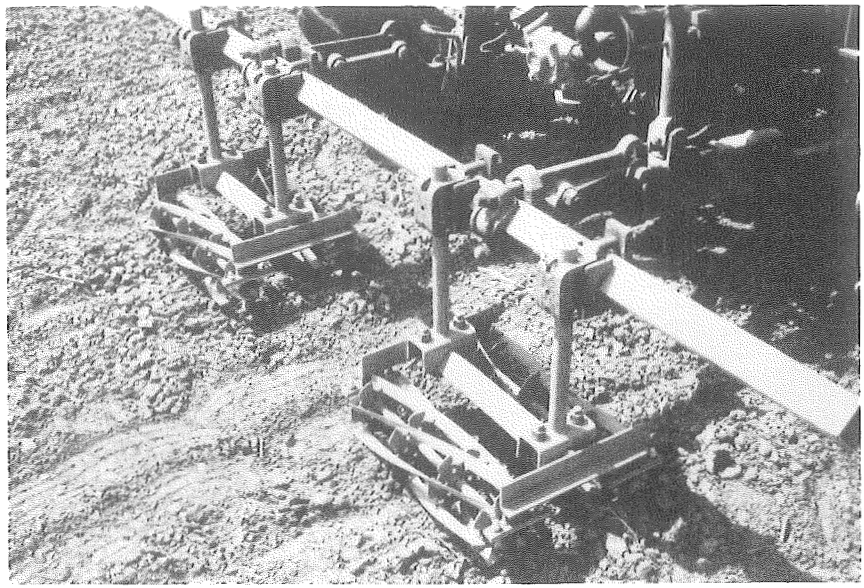


Figure 8. One of many such devices used to incorporate trifluralin in cotton soils. The concept of incorporation was ushered in primarily with the introduction of this herbicide in the mid 1960s. Such devices as pictured above generally have given more uniform incorporation of herbicides than does the conventional disk harrow.

fluchloralin (Basalin®), profluralin (Tolban®), oryzalin (Surflan®) and dinitramine (Cobex®), became available and were developed for cotton. None of these was substantially better than trifluralin, which was developed during the mid-60s.

Glyphosate (Roundup®), introduced in the 1970s, gives excellent control of several particularly difficult to control weeds such as bermudagrass (*Cynodon* spp.) and johnsongrass (*Sorghum* spp.), as well as a number of annual and perennial weeds. Since glyphosate is highly phytotoxic to cotton, special care must be exercised during application. This herbicide was the first material that was truly effective when used in the recirculating sprayer (McWhorter, 1970, 1977). Development of the ropewick applicator (Dale, 1979) and the recirculating wiper (Chandler, 1981) proved to be an even more effective means of applying glyphosate to weeds without causing injury to cotton.

The most significant cotton weed control development during the 1980s was the introduction of herbicides that were highly active against annual and perennial grassweeds, but had little or no activity against broadleaf plants. Sethoxydim (Poast®) and fluazifop (Fusilade®) were introduced during the 1980s and have enjoyed modest success. However, the effectiveness and relatively low cost of the dinitroanilines have provided stiff competition to any new herbicides for grass control in cotton.

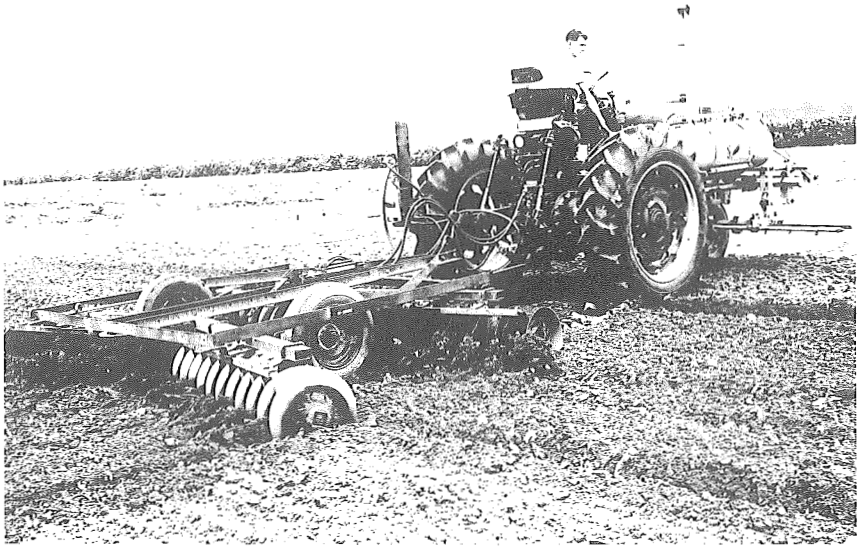


Figure 9. Incorporation of trifluralin with the conventional disk harrow. While not the most effective device for incorporating herbicides, the disk is still the most widely used means of incorporation.

By 1968, 22 herbicides were labeled and used in some areas of the United States in control of weeds in cotton (Holstun and Wooten, 1968). About this same number of chemicals are still available today, although some herbicides have passed into history to be replaced with newer materials (Chandler, 1984).

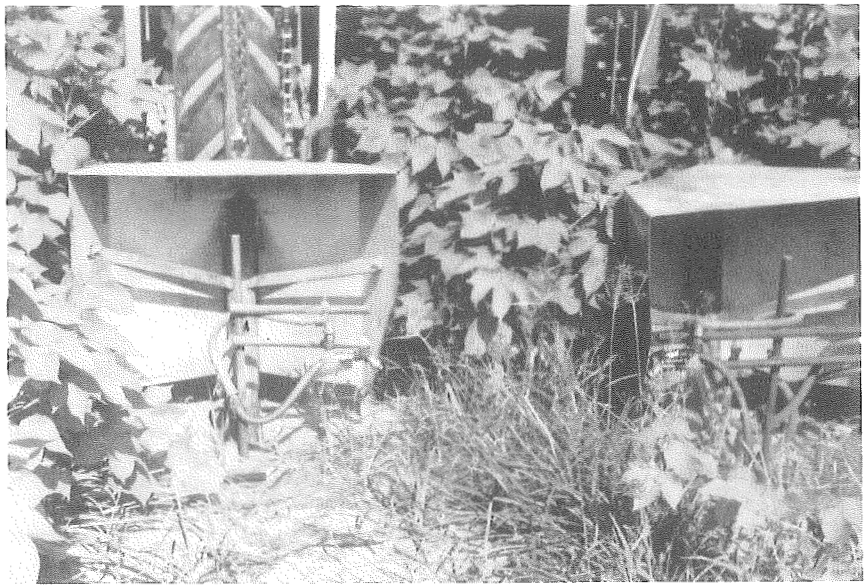


Figure 10. Devices for applying herbicides as directed sprays in cotton have undergone tremendous evolution in equipment since the 1950s. Pictured above is a more recent innovation developed for effectively applying herbicides as directed sprays in cotton. (Photo courtesy Delta Branch Experiment Station.)

Methods of Using Herbicides—Some herbicidal treatment can be used at almost any time during the growth of the cotton plant. Indeed, there are six specific periods in the cotton production cycle that offer an opportunity to use an application of herbicides. These include: applications made preplant to the foliage (PPF); preplant soil incorporated (PPI); preemergence (PRE); postemergence directed (POST/DIR); postemergence over-the-top (POST-OTT); and late postemergence or layby (LP). Herbicides can and often are applied using two or more of these application opportunities in series.

The timing of herbicide applications varies with many factors, and the best cotton growers know that maximum production efficiency demands the minimum number of applications of herbicides that will provide satisfactory weed control. Of course, there must be consideration given to soil and environmental conditions, weed species to be controlled, efficacy and cost of herbicide, level of control desired and other weed control measures employed.

The use of these treatments varies considerably in the different regions of the country. For example, preemergence and directed postemergence treatments are more frequently used in the eastern United States Cotton Belt than in the West (DeBord, 1977). On the other hand, use of preplant foliar treatments are more common in Texas than in Mississippi.

The chemical method of controlling weeds in cotton has been popular for the simple reason that herbicides work. Herbicides are highly selective and can be employed in several different ways at almost any stage of development of cotton. Major problems associated with the use of herbicides are that some are expensive; some may persist in the soil under some conditions; and some may, under some conditions, stunt or otherwise injure the cotton plant.

Problems with Herbicides—The dinitroaniline herbicides may prevent lateral root development of the cotton seedling under some conditions (Anderson *et al.*, 1967; Arle, 1968; Hacskaylo and Amato, 1968; Orr *et al.*, 1969). Research has shown that high rates of trifluralin reduce plant height, lateral root formation and yield (Baker, 1976; Gordon and Frans, 1977; Banks *et al.*, 1977). Deleterious effects of these herbicides are often influenced by adverse growing conditions, interaction with other pesticides and method and depth of incorporation; also, they are often associated with seedling disease.

A "maximum" herbicide program including the highest recommended rate of trifluralin applied preplant incorporated, fluometuron applied preemergence, fluometuron plus MSMA applied as a directed spray, and fluometuron applied post-directed at layby caused early phytotoxicity, reduced yields in some years and reduced earliness of cotton in all years (Gaylor *et al.*,1983).

In some instances there are deleterious interactions of herbicides with other pesticides employed in cotton production. For a number of years researchers have known that the combined use of a substituted urea herbicide such as diuron (Karmex®) and an organo-phosphate insecticide such as phorate (Thimet®) will increase cotton injury as compared to use of either of these pesticides alone (Hacskaylo *et al.*, 1964; Pires and Hacskaylo, 1963; Ranney, 1964).

Imazaquin (Scepter®) at low concentrations has been shown to affect growth of certain crops such as corn (Basham *et al.*, 1987) and cotton (Barnes *et al.*, 1989). Soil concentrations of imazaquin ranging from 0.007 to 0.024 μg/g reduced cotton yields 7 to 42 percent (Barnes *et al.*, 1989). Such herbicide concentrations have occurred in soil samples taken 12 to 24 months following preplant incorporated applications at rates of 140 g/ha.

SYSTEMS APPROACH

It has long been recognized that the best approach to controlling weeds in cotton is to use two or more methods employed in a systematic fashion. Soon after the introduction of herbicides in the early 1950s, investigators began evaluation of weed control systems by combining chemical methods (Harris, 1960; Snipes *et al.*, 1984). One investigator pointed out that combinations of herbicides with cross-cultivation resulted in greater production efficiency (Holstun, 1963). Other researchers have shown that efficiency in controlling weeds is dependent upon the nature of the weed pressure (Stewart *et al.*, 1983). Some investigators

have shown the effectiveness of herbicides applied may vary with different stages of development (Nastasi *et al.*, 1986). Herbicides with excellent activity on a wide range of grass weeds provide greater net return when used as over-the-top sprays following preemergence applications of fluometuron than when following preplant incorporated applications of trifluralin (Nastasi *et al.*, 1986). This research, and other studies using currently available herbicides, clearly show that the employment of chemicals plus mechanical cultivation in a total system that takes into consideration cultural methods, provide the most reliable and economical method of controlling weeds (Nastasi *et al.*, 1986).

A single postemergence application of either fluazifop or sethoxydim following a preemergence application of fluometuron resulted in better control of broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash.] and greater yield and net return than treatment with trifluralin and fluometuron applied preplant incorporated and preemergence, respectively (Byrd and York, 1987). A second application of fluazifop or sethoxydim applied later in the season increased late season control, but did not increase cotton yields or net return.

The systems approach to cotton weed control is sometimes referred to as integrated weed management (IWM). Addressing the problems of weeds in cotton in such a manner is certainly compatible with the integrated pest management (IPM) concept of dealing with cotton insect pests.

EXPECTED TRENDS IN COTTON WEED CONTROL

Of the five basic methods available for controlling weeds in cotton, the cultural method accounts for the greater portion of weed control in the normal cotton growth cycle. While it is difficult to assess the relative importance of field sanitations, planting weed-free seed, and using ideal cotton cultural practices to control weeds in the crop, it is readily observed that cotton grown under these conditions rapidly becomes sufficiently competitive to prevent weed growth. This "critical" period in which weeds must be controlled ranges from six to ten weeks for most cotton grown in the southeastern United States.

Since flame and UHF electromagnetic radiation are essentially discontinued and biological control still is in early developmental stages, weed control during this critical phase must be provided either by mechanical or chemical methods. With prevailing economic conditions, there is little argument that the use of chemical methods to control weeds in the drill row during this six to ten week period is the best alternative. In the row middles and the "skips" of skip-row cotton, the economic relationships are not so clearly defined. Under these conditions mechanical methods would probably be more cost effective. For the foreseeable future, the trend in cotton weed control will be a refinement of these methods into more effective weed management strategies.

FUTURE OUTLOOK OF COTTON WEED CONTROL

It is anticipated that there will be newer and better chemicals as well as improved mechanical devices available for weed control in cotton. The real excitement in controlling weeds in cotton will be more elegant management systems and usage of these methods. It is not unreasonable to expect that a few of our major weeds will be at least partially controlled by utilization of biological agents. Likewise, there are opportunities for the cotton breeder to contribute to better weed control by producing varieties that are better adapted to specific geographical locations and more competitive with weeds.

Utilization of emerging research techniques generally referred to as "biotechnology" will undoubtedly lead to more elegant means for weed control in cotton. It is not unreasonable to expect that such techniques will lead to the development of genetic lines of cotton that have high levels of tolerance to key herbicides. Genetically altered cotton plants would add an important dimension to the greater freedom and effectiveness of the chemical method of controlling weeds in cotton.

The computer will enable the grower to conveniently keep more definitive records about his fields, including weed problems, topography and soil characteristics. This will enable the grower to make early decisions about weed control with greater confidence. A better understanding of the effects of weeds on cotton and the development of more definitive weed action levels or weed response thresholds will contribute to improved economics in the control of weeds in cotton.

Improvements in methods available to the cotton farmer for controlling weeds can be expected. This advantage can be partially offset by newly emerging or changing weed problems. Consequently, the cotton farmer must continue to place emphasis on weed control in order to maximize production efficiency.

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Chapter 4

INTERFERENCE OF WEEDS WITH COTTON

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INTRODUCTION

The term "interference", as applied by the weed scientist, is used to define the negative influence plants exert on each other when growing in association. With respect to weeds growing in cotton, the term is most commonly used to describe the effect of weeds on the crop, although the crop certainly can have detrimental effects on weed populations as well (Street *et al.*, 1981). Weed interference in cotton can be separated into two components: competition and allelopathy.

Competition may occur when two or more plants growing in close proximity to each other draw on the same, limited-supply resource pool. The resources plants may compete for include water, nutrients, light and carbon dioxide. Under certain circumstances, oxygen and space may be considered as resources for plant growth as well. Theoretically, if all resources could be available in unlimited supply, then competition would not occur.

Allelopathy, on the other hand, results when one plant introduces into the environment a substance which is detrimental to other plants in its area of influence. Allelopathic substances are usually complex organic compounds and may be exuded from roots or leached from leaves of living plants or they may result from decaying plant residues.

In field situations, the relative contributions of competition and allelopathy to total interference are very difficult to separate, and little scientific evidence has been presented to support an allelopathic effect of weeds on cotton in the field. One weed species, unicorn-plant, has been reported as containing plant growth substances which could be removed in the laboratory by steam distillation and then applied to cotton causing growth inhibition (Riffle *et al.*, 1987). Similar effects are reported from smooth pigweed extracts (Munger *et al.*, 1984).

Production losses associated with weeds in cotton also include the disruption of management practices for other pests and crop quality reductions caused by weed residues in the harvested crop. Direct interception of insecticide and growth regulator sprays by weeds may cause reduced efficacy from these products and make additional applications necessary. Weeds present in the crop dur-

ing harvest, especially grasses, contribute to cotton grade reductions through their physical presence as trash in the lint or lint staining.

COMPETITIVE EFFECTS OF WEEDS ON COTTON

The net effect of weed competition on cotton is a reduction in the quantity of marketable products, lint and seed, usually through a reduction in the number of bolls per plant (Arle and Hamilton, 1973), although occasionally boll weight and seed number per boll are affected (Arle and Hamilton, 1975). It is this effect on yield that the producer is most concerned with. However, it is sometimes important to understand how and when weed competition occurs in order to plan the most efficient management programs. Timing of control practices, especially cultivation and herbicides, may be critical with many species in order to avoid crop loss.

WEED SPECIES EFFECTS

As with other crops, the degree of competitive damage to cotton caused by a weed population is a function of the species composition, density, and duration of that population. Certain weed species are more competitive than others with cotton because of differences in growth habit. A comparison of the relative competitive abilities of 18 broadleaf weed species with cotton is presented in Table 1. Common cocklebur, with its tall growth habit and large leaves, is the most competitive weed in cotton with nearly nine percent loss in cotton yield resulting from one weed per 30 feet of crop row (Snipes *et al.*, 1982). The next most competitive group of weeds caused from 4.7 to 6.1 percent yield loss per weed per 30 row-feet and included smooth pigweed (Stuart *et al.*, 1984), wild okra and unicorn-plant (Bridges and Chandler, 1984), and tumble pigweed (Rushing *et al.*, 1985b). A group of 11 weed species were reported to cause losses ranging from 1.7 to 3.7 percent per weed per 30 row-feet (Table 1), while prickly sida was the least competitive of the species studied causing only 0.26 percent yield loss at the same weed population (Buchanan *et al.*, 1977). In this comparison, all of the weeds were allowed to compete with the crop for the entire growing season.

Most studies on weed competition have been conducted by comparing only one weed species at a time in the crop. While this information is most useful, very few fields are infested with only one weed species. More studies such as those of Snipes *et al.* (1983) and Street *et al.* (1985) should be conducted in which mixtures of weed species were evaluated with respect to their influence on the crop.

Cotton yield losses associated with certain perennial weeds are difficult to assess on a per-weed basis. Such perennials as bermudagrass and hogpotato are most often found in patches in a field, with the patches consisting of nearly total ground cover. Brown *et al.* (1985) reported losses of 60 to 80 percent resulting from full-season competition with bermudagrass at full ground cover. Hogpo-

Table 1. Relative competitive abilities of selected annual broadleaf weeds in cotton expressed as percent crop yield loss from one weed per 30 row-feet.

Species	Cotton yield loss per weed per 30 row-ft	References
	(%)	
Common cocklebur	8.85	Snipes *et al.*, 1982
Pigweed, smooth	6.06	Stuart *et al.*, 1984
Wild okra	5.33	Bridges and Chandler, 1984
Unicorn-plant	5.03	Bridges and Chandler, 1984
Pigweed, tumble	4.66	Rushing *et al.*, 1985b
Hemp sesbania	3.68	Bryson, 1987
Buffalobur	3.43	Rushing *et al.*, 1985a
Morningglory, tall	3.43	Crowley and Buchanan, 1978
Spurred anoda	2.90	Chandler, 1977
Sicklepod	2.79	Buchanan *et al.*, 1977
Velvetleaf	2.66	Chandler, 1977
Morningglory, entireleaf	2.21	Crowley and Buchanan, 1978
Pigweed, redroot	2.16	Buchanan *et al.*, 1980
Coffee senna	1.87	Higgins *et al.*, 1986
Morningglory, ivyleaf	1.71	Crowley and Buchanan, 1978
Morningglory, pitted	1.71	Crowley and Buchanan, 1978
Jimsonweed	1.01	Oliver *et al.*, 1981
Prickly sida	0.26	Buchanan *et al.*, 1977

tato, a broadleaf perennial found in cotton in Oklahoma, has been reported to cause up to 39 percent yield loss at full ground cover (Castner *et al.*, 1987). The most widespread perennial weeds in cotton are johnsongrass and yellow nutsedge, with both weeds found over the entire cotton growing area. Johnsongrass is the most competitive of the perennial weeds studied, with yield losses of 40 percent reported from infestations of eight johnsongrass plants per 30 feet of row (Bridges and Chandler, 1987; Reynolds *et al.*, 1983). Keeley and Thullen (1981) reported cotton yield loss of nearly one percent for every johnsongrass stem per 10 square feet. Yellow nutsedge, with loss figures in the range of 0.5 percent per plant per 3 feet of row, is less competitive than johnsongrass (Keeley and Thullen, 1975, 1983; Patterson *et al.*, 1980).

WEED DENSITY EFFECTS

In general, the effect of weed density on cotton yield is linear and additive at low weed populations where weeds act independently, and becomes curvilinear at higher weed populations when intraspecific interference among weeds becomes a factor. However, in certain situations the effect of weed density on crop

yield may be sigmoidal. In these circumstances, resources may not be limiting at low weed populations so that no competition can occur. As weed populations increase, resources become limiting and competition begins, in a linear and additive relationship. At high weed populations, intraspecific competition among weeds becomes a factor and the degree of crop loss per weed becomes less, thus the sigmoidal relationship. Bridges and Chandler (1987) illustrated this relationship with johnsongrass influence on cotton. The sigmoidal relationship usually occurs only with those weed species which do not compete aggressively for light with the crop. Any weed species which grows taller than the crop would limit light availability, thus causing competition even at low weed populations, resulting in the linear and additive effect on crop yield (Figure 1).

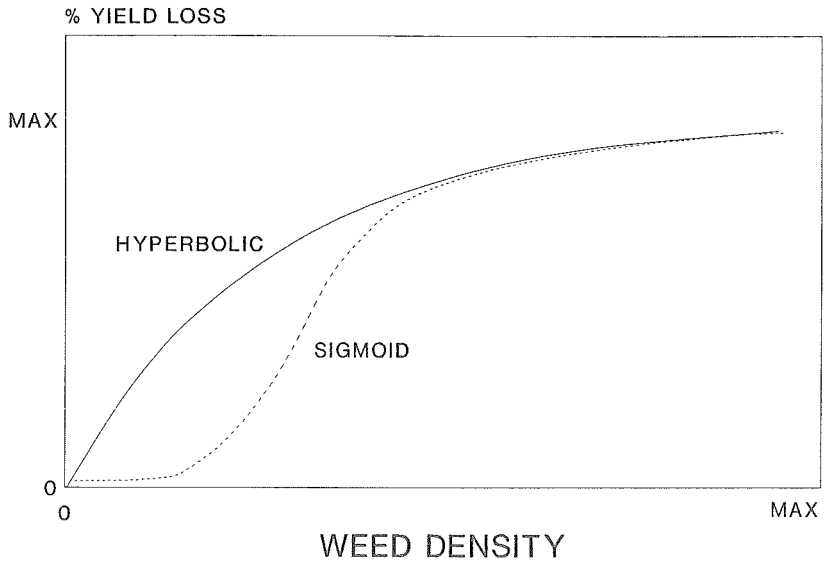


Figure 1. Comparison of the sigmoid shape curve with the hyperbolic shape showing no competitive effect at low weed populations in the sigmoid relationship versus an immediate competitive effect in the hyperbolic curve.

WEED DURATION EFFECTS

The duration of a weed population is probably as important in determining the degree of crop loss caused by weeds as is density. Weeds that emerge at the same time or before the crop are more competitive and cause greater crop loss than those that emerge later (Chandler, 1977; Buchanan *et al.*, 1980; Keeley *et al.*, 1986). Generally, cotton must be kept weed-free for 4 to 8 weeks after emergence in order to avoid crop loss. The more competitive the weed species, the longer the crop must be kept weed-free. Cotton kept free of prickly sida and velvetleaf or spurred anoda for 4 weeks yielded as well as that kept free of weeds for the

entire growing season(Chandler, 1977). However, weed-free periods of at least 8 weeks were required to prevent losses from morningglory (Keeley *et al.*, 1986) and johnsongrass (Bridges and Chandler, 1987).

In situations where weed control is to be practiced postemergence, the length of time that a weed population can remain in the crop without causing a yield reduction depends on the weed species and density. The more competitive species and higher densities must be removed earlier in the crop cycle than less competitive species and lower weed densities. As little as 3 to 4 weeks of johnsongrass competition caused significant yield loss (Bridges and Chandler, 1987), whereas 6 to 7 weeks of prickly sida competition could be tolerated without yield loss (Buchanan *et al.*, 1977).

COMPETITION FOR RESOURCES

Environmental resources for which plants may compete include light, water, nutrients, carbon dioxide, oxygen and space. In a cropping situation such as cotton culture, space is usually not considered a limiting factor since the crop stand is optimized for yield and not number of plants per unit area. In addition, weed control is usually sufficient to keep weed numbers far below the theoretical maximum for the area. In waterlogged soils, oxygen is sometimes limited temporarily. However, soil oxygen levels are usually considered not limiting for plant growth. Likewise, in a field setting, carbon dioxide levels are usually held fairly constant by natural air movements. Therefore, the main environmental resources which are likely to be limiting for plant growth in a cotton/weed association are water, nutrients and light.

Water—At some point during the growing season, water is usually limiting for plant growth except on adequately irrigated fields. Wells *et al.* (1984) found that common cocklebur growing in competition with cotton caused reduced cotton leaf water potential in non-irrigated plots but not in irrigated plots. In that same study, cotton lint yield was reduced 81 percent in dry plots compared to 62 percent reduction in irrigated plots. This study indicates that water was not the only factor involved in the competitive relationship, but certainly played a significant role in the crop yield reduction caused by the weed. In previous studies, Stuart *et al.* (1984) examined the influence of smooth pigweed on cotton water relations and found reduced cotton leaf water potential at weed populations as low as one weed per 2.4 feet of row in non-irrigated fields. In this study, smooth pigweed was able to extract water from deeper in the soil profile than was cotton, thus making the weed a better competitor for limited water than cotton. James *et al.* (1977), found no competition for water between cotton and four species of morningglories under well-watered conditions. Thus it appears that weeds compete effectively with cotton for water under conditions in which water is in limited supply.

Nutrients—In most cropping situations where fertilizer is applied on a regular

basis, plant nutrients are usually not limiting with respect to crop yield potential. In cotton production, nitrogen applications are limited to some degree in order to avoid excessive vegetative plant growth. Under these conditions of limited fertilizer applications, weeds have been shown to compete for nitrogen. Robinson (1976a) showed that the effect of high weed populations (100 percent ground cover) could be offset to some degree by adding additional nitrogen above the recommended rate for the area. Likewise, adding twice the normal rate of nitrogen overcame the yield loss caused by a weed population at one-half the natural population. On the other hand, Buchanan and McLaughlin (1975) found that nitrogen levels had no effect on the cotton/weed relationship. Whether or not competition for nutrients occurs between cotton and weeds probably depends on a number of factors, including weed species, soil moisture status, weed population level, relative emergence dates of the crop and weeds and placement of weeds relative to the crop row (Robinson, 1976b).

Light—Since sunlight is a limited resource, any weed that grows taller than cotton will shade the crop, thus effectively competing for available light. Cotton has been shown to be relatively intolerant to shade, with even high numbers of cloudy days leading to shedding of squares and bolls (Goodman, 1955; Mason, 1922). Shading by tall-growing weeds has been highly correlated with square and boll abscission as well (Hearn, 1976; Guinn, 1982). In a study aimed primarily at elucidating competitive relationships for water, Stuart *et al.* (1984) found that late in the growing season, smooth pigweed reduced the total light reaching the cotton canopy by 90 percent, resulting in a 62 percent lint yield reduction. This yield reduction was attributed to light interference since the plots were irrigated to avoid competition for water. Additional evidence of light competition has been presented by Andries *et al.* (1974) when they showed that normal leaf cotton was more competitive with weeds than okra-leaf or super okra-leaf cultivars. These narrow-leaf types allowed more light to reach the weeds resulting in more weed growth, especially at wide row spacings.

Several weeds have been shown to utilize light more efficiently than cotton (Patterson *et al.*, 1978), and are able to gain a height advantage over the crop in a relatively short time. Chandler (1977) showed that velvetleaf and spurred anoda were both nearly 50 percent taller than cotton by 10 weeks into the growing season, thus competing very effectively with the crop for light. Both weed species caused significant yield reductions in the crop. Venice mallow, however, never grew as tall as the cotton and caused no yield reduction. The growth and development of yellow nutsedge has been shown to be reduced due to light interception by cotton if the crop emerges before the weeds (Keeley and Thullen, 1978). Most studies have shown that removal of weeds by 6 to 8 weeks after crop emergence in cotton will eliminate yield losses. This seems to be sound evidence that light is the most important resource in plant competition.

ENVIRONMENTAL AND CULTURAL EFFECTS ON COMPETITION

The relative competitive abilities of both crops and weeds may be influenced to a great extent by environmental conditions. Temperature, even within the range of normal crop growth, can influence resource capture and utilization by all plants. Cotton is particularly suited to warm weather, and often grows very slowly early in the season because of cool weather. Several studies have shown most weeds to be more tolerant of cool weather than cotton, with the crop growth rate reduced far more than that of the weeds at lower temperatures (Flint *et al.*, 1983; Patterson and Flint, 1979; Potter, 1976). This differential growth rate between the crop and weeds allows the weed population to gain a competitive advantage earlier in the growing season, thus becoming even more competitive than it otherwise might be. Soil type is another factor affecting the expression of weed competition in cotton. Coarse textured soils with inherently low water and nutrient holding capacities obviously lead to competition for these two resources more readily than the finer textured soils. Also, soils which tend to form hardpans may alter the competitive relationships by severely restricting root growth.

Geographic region has been shown to exert an effect on relative competitive abilities of weeds in cotton (Oliver *et al.*, 1981). The effect of geographic region is usually one of differential weather and soil patterns. However, it is certainly possible that weeds may grow more aggressively in one latitude than in another simply due to daylength.

Changing cultural practices such as row spacing and crop cultivar may alter the competitive relationship between cotton and weeds. Several studies have shown that narrow row spacings will lead to decreased weed competition late in the season if weeds are kept out of the field for the first 3 to 4 weeks of the crop cycle (Andries *et al.*, 1974; Rogers *et al.*, 1976; Street *et al.*, 1981). Narrow rows lead to a full crop canopy sooner and shifts the competitive edge for light in favor of the crop. Unless weeds are kept out of the crop with some early-season control measure, there is no advantage to the narrow rows. Cotton cultivars that either grow taller or have more dense foliage are better competitors for light than other types (Chandler and Meredith, 1983). However, regardless of the cultivar, early-season weed control is necessary since the cultivar effect of increased shade is effective only after light competition begins, usually around 8 to 10 weeks after emergence. In general, any cultural practice which leads to a faster growing crop will give the crop a competitive advantage over weeds. Cotton is especially sensitive in this respect since it grows very slowly early in the season unless conditions are very favorable, and weeds most often have the advantage.

ALLELOPATHIC EFFECTS OF WEEDS ON COTTON

Certain weeds seem to cause greater crop yield loss than can easily be accounted for by competition. One such weed, unicorn-plant, has been found to contain compounds which can be extracted by laboratory procedures that are very inhibitory to cotton growth (Riffle *et al.*, 1987). Whether or not these same compounds are effective under field conditions has not yet been determined, but the mere existence of such allelopathic chemicals in weeds certainly holds open the possibility. Additional evidence that allelopathy might exist in the field comes from studies by Munger *et al.* (1984) in which smooth pigweed extracts were found to be toxic to field grown cotton.

In a study designed to establish optimum cover crop levels, lupine was found to have a stimulatory effect on cotton at low rates of application but at high rates was inhibitory (Lehle and Frans, 1974). This reversal of effect at increasing application levels is typical of some of the identified allelopathic chemicals. Additional research work is needed to determine which weeds may contain allelopathic compounds and if allelopathy is an effective interference mechanism in the field.

PRODUCTION LOSSES ASSOCIATED WITH WEED INTERFERENCE

Weeds may interfere with harvest operations by slowing the speed of harvest equipment. However, high populations of weeds are usually required before an effect on harvester speed occurs, and yield losses would already be so high in these cases that harvest speed is probably secondary. Some weeds are known to interfere with harvest through physically interfering with lint removal by the picker. Such species as unicorn-plant and jimsonweed have seed pods with hooked spines that may trap a significant amount of lint, thus reducing the effective yield.

Cotton quality reductions caused by trash and lint staining are common weed effects. Annual and perennial grasses may still be green at cotton harvest unless they have been desiccated chemically or by frost. The harvest operation may crush the green leaves and stems of the grass plants and release enough chlorophyll to cause significant green staining of the lint, thus leading to grade reductions (Garner and Bowen, 1961).

Significant weed populations late in the growing season may contribute to increased damage from other pests. The dense foliage of late-season weeds will cause moisture levels within the cotton canopy to be higher, creating an ideal environment for development of diseases such as boll rot. Many growers use growth regulators to keep the crop from developing excessive vegetative growth, which is also associated with boll rot. Weeds interfere with the application of growth regulators through physically intercepting the chemical spray. In addition

to increasing disease incidence, weeds also interfere with control practices for insects and mites by interfering with pesticide spray applications and by serving as alternate hosts for some of the insect pests that infest cotton. Pest management practices such as stalk cutting are also made more difficult by the presence of weeds.

SUMMARY

Weeds may interfere with cotton through competition for available resources including water, nutrients and light. The degree of competition is a function of the weed species composition of the population, the weed population density and the duration of the population. In addition, competition for these resources is regulated by the availability of the resource being competed for, the level of environmental conditions such as temperature, and cultural practices such as row spacing and cotton cultivar. The consequence of competition that is of major concern is the crop yield loss, usually as a result of fewer bolls per plant in weed-infested areas. Allelopathy, another component of interference, may also be important, although limited evidence exists for this phenomenon in the field. Production losses associated with weed interference may occur at harvest or through disruption of other management operations. Studies on weed interference have been conducted in all areas of the Cotton Belt, but more research is necessary in all areas in order to have a full understanding of the effects of weed interference.

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Chapter 5

ECONOMICS OF COTTON LOSSES CAUSED BY WEEDS

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INTRODUCTION

Man produces crops such as cotton under a controlled environment or pure culture. This is contrary to nature's ways where no one plant species can fully exploit the resources of a habitat. Thus, as long as there has been agriculture, growers have fought weeds. The universal occurrence of weeds as constant components of agricultural environments as opposed to the epidemic nature of other pests has delayed recognition of the importance of weed control in crop production. Weed control is one of the oldest agricultural practices, yet, one of the newest to receive scientific attention. In general, absence of weed control in a crop may result in no return for that crop regardless of other inputs (Harlan and DeWit, 1965; DeWit and Harlan, 1975).

Weeds are natural occurrences in the agricultural monoculture ecosystem created by man's food and fiber production systems. Cotton losses due to the presence of weeds may occur in several ways, although damage caused is not always as obvious as losses caused by other pests. These losses occur at various stages in the cotton production cycle. Weeds (a) reduce seed cotton yields; (b) reduce the quality of the cotton fiber; (c) increase production costs (costs of hand weeding, mechanical tillage, fertilizer and herbicides); (d) impede efficient irrigation and water management; (e) reduce market value of the land; (f) serve as hosts and habitats for insects, disease-causing organisms, nematodes and rodents; and (g) can cause allergenic reactions in humans (Shaw, 1964). Prior to the early 1900s, weeds in cotton were controlled by hand-hoeing. In the early 1900s, a combination of five to seven mechanical cultivations and hand-hoeing provided adequate weed control. The amount of tillage utilized was determined largely by the kind

and number of weeds, economic conditions and prevailing weather (Cates, 1917). Manpower for mechanical cultivation with half-row mule equipment required 24.3 man hours per acre in 1937-38 and 13.2 man hours per acre for one-row mule cultivation. During the same years, 33 man hours of labor per acre were required for chopping and hoeing (Langsford and Thibodeaux, 1939). The change from animal power to tractor power for cultivating cotton occurred very rapidly between 1939 to 1946 (Brown and Ware, 1958). This change to tractor power made possible more timely weed control, but control methods were very similar to those used with animal power. Tillage and crop rotations were the major methods of weed control in cotton prior to 1946.

In the early 1950s, weed control was the last key needed to complete mechanization of cotton production. It was noted that not until hoe labor was completely eliminated would the efficiencies and economics inherent in mechanization be fully realized. An integral part of this mechanization was use of preemergence chemicals and postemergence herbicidal oils (Crowe and Holstun, 1953). During the 1950s, it was stated that none of the weed control techniques were completely effective and that weed control must be a program instead of a technique. Willard (1951) states "what is particularly needed now is to work out the most economical combination of chemical and cultural methods for each weed in each crop under the widely varied conditions represented in this country". Some 20 years later, a producer made the following statement: "In order to remain in the cotton production business, an economical, effective, flexible herbicide plan is an absolute necessity for any cotton producer. This plan must be designed to meet wide weather variation; and while eliminating the necessity of all hand labor which is either unavailable or impractical to use, must also be combined with other equipment operations or eliminate their necessity for further improved efficiency and cost reduction. It is not the herbicide cost, but the elimination of many other costs or elimination of losses of income that determine the real savings and efficiency in a complete, effective cotton herbicide program" (Eller, 1971).

ECONOMICS OF CURRENT COTTON WEED MANAGEMENT SYSTEMS

In highly developed cotton production systems, where weed control is an integral part of production, increased costs of herbicides and fuel in the early 1980s focused attention toward integrated weed management systems. These systems, involving the judicious integration of manual (i.e. hand-hoeing), cultural, mechanical and chemical control procedures, have been developed and refined to current levels of use over the past four decades. During this period, producers shifted from a previously labor-intensive production system to intensive use of herbicides as the integral component for controlling weeds. In 1952, only five percent of the cotton acreage was treated with herbicides to control weeds, but

by 1966, the level had risen to 52 percent (Strickler and Hinson, 1962; Fox *et al.*, 1968). Cotton acreage treated with herbicides in 1971 and 1982 was 82 and 97 percent, respectively, and apparently has leveled off with only 94 percent of the acreage treated in 1987 (Andrilenas, 1975; Delvo and Hanthorn, 1983; Delvo, 1988). In the United States, total herbicide purchases for cotton in 1978, 1980, and 1985 were $128, $142 and $125 million, respectively (Anonymous, 1979; Anonymous, 1981; Anonymous, 1985).

Increasing costs of cotton production lowers producer's tolerance of production losses caused by weeds. The development of an economical and effective weed control program is critical to producers since expenditures on weed control further limit the resources that a producer is able to invest toward increasing production efficiency. In developing a weed control program for cotton, the producer must: (a) select the most effective herbicides; (b) consider application equipment and techniques; (c) address timing of herbicide applications; and (d) evaluate the potential use of spot treatments and supplemental hand-hoeing (Holstun and Wooten, 1966).

This chapter will address several components of weed control costs in cotton production in the United States. The first of these is actual cost of inputs used to control weeds in cotton. To do this the cost of each practice and input must be determined. To provide data which can be aggregated, weed control costs are reported for each cotton producing state, or major cotton producing region within a state. The determination of per-acre weed control costs can be done several ways. The method for development of this chapter seems to be most appropriate in providing reliable comparisons between regions and states and was consistent with time and monetary constraints.

Weed scientists or extension cotton specialists in each state were asked to provide for each major subregion in their state the usual inputs, i.e., practices, equipment and size, herbicides and rates, and hoe labor, used for weed control in cotton in 1985. The costs of inputs, i.e., equipment, herbicides and wage rates, vary widely between regions and states and are often not available. Even when they are available, methods of collecting such data vary so greatly that making comparisons between states may not be meaningful. For these reasons machinery, herbicide and labor costs for Mississippi were used for all regions (Williams *et al.*, 1985). The use of Mississippi input costs will result in some under statement of machinery and herbicide costs in many regions. The Mississippi labor rates are the minimum required by law. Wage rates, especially for hand-hoeing, vary greatly from state to state.

The use of specific data from each state reflects the latest technology and makes comparisons between regions and states meaningful. Experience indicates, however, that cotton specialists may tend to report recommended practices rather than usual practices. Thus the weed control costs reported here are somewhat higher than those reported from surveys attempting to measure average cost (Williams *et al.*, 1985). Tables 1 through 17 report regional, state and

national costs of weed control inputs for cotton as estimated by the various state cotton weed scientists and specialists.

The second aspect addressed in this chapter is yield reductions and value of these reductions resulting from weed competition. The estimates of reductions in yields and income utilize 1985 production and prices for each cotton growing state. These data are presented in Table 18. The ten most frequently reported weeds that cause cotton yield losses and the degree of loss is presented in Table 20. Table 21 indicates reductions due to weeds for cotton at four different yield potentials and four possible prices.

This chapter also attempts to assess economic losses associated with bales classed "grassy" in the United States from 1961 through 1986. Table 19 presents total bales by year, number of grassy bales and percent of the crop classed grassy. These data are taken from published reports of the Cotton Division, Agricultural Marketing Service, USDA. As the size of the crop and demand for the crop in any given year affect premiums and discounts for specific grades of cotton, it would be extremely difficult to determine the average discount for a grassy bale for each of the years included in this report. For this reason, as well as the desire to use constant dollars, the average difference between grades 41-34 and 51-34, as expressed in terms of loan values for the years 1983 through 1987, plus one cent a pound were used to establish a differential between average grade and staple and grassy bales in this evaluation. Personal communications with Mr. Hollis Bowling, Assistant Chief, Market News, Cotton Division, AMS, Memphis, Tennessee, and Mr. Larry Creed, Director, Cotton Division, AMS Classing Office, Greenwood, Mississippi, suggested that this discount would most accurately reflect prices paid for grassy bales. Thus, an average price difference of one full grade plus one cent per pound or 5.58 cents or $26.78 per bale was used in this evaluation.

The production system used by a producer and the development of an integrated weed management system may be unique for each individual field due to the great diversity in environment. However, within broad production regions throughout the Cotton Belt, general or typical weed control systems can be identified (Tables 1 to 16). The total cost for full-season weed control varied from $19.31 per acre in the Southern High Plains of Texas to $67.18 per acre in Arkansas (Tables 8 and 13). In the Southeastern states (AL, GA, FL, NC, SC, TN) excluding South Carolina and Tennessee, the average costs for full-season weed control was $41.87 per acre. The average for South Carolina and Tennessee was $53.20 per acre where an additional cultivation and post-directed herbicide application were required. In the Mid-South (AR, LA, MS, MO), the average cost for Mississippi and Arkansas was $64.62 per acre while the average cost for Missouri and Louisiana was $43.23 per acre. In the Southwest (OK, TX), the cost for full-season weed control was greatly affected by level of moisture available to the crop. In Oklahoma, cost for full-season weed control was $25.58 and $46.13 per acre for dryland and irrigated production systems, respectively (Table 12). In

Texas, the cost of full-season weed control ranged from $19.31 per acre in the Southern High Plains to $37.17 per acre in the Coastal Bend and South Texas areas where the annual rainfall is much higher and the season is longer (Table 13). In the West (AZ, CA, NM) irrigated cotton, the average cost of a full-season weed control program was $58.19 per acre.

The use of a preplant incorporated dinitroaniline herbicide (Treflan® or Prowl®) was common to all regions. In Arkansas, Louisiana, and Mississippi, a half rate at 0.75 lb per acre of norflurazon (Zorial®) applied preplant incorporated was also a common practice. There was some variation in the type of incorporation implement used with the disk most widely used. Timing of application was late winter to early spring except in the Coastal Bend and South Texas regions where an early fall application was made. The early fall application necessitates use of winter tillage to control winter annual broadleaf weeds. The total cost of applying a preplant incorporated herbicide ranged from $9.01 to $19.48 per acre with an overall average of $14.86 per acre.

At planting, a preemergence herbicide was banded over the crop row in all regions except in the dryland production region of Oklahoma (Table 12), the West (Tables 14-16) irrigated cotton where chemical activation can be a problem and in Florida (Table 3) where the preemergence treatment was applied broadcast. Where the herbicide was banded, the total cost ranged from $2.51 to $8.04 per acre with an overall average of $5.64 per acre.

Cotton fields in the Southeast and Mid-South are cultivated three or four times during the growing season with the exception of Florida where a typical weed control program contained only two cultivations. In the Southwest and West, two or three cultivations were required. The cost of a single cultivation ranged between $4 to $5 per acre depending on size of equipment. Where twelve-row equipment is used, the cost was lowered to $2.50 per acre. Most directed postemergence applications of herbicides are in conjunction with a cultivation. Generally, one to two directed postemergence herbicide applications are made prior to cotton blooming in the Southeast and Mid-South. Both broadleaf and grass herbicides are applied with the cost of material ranging between $2 to $6 per acre with a mean cost of approximately $4 per acre. In Tennessee, early season over-the-top postemergence herbicide applications are substituted for directed postemergence herbicide applications (Table 7). Typically directed postemergence applications are not made in the Southwest and West.

In regions where moisture is adequate and the growing season is long, a need exists for late-season weed control to insure against weed interference at harvest. Layby herbicide applications are generally made in the higher rainfall regions of the Tennessee Valley in Alabama, South Carolina, Arkansas, Louisiana and Mississippi and irrigated regions of Arizona and California. Cost of these applications ranged from $9 to $15 per acre depending on the rate of herbicide applied. The herbicide rate is generally higher than earlier directed postemergence treatments since residual control is needed to protect the crop until harvest.

The use of hand-hoeing was still employed as an integral part of production systems in the West and irrigated areas of Oklahoma (Tables 12 and 14-16). In Arkansas and Mississippi, weeds not controlled with herbicide programs were removed by hand-hoeing (Tables 8 and 10). The cost of hand-hoeing ranges from less than $10 per acre to more than $20 per acre. Hand-hoeing was especially important where producers are dealing with perennial weed problems. In the Southern High Plains of Texas, expensive hand-hoeing has been replaced with spot-spraying of herbicides (Table 13). This technique was widely used on two very difficult to control perennial weeds, silverleaf nightshade and johnsongrass. In large fields of skip-row cotton, small all- terrain vehicles have been used widely for spot-spraying.

The total costs of equipment used per acre related to weed control was similar in most regions except Tennessee where cost was higher, and in Texas, where the cost was considerably lower (Tables 7 and 13). Total labor cost per acre was extremely high in those areas where hand-hoeing was employed. Labor costs, excluding handhoeing in the Southeast, Mid-South, West and Oklahoma, were very similar but labor costs in Texas were lower, especially in the Southern High Plains. The total cost per acre for herbicides in Arkansas, Louisiana, and Mississippi was substantially higher than other states (Tables 8-10). Herbicide costs per acre in New Mexico, the dryland production region of Oklahoma, Southern High Plains and the Blackland Prairie of Central Texas were substantially lower than the other states.

MONETARY LOSSES WITH CURRENT COTTON WEED MANAGEMENT SYSTEMS

The importance of herbicides in cotton production systems is best understood when considering potential losses that could be expected if weeds were controlled only with non-chemical techniques. It has been estimated that cotton production in the United States without herbicides would result in a net loss of $1.5 billion or 40 percent of the 1976 total crop value (Abernathy, 1981).

An exhaustive search of literature was not able to put a time series together on change in cost of herbicides. A great deal of literature within cotton growing states reports weed control cost from time to time but a series that uses constant methodology and procedures for collecting herbicide cost data does not exist. Chapter 7 in this monograph reports quantities of herbicides used in cotton over an extended period of time.

Based on 1985 planted cotton acreage and the data presented in Tables 1 to 16, the estimated total expenditures for equipment, labor and herbicides used to control weeds in cotton was $406,851,000 or on the average of $38.50 per acre across the entire Cotton Belt (Table 17). This production expense must be considered as a loss resulting from weeds and accounts for 11.3 percent of the total value of the crop. The percentage of the regional totals spent on equipment for

both the Southeast and Southwest was 52 percent. The percentage for labor was 12 and 13 percent, respectively, while the percentage for herbicides was 36 and 35 percent, respectively, for the two regions. In the Mid-South and the West, 34 percent of the regional total was spent on equipment. Labor accounted for 19 percent while herbicide expenditures were 47 percent of the Mid-South regional total. This is indicative of the numerous herbicide applications used to control weeds in the Mid-South. In the West where considerable hand-hoeing is used, the labor expense was 43 percent of the total while herbicide expenditures accounted for 23 percent of the total.

The increased use of herbicides along with mechanical tillage since the early 1950s in cotton production systems has lead to a drastic reduction in the hand labor required to control weeds. Even with this shift, we still have weeds as major pests in cotton that resulted in a $188,335,000 loss in 1985 (Table 18). This figure represents only losses resulting from weed interference in the field. This loss represents an average lint yield reduction of 5.2 percent or 716,100 bales in the United States. Yield reduction ranged from 1.0 to 10.1 percent across the production regions. The degree of yield reduction is influenced by weed species infesting the crop, geographic location with associated environmental parameters and level of control technology applied to the weed populations in the cotton fields.

The number of grassy bales and the proportion of the United States crop that were grassy bales for the years 1961 through 1986 are presented in Table 19. The cost to producers of bales classed grassy, is variable from year to year, and is dependent upon the size of crop, demand for the crop, proportion of different grades and staples available, and differs from location to location. For this reason, it was necessary to establish a discount rate for grassy bales relative to the price paid for the average grade and staple for the U.S. crop. The difference between strict low middling, 1-1/32, 43-41 and low middling, 1-1/16, 51-34 plus one cent per pound was chosen to reflect the cost of a bale of cotton being classed as grassy. The price differences used in this analysis are official loan prices and their difference for the two grades. The use of a constant price (5.58 cents per pound or $26.78 per bale) allows a comparison of the economic cost of grassy bales over time. The average number of bales and costs in terms of reduced farm income for each of the years and for 5-year averages is also presented in Table 19.

The number of bales and the percent of the total crop which are classed grassy, thus the loss due to grassy bales, appears erratic and variable. The cost of grassy bales to producers in 1961, 1967 and 1986 were lowest for the time-period covered. The highest two years were 1963 and 1971. The average annual loss due to grassy bales is $9,431,000. If we examine 5-year average costs to producers over time, there appears to be a reduced percentage of the crop with grassy bales since 1982. The introduction of new postemergence herbicides in the early 1980s may be helping in the reduction. Certain rainfall patterns during the growth season

probably has a great influence on the number of grassy bales each year, but such an analysis is beyond the scope of this chapter.

Worldwide, approximately 100 plants have been reported as weeds in cotton. In the United States, approximately 30 plants infesting cotton fields are economically important weed species (Holm *et al.*, 1977). Approximately 80 percent of the losses from weeds in cotton can be attributed to 10 weed species (Table 20). In 1985, morningglories and nutsedges reduced cotton yields in all cotton producing states of the United States. Morningglories account for 16 percent of the losses caused by weeds in United States cotton. Pigweeds and johnsongrass caused losses in all states except one with pigweeds causing substantial losses in Oklahoma and Texas. Common cocklebur, prickly sida, crabgrasses, and spurges cause losses mainly in the Southeast and Mid-South states with common cocklebur accounting for 14 percent of the losses caused by weeds in cotton. Silverleaf nightshade caused substantial losses in the Southwest and West. Losses from bermudagrass have been reported in some states in all four production regions. Weed species with limited distribution should be monitored closely to insure against further spread since they survive under control procedures. For additional information on individual weed species see Chapter 6.

INFLUENCE OF DELETERIOUS WEEDS ON MONETARY RETURNS USING CURRENT COTTON WEED MANAGEMENT SYSTEMS

There has always been a concern with identifying economic thresholds for pests which reduce cotton yields. The term "economic threshold" has been widely used by entomologists for many years. It is less frequently used by weed scientists working in cotton but still a considerable concern to both agricultural scientists, extension people and cotton producers. Economic thresholds have different connotations for different disciplines involved in agricultural research. The economist's definition is as follows: the economic threshold for a given pest is that level of infestation where cost of reduced yield is equal to cost of an input (i.e. application of a pesticide). Stated another way, if one dollar is spent to reduce a pest infestation sufficiently to give a yield increase of $1.01, then the input is profitable.

Determination of economic thresholds is complex. The measurement of yield reductions by specific levels of pest infestation is difficult and expensive at best. This problem of exact measurement of economic thresholds for a given pest is compounded under actual cotton production systems. When we consider that a given pest, such as the boll weevil or johnsongrass, is not the only pest species in the field, but is accompanied by other harmful insects and/or weeds. The problem of determining economic thresholds is further compounded by the realities of adequate and accurate sampling techniques to determine levels of pest infestations under production conditions.

The problem of identifying economic thresholds for individual weeds or weed complexes is complicated by the long range impact of such control. It is probable that any weed infestation which results in a measurably lower yield for cotton would justify significant input if, over time, the infestation level is significantly reduced or eliminated.

It appears that before allocation of resources is devoted to the precise measurement of economic thresholds of specific weeds and/or weed complexes, a careful analysis of potential benefits should be made. Such an analysis, of necessity, should take into account the degree of probability of weed species which are not currently considered an economic pest becoming a problem.

The yield potential of a specific cotton field can be drastically reduced by interference of weeds; therefore, sound weed management decisions are mandatory throughout the season. Potential cotton yield losses from weeds are regulated by the density of specific species and duration of interference (Chandler, 1984). Monetary losses related to weed interference are regulated by seed cotton yield and current market value of lint and seed. Producers desiring to maximize profits during a given season must compare the cost of weed control per acre with the potential yield losses associated with a specific weed population. Using prior yield data and published research data, a producer can estimate potential yield losses from specific weed populations.

Calculations have been made that show the value of cotton lint sacrificed by allowing specific percentage of weed losses to occur at selected cotton values over a range of yield potentials (Table 21). For a given production level, value of the loss in yield resulting from specific weed populations will vary with the price of the cotton. For example, a field yielding 500 pounds per acre of lint with a 10 percent yield loss from weed interference would result in monetary losses of $27.50, $32.50, $37.50 or $45.50 per acre when cotton prices per pound of lint are $0.55, $0.65, $0.75 or $0.85, respectively.

Weeds such as common cocklebur that are very competitive and widely distributed within a region can cause large monetary losses. In the southeastern region of the United States, common cocklebur over a 3-year period caused a 9 to 21 percent yield loss (Dowler and Hauser, 1975). An early directed postemergence application of MSMA will provide excellent control at a cost of $6 to $7 per acre. Even with low market value and low yield potential producers will increase income potential from common cocklebur control.

Other annual broadleaf weeds such as wild okra and devilsclaw are very competitive with cotton causing losses from 10 to 20 percent (Bridges and Chandler, 1984). These weeds have limited distribution within a field and can best be controlled with hand-hoeing or spot-treatment with herbicides. Weed density dictates cost of hand-hoeing which range from $12 to $25 per acre. The producer must protect his investment with hand-hoeing on selected and limited areas. The returns on his weed control investment potentially can be very high. The producer with low yield potential must consider the long range impact of these

weeds since they are prolific seed producers and the seed have hard coats that maintain seed viability for many years. Where returns are limited, a maintenance or break even weed control program will be required if cotton production is to be maintained over time.

Numerous annual morningglory species are found in fields but in certain areas perennial morningglory species are more prevalent. In moderate to heavy infestations, morningglories reduce cotton yields from 7 to 15 percent (Crowley and Buchanan, 1978). In light infestations, yields may not be reduced, but vines can cause harvest and fiber quality losses. Severe spot infestations of morningglories can prevent cotton pickers from harvesting (Parvin *et al.*, 1985). Delay in harvest can have severe effects on yield, grades, and thus returns to farmers. At best morningglories must be desiccated before problem areas can be harvested.

To obtain full-season morningglory control, producers must use a directed postemergence herbicide in addition to early-season weed control. The cost of each additional directed postemergence treatment ranges from $8 to $12 per acre. In some regions, a portion of hand-hoeing can be attributed to morningglories. An additional investment of $10 to $20 per acre could be required for adequate control. Heavy morningglory-infested fields where the yield potential is low may be rotated with other crops where adequate control techniques are available. Light to moderate morningglory-infested fields with good yield potential can be managed for profitable returns from the additional investment for adequate control.

It is not uncommon for yield losses of 4 to 14 percent to occur from full season johnsongrass interference (Bridges and Chandler, 1987). Herbicides such as fluazifop (Fusilade®) or sethoxydim (Poast®) provide control at $12.80 to $16.00 per acre. A producer with both low yield potential and low prices may not be able to recover cost of control. Producers expecting to make a bale per acre could recover his control investment and possibly double his return if market value is high. A producer with two bale potential would double or triple his weed control investment.

Established infestations of bermudagrass can cause cotton yield losses of 30 to 50 percent (Brown *et al.*, 1985). Generally infestations are in patches across a field. Glyphosate (Roundup®) can be applied to bermudagrass in the fall after harvest or to infestations in fallow fields with cost ranging from $30 to $60 per acre. Multiple applications of sethoxydim (Poast®) or fluazifop (Fusilade®) will provide adequate control at costs ranging from $20 to $40 per acre. It is best to control bermudagrass before it becomes well established. It is easily spread with cultivators or other tillage implements. The cost of bermudagrass control is substantial but so are the potential losses. Where heavy infestations are present, rotations with more closed canopy crops such as soybeans may be appropriate.

Purple nutsedge with field coverage of 20 percent can reduce yields 15 percent or greater (Wills, 1977). Good suppression can be obtained with a preemergence application of norflurazon (Zorial®). Additional control can be obtained with di-

rected postemergence applications of DSMA or MSMA plus prometryn (Caparol®). An investment of $12 to $15 would be required for adequate control. Since this perennial establishes mainly from tubers, the extra effort and investment required for control could be justified over a period of several years.

SUMMARY

In summary, the development of an economical and effective integrated weed management system by individual producers is a necessary component in his overall production strategy. There is great diversity in the weed control strategies employed by cotton producers across the Cotton Belt due to the vast differences in the environment. These diverse environments give rise to weed communities that are unique in composition but contain some of the same pernicious species. Currently, common cocklebur, morningglories, pigweeds, nutsedges and johnsongrass are common in most weed communities across the Cotton Belt in varying intensity.

Across the Cotton Belt with current technology, weeds still cause yield reductions that total $188 million annually or 5.2 percent of the total crop value in 1985. Quality losses due to grassy bales is $9 million annually. The cost of current technology to control weeds is substantial with $406 million spent annually or 11.3 percent of the total crop value. Investments in equipment and herbicides account for 41 and 36 percent, respectively, of this production cost while the remaining 23 percent covers the labor investment. The use of hand labor for controlling weeds in some production regions is still substantial.

The future cost of controlling weeds will rise to keep pace with inflation but the key to future costs will be regulated by the cultural practices and herbicide technology employed by the producer. This in turn will dictate future shifts in species composition of weed communities that infest our cotton fields.

With current government programs and public concern for the environment, we will probably see the development and wide use of limited tillage systems for cotton. This will require the development and use of selective herbicides in place of both primary and secondary tillage operations. These changes will cause shifts in the intensity of weeds interfering with economic cotton production. The developing morningglory problem will be contained with currently emerging herbicide technology. This technology will allow purple nutsedge expansion and it will be even more important and costly to the producer.

Generally speaking, perennial weeds with great genetic diversity such as bermudagrass in the Mid-South and silverleaf nightshade in the Southwest will probably become more dominant. These types of shifts in the weed populations will be very costly to the producer but with increasing costs of production his tolerance of yield losses caused by weeds will be constricted.

Development of herbicide resistant weeds may occur. Currently very few weeds resistant to herbicides used in any crop have been reported in the Cotton

Belt. Most herbicide resistant weeds are developing in states north of the Cotton Belt. Plants developing resistance to herbicides will be more likely to occur in limited tillage systems if we grow continuous cotton. In light of this, an economical crop/herbicide sequence will be very important to future economic production of cotton.

TABLES FOR CHAPTER 5

Table 1. Estimated cost of full-season weed control in solid cotton in Alabama. Based on Alabama (Central and South) practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); field cultivator (21 ft); broadcast and incorporate 0.5 lb trifluralin/A	7.24	1.16	3.18	11.58
Plant[2]; apply 0.67 lb fluometuron/A (16-in band on 38-in row spacing)	0.47	0.00	5.70	6.17
Cultivate	3.93	1.11	0.00	5.04
Cultivate; post-direct 0.4 lb fluometuron + 0.9 lb MSMA/A (16-in band on 38-in row spacing)	5.99	1.56	4.79	12.34
Cultivate; post-direct 0.33 lb cyanazine + 0.67 lb MSMA/A (16-in band on 38-in row spacing)	4.78	1.25	2.35	8.38
TOTAL	22.41	5.08	16.02	43.51

[1]Source: Personal communication with M. G. Patterson, Auburn, AL, 1987.
[2]Preemergence application equipment cost only.

Table 2. Estimated cost of full-season weed control in skip-row (2 x 1) cotton (one acre cotton requires 1.4 acres land) in Alabama. Based on Alabama (Tennessee Valley) practices and skip-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); field cultivator (21 ft); broadcast and incorporate 0.5 lb pendimenthalin/A	6.73	1.08	2.71	10.52
Plant[2]; apply 0.6 lb fluometuron/A (16-in band on 40-in row spacing + 68-in skip)	0.76	0.00	5.10	5.86
Cultivate	3.94	0.93	0.00	4.87
Cultivate; post-direct 0.3 lb fluometuron + 0.6 lb MSMA/A (16-in band on 40-in row + 68-in skip)	4.86	1.00	3.47	9.33
Cultivate	3.21	0.80	0.00	4.01
Cultivate; post-direct 1.0 lb cyanazine/A (broadcast layby)	3.65	0.80	4.01	8.46
TOTAL	23.15	4.61	15.29	43.05

[1]Source: Personal communication with M. G. Patterson, Auburn, AL, 1987.
[2]Preemergence application equipment cost only.

Table 3. Estimated cost of full-season weed control in solid cotton in Florida. Based on Florida practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk twice (21 ft); broadcast and incorporate 0.75 lb pendimethalin/A	8.96	1.42	4.07	14.45
Plant[2]; apply 1.5 lb fluometuron/A broadcast	0.76	0.00	12.75	13.51
Cultivate	3.94	0.93	0.00	4.87
Cultivate; post-direct 0.37 lb cyanazine + 1.0 lb MSMA/A (20-in band on 40-in row spacing)	3.65	0.80	3.02	7.47
TOTAL	17.31	3.15	19.84	40.30

[1]Source: Personal communications with B. J. Brecke, Jay, FL, 1987.
[2]Preemergence application equipment cost only.

Table 4. Estimated cost of full-season weed control in solid cotton in Georgia. Based on Georgia practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.75 lb trifluralin/A	8.96	1.42	4.67	15.05
Plant[2]; apply 0.6 lb fluometuron/A (14-in band on 38-in row spacing)	0.47	0.00	5.10	5.57
Cultivate	3.93	1.11	0.00	5.04
Cultivate; post-direct 0.32 lb fluometuron + 0.64 lb MSMA/A (12-in band on 38-in row spacing)	5.99	1.56	3.78	11.33
Cultivate; post-direct 0.32 lb fluometuron + 0.64 lb MSMA/A (12-in band on 38-in row spacing)	4.78	1.25	2.27	8.30
TOTAL	24.13	5.34	15.82	45.29

[1]Source: Personal communication with S. M. Brown, Tifton, GA, 1987.
[2]Preemergence application equipment cost only.

Table 5. Estimated cost of full-season weed control in solid cotton in North Carolina. Based on North Carolina practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.5 lb trifluralin/A	8.96	1.42	3.14	13.52
Plant[2]; apply 0.5 lb fluometuron/A 12-in band on 36-in row spacing)	0.47	0.00	4.25	6.17
Cultivate	3.93	1.11	0.00	5.04
Cultivate; post-direct 0.3 lb fluometuron + 1.0 lb MSMA/A (12-in band on 36-in row spacing)	4.78	1.25	3.79	9.82
Cultivate	3.21	0.89	0.00	4.10
TOTAL	21.35	4.67	11.18	37.20

[1]Source: Personal communication with H. D. Coble, Raleigh, NC, 1987.
[2]Preemergence application equipment cost only.

Table 6. Estimated cost of full-season weed control in solid cotton in South Carolina. Based on South Carolina practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.75 lb trifluralin/A	8.96	1.42	4.67	15.05
Plant[2]; apply 0.66 lb fluometuron/a (12-in band on 38-in row spacing)	0.47	0.00	5.61	6.08
Cultivate	5.99	1.56	6.20	13.75
Cultivate; post-direct 0.66 lb fluometuron + 0.38 lb DSMA/A (12-in band on 38-in row spacing)	4.78	1.25	1.83	7.86
Cultivate; post-direct 0.8 lb cyanazine/A (broadcast layby)	4.78	1.25	3.21	9.24
TOTAL	24.98	5.48	21.52	51.98

[1]Source: Personal communication with B. J. Gossett, Clemson, SC, 1987.
[2]Preemergence application equipment cost only.

Table 7. Estimated cost of full-season weed control in solid cotton in Tennessee. Based on Tennessee practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (14 ft); broadcoast and incorporate 0.75 lb trifluralin/A	9.85	2.18	4.67	16.70
Plant[2]; apply 0.75 lb fluometuron/A (19-in band on 38-in row spacing)	0.47	0.00	6.38	6.85
Cultivate; postemergence over-the-top 0.9 lb DSMA/A (19-in band on 38-in row spacing)	5.99	1.56	1.39	8.94
Cultivate; postemergence over-the-top 0.094 lb flauzifop + 1 qt crop oil concentrate/A (19-in band on 38-in row spacing)	4.78	1.25	7.70	13.73
Cultivate	3.21	0.89	0.00	4.10
Cultivate	3.21	0.89	0.00	4.10
TOTAL	27.51	6.77	20.14	54.52

[1]Source: Personal communication with R. M. Hays, Jackson, TN, 1987.
[2]Preemergence application equipment cost only.

Table 8. Estimated cost of full-season weed control in solid cotton in Arkansas. Based on Arkansas practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Bed Conditioner (21 ft); spring tooth harrow (21 ft); broadcast and incorporate 0.75 lb trifluralin + 0.75 lb norflurazon/A	6.84	1.02	11.62	19.48
Plant[2]; apply 0.75 lb fluometuron/A (19-in band on 38-in row spacing)	0.76	0.00	6.38	7.14
Cultivate; post-direct 0.4 lb fluometuron + 1.0 lb MSMA/A (19-in band on 38-in row spacing)	3.94	0.93	5.94	10.81
Cultivate; post-direct 0.4 lb cyanazine + 0.75 lb MSMA/A (19-in band on 38-in row spacing)	3.21	0.80	5.18	9.19
Hand hoe (2.0 hr/A)	0.00	8.90	0.00	8.90
Post-direct 0.75 lb linuron/A (broadcast layby)	2.86	0.80	8.00	11.66
TOTAL	17.61	12.45	37.12	67.18

[1]Source: Personal communication with R. E. Frans, Fayetteville, AR, 1987.
[2]Preemergence application equipment cost only.

Table 9. Estimated cost of full-season weed control in solid cotton in Louisiana. Based on Louisiana practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Field cultivator twice (21 ft); broadcast and incorporate 0.75 lb trifluralin + 0.75 lb norflurozon/A	5.82	0.98	11.62	18.42
Plant[2]; apply 0.6 lb fluometuron/A (20-in band on 40-in row spacing)	0.76	0.00	5.10	5.86
Cultivate; post-direct 0.3 lb fluometuron/A (14-in band on 40-in row spacing)	3.94	0.93	2.55	7.42
Cultivate; post-direct 0.2 lb cyanazine/A (16-in band on 40-in row spacing)	3.21	0.80	0.80	4.81
Post-direct 1.2 lb cyanazine/A (broadcast layby, 6-row applicator)	2.86	0.80	4.81	8.47
TOTAL	16.59	3.51	24.88	44.98

[1]Source: Personal communication with S. H. Crawford, Baton Rouge, LA, 1987.
[2]Preemergence application equipment cost only.

Table 10. Estimated cost of full-season weed control in solid cotton in Mississippi. Based on Mississippi practices and eight-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.5 lb trifluralin + 0.48 lb norflurazon/A	5.08	0.80	7.56	13.44
Plant[2]; apply 0.62 lb fluometuron + 0.24 lb norflurazon/A (20-in band on 40-in row spacing)	0.55	0.00	7.49	8.04
Cultivate	3.77	0.71	0.00	4.48
Cultivate; post-direct 0.4 lb fluometron + 1.0 lb MSMA/A (20-in band on 40-in row spacing)	4.56	0.80	4.49	10.30
Cultivate; post-direct 0.25 lb prometryn/A (20-in band on 40-in row spacing)	3.30	0.58	1.90	5.78
Hand hoe (2.5 hr/A)	0.00	11.13	0.00	11.13
Cultivate; post-direct 1.25 lb cyanazine/A (broadcast layby)	3.30	0.58	5.01	8.89
TOTAL	20.56	14.60	26.90	62.06

[1]Source: Personal communication with H. R. Hurst, Stoneville, MS, 1987.
[2]Preemergence application equipment cost only.

Table 11. Estimated cost of full-season weed control in solid cotton in Missouri. Based on Missouri practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); bed conditioner (14 ft); broadcast and incorporate 1.0 lb pendimethalin/A	9.85	1.69	5.42	16.96
Plant[2]; apply 0.6 lb fluometuron/A (19-in band on 38-in row spacing)	0.76	0.00	5.10	5.86
Cultivate	3.94	0.93	0.00	4.87
Cultivate; post-direct 0.5 lb prometryn + 1.0 lb MSMA/A (14-in band on 38-in row spacing)	3.65	0.80	5.34	9.79
Cultivate	3.21	0.80	0.00	4.01
TOTAL	21.41	4.22	15.86	41.49

[1]Source: Personal communication with H. D. Kerr, Columbia, MO, 1987.
[2]Preemergence application equipment cost only.

Table 12. Estimated cost of full-season weed control in solid cotton in Oklahoma. Based on Oklahoma (dryland and irrigated) practices and six-row or eight-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Dryland Production (six-row equipment)				
Disk twice (14 ft); broadcast and incorporate 0.75 lb trifluralin/A	9.85	2.18	4.67	16.70
Cultivate twice	7.15	1.73	0.00	8.88
TOTAL	17.00	3.91	4.67	25.58
Irrigated Production (eight-row equipment)				
Disk twice (21 ft); broadcast and incorporate 1.0 trifluralin/A	8.96	1.42	6.23	16.61
Plant[2]; apply 0.7 lb prometryn/A (14-in band on 40-in row spacing)	0.55	0.00	5.32	5.87
Hand hoe (3 hr/A)	0.00	13.35	0.00	13.35
Cultivate 3 time	8.69	1.61	0.00	10.30
TOTAL	18.20	16.38	11.55	46.13

[1]Source: Personal communication with D. S. Murray, Stillwater, OK, 1987.
[2]Preemergence application equipment cost only.

Table 13. Estimated cost of full-season weed control in solid cotton in Texas. Based on Texas (Southern High Plains, Central Blackland Prairie, Coastal Bend and South Texas) practices and six-row, eight-row, or twelve-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Southern High Plains (twelve-row equipment)				
Spring tooth harrow (30 ft); broadcast and incorporate 0.6 lb trifluralin/A	4.49	0.45	3.74	8.68
Plant[2]; apply 0.25 lb prometryn/A (10-in band on 40-in row spacing)	0.61	0.00	1.90	2.51
Cultivate	1.19	0.41	0.00	2.32
Spot spray[3]; 2% solution of glyphosate for silverleaf nightshade or 1% solution of fluazifop for johnsongrass	1.76	0.45	1.54	3.75
Cultivate	1.74	0.31	0.00	2.05
TOTAL	10.51	1.62	7.18	19.31
Central Blackland Prairie (six-row equipment)				
Disk (21 ft); broadcast and incorporate 0.5 lb trifluralin/A	5.08	0.80	3.13	9.01
Plant[2]; apply 0.5 lb prometryn/A 10-in band on 40-in row spacing)	0.76	0.00	3.80	4.56
Cultivate twice	7.15	1.73	0.00	8.88
TOTAL	12.99	2.53	6.93	22.45

Table 13. Continued

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Coastal Bend and South Texas (eight-row equipment)				
Disk (21 ft); broadcast and incorporate 1.5 lb trifluralin/A (fall applied)	5.08	0.80	9.35	15.23
Light tillage with hipper (winter)	2.73	0.58	0.00	3.31
Plant[2]; apply 0.3 lb pendimethalin + 0.3 prometryn/A	0.55	0.00	3.91	4.46
Cultivate	3.77	0.71	0.00	4.48
Hand hoe (1.5 hr/A)	0.00	6.68	0.00	6.68
Cultivate	2.56	0.45	0.00	3.01
TOTAL	14.69	9.22	13.26	37.17

[1]Source: Personal communication with J. R. Abernathy, Lubbock, TX, D. N. Weaver, College Station, TX, and J. E. Bremer, Corpus Christi, TX, 1987.
[2]Preemergence application equipment cost only.
[3]20 percent of one acre treated.

Table 14. Estimated cost of full-season weed control in solid cotton in Arizona. Based on Arizona practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.6 lb trifluralin + 1.2 lb prometryn/A	8.96	1.42	3.74	14.12
Cultivate twice	7.15	1.73	0.00	8.88
Hand hoe (4.0 hr/A)	0.00	17.80	0.00	17.80
Cultivate; post-direct 1.5 lb prometryn/A (broadcast layby)	3.65	0.80	11.40	15.85
TOTAL	19.76	21.75	15.14	56.65

[1]Source: Personal communication with E. S. Heathman, Tucson, AZ, 1987.

Table 15. Estimated cost of full-season weed control in solid cotton in California. Based on California practices and six-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk (21 ft); broadcast and incorporate 0.5 lb trifluralin/A	8.96	1.42	3.17	13.55
Cultivate	3.94	0.93	0.00	4.87
Hand hoe (5.0 hr/A)	0.00	22.20	0.00	22.20
Cultivate; post-direct 1.4 lb prometryn/A (broadcast layby)	3.65	0.80	10.64	15.09
TOTAL	26.15	26.15	13.81	59.72

[1]Source: Personal communication with P. E. Keeley, Shafter, CA, 1987.

Table 16. Estimated cost of full-season weed control in solid cotton in New Mexico. Based on New Mexico practices and four-row equipment in 1985.

Operation[1]	1985 Cost			
	Equipment	Labor	Material	Total
	(dollars/A)			
Disk twice (14 ft); broadcast and incorporate 1.0 lb trifluralin/A	9.85	2.18	6.23	18.26
Cultivate three times	10.35	2.89	0.00	13.24
Hand hoe (6.0 hr/A)	0.00	26.70	0.00	26.70
TOTAL	20.20	31.77	6.23	58.20

[1]Source: Personal communication with R. Lee and J. D. Libbin, Las Cruces, NM, 1987.

Table 17. Estimated cost of equipment, labor and herbicides used to control weeds by state and region in United States cotton, 1985.

Region and state	Planted acreage	1985 Average total cost			Total
		Equipment	Labor	Herbicides	
	(x 1,000)	(dollars x 1,000)			
Southeast					
Alabama–Central and South	113	2,532	374	1,810	4,916
Alabama–Tennessee Valley	187	4,329	862	2,859	8,080
Florida	25	424	77	486	978
Georgia	255	6,153	1,351	4,034	11,548
North Carolina	88	1,878	410	983	3,271
South Carolina	124	3,097	679	2,668	6,444
Tennessee	340	9,353	2,301	6,847	18,501
SUBTOTAL	1,132	27,766 (52)[1]	6,264 (12)	19,687 (36)	53,717
Mid-South					
Arkansas	465	8,188	5,789	14,349	28,717
Louisiana	640	10,617	2,246	15,923	28.786
Mississippi	1,050	21,588	15,330	28,245	65,163
Missouri	152	3,254	641	2,410	6,305
SUBTOTAL	2,307	43,647 (34)	24,006 (19)	60,927 (47)	128,971
Southwest					
Oklahoma–dryland	279	4,743	1,090	1,302	7,135
Oklahoma–irrigated	91	1,656	1,490	1,051	4,197
Texas–Southern High Plains	4,107	43,164	6,653	29,488	79,305
Texas–Central Blackland Prairie	215	2,792	543	1,489	4,824
Texas–Coastal Bend and South Texas	678	9,959	6,251	8,990	25,200
SUBTOTAL	5,370	62,314 (52)	16,027 (13)	42,320 (35)	120,661
West					
Arizona	360	7,113	7,830	5,450	20,393
California	1,330	26,280	34,779	18,367	79,426
New Mexico	70	1,414	2,223	436	4,073
SUBTOTAL	1,760	34,807 (34)	44,832 (23)	24,253 (23)	103,892
TOTAL	10,569	168,535	91,129	147,187	406,851

[1]Percent of regional total

Table 18. Estimated average annual losses caused by the ten most frequently reported weeds by states in United States cotton, 1985.

Region and state	Estimated loss from potential production		
	Reduction[1]	Quantity	Value[2]
	(%)	(bales)	(dollars x 1,000)
Southeast			
Alabama	6.0	26,000	6,838
Florida	10.0	2,300	605
Georgia	8.0	31,200	8,205
North Carolina	8.0	9,600	2,525
South Carolina	8.5	15,500	4,077
Tennessee	10.1	40,400	10,625
SUBTOTAL	—	125,000	32,875
Mid-South			
Arkansas	9.8	64,700	17,016
Louisiana	8.4	66,700	17,542
Mississippi	1.7	28,900	7,601
Missouri	10.0	18,500	4,866
SUBTOTAL	—	178,800	47,025
Southwest			
Oklahoma	6.2	16,100	4,234
Texas	6.0	258,000	67,854
SUBTOTAL	—	274,100	72,088
West			
Arizona	10.0	102,000	28,826
California	1.0	31,000	8,153
New Mexico	6.9	5,200	1,368
SUBTOTAL	—	138,200	36,347
TOTAL	—	716,100	188,335

[1]Whitwell, Ted and J. H. Higgins. 1986. Report of 1985 cotton and weed loss committee. 1986 Proc. Beltwide Cotton Prod. Res. Conf. pp. 255.

[2]Total United States bales produced in 1985 was 13,626,000 with a total value of approximately $3,583,638,000. Calculation of value was based on the average 1985 United States price of $263 per bale. Ginned bale weight was 480 pounds.

Table 19. Losses due to grassy bales by year in United States cotton, 1961-1986.

Production year	Total production	Total grassy	Percentage grassy	Value loss[1]
	(bales)	(bales)	(%)	(1,000 dollars)
1961	14,263,365	156,008	1.0	4,178
1962	14,754,396	312,220	2.1	8,361
1963	15,128,775	572,404	3.7	15,329
1964	15,032,314	410,928	2.7	11,005
1965	14,830,810	417,889	2.8	11,191
1966	9,491,197	256,044	2.6	6,857
1967	7,370,293	142,508	1.9	3,816
1968	10,838,384	318,291	2.9	8,524
1969	9,860,230	416,736	4.2	11,160
1970	10,055,237	377,298	3.7	10,104
1971	10,133,419	575,473	5.6	15,411
1972	13,175,522	513,671	3.8	13,756
1973	12,532,901	371,657	2.9	9,953
1974	11,239,735	444,113	3.9	11,893
1975	8,097,552	243,743	3.0	6,527
1976	10,284,056	344,516	3.4	9,226
1977	13,909,121	483,347	3.5	12,944
1978	10,459,210	332,017	3.2	8,891
1979	14,165,664	499,874	3.5	13,387
1980	10,724,266	281,752	2.6	7,545
1981	15,072,854	421,707	2.8	11,293
1982	11,429,648	435,119	3.8	11,652
1983	7,413,334	186,142	2.5	4,985
1984	12,418,749	239,207	1.9	6,406
1985	12,837,088	261,022	2.0	6,990
1986	9,236,839	142,758	1.5	3,823
Average	11,721,344	352,170		9,431
Avg. 61-65	4,801,932	373,890		10,013
Avg. 66-70	9,523,068	302,172		8,092
Avg. 71-75	11,035,826	429,731		11,508
Avg. 76-80	11,908,462	388,301		10,399
Avg. 81-86	11,401,419	280,993		7,525

[1]The average price difference of one full grade (0.0458 cents/lb) plus one cent per pound or 5.58 cents or $26.78 per bale was used to obtain these values.

Table 20. Estimated reduction in percentage of cotton yields caused by the ten most frequently reported weeds by state, 1985.[1]

Region and state	Total percent cotton loss	Morningglories	Common cocklebur	Pigweeds	Nutsedges	Johnsongrass	Prickly sida	Silverleaf nightshade	Crabgrass	Bermudagrass	Spurges
					(percentage of total %)						
Southeast											
Alabama	6	10	11	10	10	15	14	—	—	10	1
Florida	10	20	20	5	9	—	—	—	—	—	—
Georgia	8	6	22	1	10	4	4	—	2	—	1
North Carolina	8	30	15	6	3	2	8	—	2	3	1
South Carolina	8.5	15	19	1	15	3	8	—	1	6	4
Tennessee	10.1	10	25	6	3	12	10	—	5	5	5
Mid-South											
Arkansas	9.8	20	10	5	5	10	10	—	6	5	14
Louisiana	8.4	15	15	5	8	4	11	—	4	—	4
Mississippi	1.7	17	27	5	2	8	8	1	3	3	8
Missouri	10.0	20	20	—	4	4	17	—	5	5	8
Southwest											
Oklahoma	6.2	9	—	36	4	15	2	22	1	—	—
Texas	6.0	5	7	23	6	7	—	18	—	2	—
West											
Arizona	10.0	10	1	10	10	7	—	9	—	6	1
California	1.0	10	—	15	16	8	—	25	—	4	—
New Mexico	6.9	25	3	2	12	10	—	9	—	3	—

[1]Whitwell, Ted and J. H. Higgins, 1986. Report of 1985 cotton weed loss committee. 1986 Proc. Beltwide Cotton Prod. Res. Conf. pp. 255.

Table 21. Value of cotton lint sacrificed by allowing specific weed losses to occur at selected cotton prices over a range of yield potentials.

Cotton price	Potential yield loss	Potential cotton lint yields (lb/A)			
		250	500	750	1000
		Potential monetary losses			
(dollars/lb)	(%)	(dollars/A)			
	2	2.75	5.50	8.25	11.00
	5	6.88	13.75	20.64	27.52
	7	9.63	19.26	28.89	38.52
$0.55	10	13.75	27.50	41.25	55.00
	12	16.50	33.00	49.50	66.00
	15	20.63	41.26	61.89	82.52
	20	27.50	55.00	82.50	110.00
	2	3.25	6.50	9.75	13.00
	5	8.13	16.26	24.39	32.50
	7	11.38	22.76	34.14	45.52
$0.65	10	16.25	32.50	48.75	65.00
	12	19.51	39.02	58.53	78.04
	15	24.38	48.76	73.14	97.52
	20	32.50	65.00	97.50	130.00
	2	3.75	7.50	11.25	15.00
	5	9.38	18.76	28.14	37.52
	7	13.13	26.26	39.39	52.52
$0.75	10	18.75	37.50	56.25	75.00
	12	22.50	45.00	67.50	90.00
	15	28.13	56.26	84.39	112.52
	20	37.50	75.00	112.50	150.00
	2	4.25	8.50	12.75	17.00
	5	10.63	21.26	31.89	42.52
	7	14.88	29.76	44.64	59.52
$0.85	10	21.25	42.50	63.75	85.00
	12	25.50	51.00	76.50	102.00
	15	31.88	63.76	95.64	127.52
	20	42.50	85.00	127.50	170.00

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Chapter 6

THE CHANGING WEED PROBLEM IN COTTON

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INTRODUCTION

Over the past two decades, cotton (*Gossypium hirsutum* L.) researchers, extension personnel and producers have become increasingly concerned with the effects of agronomic practices, especially weed control methods, on the changes observed in weed populations. Numerous instances have arisen which demonstrate that instead of being constant, the weed problem is dynamic and ongoing. Shifts in dominant weeds do occur, and those shifts must be considered when devising weed management systems (Swanson, 1972). The increase in difficult-to-control weeds is a matter of some anxiety. It does little good in the long term to fully control one weed species if the inevitable consequence is its replacement by another weed even more difficult to control. The crops and cultivars grown, cultural methods employed, chemicals used, etc. and all permutations and combinations of such factors can contribute to modification in weed populations. However, no one has described the situation more succinctly than Buchanan (1971b) when he wrote, "Few subjects have been discussed so much with so little data." With that in mind, we proceed.

Holm (1978) estimated that about 200 species are involved worldwide in 95 percent of man's weed problems. He further stated that about 80 species are primary weeds and most troublesome while approximately 120 are secondary. The 200 weeds are drawn from much less than one percent of the world's plant species. Over 100 species of plants are weeds in cotton fields (Holm *et al.*, 1977); but more importantly, some of the world's most noxious weeds are major problems in cotton in the United States including bermudagrass [*Cynodon dactylon* (L.) Pers.] , purple nutsedge (*Cyperus rotundus* L.), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], goosegrass [*Eleusine indica* (L.) Gaertn.], johnsongrass [*Sorghum halepense* (L.) Pers.] and common purslane (*Portulaca oleracea* L.).

In sharp contrast to most agronomic crops such as corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.], growth of cotton is relatively slow during the first several weeks after planting, thereby offering little competition to weeds.

Consequently, weeds must be controlled especially during that time. Many methods are available to accomplish weed control. Zimdahl (1981) classifies them into biological, cultural (crop rotation and fertility management), mechanical (hoeing, hand pulling, roguing, cultivating, fallowing and mowing), nonmechanical (flaming, mulching and water management), legal (quarantines, entry laws and seed laws) and chemical.

When weed control in the United States is allotted to sources, human labor is responsible for less than 5 percent, tractors and cultural equipment for some 40 percent and herbicides for about 55 percent (Klingman, 1978). According to Zimdahl (1981), no weed control method has ever been abandoned; all are still used regularly in some crops in the world today. In fact, hand labor is still used to some extent on approximately 25 percent of United States cotton. Zimdahl (1981) also pointed out that crops, including cotton, which were manually weeded were also frequently cultivated. He described cotton as being cultivated an average of 2.9 times per year.

In the early 1920s when a production unit was still one man, one mule and 10 to 20 acres of cotton, cultivations were a necessity (Agelasto *et al.*, 1922). Whenever large crabgrass [*Digitaria sanguinalis* (L.) Scop.], johnsongrass, or other weeds were present in abundance, the fields would have to be hoed one to three times per season in addition to numerous cultivations. To illustrate the importance still placed on cultivation in this decade, a progressive cotton farmer (Burnett, 1981) made the clever observation that, "A good cultivator that is properly adjusted can cover up a lot of mistakes." Undoubtedly, he was referring to control of weed escapes. Mechanical cultivation is the most important method of weed control in western irrigated cotton and serves as the base for comparisons there with other control methods (Miller *et al.*, 1977). However, the relative importance of weed control methods has changed; herbicides are now generally the dominant method used in developed countries. Wills (1977) reported that 8 percent of the cotton in the Mississippi Delta in 1952 was treated with herbicides; by 1961, approximately 75 percent of the cotton acreage was treated; and by 1976, herbicide application to cotton averaged more than four treatments per acre. Researchers in the Southwest estimate that 70 to 80 percent of the cotton acreage was treated with herbicides by 1975 and that Treflan® (trifluralin) was by far the most widely used herbicide (Miller, 1976). A more detailed discussion of this topic may be found in Chapter 7 "Herbicide Use Trends in Cotton."

Weed shifts are frequently mentioned in popular publications and abstracts; however, few definitive studies using long-term data have been conducted to document those trends. No doubt, there are weed shifts (sometimes called "ecological shifts") occurring. Are these true ecological shifts resulting in long-term effects, or are the shifts only short-term responses to management? When devising optimum control strategies, it is important to know whether one is coping with changes within species or with changes in relative proportions among species. This chapter describes the changes in the weed spectrum which have oc-

curred over time in cotton fields of the United States. It tells, where possible, why those shifts have occurred; and it suggests appropriate actions to minimize such problems in the future. Included are tables, taxonomic keys and photographs to facilitate the identification of the major weeds in cotton. Proper identification is an essential prerequisite for successful control programs.

HISTORICAL PERSPECTIVE

The changing weed problem in cotton cannot be assessed without also tracing the changes which have occurred in the crop itself. Many developments over time in cotton, especially changes in its geographical distribution and production methods, have impacted on weeds, their development and distribution. The history of crop and weed are intertwined and interdependent.

GEOGRAPHICAL DISTRIBUTION

The first European colonists to grow cotton in the present-day United States were the Spanish in Florida in 1556 (Natural Fibers Econ. Res., 1975). The first attempt by English colonists was at Jamestown, Virginia, in 1607 (Gray, 1933). Cotton was subsequently introduced into North Carolina in 1664, South Carolina in 1733 and Georgia in 1734 or 1735. The French were cultivating the crop in Louisiana by 1758, if not before (Collings, 1926).

Until the invention of the gin by Eli Whitney in 1793, cotton was a relatively minor crop in the colonies and later in the early United States. It was grown as a garden plant (Gray, 1933) for domestic use or in very small fields of two acres (one acre = 0.4 hectare) or less, usually considerably less (Scruggs, 1976). Essentially nothing is known of the weeds in the cotton plantings of that time. However, if gardeners in that era were like those of current times, they classified their plants into two categories, *i.e.*, "favored ones" which were encouraged and "all others" which were not. The degree of weed control likely ran the gamut from none to complete—depending upon the individual. The primary tool of the time for weed control was the hoe (Gray, 1933).

Until 1793, the major limitation to producing cotton was the difficulty in separating the lint from its firmly attached seed. A full day's work was involved in the hand removal of one pound (0.45 kilogram) of lint from its seed (Bruchey, 1967; Scruggs, 1976). As a result, only about 10,000 equivalent 500-pound bales were being produced annually in the United States at that time (Todd, 1950). Whitney's simple (in retrospect), hand-cranked enGINe (Bruchey, 1967; Scruggs, 1976) increased the efficiency of that process 50-fold (Natural Fibers Econ. Res., 1975). With that "tedious, boring, slow" (Scruggs, 1976) problem alleviated to a large degree, acreage and production in South Carolina and Georgia virtually exploded. Within four years, production had doubled that of 1794; and within 10 years, production was greater than eight times that of 1794. Less than 150,000

bales of cotton were being produced in the United States at the end of the War of 1812.

By 1859, production had increased over 30 times that of 1812. The gin made growing cotton enormously profitable, especially if large supplies of cheap labor were available (Gray, 1933). It unintentionally and indirectly perpetuated and encouraged the expansion of slavery (Collings, 1926). Cotton did indeed become "King", but it did so at a fierce human cost. For example, in 1790 a group of counties in middle Georgia had slaves comprising 26 percent of its population; but by 1860, their proportion had increased to 60 percent (Gray, 1933).

As the United States expanded westward, cotton went with it—from the Southeast into the Mid-South, into the Southwest and eventually into the irrigated West. Maps included in Gray's (1933) masterpiece show only limited cotton being produced in South Carolina and Georgia in 1791. By 1801, production had increased immensely in those two states as well as spread into North Carolina, Virginia and Tennessee. By 1811, production had increased greatly in those areas; by then, it included the Territory of Orleans (now Louisiana) as well. By 1821, Mississippi and Alabama also were included. By 1829, cotton had spread into Arkansas, Florida (Gray, 1933) and Indian Territory (now Oklahoma) (Nall, 1977). By 1839, production in most areas continued to expand remarkably, but increased more rapidly in the Mid-South than in the Southeast. Missouri was growing cotton by this time. More than three-fourths of the cotton produced in the United States in 1839 came from east of the Mississippi River (Agelasto *et al.*, 1922).

Although cotton had been grown in Texas since at least 1822 when it was a possession of Mexico (Natural Fibers Econ. Res., 1975), it was not until the late 1840s that the state became a major producer (Gray, 1933). In the Southeast and Mid-South, "the principal outlines of the Cotton Belt were formed in the twenty-five years from 1815 to 1840" (Gray, 1933). Within those states until the 1840s, rivers were the primary means of transportation to markets and supplies; and the first settlements were near them. In 1833, railroads began building in the South; they gradually opened up the interiors of states for settlement and shifted somewhat the channels of trade (Todd, 1950).

In the 1850s, production increased dramatically in Georgia-Alabama-Tennessee, the Mid-South and Texas. In 1859 on the eve of the Civil War, the top 10 cotton-producing states were (in decreasing order) Mississippi, Alabama, Louisiana, Georgia, Texas, Arkansas, South Carolina, Tennessee, North Carolina and Florida (Agelasto *et al.*, 1922; Gray, 1933). In all states, production had increased; but the center of production was shifting westward. In 1801, South Carolina and Georgia produced 80 percent of the crop. By 1842, they produced only 29 percent while Alabama and Mississippi produced 41 percent. By 1859, South Carolina-Georgia had fallen to 20 percent while Alabama-Mississippi produced over 43 percent, Louisiana over 14 percent and Texas about 8 percent (Todd, 1950).

The Civil War and its aftermath created havoc upon the cotton industry. The entire financial, production, marketing, shipping, manufacturing and export networks of United States cotton were disrupted (Todd, 1950). The slave labor force had been freed and, in many cases, was not gainfully employed for one or two years after the War. Ultimately, the sharecropping system was devised (Todd, 1950; Fite, 1979); and acreage and production began to climb once more. However, it wasn't until 1879 that post-War production had recovered to pre-War levels (Fite, 1979). All states that year, except Alabama and Louisiana, produced more cotton than in 1859 (Agelasto *et al.*, 1922). By 1880, the South had twice the railroad mileage it had in 1860 (Todd, 1950). By 1899, cotton was planted in Arizona (Agelasto *et al.*, 1922).

By 1919, New Mexico was planting cotton to stay; and so was California (Agelasto *et al.*, 1922). Sporadic attempts had been made to commercially produce cotton in New Mexico prior to the Civil War (Agelasto *et al.*, 1922) and in California since 1865 (LaFerney, 1975). By 1929, the center of production had shifted westward, largely because of increased acreage in Texas and Oklahoma. Directly or indirectly, the change can be at least partially attributed to the invasion of the boll weevil (*Anthonomus grandis* Boh.), especially into the Mid-South and Southeast. In 1921, about one-third of the United States cotton crop had been destroyed by that one insect. Part of the Southwest and all of the West are hot and dry—conditions considered detrimental to the weevil. The dryness of the region was also considered an advantage in the timely cultivation of the soil, in reducing the number of cultivations required and in suppressing weed growth. Economics of production also were partly responsible for the shift. In the Southeast around 1930, 100 to 125 man-hours of labor were required per acre of cotton; whereas, 50 to 60 hours were required in the Blacklands of Texas, and 35 to 40 were required in West Texas (Landon, 1930). In the Southeast, farms with 10 to 20 acres of cotton were common while in the West, 100 acres of cotton per farm were not unusual (Landon, 1930). In the West (except for the eastern counties in New Mexico), cotton essentially cannot be grown without irrigation.

In the 25-year span from 1950 to 1975, the percentages of cotton production in the United States decreased in the Southeast and Mid-South from 16.7 to 7.3 percent and from 35.1 to 30.0 percent, respectively; stayed approximately the same in the Southwest (31.8 and 30.9 percent, respectively) and increased in the West from 16.4 to 31.8 percent (Sayre, 1979).

EARLY CROP CULTURE

From the late 1700s until the Civil War, the literature dealing with the production of cotton contains numerous experiences, opinions and ideas of plantation owners on the best methods to cultivate cotton and control weeds. As late as 1854, cotton and weed stalks from the previous crop were pulled or broken with clubs, then gathered and burned (Bruchey, 1967). Weed seed destroyed by fire were a benefit, but many seed likely fell to the ground when the plants were

pulled or broken. The primary tool for land preparation was the plow stock until 1870 (Smith, 1950). Any working of the land prior to planting would contribute to weed suppression.

Application of livestock manure to cotton fields occurred as early as 1776 (Scruggs, 1976). Increases in productivity were accompanied by introductions of undigested weed seed into the fields in the manure. Philips in 1817 (Turner, 1857) observed marked differences in yield between cotton with *vs.* without manure. In 1842 or 1843, Turner (1857) tested stable manure and cottonseed "as a manure" and doubled yields from less than one-half bale per acre to a bale. He also advocated planting "peas" {probably the cowpea [*Vigna unguiculata* (L.) Walp. ssp. *unguiculata*]} when corn was "laid by," in so doing giving "shade to the land" and a "large amount of manure." He stated that, "Peas gather sustenance from the air as well as the land, and thus you return all to the land taken up by the pea, and more too." He suggested a rotation of cotton, corn, grain and fallow. Summer (Turner, 1857) stated that the original productivity of the soil could be restored by "judicious manuring." Hammond (Turner, 1857) also believed cotton should follow cotton or fallow land, but not small grains or corn. He believed that, "Every kind of manure is valuable for Cotton. Every kind of compost, green crops turned in, cotton seed, and even naked leaves listed and left to rot, improves this crop." By 1860, many Georgia farms had been reclaimed through the application of guano and other fertilizers (Todd, 1950). When receiving an annual application of farmyard manure, cotton could easily be grown year after year for at least 11 years on the same field (Christidis and Harrison, 1955).

Shortly before and after the invention of the gin, most farmers were planting cotton in "hills" (one to several plants clumped together and separated by blank spaces on all sides from adjacent plants). Early planters in Georgia believed that cotton required space to extend its limbs and that branches should slightly interlock in all directions (Turner, 1857); therefore, cotton was planted in hills five to eight feet (one foot = 30.5 centimeters) apart (Gray, 1933). The large spaces between plants were ideal for weed germination and growth. They also contributed to late crop maturity and encouraged late-season insect and disease problems. After 1800, planting on ridges three to six feet apart was generally employed. Planters believed it was necessary to space the ridges farther apart on better ground (Turner, 1857; Gray, 1933). They also tended to plant early by today's standards (Gray, 1933). Hammond (Turner, 1857) believed that planting was generally done too early. One exception he was willing to make was on "new ground and rich fresh land" that has a "tendency to make weed."

A few planters on the richer soil used a "dibble" (a small hand implement to make holes in the soil for the seed) when planting in hills, but most planted in drill fashion (Gray, 1933). Hammond (Turner, 1857) believed the dibble, though "tedious," did not require as much time as to drill and then to thin. The hoe was used for opening the furrow in earlier times; a small plow was used for that purpose

later (Gray, 1933). Seed were planted by hand dropping until after 1840 (Danhof, 1972).

Overseeding [three to four bushels per acre (one bushel = 35.2 liters)] was practiced to ensure getting a regular, even stand (Gray, 1933) because the planting seed were of unknown quality and because of the lack of means to cope with seedling disease (Wilkes and Corley, 1968). The planters then thinned (earlier term, "scraped"; later term, "chopped") out the excess cotton seedlings (which in themselves could be viewed as "weeds") by various means (Turner, 1857; Moorhouse and Nicholson, 1908). Subsequently, less seed were planted more carefully to avoid some of the laborious thinning (Gray, 1933). Thinning originally was hand work (Scruggs, 1976); later, the hoe was used for that purpose and for weed control (Gray, 1933).

Early thinning was recommended. Chambers (Turner, 1857) specified the third or fourth true-leaf stage as the proper time for thinning. Some planters thinned their cotton the first time over the field; others gradually thinned to a stand. Chambers in 1852 (Turner, 1857) advocated rows four feet apart with individual plants in the row spaced at distances of 15 to 20 inches (one inch = 2.54 centimeters); whereas, Hammond (Turner, 1857) recommended rows three feet apart with individual plants spaced 14 inches. Thorpe in 1854 (Bruchey, 1967) advised that rows be five to six feet apart with individual plants thinned to 24 inches. Clearly, little consensus on planting distances was evident during this era.

Cotton was a labor-demanding crop. Except for tobacco (*Nicotiana tabacum* L.), sugarcane (*Saccharum* spp.) and certain vegetables, cotton required more labor than any other crop grown in the South (Turner, 1857; Duggan and Chapman, 1941; Todd, 1950). Fields were tended as many as 22 times per year in Mississippi (Hildebrand, 1941) and 19 times per year in Texas (M. L. Verhalen, 1987, personal communication). Originally, the labor was provided by man—later, by man and animal (Gray, 1933).

Around 1790, the tools and implements in use by American farmers were simple and made largely of wood plus some iron. By 1790, seedbeds were being prepared by animal-powered plows (Danhof, 1972); hoes were used through the remainder of the season. In 1797, Thomas Jefferson patented a moldboard plow with an iron shear; by 1837, an all-steel plow was being utilized (Timmons, 1970). From 1790 to 1840, substantial changes were made in the design of tools and implements, in the use of animal for human labor and in the use of metal instead of wood (Danhof, 1972). In the 1840s and 1850s, the idea was expressed as "substituting mule power for man power" (Moore, 1986).

Extensive, rather than intensive, methods of cultivation were employed to produce the maximum crop per hand. Usually advocated were 5 to 10 acres of cotton, five to nine of corn and several of small grains for a total of up to 20 acres per hand (Turner, 1857; Gray, 1933; Bruchey, 1967). Progressive planters used horse-drawn implements as much as possible to minimize hoe labor (Turner, 1857; Gray, 1933). "Inventions and improvements in metal implements and tools

came along at a rapid pace, at least by 19th century standards" (Timmons, 1970). The wheel cultivator with steel shovels was invented in 1848, followed by the straddle-row cultivator in 1856 (Timmons, 1970). One tool, the scraper, allowed a hand to clean and thin 1.25 acres per day compared to the 0.75 acres done previously (Gray, 1933).

Planters advocated cultivations every 7 (Hubbard, 1923; Brown, 1927) to 10 (Turner, 1857) to 14 days (Moorhouse and Nicholson, 1908; Christidis and Harrison, 1955), especially after rain (Morrow, 1897; Collings, 1926). It was considered particularly important when cultivating to cover small grass at the base of the cotton plant with soil (Turner, 1857). Most southern farmers, working with hand tools or equipment pulled by one or two mules, exhibited low productivity—about 250 pounds of lint per acre (Fite, 1979). Harvest was by hand picking seedcotton (usually three times per season) and depositing it into sacks tied to the waist. It was later emptied into baskets or onto large sheets (Gray, 1933).

Between 1841 and 1895, the labor required to produce an acre of cotton declined from an estimated 148 man-hours to 102. By 1930, only 71 hours were required in south Texas; fewer still were demanded in northwest Texas. Thus, within 90 years, labor had been reduced over 50 percent in some areas because of the invention and use of better plows, planters, disks and cultivators (Fite, 1950). The equipment used in the field generally progressed in an uneven manner from single-animal (horse or mule), half- or single-row, walking-type implements to multiple-animal, two-row, riding implements. As recently as the 1930s, the mule was "the symbol of southern agriculture" (Fite, 1979). However, over the Cotton Belt as a whole, labor requirements dropped very little between 1895 and 1930 (Fite, 1950; Smith, 1950). Yet, labor productivity did increase. Parker (1979) calculated the preharvest labor required for cotton production in seven regions of the South for two time periods, 1840-1860 and 1900-1920 (Table 1). He assumed that harvest techniques between the two periods had not changed. Taking into account picking time and differential yield levels for the two periods in each region, he calculated that average productivity rose 35 percent between the 1840-1860 period and the 1900-1920 period. About one-third of that amount could be attributed to movement west to new, fertile lands and about two-thirds to other causes. Preharvest labor per acre was less in 1900-1920 in all regions than it had been in 1840-1860. The increased efficiency was less than five percent in the Gulf Coastal Plain and in the Eastern Hilly regions, but it was 32 to 45 percent greater elsewhere. Hoe labor per acre decreased with time in all regions except the Eastern Hilly region; whereas, cultivation labor per acre increased in all except the Western Hilly region.

Before the Civil War, two contemporaneous systems of cotton culture existed throughout the South (Moore, 1986). "Hill farmers" (a) used light "shovel" plows (until 1840) which penetrated only the top two or three inches of the soil, (b) planted up and down hillsides, (c) abandoned older and cleared new fields each year, (d) planted green-seeded cotton cultivars, (e) planted cowpea or other cover

Table 1. Total preharvest, hoe and cultivation labor required for cotton in seven regions of the South for two time periods. (Information adapted from Parker, 1979.)

Regions of the South[1]	Preharvest labor		Hoe labor		Cultivation labor	
	1840-1860	1900-1920	1840-1860	1900-1920	1840-1860	1900-1920
	(man-hours/acre)					
Atlantic Coastal Plain	95.9	64.9	56.2	24.7	12.5	21.7
Gulf Coastal Plain	81.4	77.4	30.4	29.8	19.4	22.8
Piedmont	117.4	74.7	43.6	24.6	21.8	24.9
Eastern Hilly	74.5	72.8	23.6	28.5	18.5	22.9
Western Hilly	88.5[2]	48.4	27.0[2]	17.4	33.3[2]	14.8
River Bottom	98.2[2]	66.3	54.3[2]	31.6	20.2[2]	21.6
Black Waxy-Gulf Prairie	50.4[2]	32.0	18.4[2]	10.7	7.8[2]	8.4

[1]Regions are comprised of portions of states as follows:
Atlantic Coastal Plain —Georgia, North Carolina, South Carolina, Virginia;
Gulf Coastal Plain —Alabama, Louisiana, Mississippi;
Piedmont —Alabama, Georgia, North Carolina, South Carolina, Virginia;
Eastern Hilly —Alabama, Georgia, Mississippi, North Carolina, Tennessee;
Western Hilly —Arkansas, Louisiana, Missouri, Oklahoma, Texas;
River Bottom —Arkansas, Louisiana, Mississippi, Missouri, Tennessee;
Black Waxy-Gulf Prairie —Louisiana, Texas.
[2]Estimated values.

crops in the fall, (f) fertilized corn with cottonseed, (g) tended to use plows rather than hoes and (h) usually used oxen or horses for power. "River planters" (a) plowed deeply with a turning plow, (b) planted on a relatively flat surface or horizontally across hillsides, (c) tended to grow cotton continuously on the same fields, (d) planted a black-seeded cultivar (which outyielded the green-seeded one), (e) did not plant cover crops in the fall, (f) did not use cottonseed for fertilizer, (g) tended to use plows less and hoes more and (h) usually used mules for power. Over time, the hill farmers adopted the higher yielding cultivar and began to lay off sloping rows and drainage ditches to minimize erosion; and the river planters began to plant the cowpea and use cottonseed for fertilizer. In the 1840s and 1850s, the hill farmers replaced their shovel plows with "sweeps, double shovels, side harrows, cotton scrapers and cultivators of adjustable widths." Improved cast iron and steel turning plows and planting machines became common.

Most improvements were forgotten after the War—particularly horizontal culture that didn't become common again until the 1930s (Moore, 1986).

Newsom (Coleman, 1968), a prominent farmer in Washington County, Georgia, authored an incomplete document on cotton culture in the 1880s. He planned on 10 acres of cotton per hand. He incorporated plant debris from the previous crop, cottonseed, manure and guano prior to planting. He wrote that, "Cleaning and raking out my Fence Corners is something I have always neglected or rather I have never had time unless hiring extra for it and always valued the money more than the Extra looks of my Fence." Those weedy fence corners served as sources of weed propagules to reinfest his fields. Newsome wasn't (and isn't today) alone in that attitude.

Recommendations by the Oklahoma Agricultural Experiment Station near the turn of the century (Morrow, 1897) included deep plowing prior to planting in rows 3.5 to 4 feet apart. Plants in the rows were to be thinned early in hills 12 to 24 inches apart (one to three plants per hill). Farmers were strongly advised to keep "weeds and grass" under control, especially when cotton plants were small. In the early days of Oklahoma statehood (1907 and later), cotton in the eastern part of the state was grown in fields of 3 to 20 acres and tilled with single-row implements. In the central and western parts of the state, fields were 60 to 100 acres in size and tilled with multi-row equipment (Nall, 1977).

Averages by areas in 1914 in the Southeast for plowing ranged from five to seven inches deep with 2.5 to 3.5 tillage operations between plowing and planting. Planting was with a drill at a row width of three to four feet with 2.5 to 5.5 pecks (one peck = 8.8 liters) of cottonseed planted per acre. After planting, 5 to 6.5 cultivations were practiced. In the Mid-South, averages by areas for plowing ranged from four to five inches deep with 1.5 to 2.5 additional tillage operations before planting. Planting was at a row width of 3.5 to 4 feet and at a seeding rate of 3 to 5.5 pecks per acre. After planting, 5 to 9.5 cultivations were practiced. In the Southwest, averages by areas for plowing ranged from four to six inches deep followed by 2 to 2.5 tillage operations before planting. Planting was done at a row width of 3 to 3.5 feet with 2 to 5.5 pecks of cottonseed per acre. After emergence, some 4.5 to 5.5 cultivations were practiced. In all three regions, stands in the row after emergence were thinned with a hoe to one or two seedlings 12 to 24 inches apart followed by one or two weedings later in the season (Cates, 1917).

In 1932 (Brown, 1938), a survey of the 15 highest cotton-producing states revealed that planting was being done primarily with one-row planters in the Southeast and Mid-South and with two-row planters in the Southwest and West. Seed planted ranged from 12 pounds per acre to two bushels. The lesser amounts tended to be in the Southwest and West. Average row spacings ranged from three to four feet with 3.5 feet being the most popular. Plant spacings within the row ranged from 6 to 18 inches between hills with one to three plants per hill. Thinning was done almost entirely with hoes. Cultivation was accomplished with one- and two-mule cultivators. Some two-row equipment was in operation, and tractors

were beginning to be used in Arizona. Three to nine cultivations were practiced until blooming, the plants got too large and/or until around August 1.

PLANTING, THINNING AND NONCHEMICAL WEED CONTROL

Planting, thinning and cultivating for weed control are interrelated. The practices employed in one phase influence what is done, or not done, in the others. As methods of seedbed preparation and planting evolved, so did techniques of thinning and weed control. By the early 1900s the burning of previous crop residues was no longer recommended (Cates, 1917; Morgan, 1917). Brown (1927) discouraged the practice because of the loss of organic matter, nitrogen and other nutrients. The development of the mechanical stalk cutter facilitated stalk destruction and reduced the advantages associated with burning. About 1925, the two-row, tractor-drawn, rolling-type stalk cutter came into use (Brown and Ware, 1958). Rather quickly, they were expanded into four-row cutters, many of which were custom-made by blacksmiths (M. L. Verhalen, 1987, personal communication). Tractor-mounted stalk cutters and shredders were available by 1957 (Street, 1957b).

Following stalk destruction and disposal, seedbed preparation was accomplished by forming a bed with a middlebreaker or flatbreaking with a plow (Street, 1957b). Flatbreaking was considered essential when cotton followed a hay crop such as alfalfa (*Medicago sativa* L.) or in extremely weedy fields, particularly those with perennials such as johnsongrass, bermudagrass and "coco" or "nutgrass" (purple nutsedge) (Brown and Ware, 1958). For seedbed preparation, Sayre (1979) lists the major developments in cotton mechanization in the 1950s as hardpan breakup through deep tillage using subsoilers, chisels and/or two-way middle busters and moldboard plows; firm seedbeds were created using four-row, front-mounted cultivators combined with four-row, rear-mounted planters; and the application of anhydrous ammonia was accomplished using improved equipment. In the 1960s, he lists "do all" type finishing harrows and mechanically incorporated herbicides. In the 1970s, he cites use of the parabolic curve in tillage equipment, minimum or narrow-skip systems, large horsepower tractors with 8- to 12-row equipment and combination disk-chisel plows.

Typical recommendations for planting, thinning and weed control in the first half of the 20th century are sampled below. Webber and Boykin (1907) advocated rows three to four feet apart and thinning to hills spaced 12 to 20 inches in the row with one to three plants per hill, then thinning a few days later to one plant—the most vigorous in each hill. Morgan (1917) recommended rows 3.5 feet apart and that plants after thinning in poor soils be spaced 12 inches; in medium soils, 18 to 20 inches; and in very productive soils, 24 to 30 inches. Some farmers (Collings, 1926) and researchers (Brown, 1927, 1938) claimed larger yields when two plants were left to the hill; others found no detrimental effects with three (Morrow, 1897; Smith, 1950) or even up to five (Smith, 1950; Christidis and Harrison, 1955). Under boll weevil conditions, earlier thinning and closer plant spac-

ings (6 to 12 inches in the row) were considered superior in terms of yield (Collings, 1926) and earliness (Morrow, 1897; Collings, 1926). Moorhouse and Nicholson (1908) recommended thinning at the third true-leaf stage while Smith (1950) suggested the fourth to sixth true leaf or earlier. When thinning, any weeds in the row were also removed at that time (Moorhouse and Nicholson, 1908; Christidis and Harrison, 1955; Brown and Ware, 1958).

Thinning cotton has been accomplished by various means. Where cotton was planted in hills and the seedlings were clumped together, thinning by hand may have been necessary (Christidis and Harrison, 1955). However, the hoe was much more commonly used (Webber and Boykin, 1907; Bruchey, 1967). The extent of the labor involved can be more fully appreciated if one considers that with 40-inch rows, "A hoe laborer must walk 2½ miles and make at least 20,000 strokes with a hoe to...thin an acre of cotton" (Wilkes and Corley, 1968). After planting, it was not uncommon to harrow across the rows, thereby destroying many small weeds and simultaneously accomplishing some thinning (Collings, 1926). The rotary hoe acts in a similar manner in that many tiny weeds in the row are destroyed; but in the process, some cotton seedlings are sacrificed (Brown and Ware, 1958). Because the tractor is operated at a high rate of speed [5 to 10 miles per hour (one mile per hour = 0.48 meter per second)] (Smith, 1950), the method is not very expensive (Christidis and Harrison, 1955). It can be used until cotton is four to six inches tall or taller (Smith, 1950; Brown and Ware, 1958). However, coarse trash, such as sorghum [*Sorghum bicolor* (L.) Moench] stalks, interferes with its operation (Brown and Ware, 1958). Like the harrow, the rotary hoe is of greater value in weed control than in thinning.

In the 1920s and 1930s, cotton was sometimes cross-plowed at right angles to the direction of the rows, leaving hills so that the fields could be cultivated in two directions (Brown, 1927, 1938). Doing so, eliminated hand thinning and reduced the hoeing necessary for weed control (Wilkes and Corley, 1968). Cross-plowing made it possible to control coco grass (purple nutsedge), but yields were less than with drilled cotton, closer spacing and good cultivation (Brown, 1927, 1938). However, the practice may have been economical when hand labor was scarce and weeds were threatening the crop (Brown and Ware, 1958). The practice was largely restricted to land that was level because it accelerated erosion if the land were sloping at all (Street, 1957b).

Mechanical choppers were used extensively around 1950 (Smith, 1950) and were satisfactory under most conditions (Wilkes and Corley, 1968). These choppers had revolving cylinder knife blades that blocked out hills regular distances apart. The machines required perfect stands, beds of uniform height and few weeds in the row (Brown and Ware, 1958). Studies of the tool in Arkansas showed a savings of 5.85 man-hours per acre. Flame choppers were tried for a time in the 1950s, but they were apparently too hazardous to remaining plants (Smith, 1950).

Cross-plowing, mechanical chopping and flame chopping required uniform

stands. Small skips before thinning often became large skips afterwards. Eventually, it occurred to someone that if fewer seed were planted, fewer seedlings would have to be removed in thinning. Planting to a stand became an attainable goal (Duggan and Chapman, 1941) and was in considerable practice by the late 1950s (Brown and Ware, 1958). Seed delinting permitted more accurate metering of seed for precision planting to a desired stand (Wilkes and Corley, 1968). It was also recognized that planting in such a manner was a precondition for the successful use of chemicals in weed control (Brown and Ware, 1958). Planting in hills, rather than heavy seeding in drills, eliminated the need for hand thinning (Sayre, 1979).

Sayre (1979) characterized the major developments in cotton mechanization for planting in the 1950s as encompassing precision seed monitoring, low-mounted hoppers, rubber-tired press wheels, improved openers, high speed hill-drop attachments, widespread use of four-row planters and planter attachments applying liquid fertilizers and herbicides. For the 1960s, he cites unit planters (with tool bar attached) for up to eight rows, larger and higher speed tractors, dual press wheels, removal of hill-drop mechanisms, improved seed delinting and development of planters equipped for pesticide applications. For the 1970s, he lists planters with operating speeds up to 10 miles per hour, planters using vacuum and air pressure metering and depth control and electronic metering systems.

In the early 1900s, tillage practices in cotton were considered to be relatively poor (Morgan, 1917; Collins, 1926). A number of farmers during the 1920s cultivated alternate middles each week, thus making a complete cultivation every two weeks (Collings, 1926).

Most cultivation studies in cotton have demonstrated that it should be shallow and that it should be used only to control weeds. Deep cultivation causes "slight reductions in yields, slower traveling speeds, and higher power requirements" (Wilkes and Corley, 1968). However, cultivation alone is ineffective in controlling weeds (Smith, 1950). It can control weeds between the rows and very small weeds in the row by moving soil to the base of the cotton plant. The hoe was considered necessary to control most weeds in the drill. Brown (1927) stated that, "Hoeing is expensive tillage, but apparently there is no way to avoid it." An attempt to do just that in Mississippi was summarized in 1944 by Williamson (Sayre, 1979) as, "Under favorable weather conditions, cotton was produced without hand labor by cross-plowing, flaming and machine picking; however, the machine-picked cotton was three grades below hand-picked check plots and about 15 percent of the cotton was left in the field."

Flame cultivation, mentioned above, was first used successfully in 1944 and was in widespread use by the late 1950s. Butane and propane were the most common fuels, and treatments were often repeated every four to six days as required (Smith, 1950; Christidis and Harrison, 1955). Flaming controls small weeds in the cotton row and middles. The cotton plants, however, must be at

least six to eight inches tall with bark on its lower stem and with a stem diameter at the base of 3/16 inch or more (Brown and Ware, 1958). The size differential between crop and weed was very important. Before herbicides were available, some hand labor usually was required to create that differential and to suppress weeds between planting and the first flaming (Street, 1957b).

Sayre (1979) believes the major developments in cotton mechanization for cultivation in the 1950s to be high speed sweeps, flame cultivation, chemical weed-control equipment, cross-plowing, rolling hoes for light weed control and the use of aircraft for weed-control applications. For the 1960s, he lists the shifting of cultivating equipment from the front to the rear of the tractor, use of shields for herbicide application and rolling shields. For the 1970s, he cites the availability of 8- to 12-row units, improved attachments for postdirected herbicides, the development of the S-tine high-speed cultivator and development of the recirculating sprayer for weed control.

MECHANIZATION

Cotton was "notoriously resistant to mechanization" (Fite, 1950). Reasons can be traced to several plant characteristics of the crop which make it difficult to mechanize, the specialized labor skills required at various times during the season, the plentiful supply of labor until World War II, the small farms of uneven topography on which cotton was generally produced, the inertia of custom and tradition and the sharecropper system then in effect (Fite, 1950).

The first major advance in cotton mechanization was in the use of the tractor. The gasoline-powered, row-crop tractor was introduced in 1924 (Sayre, 1979). The development of tractor-mounted duckfoot and blade cultivators in the 1920s and 1930s aided in the shift from horses to tractors (Timmons, 1970), as did tractor-mounted plows, middlebreakers and planters (Brown and Ware, 1958). During the transition period, it was not unusual for tractors and horses (or mules) to be used for different operations in the same field until it became apparent that anything a horse could do in cotton production, a tractor could do more effectively and efficiently. Cultivation to control weeds could be done in a more timely, uniform, controlled fashion. For example, one cotton producer in Texas (M. L. Verhalen, 1987, personal communication) believed that johnsongrass on his farm got worse each year when cultivating with teams of horses because he couldn't get over his cotton acreage fast enough. The difference that a tractor and implements can make is illustrated by a comparison of areas covered in a day. Tractor-mounted rotary hoes over the row and sweeps in the middles between rows could be used to cultivate 80 acres per day compared to 0.75 acre for a man, mule and half-row cultivator (Street, 1957b). The row-crop tractor was the essential component for clean cultivation of cotton (Sayre, 1979).

By 1927 in Texas, tractors with two- and four-row detachable equipment were allowing 200 acres of cotton to be grown as easily as 25 acres in the Southeast (Fite, 1950). In southwestern Oklahoma, tractors increased from 3,134 in 1929 to

8,200 in 1939 (Nall, 1977). In 1930, only four percent of southern farmers were using tractors. A United States government policy decision, however, quickly changed that percentage. In 1933, the Agricultural Adjustment Act reduced cotton production by approximately 10 million acres. Between 1935 and 1940 as a consequence, numerous sharecroppers were evicted, farm numbers declined, farm size increased and tractor use almost doubled to 7.9 percent of southern farmers (Fite, 1979).

During World War II, the shift to tractors was particularly rapid, primarily due to a shortage of labor (Fite, 1950). From 1939 to 1946, tractor use for breaking cotton land increased from 10 to 38 percent in the Southeast, 16 to 42 percent in the Mid-South, 48 to 84 percent in the Southwest and 81 to 94 percent in the West. For planting, tractor use increased from 2 to 13 percent in the Southeast, 4 to 16 percent in the Mid-South, 42 to 78 percent in the Southwest and 64 to 81 percent in the West. For cultivation, use of tractors rose from 2 to 11 percent in the Southeast, 6 to 18 percent in the Mid-South, 40 to 82 percent in the Southwest and 69 to 87 percent in the West (Brown and Ware, 1958). By 1948, the use of tractors was virtually complete in the San Joaquin Valley of California (Fite, 1950). By 1960, tractors were used for 99 percent of the land preparation, planting and cultivation of United States cotton and for 41 percent of its harvest (Natural Fibers Econ. Res., 1975).

In 1941, an average of about 85 man-hours of labor were required to produce and market one acre of cotton compared to 37 hours for corn, 20 for wheat (*Triticum aestivum* L.), 15 for oat (*Avena sativa* L.) and 16 for hay (Duggan and Chapman, 1941). The two phases of cotton production at that time requiring the most human labor were thinning-weed control and harvest (Duggan and Chapman, 1941; Fite, 1950). Harvest was the more limiting of the two (Agelasto *et al.*, 1922) requiring a third of all hours used to produce the crop (Duggan and Chapman, 1941). Fite (1950) stated that, "Even with primitive one-mule half-row equipment a man can plant and cultivate more cotton than he can pick by hand." Morrow (1897) described harvest as "the most tiresome, troublesome and costly" of cotton operations while Street (1957a) called it "extremely burdensome" and "human drudgery."

Although harvest required more labor than thinning-weed control, it was the first of the two to yield to a solution. The initial patent for a cotton picker (mule drawn) was assigned to Rembert and Prescott in 1850 (Hurt, 1979). Some 1,800+ patents later (Street, 1957a; Hurt, 1979) in 1941, the first commercially successful spindle-type, one-row cotton picker was produced by the International Harvester Co. (Hildebrand, 1941; Fite, 1979; Sayre, 1979). The Depression had retarded commercial sales and use of mechanical harvesters for about a decade. During that era, labor was plentiful and cheap; money was scarce and lint prices were low. The spindle picker of 1958 was 100 times more efficient than hand picking (Brown and Ware, 1958).

The idea of stripping cotton originated in the early 1870s, was tried in 1914 but

didn't become a general practice until 1926 (Fite, 1950; Street, 1957a). In 1925, a farmer near Lubbock, Texas, dragged a section of picket fence down the rows in his fields and harvested faster than a dozen men. The following year, "sleds" were constructed that stripped as much in one day as could normally be harvested in three to four weeks (Natural Fibers Econ. Res., 1975). In southwest Oklahoma, one man could gather about nine bales per day with a sled (Nall, 1977). Gins in the Southwest incorporated special equipment to cope with such roughly harvested material (Fite, 1950). Machines to strip cotton were available from Deere and Co. in 1931; but the Depression here also discouraged sales, and production halted (Fite, 1950; Street, 1957a). As shortages of labor began to occur during World War II, use increased. Deere and Co. sold 4,400 units from 1946 through 1948 (Street, 1957a). The machine stripper of 1958 was 200 times more efficient than hand picking (Brown and Ware, 1958).

In 1948, about 5 percent of the United States cotton crop was harvested with machines (Fite, 1950); in 1955, about 25 percent (Street, 1957a); in 1960, about 50 percent; in 1965, about 80 percent (Sayre, 1979) and in 1973, more than 98 percent (Natural Fibers Econ. Res., 1975).

Sayre (1979) records the major developments in cotton harvesting in the 1950s as specialized air and ground application of defoliants; wetting agents for spindle pickers; modified drum heights; synchronization of the picker head with forward ground speed; improved pressure plates, spindle types and plant lifters; the two-row, self-propelled picker; improved air control in the picker head; improved cotton grades from mechanical picking and the development of brush-type strippers flexible for row widths. For the 1960s, he lists improved synchronization of the hydrostatic transmission, air conveying systems, brush stripper rolls, bur-extractor cotton strippers, jet-air boll separators for strippers and the increased capacity of spindle pickers with larger power units and baskets and with more aggressive spindles. For the 1970s, he lists lighter heads with aluminum bars and faster operating speeds; automatic head controls; the seed cotton module system; four-row, brush-roll strippers; increased harvesting capacity in spindle pickers and the water-soluble oil spindle cleaner.

Mechanical harvest necessitated late-season control of fall vines, grass and other weeds (Brown and Ware, 1958). While late-emerging weeds may have little or no effect on yield and few consistent effects on fiber properties of the current crop, they can cause difficulties in harvest and lower lint grades due to increased trash content. Late-season weeds also reinfest the soil with large quantities of seed that increase infestations in future crops.

ADAPTATIONS OF WEEDS TO THEIR ENVIRONMENT

Weeds rapidly adapt to a variety of soils, climatic regimes and cultural practices. The intensity and duration of the selective factors they have faced and their mechanisms of adaptation contribute to current prevalence and persistence of certain species. Weeds are resilient. Even though controlled for many years, they

may immediately reappear as serious problems with only a slight reduction in control efforts. Weed scientists are also acutely aware that regardless of how effective and sophisticated their control systems are, there is always "...the weed around the corner waiting to come in..." (Minotti and Sweet, 1981). Effective control of a current problem species can release from competition species previously suppressed. The differences among weed species in morphological and physiological characters, response to control measures and adaptability are likely wide enough to ensure new problems, even in systems making maximum use of crop competitiveness.

Buchanan *et al.* (1975) reported that weeds varied greatly in their ability to tolerate low soil pH. They investigated 10 warm-season and 6 cool-season weeds at soil pH's ranging from 4.7 to 6.3. Showy crotalaria (*Crotalaria spectabilis* Roth), coffee senna (*Cassia occidentalis* L.) and large crabgrass (*Digitaria sanguinialis)* were highly tolerant to low pH while redroot pigweed (*Amaranthus retroflexus* L.) and Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.] among others exhibited severe growth reduction. Although not documented, it is likely that the high pH soils of the West would likewise segregate weeds according to pH.

Hoveland *et al.* (1976) reported broadly different tolerances of 10 warm-season and 7 cool-season weeds to low soil phosphorus or potassium levels. This differential response to soil fertility may partially account for the presence *vs.* absence of weeds among locations, and thus indirectly influence weed control programs. Kempen (1984) reported that weeds in California were clearly associated with certain soil types. Groundcherry (*Physalis* spp.) and field bindweed (*Convolvulus arvensis* L.) were associated with fine-textured soils while black nightshade (*Solanum nigrum* L.) and bermudagrass (*Cynoden dactylon)* were more frequently associated with coarse-textured soils. Hoveland and Buchanan (1972) showed that weeds have differing tolerances to flooded soil conditions. This in part may explain why fall panicum (*Panicum dichotomiflorum* Michx.) is more prevalent in wetter environments than Texas panicum (*Panicum texanum* Buckl.).

Because weed species respond differently to changes in pH, nutrients, moisture as well as temperature and shading, competitive relationships among weeds may vary from season to season and be altered sufficiently to shift dominance from one species to another (Minotti and Sweet, 1981). They observed a field heavily infested with accumulated seed of both common lambsquarters (*Chenopodium album* L.) and redroot pigweed *(Amaranthus retroflexus).* The species dominating in each growing season depended upon the spring weather conditions. Cooler, wetter springs favored lambsquarters; whereas, pigweed dominated in springs with extended warm periods. To an observer, the environmental differences between successive spring seasons might appear to be causing a shift in the dominance of the weeds present when, in fact, only a short-term response by the weeds to current environment was taking place.

CHEMICALS AND WEED SHIFTS

Controlling weeds with chemicals was the last great frontier crossed in the "total" mechanization of cotton. Brown (1969) cites the application of arsenic compounds to control johnsongrass in Texas before 1900 as probably the earliest recorded use of herbicides in cotton. Oils were used in the 1920s through 1940s for selective control of weeds (Timmons, 1970), but the "true" chemical age in cotton weed control was not firmly established until the mid-1950s (Natural Fibers Econ. Res., 1975) when a concentrated effort was made to substitute chemicals for the hoe (Sayre, 1979). Prior to this time, a number of nonselective chemicals were used as soil sterilants; but these had limited potential for use in crops. The economic benefits of chemicals were quickly realized; and their application became widespread, but not without mishap. In 1951, Premerge® (dinitro, dinoseb) was applied as a preemergence treatment on large acreages in Mississippi. Following a hot dry spring, considerable damage to cotton was encountered. Because of that experience, the impetus to use herbicides was retarded for a few years. However, the incident did impress upon the industry the importance of adequate testing of chemicals prior to widespread use (Brown, 1969; Sayre, 1979).

In 1947, about 150 man-hours of labor (using one-row, mule-drawn equipment) were required to produce a bale of cotton. Approximately 130 of those hours were for weed control and harvesting. Some 20 years later, only 30 hours were required when chemicals were applied (Brown, 1969). In 1957 in the Mississippi Delta, 155 man-hours of labor (using one-row, mule-drawn equipment) were estimated for production of a bale of cotton. With land preparation and cultivation using tractors, it could be reduced to 132 hours. Using the rotary hoe, flame cultivation, mechanical picking and some hand hoeing, the hours per bale could be reduced to about 30. With an assured method of weed control, estimated labor required would be only 10 to 12 hours per bale (Street, 1957b).

With herbicides, many producers no longer utilize hand hoeing. Such a practice is premature in that herbicides are not generally effective over an entire season nor are all weeds adequately controlled by the herbicides available. Herbicides reduce, but do not eliminate, the need for hoeing and/or cultivating. Reduced tillage because of herbicide use allows weeds tolerant or resistant to those herbicides to increase. Minimum tillage exaggerates the problem. Numerous authors (McWhorter, 1962; Frans, 1969; Hamilton, 1969; Smith, 1973; Abernathy, 1975, 1978, 1979; Clayshulte, 1975; Stedman, 1975; Buchanan, 1976; Whitworth, 1977) from throughout the Cotton Belt believe that heavy usage of herbicides has reduced dependence on mechanical weed control, that reduction in cultural practices has indirectly allowed more plants to escape (some of which may be herbicide resistant) and that the invasion of new weed species has generally gone unchecked until they are well established. "Hand labor, including hoeing, grubbing, and spot treatments, should be used as needed to control surviving weeds. Noncontrol of escapes may reduce costs temporarily, but it will perpetuate weed

problems; and it may permit disastrous shifting of weed populations from controllable to resistant species" (Holstun and Wooten, 1968).

The response of weed populations to control measures is poorly understood. Although not extensively documented in the literature, cultural practices undoubtedly have produced some shifts in weed species. Herbicides, however, have probably played the major role, and changes in populations of weeds in cotton fields with the continued use of herbicides is one of the principal problems in weed science today (Buchanan, 1971b). Whether combinations of herbicides influenced those shifts is speculative. The position could be taken that the greater the number of species controlled, the greater the probability of an uncontrolled species increasing.

In 1965, Danielson *et al.* (1968) stated that cotton was one of the crops in which herbicide use was increasing most rapidly—in part due to the development and rapid acceptance of Treflan®. By 1968, approximately 85 percent of the cotton acreage in the United States received one or more herbicide treatments (Brown, 1969). By 1974, Buchanan (1974b) reported that over 95 percent of cotton grown in the United States was treated with herbicides; and in 1978, Jordan (1978) reported that almost all cotton growers used herbicides in a management program where they applied from one to five separate treatments per year to a single field. In 1965, cotton producers had treated approximately 49 percent of the harvested cotton acreage with herbicides before the crop emerged and 43 percent after emergence. While the use of preemergence treatments more than doubled from 1962 to 1965, the percentage of cotton treated postemergence increased even more.

Whitworth (1971) recognized that selective herbicides are relied upon almost entirely for weed control in cotton and that, at least in New Mexico, the most difficult-to-control weeds were present in increasing numbers because of the overdependence on those herbicides and because of large reductions in hoeing and cultivation. He specifically attributed problems with field bindweed *(Convolvulus arvensis)*, nutsedge (*Cyperus* spp.), johnsongrass, *Flaveria* spp. and spurred anoda [*Anoda cristata* (L.) Schlecht.] to continued use of selective herbicides without adequate supplementation by other methods. Whitworth (1969) had previously stated that, "One must plan ahead to take care of the weeds that tolerate or escape the treatment. Otherwise, the use of selective herbicides will increase rather than decrease the problem of weeds in our cotton fields." Jackson (1970) concluded that the ready acceptance of an easy, time-convenient, preplant application of herbicides as a complete program rather than a tool in a program has led to a simple swapping of one set of weed problems for another. Likewise, Swanson (1972) noted that as effective controls are developed for one weed or group of weeds, a new species soon appears. Whitworth (1978) stated that, "Overdependence on a single herbicide has resulted in a buildup of heavy populations of some species of weeds which have been called pernicious due to their persistent and troublesome nature. Perhaps insidious would be a better term

since they have been there all the time just waiting and 'watching for an opportunity to ensnare', and ensnare they did as the use of a single herbicide released these species from the competition of others."

Probably no other group of herbicides has been given so much "credit," or perhaps more appropriately "blame," for causing weed shifts as the dinitroanilines (Treflan®, Prowl®, etc.). In the Southeast, Buchanan *et al.* (1975), Buchanan (1979) and French (1979) attributed the widespread use of dinitroaniline herbicides with a decline in grass weed problems, but with an increase in broadleaf weeds such as prickly sida (*Sida spinosa* L.), tropic croton (*Croton glandulosus* var. *septentrionalis* Muell.-Arg.), common cocklebur (*Xanthium strumarium* L.), sicklepod (*Cassia obtusifolia* L.) and morningglory (*Ipomoea* spp.) and in perennial weeds (most notably nutsedge). The management of some weeds has been so successful that other difficult-to-manage weeds, even though formerly present, are now troublesome. This replacement of one problem species or group of species by another is viewed as a weed shift.

In the Mid-South, Frans (1969) suggested that widespread use of Treflan® with the attendant reduction in cultivation and hand hoeing was responsible for decreased populations of large crabgrass and other annual grasses, but for increased populations of yellow nutsedge (*Cyperus esculentus* L.), purple nutsedge, prickly sida, common cocklebur, sicklepod, bristly starbur (*Acanthospermum hispidum* DC.), johnsongrass and several morninglories. As early as 1970, Ivy and Baker (1972) recognized that Treflan® could not control prickly sida. Although not mentioning the dinitroaniline herbicides specifically, Jordan (1978) noted that continuous use of herbicides in a cotton program had shifted the weed spectrum from easy-to-control annual grasses to difficult-to-control broadleaf weeds, perennial grasses and sedges. The most troublesome weeds cited were perennials such as bermudagrass, johnsongrass and purple nutsedge; species closely related to cotton such as velvetleaf (*Abutilon theophrasti* Medik.), spurred anoda and prickly sida; as well as several members of the spurge family (Euphorbiaceae). Chandler and Oliver (1979) credited the increased occurrence of spurred anoda in a 10-year period with the herbicidal control of annual weeds which had previously hindered its growth.

In the Southwest, Smith (1973) and Abernathy (1975) reported that preplant herbicides had provided excellent control of pigweed (*Amaranthus* spp.) and grassy-type weeds, but had altered competition in favor of species which never before had an opportunity to become abundant. Reduced cultivation also encouraged increase of troublesome annual species, but especially of perennials. Infestations of deep-rooted perennial broadleaf weeds were particularly dramatic on the Texas High Plains. Increases in silverleaf nightshade (*Solanum elaeagnifolium* Cav.), woollyleaf bursage [*Ambrosia grayi* (A. Nels.) Shinners], hogpotato [*Hoffmanseggia glauca* (Ortega) Eifert] and Texas blueweed (*Helianthus ciliaris* DC.) were noted. Abernathy *et al.* (1976) also noted that the continuous use of dinitroanilines had caused an increase in lanceleaf sage (*Salvia*

reflexa Hornem.), oakleaf thornapple (*Datura quercifolia* H. B. K.), prairie sunflower (*Helianthus petiolaris* Nutt.), rough blackfoot (*Melampodium hispidum* H. B. K.), spurred anoda and tall morningglory [*Ipomoea purpurea* (L.) Roth]. Supak (1978) relates the spread of lanceleaf sage to the widespread use of dinitroaniline herbicides which cannot control it successfully.

In the West prior to 1964, many cotton fields in California were heavily infested with numerous species of summer annual broadleafs and grasses (Fischer, 1975). He stated that as a consequence of the continuous use of dinitroanilines, those weeds were replaced by common cocklebur, tolguacha [sacred datura (*Datura innoxia* Mill.)], common sunflower (*Helianthus annuus* L.), groundcherry, nightshade (*Solanum* spp.), mare's tail {horseweed [*Conyza canadensis* (L.) Cronq.]}, johnsongrass, yellow or purple nutsedge, field bindweed, sowthistle (*Sonchus* spp.) and prickly lettuce (*Lactuca serriola* L.). Taylor and Heathman (1977) likewise observed the exclusive use of dinitroanilines caused an increase in groundcherry, spurred anoda and nutsedge. Whitworth (1977) noted that in situations where the stands of perennial weeds were initially thin and scattered, applications of dinitroanilines removed the early-season annual weeds so that the perennials grew unchecked and became serious problems that herbicides alone could not control. Several other weed problems have also evolved since the introduction of dinitroanilines; Taylor and Heathman (1978) named Wright groundcherry (*Physalis wrightii* Gray); Kempen and Woods (1979) indicated two major solanums [black nightshade and hairy nightshade (*Solanum sarrachoides* Sendtner)] and several other nightshades and groundcherries; and Kempen (1984) added yellow nutsedge to the list.

Herbicides other than the dinitroanilines have also been recognized as causing weed shifts. In a three-year field study, Baker (1982) examined the effects of annual applications of Cotoran® (fluometuron), Bladex® (cyanazine), Karmex® (diuron) and Zorial® (norflurazon) to the same cotton plots each year. In his study, Cotoran® was the most effective herbicide while the others had control problems which, with continued long-term use, could lead to serious weed problems. Bladex® failed to control annual grasses effectively, Karmex® failed to control prickly sida, and Zorial® did not control pitted morningglory (*Ipomoea lacunosa* L.). Dowler and Hauser (1974) repeated applications of Cotoran® for three consecutive years in cotton and caused decreased annual broadleaf weed populations of prickly sida, pigweed, smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.], sicklepod and tropic croton and shifted the weed population to yellow nutsedge and to annual grass species including large crabgrass, crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.], goosegrass and Texas panicum. Wills (1977) reported that increased use of herbicides, reductions in cultivation and hoeing and the adoption of skip-row cotton culture allowed purple nutsedge to evolve as a serious weed between 1940 and 1977.

After three annual applications, Weber *et al.* (1974) found that Caparol® (prometryn) and Cotoran® greatly decreased large crabgrass populations and in-

creased populations of yellow nutsedge and crowfootgrass. In contrast, applications of Treflan® greatly decreased large crabgrass and crowfootgrass populations, but the plots became completely infested with yellow nutsedge. Caparol® and Treflan® did not affect total weed density, but did affect which weed species were present. Each herbicide was more effective on certain weed species than on others, and this differential response caused a shift in weed populations as susceptible weeds were replaced by resistant ones.

Weed shifts are not always observed. Dowler and Baker (1975) used five distinctly different weed control systems, including conventional and high-population cotton during a two-year period, to control large crabgrass, Texas panicum and Florida pusley (*Richardia scabra* L.). In this short period, they did not significantly affect weed-species composition. Dowler *et al.* (1974) were unable to show a species composition change following four years of crop rotations and herbicide programs.

Not all weed problems have been solved by herbicides, and herbicides have even caused some weed problems. However, they remain the foundation of the present, highly necessary and largely successful fight against the profit-robbing nature of weeds.

ROTATIONS

Scientists have evaluated the effects of crop rotations on cotton production for many years (Jernigan, 1979). One of the earliest such studies (still in existence) was begun in 1896 at Auburn University to show the value of using winter legumes in a cotton-corn rotation. Much of the initial interest was in fertility rather than in weed control. However, it was recognized as early as 1908 that rotations were useful in the eradication of noxious weeds and in reducing the severity of insects and fungus diseases which can become common under continuous cotton (Moorhouse and Nicholson, 1908).

Prior to the late 1940s, rotations at irregular intervals were practiced in cotton usually with legumes somewhere in the cropping cycle (Cates, 1917). Webber and Boykin (1907) advocated rotations of cotton, followed by crimson clover (*Trifolium incarnatum* L.); corn and wheat, followed by cowpea or cotton; corn, with cowpea and oat, with cowpea. Morgan (1917) listed a number of possible rotations with one or two years of cotton in a three- to four-year cycle. The nitrogen-fixing crops he recommended were crimson clover, cowpea and/or peanut (*Arachis hypogaea* L.). Collings (1926) listed four rotations utilizing velvet bean [*Mucuna deeringiana* (Bort.) Merr.] and soybean. Brown (1927), in the first edition of his book, included three rotations for cotton utilizing cowpea or soybean in combination with corn and oat. When cotton appeared in the rotation, he suggested rye (*Secale cereale* L.) be planted between the crop rows after the first picking. In the second edition, he (1938) recommended the same rotations except that rye and vetch (*Vicia* spp.) were to be planted in the cotton middles. In the third edition (Brown and Ware, 1958), only two rotations were provided; and the

crops suggested in sequence are weighted more heavily toward summer legumes such as lespedeza (*Lespedeza* spp.).

In Georgia during a 15-year period between 1931 and 1946, continuous cotton was fertilized annually with 600 pounds of 6-6-4 per acre; and yields remained about the same as cotton grown in any rotation system studied, with or without legumes (Christidis and Harrison, 1955). Anhydrous ammonia (a relatively inexpensive fertilizer) became available to farmers in 1947 and was in widespread use by the mid-1950s (Street, 1957b). As a result, planting winter cover crops essentially ceased during the late 1940s and 1950s (Jernigan, 1979).

More recently, the concept of herbicide and crop rotation for weed control was introduced (McWhorter, 1962; Buchanan, 1974b; Hauser, 1974). To control a broader spectrum of weeds, McWhorter (1962) suggested the rotation of crops to allow the use of different herbicides, while Hauser (1974) recommended alternating herbicides applied to a single crop. Buchanan (1981) offered the example of common cocklebur which is difficult to control in cotton, but which is easily controlled in corn, grain sorghum or soybean with phenoxy herbicides. These authors recognized that weed shifts or management difficulties of specific weeds were increasing and their suggestions for crop and/or herbicide rotations were part of their solutions to the problem.

Research studies provide data on weed shifts as a consequence of certain herbicides and/or crop rotations. A crop-rotation study at Tifton, Georgia, showed that herbicide use killed 99 percent of yellow nutsedge by the end of a three-year rotation of corn, cotton and peanut (Hauser, 1974). Dale and Chandler (1977) reported changes in weed seed composition in the soil because of cropping history. More broadleaf weed seed and fewer grass and nutsedge seed were present in their continuous cotton treatment than when cotton followed corn. In other research, Dale and Chandler (1979) effectively controlled johnsongrass by a cropping sequence of corn-cotton-cotton-corn in which Treflan®, Cotoran® and MSMA were used for weed control in cotton. Likewise, Jernigan (1979) prevented grain sorghum from being infested with johnsongrass by rotating it with cotton and using dinitroaniline herbicides for weed control. Keeley *et al.* (1983) reported that intense management of cotton for three years with multiple herbicide applications and hoeing reduced yellow nutsedge tubers by 98 to 99 percent. They found similar results when cotton was grown in rotation with potato (*Solanum tuberosum* L.) or when land was fallowed following barley (*Hordeum vulgare* L.).

Certain weeds are easier to control in some crops than in others, and single approaches to weed control are not as successful as multiple approaches. Various individuals have investigated the effects of two-, three- and four-year crop-herbicide rotations on the species composition of weed populations. Dowler *et al.* (1974), in a four-year study, compared herbicide-crop rotations involving corn, cotton, peanut and soybean grown continuously or in rotation. They showed that herbicides more effectively controlled weeds than did cultural prac-

ping sequence studied. Although rotation greatly reduced weed numbers, the species composition of the weed population was not altered significantly. They concluded that a study such as this must be continued for longer than four years to eliminate a specific weed or to change the composition of the weed population. Apparently, the supply of viable weed seed in the soil had not been depleted by the end of the study; and/or the reintroduction of such seed had not been prevented.

HERBICIDE RESISTANCE WITHIN WEED SPECIES

Recent documentation of herbicide resistance within certain weed species (LeBaron and Gressel, 1982) is cause for concern as are the reports of several such weeds increasing in number and in geographic distribution. Such trends likely presage even greater difficulties in future weed control and greater prevalence of these species.

A few weeds in cotton have exhibited differential herbicide resistance or tolerance. For example, as early as 1969, it was demonstrated that strains or biotypes of johnsongrass respond differently to DSMA and MSMA (Hamilton, 1969). Some strains were tolerant while others were susceptible. Chandler (1981) documented differential susceptibility to five herbicides at two rates of several bermudagrass biotypes collected in Mississippi cotton fields from a geographical area of only eight Delta counties. Mudge *et al.* (1984) reported the development of a dinitroaniline-resistant biotype of goosegrass in South Carolina.

Horseweed resistance to herbicides, including AAtrex® (atrazine) and methylthio-s-triazines, has been reported in Hungary (Lehoczki *et al.*, 1984). The resistance occurred in vineyards "where atrazine had been applied continuously" for approximately 12 years. Wilson *et al.* (1985) in the United States suspect paraquat resistance in horseweed because of its extensive recovery following treatment with that herbicide. Caparol®, a methylthio-s-triazine, and paraquat are widely used for weed control in cotton produced under conservation tillage. The continued use of those herbicides and the increased prevalence of horseweed pose a potentially serious problem in those areas where the weed and conservation tillage coincide.

To date, the development of herbicide resistance or tolerance has not been a major problem in the weeds of cotton, as it has been for insecticide resistance or tolerance in the insects of the crop (Brown, 1968); but theoretically, it could become one. According to Parker (1977), intraspecific selection for resistant weed strains will tend to occur in monoculture when one class of herbicides is used repeatedly over a number of years. However, with the wide range of herbicides now available, the likelihood of a species developing resistance does not have to be as great as in the past. Combination and rotation of herbicides can be practiced which should help prevent or reduce selection for resistance or tolerance within a species. Parker (1977) states that self-pollinated species will not show increased herbicide resistance as rapidly as those which are cross polli-

nated. This may be true if the resistance is quantitatively inherited (regulated by many genes each of small effect and greatly influenced by environment) and if the genes are widely scattered throughout the population. It definitely is not true if the resistance is qualitatively inherited (regulated by one or two, never more than a few, genes each of large effect and largely independent of the environment).

INTEGRATED PEST MANAGEMENT

Following an examination of individual management techniques and their effects on weed populations, a consideration of integrated pest management (IPM) would logically be the next step. However, the publications professing to discuss IPM that we examined are actually not doing so in the strict sense of the word. To be IPM, the program must, among other things, actually integrate control or management tactics. In most cases the pest disciplines and the pests classified within them are discussed individually rather than collectively (Cotton Study Team, 1975; IPM Manual Group, 1984). The Cotton Study Team (1975) primarily discusses only insect management in the section on IPM and not the integration of management strategies among pests. The IPM Manual Group (1984) has excellent individual chapters on management and of individual pests within each discipline, but no true integration of these within or among disciplines. Baldwin and Santelmann (1980) have discussed the role of weed science in IPM and some of the obstacles which must be overcome before the discipline can truly be considered as integrated. Recently, scientists (Frick and Chandler, 1978; Gaylor *et al.*, 1983; Miller *et al.*, 1979; Walker and Sciumbato, 1979) have been more frequently conducting and reporting multidisciplinary research; and in the future, more information will undoubtedly be available as the data base expands. However, at present IPM appears to be more a concept or goal than a practice. Until it actually becomes a practice, it can and will have little or no influence on weed population shifts.

SHIFTS BY GEOGRAPHICAL REGIONS

PRIOR TO 1940

Early cotton producers often distinguished between "grass" and "weeds" (Turner, 1857; Bruchey, 1967) with the latter presumably including all unwanted, broadleaf plants. In later times, johnsongrass (Plate 6-39[1]) was discriminated from other grasses—probably because of its great competitiveness and distinctive characters above and below the soil surface. Of course, prior to its introduction into the United States around 1830 for use as a forage crop (Ocumpaugh and Rouquette, 1985), it was not a weed in cotton fields. The introduction of bermudagrass (Plate 6-46) in 1751, or earlier, for the same reason (Burton and Hanna, 1985) was a similar case. Planters realized the importance of weed control, particularly of grass, early in the season. Hammond (Turner, 1857) stated that, "In

[1]Plates are located in the Appendix at the end of this chapter.

cultivating Cotton, whether with the plough or hoe, the chief object is to keep down the grass, which is its greatest antagonist, bringing all, or almost all other evils in its train." He further referred to grass as "that mortal enemy." Fite (1979) wrote that, "Many cotton farmers literally hated grass." The legislators of several southern states, more interested in cotton and corn than in pastures, went so far as to pass laws prohibiting the introduction and planting of bermudagrass (Burton and Hanna, 1985). As might be expected, the laws did not produce their intended effect.

In 1852, Chambers (Turner, 1857) presented an essay on cotton culture before the Southern Central Agricultural Association of Georgia. He reported that the first operation performed after a cotton stand was established was to chop or thin the cotton. A careful plowman followed "throwing a little light dirt into the spaces made by the hoe, and a little also about the roots of the cotton, covering and leaving covered, all small grass which may have sprung up...This is known to practical planters, to be the crop of grass which escapes the hoe, and does mischief to the cotton." Chambers continued to describe tasks performed to control grass, but only occasionally mentioned "weeds."

A colorful description written in 1854 (Bruchey, 1967) describes the general attitude toward weed and grass control:

> "The pleasant month of May is now drawing to a close, and vegetation of all kinds is struggling for precedence in the fields. Grasses and weeds of every variety, with vines and wild flowers, luxuriate in the newly-turned sod, and seem to be determined to choke out of existence the useful and still delicately-grown cotton. It is a season of unusual industry on the cotton plantations, and woe to the planter who is outstripped in his labors, and finds himself 'overtaken by the grass'. The plow tears up the surplus vegetation, and the hoe tops it off in its luxuriance. The race is a hard one, but industry conquers; and when the third working over of the crop takes place, the cotton plant, so much cherished and favored, begins to overtop its rivals in the fields—begins to cast a chilling shade of superiority over its now intimidated groundlings, and commences to reign supreme. Through the month of July,...the plow and hoe are still in requisition."

In a worst-case scenario, however,

> "If it continues to rain after the final planting is finished, then a fresh source of danger is opened. For the grass and the weeds grow as fast as the cotton, and are shortly very difficult to remove. They are not only numerous and well rooted, but cutting them out is difficult to accomplish, without injuring the cotton plants. In the years of labor shortage, it is often impossible to clean the fields, and in midsummer you will see the cotton plants practically concealed under the grass and weeds wav-

ing above them. Such fields 'got in the grass' so badly, that the farmer was unable to secure the labor necessary to clean them. The acreage thus 'abandoned' may amount to a considerable percentage of the total amount..." (Hubbard, 1923).

In 1914, 25 or more farmers in each of 19 areas (primarily counties) throughout the Southeast, Mid-South and Southwest were surveyed as to their usual practices in cotton cultivation (Cates, 1917). That survey serves as a reference point for the actual practice "of the art" throughout the Cotton Belt of the time. All surveyed sites reported that cotton was grown on the best land, that cotton was the principal cash crop, and that no definite crop rotations were practiced, but crops were generally rotated in a sporadic manner. Cotton normally followed cotton, corn or another row crop. The most troublesome weeds at that time by area are summarized in Table 2. By 1914, farmers were discriminating much better than previously among various weeds...though it is not always possible now to identify the weeds indicated. For example, "pigweed" and "careless weed" are now generally regarded as synonyms for the same general type of weed (*Amaranthus* spp.) (Plates 6-3 through 6-6); but from two areas reported, both names were given. No scientific names were provided in the publication. Crabgrass (Plate 6-37), cocklebur (Plates 6-15 and 6-16) and johnsongrass were problems almost everywhere that cotton was grown in 1914. Nutgrass (nutsedge)

Table 2. Most troublesome weeds in 19 cotton-growing areas of 12 states in 1914. (Information adapted from Cates, 1917.)

Most troublesome weeds[1]	Southeast									Mid-South					Southwest					Totals
	AL	FL	GA[2]	GA[3]	GA[4]	NC[5]	NC[6]	SC	TN	AR	LA	MS[7]	MS[8]	MO	OK	TX[9]	TX[10]	TX[11]	TX[12]	
crab-grass	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*		17
cocklebur	*		*	*	*	*		*	*	*	*	*	*	*	*	*	*	*		16
Johnson grass	*						*		*	*		*	*		*	*	*	*	*	11
morning-glory									*	*		*	*	*	*	*	*		*	9
careless weed									*		*	*		*	*	*		*	*	8
Bermuda grass	*	*		*	*			*		*	*							*		8
nut-grass	*	*						*	*	*		*	*							7
coffee weed	*	*	*	*								*								5
pigweed					*	*					*			*						4
smartweed						*			*						*					3
wild coffee					*			*												2
ragweed			*								*									2
buffalo grass																	*		*	2
wild onion							*													1
hurrah grass																*				1
lamb's quarters															*					1
beggarweed		*																		1

[1]Names (including spellings and capitalizations) as used in the original publication have been retained.

[2]Pike Co. [3]Tift Co. [4]Bulloch Co. [5]Robeson Co. [6]Mecklenburg Co. [7]Mississippi Delta. [8]Monroe Co. [9]Ellis Co. [10]Lavaca Co. [11]Houston Co. [12]Bexar Co.

(Plates 6-27 through 6-30) appears to have been originally a weed of the Southeast and Mid-South before spreading to the Southwest. This was probably true for bermudagrass as well. Morningglory (Plates 6-20 through 6-26) was likely a weed of the Mid-South and Southwest before spreading to the Southeast. A number of other weeds [*e.g.*, hurrah grass (assumed to be Texas panicum) (Plate 6-44)] were apparently very local in distribution. Until cotton had spread to an area where a potential weed occurred or *vice versa*, that weed could hardly have been a problem in the crop. Across that vast area from the Carolinas to Texas, the list of most prevalent and troublesome weeds at each location was rather small. A grass was the most prevalent weed reported with 17 of 19 sites listing crabgrass; also reported were 11 sites for johnsongrass, 8 for bermudagrass, 2 for buffalo grass (probably also referring to Texas panicum) and 1 for hurrah grass. Cocklebur was the most reported broadleaf species with 16 out of 19 sites reporting it as prevalent and troublesome. Ten sites reported pigweed while morningglory was reported from nine. Nutsedge was listed for seven sites; and the legumes, coffee weed and Florida beggarweed (Plates 6-50 and 6-51), were reported for seven and one sites, respectively. Depending on the area, "coffee weed" probably indicated either sicklepod (Plates 6-48 and 6-49) in the Southeast or hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. *ex* A. W. Hill (Plates 6-52 and 6-53)] in the Mid-South. Three sites reported smartweed (*Polygonum* spp.) (Plate 6-65), two listed ragweed (*Ambrosia* spp.) (Plates 6-13 and 6-14), one reported lambsquarters (Plate 6-10) and another listed wild onion (*Allium canadense* L.).

A few years later, Collings (1926) reported the most prevalent and troublesome weeds from four areas in the Cotton Belt. In the Yazoo County area of the Mississippi Delta, he listed nutgrass, large crabgrass, common cocklebur, morningglory, johnsongrass, careless weed and coffeeweed. From the Blackbelt area of northeast Texas, were indicated careless weed, bunch grass (identity unknown), common cocklebur, morningglory and johnsongrass. In south-central Tennessee, were inventoried crabgrass, careless weed, nutgrass, common cocklebur, snakeweed (identity unknown), morningglory and johnsongrass. From the Coastal Plain of North Carolina, were reported crabgrass, common cocklebur, snakeweed and pigweed.

As recently as 50 years ago, the cotton farmer's solution to his weed problems was a relatively straightforward attack with physical force. His weapons were animal-drawn tillage implements and, in many situations, his hands or hand-held tools, particularly the hoe.

1940 THROUGH 1969

More than 90 percent of current weed control technology has been developed since 1940 and much of it since 1960 (Shaw, 1979). Neely and Brain (1944) reported that the main problems in the Mississippi Delta were grasses [principally crabgrass and "watergrass" (*Echinochloa* spp.) (Plates 6-41 and 6-42)] and pigweed. They observed that if cotton were only cultivated and not hoed or flamed,

"At the time the first picking was made, the cotton plants were completely 'wrapped' in crabgrass, 'watergrass', a species of panicum (Plates 6-43 through 6-45), morningglory, and two other types of 'tie vines'." They also found some "nut grass" and an occasional johnsongrass plant. From these statements, the weed spectrum apparently had changed very little from 1857 to 1944. Grasses continue to be mentioned into the late 1950s and early 1960s. As late as 1953, large crabgrass was still considered a major problem to cotton producers in Missouri; and research was initiated to control it (Foy, 1959). In the early 1960s, Colwick *et al.* (1960) specifically mentioned weedy grasses in cotton and discussed how those grasses affected cotton grades.

In the late 1940s, an effective method for applying anhydrous ammonia was devised (Street, 1957b). How this development affected weed control or shifts in weed species will probably never be known because there was no longer an apparent need to rotate cotton or other crops with legumes to add nitrogen to the soil. This reduction in rotations or shift toward monoculture undoubtedly encouraged some weeds to become more prevalent at the expense of others; and the increased nitrogen level of the soil probably did so as well. The additional nitrogen also likely encouraged more weed growth of all weeds present.

Large-scale use of herbicides for weed control in cotton began in the 1950s, and hand hoeing changed from a primary to a supplementary method of weed control (see Chapter 7 for a more thorough discussion). Throughout the 1950s and early 1960s, much attention was given to minimizing the disturbance of soil treated with herbicides. It was assumed that disturbing treated soil, or movement of soil into treated areas, would be detrimental to the residual action of the chemicals (Holstun and Wooten, 1968).

Weed composition appeared to be shifting in the late 1950s as broadleaf weeds and perennials were cited more frequently as troublesome. A farm survey by Miller and Foy (1956) reported that 12 percent of California cotton was infested with annual grasses [watergrass, hairy crabgrass (large crabgrass), lovegrass (*Eragrostis* spp.) and field sandbur (*Cenchrus incertus* M. A. Curtis) (Plate 6-47)], 13 percent with annual broadleaf weeds [pigweed, common lambsquarters, puncturevine (*Tribulus terrestris* L.) and purslane (*Portulaca* spp.) (Plate 6-66)] and 12 percent with perennials [johnsongrass, bermudagrass, nutgrass (nutsedge), field bindweed (Plate 6-19), Russian knapweed (*Centaurea repens* L.) and white horse nettle (silverleaf nightshade) (Plates 6-69 and 6-70)]. Danielson *et al.* (1968) published the results of a survey conducted from 1959 through 1965 for the five most important weeds of cotton by state. It is noteworthy that no member of the Malvaceae, Euphorbiaceae or Solanaceae families were reported among those weeds, except that Arkansas had about 30 percent of its acres infested with the Malvaceae, prickly sida (Plates 6-55 and 6-56). Alabama and Georgia were the only states to list a Leguminosae family member (sicklepod). The West listed no perennial Convolvulaceae family member. Weeds indicated among the five most important in at least four states were barnyardgrass (Plate

6-42), common cocklebur, crabgrass, johnsongrass, morningglory, nutsedge and pigweed. Of these nationally or regionally important weeds, infestations were reported as declining in two or more states for crabgrass, johnsongrass, morningglory and pigweed.

Wills (1977) reported that in 1957 purple nutsedge (Plates 6-27 and 6-28) was ranked below large crabgrass, morningglory, common cocklebur and ragweed as a severe weed problem in the Mississippi Delta; however, by the 1970s purple nutsedge was a leading problem. Nutsedge control into the early 1960s was accomplished with extensive cultivation (including cross-cultivation) and hand hoeing. When skip-row culture began, cross-plowing was discontinued. The reduced cultivation favored nutsedge, and the large skip area (without shade) also encouraged the weed. Herbicides began replacing hand hoeing; thus, another effective control method was cast aside. The pronounced change to herbicides in the 1960s caused yet even greater weed shifts. The first herbicides successfully controlled many broadleaf and grass weeds. However, those herbicides did not control nutsedge and, in fact, encouraged its growth by removing competition from other weed species.

The use of herbicides increased rapidly in cotton. Between 1959 and 1962, a 250 percent increase was noted in cotton acreage treated (Shaw, 1964). During the same time period, the only major agronomic crops to show a larger increase in acreage treated were soybean and peanut. Shaw (1979) later reported that between 1950 and 1979, mechanical power use increased 30 percent, herbicide use increased 700 + percent and hand labor decreased 40 percent.

1970 THROUGH 1986

Numerous authors (Buchanan, 1974c; Mullendore, 1976; Jordan, 1978; Whitwell, 1982; Bryson, 1985; Vargas and Heathman, 1987) have reported results of surveys and/or projections of important weeds in cotton. In the survey by Buchanan (1974c), among the top 10 most important weeds of cotton were pigweed and nutsedge in 12 states, johnsongrass in 10 and common cocklebur and crabgrass in 8. His survey further showed that Solanaceae weeds were listed by three states, Malvaceae by seven and Euphorbiaceae by eight while four states listed Leguminosae weeds. The inclusions of Malvaceae and Solanaceae weeds were the only major changes from those reported 57 years earlier by Cates (1917). Mullendore (1976) considered the 10 worst weeds in United States cotton to be annual morningglory, johnsongrass, nutsedge, common cocklebur, prickly sida, spurred anoda (Plates 6-57 and 6-58), spurge (*Euphorbia* spp.) (Plates 6-35 and 6-36), croton (*Croton* spp.) (Plates 6-33 and 6-34), silverleaf nightshade and bermudagrass.

Whitwell (1982) summarized the results of the 1981 Beltwide Cotton Production Weed Loss Committee and noted that large-seeded broadleaf annual weeds and perennial weeds accounted for 10 genera in their survey. He also summarized the 10 genera which caused the greatest yield losses and those which in-

fested the largest area. Seven genera were common to both lists—*Ipomoea* (Plates 6-20 through 6-26), *Sorghum, Amaranthus*, *Sida* (Plates 6-55 and 6-56), *Cyperus* (Plates 6-27 through 6-30), *Solanum* (Plates 6-69 through 6-78) and *Digitaria* (Plate 6-37). The genera *Xanthium* (Plates 6-15 and 6-16), *Cynodon* and *Cassia* (Plates 6-48, 6-49 and 6-54) appeared as weeds that severely reduced yields, but did not infest large acreages. *Salsola*, *Echinochloa* and *Panicum* (Plates 6-43 through 6-45) infested large acreages, but did not cause great yield losses. Even after 20 years of dinitroaniline use, the grasses were still present in sufficient numbers to pose a future threat of becoming serious weeds again. They were apparently held in check with effective annual applications of herbicides, but were not eliminated.

In 1971, the Southern Weed Science Society (SWSS) published its first weed survey of the southern states in their Research Report (Buchanan, 1971a). In 1975, the Beltwide Cotton Production-Mechanization Conference published the results of a 1974 weed survey (Hurst, 1975). Results reported in 1971, 1974, 1977, 1980, 1983 and 1986 by the SWSS have been compiled into Tables 3 through 8. The above reporting years correspond to crop years of 1970, 1973, 1976, 1979, 1982 and 1985, respectively. Table 3 includes survey results from the Southeast for the most common (frequently found) weeds in cotton for the above six years. Members of the broadleaf families Amaranthaceae, Compositae, Convolvulaceae, Euphorbiaceae, Leguminosae and Malvaceae were counted among the 10 most common weeds in all years. Cyperaceae and Gramineae were narrowleaf families represented among the 10 most common in all years. Common lambsquarters of the Chenopodiaceae family was common during 1970, 1973 and 1976; but was no longer reported in the Southeast after that time. Pennsylvania smartweed (*Polygonum pensylvanicum* L.) (Plate 6-65) of the Polygonaceae family was listed in 1970 and 1985 only. Florida pusley (Plates 6-67 and 6-68) of the Rubiaceae family was consistently listed in 1973 and thereafter, but only Florida reported this weed as common.

Generally, the Amaranthaceae, Compositae, Convolvulaceae, Cyperaceae, Euphorbiaceae, Gramineae, Leguminosae and Malvaceae families appear among the 10 most common and 10 most troublesome (difficult to control) weeds of the Southeast states (Tables 3 and 4, respectively). Nutsedge and johnsongrass consistently appeared in all years. Bermudagrass appeared in 1970 and in 1979 through 1985 as a most troublesome weed and also appeared on the most common list in 1985. During this 15-year reporting period, no apparent trend existed for reduced numbers of families from either category over time; and in fact, there seems to be a trend for more representatives per family over time. For example, the Gramineae were listed in 1970 with three and four representatives on the most common and most troublesome lists, respectively. By 1985, the most common list showed six grasses while the most troublesome list included seven. One change not illustrated by these tables is that over time, the rankings changed

Table 3. Most common weeds present in cotton of the Southeast in selected crop years.[1]

1970[2]	1973[3]	1976[4]	1979[5]	1982[6]	1985[7]
Amaranthaceae pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed
Chenopodiaceae common lambsquarters	**Chenopodiaceae** common lambsquarters	**Chenopodiaceae** common lambsquarters			
Compositae common cocklebur common ragweed	**Compositae** common cocklebur common ragweed	**Compositae** common cocklebur common ragweed	**Compositae** bristly starbur common cocklebur common ragweed	**Compositae** common cocklebur common ragweed	**Compositae** common cocklebur common ragweed
Convolvulaceae morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory
Cyperaceae nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]
Euphorbiaceae spotted spurge woolly croton	**Euphorbiaceae** spotted spurge tropic croton	**Euphorbiaceae** spotted spurge tropic croton	**Euphorbiaceae** spurge tropic croton	**Euphorbiaceae** spurge tropic croton	**Euphorbiaceae** croton spurge
Gramineae goosegrass johnsongrass[8] large crabgrass	**Gramineae** fall panicum field sandbur goosegrass johnsongrass[8] large crabgrass	**Gramineae** fall panicum goosegrass johnsongrass[8] large crabgrass	**Gramineae** goosegrass johnsongrass[8] large crabgrass	**Gramineae** goosegrass fall panicum johnsongrass[8] large crabgrass Texas panicum	**Gramineae** bermudagrass[8] field sandbur goosegrass johnsongrass[8] large crabgrass Texas panicum
Leguminosae sicklepod	**Leguminosae** Florida beggarweed sicklepod	**Leguminosae** Florida beggarweed sicklepod	**Leguminosae** Florida beggarweed sicklepod	**Leguminosae** Florida beggarweed sicklepod	**Leguminosae** Florida beggarweed sicklepod
Malvaceae prickly sida	**Malvaceae** prickly sida	**Malvaceae** prickly sida	**Malvaceae** prickly sida velvetleaf	**Malvaceae** prickly sida velvetleaf	**Malvaceae** prickly sida velvetleaf
Polygonaceae Pennsylvania smartweed					**Polygonaceae** Pennsylvania smartweed
	Rubiaceae Florida pusley	**Rubiaceae** Florida pusley	**Rubiaceae** Florida pusley	**Rubiaceae** Florida pusley	**Rubiaceae** Florida pusley
			Solanaceae jimsonweed	**Solanaceae** jimsonweed	

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Buchanan (1971a).
[3]Information adapted from Buchanan (1974a).
[4]Information adapted from McCormick (1977).
[5]Information adapted from Palmer (1980).
[6]Information adapted from Elmore (1983).
[7]Information adapted from Elmore (1986).
[8]Denotes a perennial species or mixtures containing perennials.

somewhat; but any weed that continued to be listed in the top 10 cannot be disregarded from a control standpoint.

The survey results from the Mid-South do not depict a large shift in weed composition over this time period (Tables 5 and 6). For the most part, the species and families occurring as most common weeds also appeared as most troublesome. Pigweed did not appear as one of the most troublesome weeds in 1985, but it had ranked near the bottom of the 10 in previous years. The rankings changed slightly, but the trend was surprisingly often to an even higher ranking in both

Table 4. Most troublesome weeds present in cotton of the Southeast in selected crop years.[1]

1970[2]	1973[3]	1976[4]	1979[5]	1982[6]	1985[7]
Amaranthaceae	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**
pigweed	pigweed	pigweed	pigweed	pigweed	pigweed
	Chenopodiaceae	**Chenopodiaceae**			
	common lambsquarters	common lambsquarters			
Compositae	**Compositae**	**Compositae**	**Compositae**	**Compositae**	**Compositae**
common cocklebur	common cocklebur	common cocklebur	bristly starbur	common cocklebur	common cocklebur
common ragweed	common ragweed	common ragweed	common cocklebur	common ragweed	
			common ragweed		
Convolvulaceae	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**
morningglory	morningglory	morningglory	morningglory	morningglory	morningglory
Cyperaceae	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**
nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]
Euphorbiaceae	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**
croton	spurge	spurge	spurge	spurge	spurge
spurge	tropic croton	tropic croton	tropic croton	tropic croton	tropic croton
Gramineae	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**
bermudagrass[8]	fall panicum	fall panicum	bermudagrass[8]	bermudagrass[8]	bermudagrass[8]
fall panicum	field sandbur	goosegrass	field sandbur	broadleaf	broadleaf
johnsongrass[8]	goosegrass	johnsongrass[8]	goosegrass	signalgrass	signalgrass
large crabgrass	johnsongrass[8]	large crabgrass	johnsongrass[8]	fall panicum	fall panicum
	large crabgrass		large crabgrass	goosegrass	goosegrass
			Texas panicum	johnsongrass[8]	johnsongrass[8]
				large crabgrass	large crabgrass
				Texas panicum	Texas panicum
Leguminosae	**Leguminosae**	**Leguminosae**	**Leguminosae**	**Leguminosae**	**Leguminosae**
sicklepod	Florida beggarweed	Florida beggarweed	coffee senna	Florida beggarweed	Florida beggarweed
	sicklepod	sicklepod	Florida beggarweed	sicklepod	sicklepod
			sicklepod		
Malvaceae	**Malvaceae**	**Malvaceae**	**Malvaceae**	**Malvaceae**	**Malvaceae**
prickly sida	prickly sida	prickly sida	prickly sida	prickly sida	prickly sida
	spurred anoda	spurred anoda	velvetleaf	spurred anoda	spurred anoda
	velvetleaf	velvetleaf		velvetleaf	velvetleaf
	Rubiaceae	**Rubiaceae**	**Rubiaceae**		**Rubiaceae**
	Florida pusley	Florida pusley	Florida pusley		Florida pusley
	Solanaceae	**Solanaceae**			
	jimsonweed	jimsonweed			
			Vines		
			unspecified[8]		

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Buchanan (1971a).
[3]Information adapted from Buchanan (1974a).
[4]Information adapted from McCormick (1977).
[5]Information adapted from Palmer (1980).
[6]Information adapted from Elmore (1983).
[7]Information adapted from Elmore (1986).
[8]Denotes a perennial species or mixtures containing perennials.

categories. Bignoniaceae was reported by itself for the first time in 1985; this family was probably included previously among the unspecified vines.

In the Southwest, fewer families and species appear as major weed problems (Tables 7 and 8). Perennial weeds occupy several positions in the tables. Pigweed is among the most common weeds, but it is rarely listed as a troublesome weed. Field bindweed, a perennial, has emerged as one of the more troublesome weeds

Table 5. Most common weeds present in cotton of the Mid-South in selected crop years.[1]

1970[2]	1973[3]	1976[4]	1979[5]	1982[6]	1985[7]
Amaranthaceae	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**
pigweed	pigweed	pigweed	pigweed	pigweed	pigweed
Compositae	**Compositae**	**Compositae**	**Compositae**	**Compositae**	**Compositae**
common cocklebur	common cocklebur	common cocklebur	common cocklebur	common cocklebur	common cocklebur
Convolvulaceae	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**
morningglory	morningglory	morningglory	morningglory	morningglory	morningglory
Cyperaceae	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**
nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]
Euphorbiaceae	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**
spurge	spurge	spurge	spurge	spurge	spurge
Gramineae	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**
goosegrass	bermudagrass[8]	bermudagrass[8]	barnyardgrass	barnyardgrass	broadleaf
johnsongrass[8]	broadleaf	broadleaf	bermudagrass[8]	bermudagrass[8]	signalgrass
large crabgrass	signalgrass	signalgrass	broadleaf	broadleaf	goosegrass
	goosegrass	goosegrass	signalgrass	signalgrass	johnsongrass[8]
	johnsongrass[8]	johnsongrass[8]	goosegrass	goosegrass	large crabgrass
	large crabgrass	large crabgrass	johnsongrass[8]	johnsongrass[8]	
			large crabgrass	large crabgrass	
	Leguminosae	**Leguminosae**		**Leguminosae**	**Leguminosae**
	hemp sesbania	hemp sesbania		hemp sesbania	hemp sesbania
	Malvaceae	**Malvaceae**	**Malvaceae**	**Malvaceae**	**Malvaceae**
	prickly sida	prickly sida	prickly sida	prickly sida	prickly sida
	spurred anoda	spurred anoda			
	velvetleaf				
	Polygonaceae				
	redvine[8]				

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Buchanan (1971a).
[3]Information adapted from Buchanan (1974a).
[4]Information adapted from McCormick (1977).
[5]Information adapted from Palmer (1980).
[6]Information adapted from Elmore (1983).
[7]Information adapted from Elmore (1986).
[8]Denotes a perennial species or mixtures containing perennials.

as have several solanums. The addition of the Solanaceae family to the lists of most common and most troublesome weeds is probably the biggest change from the regions east of Oklahoma and Texas. Another major difference is that the Compositae are not on either list for the Southwest.

Sources of information by year for states in the West are footnoted at the bottom of each table. This information was adapted primarily from the Proceedings of the Beltwide Cotton Production Research Conference. If information were given on acres infested by each of the weed species, they were ranked and considered as most common weeds (Table 9). If losses were given, those values were ranked by species and used to establish the most troublesome weed category (Table 10). A definite increase was noted in perennials as most troublesome weeds. Field bindweed was consistently present, but was not listed as troublesome until 1978. The grasses are represented by a small, but relatively consistent, group of two annuals (panicum and barnyardgrass) and two perennials (bermu-

Table 6. Most troublesome weeds present in cotton of the Mid-South in selected crop years.[1]

1970[2]	1973[3]	1976[4]	1979[5]	1982[6]	1985[7]
	Amaranthaceae pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	
					Bignoniaceae trumpetcreeper[8]
Compositae common cocklebur	**Compositae** common cocklebur	**Compositae** common cocklebur	**Compositae** common cocklebur	**Compositae** common cocklebur	**Compositae** common cocklebur
Convolvulaceae morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory
Cyperaceae nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]	**Cyperaceae** nutsedge[8]
Euphorbiaceae hophornbeam copperleaf spotted spurge	**Euphorbiaceae** spotted spurge	**Euphorbiaceae** spotted spurge	**Euphorbiaceae** spotted spurge	**Euphorbiaceae** spotted spurge	**Euphorbiaceae** spotted spurge
Gramineae bermudagrass[8] johnsongrass[8]	**Gramineae** barnyardgrass bermudagrass[8] broadleaf signalgrass goosegrass johnsongrass[8]	**Gramineae** barnyardgrass bermudagrass[8] broadleaf signalgrass goosegrass johnsongrass[8]	**Gramineae** barnyardgrass bermudagrass[8] goosegrass johnsongrass[8] large crabgrass	**Gramineae** barnyardgrass bermudagrass[8] broadleaf signalgrass goosegrass johnsongrass[8]	**Gramineae** barnyardgrass bermudagrass[8] broadleaf signalgrass goosegrass johnsongrass[8]
				Leguminosae hemp sesbania	**Leguminosae** hemp sesbania
Malvaceae prickly sida spurred anoda	**Malvaceae** prickly sida spurred anoda velvetleaf	**Malvaceae** prickly sida spurred anoda velvetleaf	**Malvaceae** prickly sida spurred anoda velvetleaf	**Malvaceae** prickly sida spurred anoda velvetleaf	**Malvaceae** prickly sida
Polygonaceae redvine[8]	**Polygonaceae** redvine[8]		**Polygonaceae** redvine[8]	**Polygonaceae** redvine[8]	**Polygonaceae** redvine[8]
	Vines unspecified[8]	**Vines** unspecified[8]	**Vines** unspecified[8]		

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Buchanan (1971a).
[3]Information adapted from Buchanan (1974a).
[4]Information adapted from McCormick (1977).
[5]Information adapted from Palmer (1980).
[6]Information adapted from Elmore (1983).
[7]Information adapted from Elmore (1986).
[8]Denotes a perennial species or mixtures containing perennials.

dagrass and johnsongrass). Junglerice [*Echinochloa colonum* (L.) Link] (Plate 6-41) is probably included in the annual grasses because the surveys used listed *Echinochloa* spp. Based on other reports, we assumed that barnyardgrass would appear more frequently than junglerice; therefore, it is listed in Tables 9 and 10.

Tables 11 and 12 summarize distributions by region and state since 1970 for the most common and most troublesome weed families, respectively. Those families occurring most commonly in all regions and states include Amaranthaceae, the annual Convolvulaceae and the annual Gramineae (Table 11). Cyperaceae are listed in all except Tennessee as are the perennial Gramineae in all except Florida. Compositae are common except in the Southwest. Euphorbiaceae are generally common except in the West. Leguminosae and Malvaceae predominate in the Southeast and Mid-South. The perennial Solanaceae are common through-

Table 7. Most common weeds present in cotton of the Southwest in selected crop years.[1]

1970[2,3]	1973[4]	1976[2,5]	1979[6]	1982[7]	1985[8]
				Aizoaceae carpetweed	**Aizoaceae** carpetweed
Amaranthaceae pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed	**Amaranthaceae** pigweed
Chenopodiaceae common lambsquarters					
Convolvulaceae field bindweed[9]	**Convolvulaceae** field bindweed[9] morningglory	**Convolvulaceae** field bindweed[9] morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory	**Convolvulaceae** morningglory
Cyperaceae nutsedge[9]	**Cyperaceae** purple nutsedge[9,10]		**Cyperaceae** purple nutsedge[9,10] yellow nutsedge[9,10]	**Cyperaceae** purple nutsedge[9,10] yellow nutsedge[2,9]	**Cyperaceae** purple nutsedge[9,10] yellow nutsedge[2,9]
	Euphorbiaceae spotted spurge	**Euphorbiaceae** spurge	**Euphorbiaceae** spurge	**Euphorbiaceae** spurge	**Euphorbiaceae** spurge
Gramineae barnyardgrass johnsongrass[9] large crabgrass Texas panicum	**Gramineae** barnyardgrass[2] broadleaf signalgrass browntop panicum[10] johnsongrass[9] junglerice[2] large crabgrass Texas panicum	**Gramineae** barnyardgrass johnsongrass[9] large crabgrass Texas panicum	**Gramineae** barnyardgrass broadleaf signalgrass browntop panicum johnsongrass[9] junglerice large crabgrass Texas panicum	**Gramineae** broadleaf signalgrass browntop panicum johnsongrass[9] junglerice large crabgrass Texas panicum	**Gramineae** broadleaf signalgrass browntop panicum johnsongrass[9] junglerice large crabgrass Texas panicum
	Portulacaceae common purslane	**Portulacaceae** common purslane	**Portulacaceae** common purslane	**Portulacaceae** common purslane	**Portulacaceae** common purslane
Solanaceae horsenettle[9]	**Solanaceae** silverleaf nightshade[9]	**Solanaceae** silverleaf nightshade[9]	**Solanaceae** silverleaf nightshade[9]	**Solanaceae** silverleaf nightshade[9]	**Solanaceae** silverleaf nightshade[9]

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Oklahoma only.
[3]Information adapted from Buchanan (1971a).
[4]Information adapted from Buchanan (1974a).
[5]Information adapted from McCormick (1977).
[6]Information adapted from Palmer (1980).
[7]Information adapted from Elmore (1983).
[8]Information adapted from Elmore (1986).
[9]Denotes a perennial species or mixtures containing perennials.
[10]Texas only.

out the Southwest and West. Those families most troublesome in all regions and states include the annual Convolvulaceae, Cyperaceae and the annual Gramineae (Table 12). The perennial Gramineae were most troublesome in all states except Florida. Generally distributed throughout the Cotton Belt, but not troublesome in every state, were Amaranthaceae, Euphorbiaceae and Malvaceae. Compositae are most troublesome everywhere except in the Southwest. Leguminosae and perennial vines (Plates 6-8, 6-9 and 6-64) are generally most troublesome in the Southeast and Mid-South, while Polygonaceae is in the Mid-South. Solanaceae, especially the perennials, are most troublesome in the Southwest and West as are the perennial Convolvulaceae.

Table 8. Most troublesome weeds present in cotton of the Southwest in selected crop years.[1]

1970[2,3]	1973[4]	1976[2,5]	1979[6]	1982[7]	1985[8]
Amaranthaceae					**Amaranthaceae**
pigweed					pigweed
Convolvulaceae	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**
field	field	field	field	field	field
bindweed[9]	bindweed[9]	bindweed[9]	bindweed[9]	bindweed[9]	bindweed[9]
	morningglory	morningglory	morningglory	morningglory	morningglory
Cyperaceae	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**
yellow nutsedge[9]	purple nutsedge[9,10]	yellow nutsedge[9]	purple nutsedge[9,10]	purple nutsedge[9,10]	purple nutsedge[9,10]
	yellow nutsedge[9]		yellow nutsedge[2,9]	yellow nutsedge[2,9]	yellow nutsedge[2,9]
				Euphorbiaceae	**Euphorbiaceae**
				spurge	spurge
Gramineae	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**
barnyardgrass	bermudagrass[9]	johnsongrass[9]	bermudagrass[9]	bermudagrass[9]	bermudagrass[9]
johnsongrass[9]	broadleaf		broadleaf	broadleaf	broadleaf
junglerice	signalgrass		signalgrass	signalgrass	signalgrass
large crabgrass	johnsongrass[9]		johnsongrass[9]	johnsongrass[9]	johnsongrass[9]
Texas panicum	Texas panicum		Texas panicum	Texas panicum	Texas panicum
Malvaceae	**Malvaceae**	**Malvaceae**	**Malvaceae**	**Malvaceae**	**Malvaceae**
prickly sida	prickly sida	prickly sida	alkali sida[10]	alkali sida[10]	alkali sida[10]
	Venice mallow	Venice mallow	prickly sida[2]	prickly sida	prickly sida
				Martyniaceae	**Martyniaceae**
				devil's-claw	devil's-claw
	Portulacaceae	**Portulacaceae**	**Portulacaceae**	**Portulacaceae**	
	common purslane	common purslane	common purslane	common purslane	
Solanaceae	**Solanaceae**	**Solanaceae**	**Solanaceae**	**Solanaceae**	**Solanaceae**
horsenettle[9]	buffalobur	buffalobur	buffalobur	buffalobur	buffalobur
	horsenettle[9]	horsenettle[9]	horsenettle[9]	horsenettle[9]	silverleaf
	silverleaf	silverleaf	silverleaf	silverleaf	nightshade[9]
	nightshade[9]	nightshade[9]	nightshade[9]	nightshade[9]	

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Oklahoma only.
[3]Information adapted from Buchanan (1971a).
[4]Information adapted from Buchanan (1974a).
[5]Information adapted from McCormick (1977).
[6]Information adapted from Palmer (1980).
[7]Information adapted from Elmore (1983).
[8]Information adapted from Elmore (1986).
[9]Denotes a perennial species or mixtures containing perennials.
[10]Texas only.

Table 9. Most common weeds present in cotton of the West in selected crop years.[1]

1978[2]	1980[3]	1983[4]	1986[5]
Amaranthaceae	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**
pigweed	pigweed	pigweed	pigweed
Chenopodiaceae	**Chenopodiaceae**	**Chenopodiaceae**	**Chenopodiaceae**
common lambsquarters	common lambsquarters	common lambsquarters	common lambsquarters
Compositae	**Compositae**	**Compositae**	**Compositae**
common sunflower	common sunflower	common sunflower	common sunflower
common cocklebur	common cocklebur	common cocklebur	common cocklebur
Convolvulaceae	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**
field bindweed[6]	field bindweed[6]	field bindweed[6]	field bindweed[6]
morningglory	morningglory	morningglory	morningglory
Cyperaceae	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**
nutsedge[6]	nutsedge[6]	nutsedge[6]	nutsedge[6]
	Euphorbiaceae	**Euphorbiaceae**	**Euphorbiaceae**
	spurge	spurge	spurge
Gramineae	**Gramineae**	**Gramineae**	**Gramineae**
barnyardgrass	barnyardgrass	barnyardgrass	barnyardgrass
bermudagrass[6]	bermudagrass[6]	bermudagrass[6]	bermudagrass[6]
johnsongrass[6]	johnsongrass[6]	johnsongrass[6]	johnsongrass[6]
	panicum	panicum	panicum
	Leguminosae	**Leguminosae**	**Leguminosae**
	hemp sesbania	hemp sesbania	hemp sesbania
	Malvaceae	**Malvaceae**	**Malvaceae**
	spurred anoda	spurred anoda	spurred anoda
Portulacaceae	**Portulacaceae**	**Portulacaceae**	**Portulacaceae**
common purslane	common purslane	common purslane	common purslane
Solanaceae	**Solanaceae**	**Solanaceae**	**Solanaceae**
groundcherry[6]	groundcherry[6]	groundcherry[6]	groundcherry[6]
nightshade[6]	nightshade[6]	nightshade[6]	nightshade[6]

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Everett (1979).
[3]Information adapted from Whitwell *et al.* (1981).
[4]Information adapted from Whitwell and Everest (1984).
[5]Information adapted from Patterson and Monks (1987).
[6]Denotes a perennial species or mixtures containing perennials.

Table 10. Most troublesome weeds present in cotton of the West in selected crop years.[1]

1973[2]	1976[3]	1978[4]	1980[5]	1983[6]	1986[7]
Amaranthaceae		**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**	**Amaranthaceae**
pigweed		pigweed	pigweed	pigweed	pigweed
Chenopodiaceae					**Chenopodiaceae**
common lambsquarters					common lambsquarters
Compositae			**Compositae**	**Compositae**	**Compositae**
common sunflower			common sunflower	common sunflower	common sunflower
			common cocklebur	common cocklebur	common cocklebur
Convolvulaceae	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**	**Convolvulaceae**
morningglory	morningglory	field bindweed[8]	field bindweed[8]	field bindweed[8]	field bindweed[8]
		morningglory	morningglory	morningglory	morningglory
Cyperaceae	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**	**Cyperaceae**
nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]	nutsedge[8]
Euphorbiaceae	**Euphorbiaceae**		**Euphorbiaceae**	**Euphorbiaceae**	**Euphorbiaceae**
hyssop spurge	hyssop spurge		spurge	spurge	spurge
Gramineae	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**	**Gramineae**
barnyardgrass	bermudagrass[8]	barnyardgrass	barnyardgrass	barnyardgrass	barnyardgrass
bermudagrass[8]	johnsongrass[8]	bermudagrass[8]	bermudagrass[8]	bermudagrass[8]	bermudagrass[8]
cupgrass		johnsongrass[8]	johnsongrass[8]	johnsongrass[8]	johnsongrass[8]
johnsongrass[8]			panicum	panicum	panicum
junglerice					
			Leguminosae	**Leguminosae**	**Leguminosae**
			hemp sesbania	hemp sesbania	hemp sesbania
Malvaceae			**Malvaceae**	**Malvaceae**	**Malvaceae**
spurred anoda			spurred anoda	spurred anoda	spurred anoda
Solanaceae	**Solanaceae**	**Solanaceae**	**Solanaceae**	**Solanaceae**	**Solanaceae**
groundcherry[8]	lanceleaf	groundcherry[8]	groundcherry[8]	groundcherry[8]	groundcherry[8]
nightshade[8]	groundcherry	nightshade[8]	nightshade[8]	nightshade[8]	nightshade[8]

[1]Family names listed in bold print; common names of family members listed underneath them.
[2]Information adapted from Buchanan (1974c).
[3]Information adapted from Taylor and Heathman (1977).
[4]Information adapted from Everett (1979).
[5]Information adapted from Whitwell *et al.* (1981).
[6]Information adapted from Whitwell and Everest (1984).
[7]Information adapted from Patterson and Monks (1987).
[8]Denotes a perennial species or mixtures containing perennials.

Table 11. Alphabetical list of the most common weed families and their distributions among regions and states (1970 through 1986).[1]

	Southeast						Mid-South			Southwest		West			
Weed families[2]	AL	FL	GA	NC	SC	TN	AR	LA	MS	OK	TX	AZ	CA	NM	Totals
Aizoaceae A										*					1
Amaranthaceae A	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
Chenopodiaceae A				*		*				*		*	*		5
Compositae A	*	*	*	*	*	*	*	*	*			*	*	*	12
Convolvulaceae A	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
P										*		*	*		3
Cyperaceae P	*	*	*	*	*		*	*	*	*	*	*	*	*	13
Euphorbiaceae A	*		*	*	*	*	*	*	*	*	*	*			11
Gramineae A	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
P	*		*	*	*	*	*	*	*	*	*	*	*	*	13
Leguminosae A	*	*	*	*	*			*	*			*			8
Malvaceae A	*		*	*	*	*	*	*	*					*	9
Polygonaceae A				*		*									2
P							*								1
Portulacaceae A										*		*	*		3
Rubiaceae A		*	*												2
Solanaceae A						*									1
P										*	*	*	*	*	5

[1]Information adapted from Tables 3, 5, 7 and 9.
[2]The A following family names indicates annual species while the P denotes perennials.

Table 12. Alphabetical list of the most troublesome weed families and their distributions among regions and states (1970 through 1986).[1]

	Southeast						Mid-South			Southwest		West			
Weed families[2]	AL	FL	GA	NC	SC	TN	AR	LA	MS	OK	TX	AZ	CA	NM	Totals
Amaranthaceae A	*	*		*	*	*	*	*		*		*	*	*	11
Bignoniaceae P									*						1
Chenopodiaceae A				*										*	2
Compositae A	*	*	*	*	*	*	*	*	*			*	*	*	12
Convolvulaceae A	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
P										*	*	*	*	*	5
Cyperaceae P	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
Euphorbiaceae A	*		*	*	*	*	*	*	*	*		*	*		11
Gramineae A	*	*	*	*	*	*	*	*	*	*	*	*	*	*	14
P	*		*	*	*	*	*	*	*	*	*	*	*	*	13
Leguminosae A	*	*	*	*	*			*	*			*			8
Malvaceae A	*		*	*	*	*	*	*	*	*	*			*	11
Martyniaceae A										*					1
Polygonaceae P							*		*						2
Portulacaceae A										*					1
Rubiaceae A		*													1
Solanaceae A	*					*				*		*	*	*	6
P										*	*	*	*	*	5
Vines P	*					*	*		*						4

[1]Information adapted from Tables 4, 6, 8 and 10.
[2]The A following family names indicates annual species while the P denotes perennials.

PRESENT SITUATION AND A LOOK TOWARD THE FUTURE

Over the past three decades, control of weeds in cotton has evolved from a mechanical and hand labor operation to primarily a chemical approach. In some areas, especially the Southeast and Mid-South, more herbicides are used on cotton than on any other major row crop (Banks, 1985). Further, the types of herbicides and methods of application used vary greatly from region to region in the United States (Patterson and Monks, 1987). Preplant foliar applications are not heavily used in any region; however, Louisiana reported treating 20 percent of its cotton acreage with Roundup® (glyphosate). Over 90 percent of the cotton acreage in the Southeast and Southwest received a preplant incorporated treatment of a dinitroaniline alone. The Mid-South treats approximately 80 percent of its cotton with a dinitroaniline alone; however, an additional 10 percent is treated with a preplant incorporated tank mixture which contains a dinitroaniline. Most of the remaining area is treated with other herbicides which results in most land in the Mid-South receiving a preplant incorporated treatment. In the West, from 48 percent of the cotton in New Mexico to 90 percent in California is treated with a dinitroaniline alone. In Arizona, most of the cotton land is treated with a tank mixture which contains a dinitroaniline; while in New Mexico, Caparol® alone is used as a preplant incorporated treatment on 27 percent of the cotton land. Preemergence applications are not used in the arid, irrigated West. Cotoran® is the most heavily used preemergence herbicide in the Southeast and Mid-South, but it is used on less than two percent of land in the Southwest. Generally, postemergence directed treatments are heavily used in the Southeast and Mid-South; whereas, in the Southwest and West, they are used to a much lesser extent. Slightly over 30 percent of the cotton land in Arizona receives post-directed treatments; however, only 6 percent of California cotton is treated in this manner. The selective over-the-top, postemergence herbicides for grass control have been registered for five years; however, by the end of their second year of use they were used primarily as spot treatments on 60 percent of the cotton in Tennessee, 30 percent in Louisiana, 18 percent in Texas, and 15 percent in Alabama and North Carolina. Mississippi, Arkansas, Arizona, Louisiana and Texas report that 50, 30, 25, 20 and 20 percent, respectively, of their cotton land is subjected to spot treatments. Layby treatments are not used extensively in Tennessee, Texas, Oklahoma, Florida or North Carolina. There is considerable usage of such treatments in Arkansas, Louisiana and Mississippi.

In the Southeast and Mid-South, weeds that cause the largest reductions in cotton yield are common cocklebur, morningglory and prickly sida. In the Southwest and West, those weed species are pigweed, nightshade and several species of morningglory. Bonner (1987) reported that in the Southeast and Mid-South, spurge species and prickly sida are becoming more troublesome. Texas and Oklahoma are now listing devil's-claw [*Proboscidea louisianica* (Mill.) Thellung] (Plates 6-62 and 6-63) as a widespread problem in dryland cotton. Thistle species

are considered as problems under irrigation in Arizona, California and Texas. Many growers and technical personnel believe the nightshade species are the most serious weed problem in the Southwest and West.

The most recent major change in cotton production has been the renewed interest in no tillage, reduced tillage or conservation tillage. Keeling and Abernathy (1987) claimed that reduced tillage systems can increase yield, decrease production cost and reduce soil erosion; but that new weed control programs must be developed for use in place of traditional preplant incorporated herbicides and tillage operations. Relatively little information describing weed research in cotton to develop no-tillage or minimum-tillage systems has been published. Ordinarily, this would suggest that little work had been done in the area; however, McWhorter and Jordan (1985) conducted a survey among weed scientists in most cotton-producing states and found, to the contrary, that considerable research comparing such systems had been attempted. Little had been published because the results were largely negative, and many experiments were abandoned. The problems most frequently encountered with reduced tillage were in obtaining an adequate stand of cotton, in not controlling perennial weeds and in the greater difficulty of controlling annual weeds. The requirement for cultivation in cotton has diminished over the past 10 years, but cultivation will be required in most situations until a great improvement has been made in efficacy of the herbicides available to producers. The reader is referred to Chapter 9 "Reduced-Tillage Systems."

Porterfield and Davidson (1974) published a study comparing 11 tillage systems at two dryland locations in Oklahoma over a 5-year period. In systems where herbicides were the only or major form of weed control, plots were heavily infested with perennial weeds. In systems combining mechanical and chemical weed control, those weed shifts were less pronounced. Extensive tillage at planting time was essential for satisfactory weed control and maximum lint yield. Yield was enhanced by tillage prior to planting and further enhanced by tillage after emergence. Minimum tillage plots had the highest soil moisture; but they also had the highest soil strength, reduced stands, stunted plants with red stem color, reduced lint yield and often were so weedy as to be rated "unacceptable for machine harvesting."

The report by McWhorter and Jordan (1985) may be used as a base to discuss weeds of the future or the anticipated management difficulty of present weeds. Have we really experienced a shift in weed species composition, or have we only temporarily traded easy-to-control weeds for those which are more difficult-to-control as Jackson (1970) has suggested? As we enter a time when conservation or reduced tillage on erodible acres is apparently to be government mandated, assumptions about weed shifts may be very important. Kempen (1984) reported that after 20 years of usage of dinitroaniline herbicides on cotton, the susceptible weeds (barnyardgrass and pigweed species) were still commonly present. They were not necessarily common problems in fields, but they were present and fully

capable of becoming problems if no herbicides were applied. The resilience of weeds was mentioned previously in this chapter, and that characteristic may most accurately describe this dynamic process.

A number of shifts in weed composition are likely to occur with reduced tillage. There undoubtedly will be increased problems with perennials. Among the annual weeds, reduced tillage will favor those which germinate on or near the soil surface and those which germinate early in the season. Species such as annual bluegrass (*Poa annua* L.), large crabgrass, purslane and tumble mustard (*Sisymbrium altissimum* L.) germinate at or near the soil surface. They would have a higher percentage of their seed in a position favorable for germination than if tillage distributed them throughout the soil profile. Thus, reduced tillage provides these weeds an advantage over species such as wild oat (*Avena fatua* L.), annual morningglory and many others that germinate from greater depths. The early germinating species are favored by reduced tillage because some will have already germinated by the time the crop is planted, thus giving them a competitive edge over weeds that germinate later as well as over the crop itself.

With the management tools available to us, we have achieved success in suppressing the populations of some weed species. Some have been so well controlled that they are no longer considered troublesome, but some scientists view such weeds as only "lurking in the shadows," waiting to increase their numbers. We contend that weed species composition has changed little over time; however, the proportions in the composition have changed. No weed has ever become extinct; a superficial examination of escapes in fields and of fence rows, ditches and other disturbed areas should verify that premise. Provided the opportunity, such weeds through time would reexert the prominence once demonstrated.

A diagram (Figure 1) is provided to illustrate perceived shifts, management difficulties and/or emphasis received by four general classes of weeds in United States cotton from 1850 to the present (with projections to the year 2000). The trends described are based on a synthesis of data compiled from numerous formal and informal reports, including testimonials, about the common and troublesome weeds in cotton. The result is an interpretation of past, present and future weed problems in cotton that can be considered from many perspectives. From 1850 (and before) to 1940, annual grasses and small-seeded broadleafs were viewed by most producers as the most serious threats to effective cotton production. With the development of urea herbicides (Karmex®, etc.) during the 1950s, a decline was noted in the prevalence or control difficulty of the small-seeded broadleaf weeds. The grasses declined to some extent during this time, but their major decline did not come until later. As small-seeded broadleaf weeds gradually declined, large-seeded broadleaf and perennial weeds began to increase. The void created as the small-seeded broadleaf weeds were gradually controlled was slowly filled by these "new" weeds. In reality, those weeds had been present all the time, but they were restricted in area of distribution and/or in population size

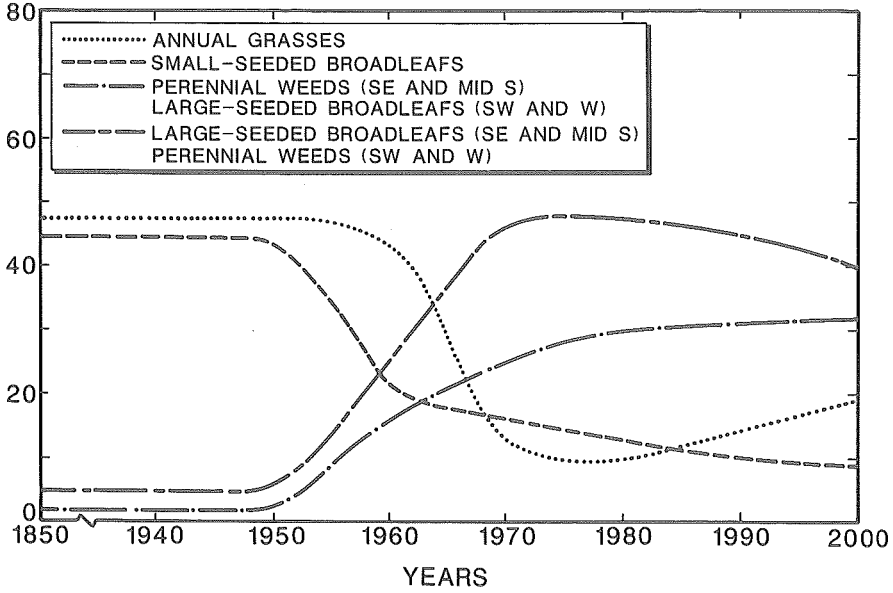


Figure 1. Perceived shifts, management difficulties and/or emphasis received by four general classes of weeds in United States cotton over a 150-year period.

(Whitworth, 1978; M. L. Verhalen, 1987, personal communication). During the 1960s, when the dinitroaniline herbicides were gaining rapid acceptance by cotton producers, a rapid decline in annual grasses and accelerated decline of small-seeded broadleaf weeds was coupled with a proportionate increase in large-seeded broadleaf and perennial weeds.

Differences between regions with respect to relative importance of perennial weeds *vs.* large-seeded broadleafs were apparent. Oklahoma and Texas in the Southwest and New Mexico, Arizona and California in the West may be more accurately depicted at present as having more difficult problems with perennial weeds than from large-seeded broadleaf types; whereas, the reverse is true in the Southeast and Mid-South. During the time span covered by this diagram (Figure 1), a continual decline is traced for the small-seeded broadleaf weeds because a number of herbicides from several chemical families are very effective for control of such weeds (including several chemicals that do not require incorporation). The annual grasses are depicted as slightly increasing in the future primarily because they, as a group, represent a large number of species and they are commonly present. With the likely increased emphasis on reduced tillage and the corresponding decreased use of preplant incorporated dinitroanilines, those weeds will be more likely to escape. The grasses may never again be as prominent as they were in the 1800s to 1940s; but because of the limitations of the selective postemergence grass-control herbicides now available, the grasses will

probably exhibit some increase. Because the large-seeded broadleaf types in the Southeast and Mid-South and the perennial types in the Southwest and West have become so important in recent times, it is likely that a great deal of research and development will be centered on those weeds. The slight decline shown in their importance is a prediction of some success in those efforts. Currently, cotton producers would welcome selective over-the-top herbicides for broadleaf weed control. Should herbicide resistance develop, these trends will be influenced depending upon when and in which of the four general classes of weeds it takes place.

The weed problem in cotton is dynamic. Shifts in the abundance and distribution of particular weed species have occurred as producers have moved from one part of the country to another; changed methods of land preparation, thinning and cultivation; employed different management practices and applied different herbicides. In some instances, control has been achieved. In others, one weed, or class of weeds, has simply been replaced by another even more difficult to control. The keys to future success in the struggle between man and cotton *vs.* weeds are to use those techniques which have been proven effective and to continue the investigation of weed ecology and their responses to man's management systems to discover new and better techniques of weed control.

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Chapter 6

APPENDIX

WEED IDENTIFICATION

Weed control may be accomplished by using an array of biological, cultural, mechanical, nonmechanical, legal and/or chemical methods (Zimdahl, 1981). Some methods are more effective against particular weeds than are others. Herbicides, for example, differ both in the spectra of weeds that they affect and in the degree of their control. Regardless of the method used, potentially troublesome weeds can be controlled more efficiently if they are identified early and appropriate control measures implemented, rather than waiting until they have become an established, widespread problem. The adage "Know thy enemy" certainly is applicable. Knowing the characteristics of the weed and its weak points allows the producer to employ the most efficient and effective methods to deal with current or potential weed problems.

To assist the cotton producer and others in the rapid identification of common weeds, a taxonomic key and photographs have been provided. The key and photos describe many, but not all, of the troublesome species likely to be encountered in cotton fields throughout the United States. Individuals ready to provide assistance in identifying weeds and correcting problems include the local county extension agent and the weed science specialists and taxonomists at state universities. The scientific and common names used appear in the "Composite List of Weeds" (Standardized Plant Names Subcommittee, Weed Sci. Soc. Am., 1984).

Although a taxonomic key looks intimidating at first, its use is quite easy. For individuals who have not used one before, the following comments are offered. A key simply presents the user with a progressive series of choices between pairs of alternative features that can be observed. For example, following examination of an unknown weed, the user might be required to choose between "plant a trailing or climbing vine" or "plant erect or prostrate, but not a trailing or climbing vine." Selection of the most applicable alternative leads the user to other pairs of alternatives and ultimately to a scientific name. Using a key is thus analogous to following a path on which each junction is a "Y". To reach the proper destination, the traveler must take the correct fork in the road at each intersection.

The pair of alternative features is referred to as a couplet, and alternatives of a single couplet as leads. To facilitate use of the key, the couplets are successively indented to the right with both leads of a single couplet equally indented and numbered. One commences keying at Couplet 1 by reading both leads, observing the plant's features and making a decision as to which lead applies. After one of the two leads has been selected, proceed to the first indented couplet immedi-

ately under the choice. Disregard couplets under nonselected leads. Continue to follow the successively indented couplets until a name is reached. Sometimes the leads of a single couplet will be separated by numerous other couplets; the numbers thus help in locating the leads. Read both leads and observe the plant carefully before making a decision. While the first choice may be applicable, the second may be better. Different characters in the leads are separated by semicolons, while commas are used to separate aspects of one character. Should a couplet be encountered where the selection of a lead is tenuous, proceed both ways. Subsequent inappropriate couplets generally will indicate a wrong choice.

TAXONOMIC KEY TO WEEDS OF COTTON

1. Plants grass-like; leaves linear to lanceolate; veins extending length of blade parallel to each other; fibrous root system; flowers hidden by 1 or 2 brown-green bracts; monocots (other lead No. 1 on page 174)

   2. Stems triangular in cross-section; margins of leaf sheaths fused; ligules absent; flower hidden by 1 scale; nutsedges (*Cyperus* spp.)

      3. Spikelet scales dark reddish brown; leafy bracts below spikelets 3-4, more or less equal in length to inflorescence; spikelets 20-65 ..... *Cyperus rotundus* (purple nutsedge) Plates 6-27 and 6-28

      3. Spikelet scales golden-brown or golden-green; leafy bracts below spikelets 5-10, longer than inflorescence; spikelets 70-350 ..... *Cyperus esculentus* (yellow nutsedge) Plates 6-29 and 6-30

   2. Stems round or flattened in cross-section, never triangular; margins of leaf sheaths overlapping; ligules present; flower hidden by 2 scales; grasses

      4. Plants perennial, spreading by rhizomes and/or stolons

         5. Spikelets surrounded by bristles, dropping from inflorescence at maturity, bristles remaining attached to rachis ..... *Setaria* spp. (foxtails)

         5. Spikelets not surrounded by bristles

            6. Leaf blades 12-25 mm wide with white midrib; rhizomes stout, scaly; spikelets large, borne in pairs in open pyramidal panicles ..... *Sorghum halepense* (johnsongrass) Plate 6-39

6. Leaf blades 2-5 mm wide with green midrib; rhizomes slender; spikelets small, borne in 1-sided spikes; spikes 3-7, digitate at apex of elongated leafless stem ..... *Cynodon dactylon* (bermudagrass) Plate 6-46

4. Plants annual, tufted, lacking rhizomes or stolons

7. Spikelets bristly or surrounded by bristles or enclosed in a spiny bur

8. Spikelets enclosed in a spiny bur of stout, sharp, flattened, fused spines; leaf sheaths strongly compressed and keeled ..... *Cenchrus incertus* (field sandbur) Plate 6-47

8. Spikelets bristly or surrounded by bristles; leaf sheaths round or keeled

9. Spikelets borne in single bristly inflorescence terminating stem; bristles arising below spikelets; ligule a ring of hairs ..... *Setaria* spp. (foxtails)

9. Spikelets borne in 9-12 short 1-sided racemes arranged along an elongated axis; spikelets bearing stout bristle; ligule absent ..... *Echinochloa crus-galli* (barnyardgrass) Plate 6-42

7. Spikelets borne in open panicles or in 1-sided spikes and racemes, not surrounded by bristles nor enclosed in a spiny bur

10. Spikelets borne in a cylindrical inflorescence terminating stem; spikelets paired, one sessile and sunken in the rachis, the other smaller and borne on a flattened stalk; inflorescence breaking apart at maturity ..... *Rottboellia exaltata* (itchgrass)

10. Spikelets borne in open panicles or in 1-sided spikes and racemes; spikelets not paired; inflorescence not breaking apart at maturity

11. Spikelets borne on long or short branches in open spreading panicles

    12. Panicles open, spikelets borne near ends of long spreading branches; leaf sheaths without hairs; spikelets without conspicuous transverse ribs ..... *Panicum dichotomiflorum* (fall panicum) Plate 6-43

    12. Panicles narrow, spikelets borne along sides of short ascending branches; leaf sheaths with pustulate-based hairs; spikelets with conspicuous transverse ribs ..... *Panicum fasciculatum* (browntop panicum) Plate 6-45

11. Spikelets borne in 1-sided spike and racemes or panicle branches appressed to rachis and spikelets clustered together

    13. Spikelets borne in 1-sided spikes, pedicels absent, laterally compressed, each with 3-9 florets; florets dropping from plant at maturity

        14. Spikelets with stout bristles; spikes digitate at end of stem; hairs present only on margins of blades ..... *Dactyloctenium aegyptium* (crowfootgrass)

        14. Spikelets without stout bristles; spikes subdigitate at end of stem; hairs present on margins and upper surface of blades ..... *Eleusine indica* (goosegrass) Plate 6-38

    13. Spikelets borne in 1-sided racemes, pedicels present, dorsally compressed, each with 1 hardened floret; entire spikelets dropping from plant at maturity

15. Racemes 4-6, subdigitate, long; ligules membranous; sheaths with pustulate-based hairs ..... *Digitaria sanguinalis* (large crabgrass) Plate 6-37

15. Racemes numerous, borne along an elongated axis; ligules absent or ciliate or ciliate-membranous; sheaths with or without hairs

16. Ligules absent; leaf sheaths generally without hairs

17. Plants 30-60 cm tall; spikelets oval, without bristles ..... *Echinochloa colonum* (junglerice) Plate 6-41

17. Plants robust, 100-200 cm tall; spikelets elliptic, usually with stout bristles ..... *Echinochloa crus-galli* (barnyardgrass) Plate 6-42

16. Ligules present, ciliate-membranous or ciliate; leaf sheaths hairy

18. Leaf sheaths hairy only on margins; racemes 2-6 and long ..... *Brachiaria platyphylla* (broadleaf signalgrass) Plate 6-40

18. Leaf sheaths densely hairy; racemes numerous and short

19. Spikelets 2-3 mm long, with conspicuous transverse ribs, without hairs; ligules ciliate ..... *Panicum fasciculatum* (browntop panicum) Plate 6-45

19. Spikelets 4-6 mm long, without conspicuous transverse ribs, with soft hairs; ligules ciliate-membranous ..... *Panicum texanum* (Texas panicum) Plate 6-44

1. Plants not grass-like; leaves broad, variously shaped, rarely linear; veins forming netted pattern; taproot system typically present; flowers visible, not hidden; dicots

   20. Plant a trailing or climbing vine; tendrils present or absent (other lead No. 20 on page 177)

      21. Leaves opposite; fruits pod-like, 5-15 cm long

         22. Leaves simple, triangular-lanceolate to deltoid, cordate; annual from fleshy taproot; flowers white, 4-6 mm long ..... *Ampelamus albidus* = *Cynanchum laeve* (honeyvine milkweed) Plate 6-7

         22. Leaves compound with 9-11 leaflets; perennial from woody roots; flowers orange-red, tubular, 60-90 mm long ..... *Campsis radicans* (trumpetcreeper) Plates 6-8 and 6-9

      21. Leaves alternate; fruits spherical or slightly elongated, less than 5 cm long

         23. Flowers small, yellow or yellow-green; tendrils present

            24. Leaves simple, ovate to lanceolate; flowers borne in terminal spike-like clusters; fruit a 3-sided achene held at maturity within a green structure 1-3 cm long ..... *Brunnichia ovata* (redvine) Plate 6-64

            24. Leaves compound, the leaflets small, in 3's and toothed; flowers borne in the leaf axils; fruit 3-parted, inflated, 3-4.5 cm in diameter ..... *Cardiospermum halicacabum* (balloonvine)

         23. Flowers large, white or red or pink or blue-purple; tendrils absent

25. Flowers white or white with vertical bands of pink; perennial from long stout root; stems often forming dense tangle; stigmas 2, linear, more or less flattened; cotyledon apex notched, not 2-lobed ..... *Convolvulus arvensis* (field bindweed) Plate 6-19

25. Flowers blue-purple to red or white or white with purple-red center; annual from slender taproot or perennial from woody tuberous root or perennial from branched roots; stigma 1, spherical; cotyledon apex 2-lobed; morningglories (*Ipomoea* spp.)

26. Stems bearing fleshy prickles; flowers about 8 cm long, open at night and in early morning; leaves cordate, without hairs ..... *Ipomoea turbinata* (purple morningglory) Plate 6-21

26. Stems without fleshy prickles; flowers 1.5-8 cm long, open all morning or all day; leaves cordate or 3-lobed, with or without hairs

27. Perennial from woody tuberous root; flowers white with purple-red center, 5-8 cm long; seed with fringe of long tawny hairs; point of cotyledon attachment to stem below ground ..... *Ipomoea pandurata* (bigroot morningglory)

27. Annual from slender taproot or perennial from branched roots; flower colors various but not white with purple-red center, 1.5-6 cm long; seed without fringe of hairs; point of cotyledon attachment to stem visible aboveground

28. Leaves deeply palmately 3-7 lobed (almost compound); flowers 1.5-2.3 cm long, pale lavender pink with a dark center; cotyledon lobes very narrow and with little separation; stalks of flowers spirally coiled ..... *Ipomoea wrightii* (palmleaf morningglory) Plate 6-22

28. Leaves cordate or shallowly 3-lobed; flowers 2-6 cm long, white or blue or lavender; cotyledon lobes broad and angle of separation acute or obtuse; stalks of flowers not spirally coiled

    29. Stems bearing hairs; stalks of flowers bearing hairs bent sharply down; cotyledons moderately indented and rounded

        30. Hairs of stem lying flat; flowers 4-6 cm long, purple to white; sepals short with blunt tips ..... *Ipomoea purpurea* (tall morningglory) Plate 6-26

        30. Hairs of stem spreading; flowers 2.5-4.5 cm long, lavender to blue; sepals long with abruptly pointed tips

            31. Leaves 3-lobed ..... *Ipomoea hederacea* (ivyleaf morningglory) Plate 6-25

            31. Leaves cordate ..... *Ipomoea hederacea* var. *integriuscula* (entireleaf morningglory) Plate 6-20

    29. Stems and stalks of flowers without hairs; cotyledons deeply indented and pointed

        32. Flowers white, rarely lavender, 1.8-2.3 cm long; annual from slender taproot; seed black and shiny ..... *Ipomoea lacunosa* (pitted morningglory) Plate 6-24

32. Flowers rosy-lavender to purple-rose, 2.8-5.5 cm long; perennial from branched rootstalk; seed dark brown ..... *Ipomoea trichocarpa* var. *torreyana* (cotton morningglory) Plate 6-23

20. Plant erect or prostrate but not a trailing or climbing vine; tendrils absent

33. Stems flat on ground or only tips ascending, spreading radially; annual from slender taproot

34. Leaves 3-6 in a whorl at each node; flowers small, white, borne in leaf axils ..... *Mollugo verticillata* (carpetweed) Plates 6-1 and 6-2

34. Leaves alternate or opposite at each node; flowers borne in leaf axils or at stem tips

35. Leaves opposite, widest below middle, often with a red spot; stems not fleshy; flowers cup-shaped, white, small, with yellow glands, borne in leaf axils ..... *Euphorbia maculata* (spotted spurge) Plate 6-35

35. Leaves alternate or occasionally appearing opposite; flowers white or yellow, small

36. Leaves always alternate, ovate, irregularly toothed; stems not fleshy; flowers borne in leaf axils, white ..... *Solanum sarrachoides* (hairy nightshade) Plates 6-75 and 6-76

36. Leaves alternate or occasionally appearing opposite, widest above middle; stems fleshy; flowers borne at stem tips, yellow ..... *Portulaca oleracea* (common purslane) Plate 6-66

33. Stems erect or ascending, not flat on ground nor spreading radially; annual or perennial

37. Leaves compound, alternate, stipulate; fruit a pea-like pod; flowers resembling butterfly, yellow or white to pink and purple; legumes

38. Leaves with 3 elliptic to ovate leaflets; perennial from woody rootstock; flowers white or pink to purple; pods 1.5-2.5 cm long, with 5-7 round segments each with hooked hairs and separating at maturity ..... *Desmodium tortuosum* (Florida beggarweed) Plates 6-50 and 6-51

38. Leaves with 6-70 leaflets; annuals; flowers yellow; pods 8-20 cm long and not segmented

39. Leaflets 20-70, small; stems 75-200 cm tall; pods 3-4 mm wide and 10-20 cm long ..... *Sesbania exaltata* = *Sesbania macrocarpa* (hemp sesbania) Plates 6-52 and 6-53

39. Leaflets 6-12, large; stems 50-150 cm tall; pods 5-9 mm wide and 8-20 cm long

40. Leaflets 8-12, lanceolate to ovate; pods 7-10 mm wide; conspicuous gland at base of petiole ..... *Cassia occidentalis* (coffee senna) Plate 6-54

40. Leaflets 6, widest above middle; pods 5-6 mm wide; conspicuous gland between lowest pair of leaflets ..... *Cassia obtusifolia* (sicklepod) Plates 6-48 and 6-49

37. Leaves simple, alternate or opposite, with or without stipules; fruit a berry or capsule or achene; flower colors various

41. Leaves all opposite or leaves opposite below and alternate above

42. Leaves opposite below and alternate above; flowers borne in small inconspicuous heads; foliage typically aromatic (camphor or resin) ..... *Ambrosia artemisiifolia* (common ragweed) Plates 6-13 and 6-14

42. Leaves all opposite; flowers separate or borne in conspicuous heads; foliage with mint-like odor or not aromatic

43. Stems square; leaves with mint-like odor; flowers blue, borne in terminal racemes .... *Salvia reflexa* (lanceleaf sage)

43. Stems round or flattened; leaves without mint-like odor; flowers inconspicuous or white

44. Leaves elliptic to oblong, edges toothed

45. Leaves 2-10 cm long; flowers borne in heads, white; all branches opposite; foliage roughly hairy; fruit an achene ..... *Eclipta prostrata* = *Eclipta alba* (eclipta)

45. Leaves 1-3 cm long; flowers not borne in heads; branches alternate; foliage without hairs; fruit a small but conspicuous 3-lobed capsule ..... *Euphorbia hyssopifolia* (hyssop spurge) Plate 6-36

44. Leaves widest above the middle, edges smooth or toothed

46. Flowers borne in spiny heads in leaf axils; spines hooked ..... *Acanthospermum hispidum* (bristly starbur) Plates 6-11 and 6-12

46. Flowers clustered but separate, not in spiny heads, clusters at ends of stems; stipules forming bristly sheath at node ..... *Richardia scabra* (Florida pusley) Plates 6-67 and 6-68

41. Leaves all alternate

47. Stout spines or bristles present on stems and/or leaves and/or fruits

48. Leaf edges bearing spines; leaves elongated, widest above the middle and clasping the stem; flowers are borne in heads ..... *Sonchus* spp. (sowthistles)

48. Leaf edges not bearing spines; leaves variously shaped; flowers separate or borne in spiny heads

49. Flowers not conspicuous, borne in spiny heads

50. Taprooted annual; leaves large, cordate to deltoid; heads oblong, 2-3 cm long; spines many and hooked ..... *Xanthium strumarium* (common cocklebur) Plates 6-15 and 6-16

50. Rhizomatous perennial forming large colonies; leaves 3-lobed, silvery-gray; heads spherical, 5 mm in diameter; spines 9-15, straight or curved ..... *Ambrosia grayi* (woollyleaf bursage)

49. Flowers conspicuous with showy petals, not borne in spiny heads

51. Stems and midnerve of leaf blades armed with stiff spines or prickles; flowers wheel-shaped or slightly bell-shaped; fruit a berry; stamens opening by apical pores; nightshades (*Solanum* spp.)

52. Flowers bright yellow; sepals densely covered with stout spines; leaves deeply cleft into narrow lobes; taprooted annual ..... *Solanum rostratum* (buffalobur) Plate 6-72

52. Flowers blue-violet to white; sepals without spines; leaves oblong or broad, not deeply divided; perennial from deep rootstock

    53. Leaves oblong, silvery gray-green; surfaces velvety due to dense covering of stellate hairs ..... *Solanum elaeagnifolium* (silverleaf nightshade) Plates 6-69 and 6-70

    53. Leaves broadly ovate to elliptic, green, irregularly lobed to toothed; surfaces not velvety ..... *Solanum carolinense* (horsenettle) Plate 6-71

51. Stems and leaves without spines or prickles; flowers tubular; fruit a capsule; stamens splitting open by longitudinal slits; thornapples (*Datura* spp.)

    54. Corolla 15-20 cm long; calyx tubular in cross-section; branches numerous; perennial ..... *Datura innoxia* = *Datura meteloides* (sacred datura)

    54. Corolla 6-12 cm long; calyx angular in cross-section; branches few; annual

        55. Stems densely hairy, gray-green; capsules both spiny and hairy ..... *Datura discolor* (small datura)

        55. Stems slightly hairy or without hairs, green; capsules spiny but not hairy

            56. Spines of capsule 10-30 mm long, flattened at base; capsule spherical; tips of calyx 3-4 mm long, about equal in length ..... *Datura ferox* (no common name)

56. Spines of capsule 3-10 mm long, slightly flattened; capsule slightly elongated, ovoid; tips of calyx 5-10 mm long, unequal in length ..... *Datura stramonium* (jimsonweed) Plates 6-79 and 6-80

47. Stout spines not present, stems and leaves variously hairy or lacking hairs

57. Flowers distinctly 2-lipped or butterfly-like; fruit a large elongated pod 3-15 cm long

58. Foliage foul smelling, densely covered with glandular hairs; leaves heart-shaped, 5-20 cm wide, estipulate; fruit splitting at maturity and forming two large curved horns or claws ..... *Proboscidea louisianica* (devil's-claw or unicorn-plant) Plates 6-62 and 6-63

58. Foliage without hairs; leaves elongated, widest above the middle, 3-5 cm wide, stipulate; fruit an elongated pod, 3-4 cm long ..... *Crotalaria spectabilis* (showy crotalaria)

57. Flowers with radial symmetry, showy or inconspicuous; fruit a capsule or berry or achene less than 2 cm in diamater

59. Petals not showy, flowers small, inconspicuous, often tightly clustered at stem ends or on stalks arising in leaf axils

60. Stems turning red as plant matures and dark longitudinal lines apparent; fruit a small papery achene; flowers with both stamens and pistils, rarely unisexual

61. Leaves linear with 1 major vein; flowers borne in axils of reduced leaves near ends of stems ..... *Kochia scoparia* (kochia)

61. Leaves ovate to diamond-shaped with numerous prominent veins; flowers borne in terminal inflorescences above the foliage

62. Leaves lanceolate to diamond-shaped, irregularly toothed, lower surfaces with mealy appearance; flowers 5-sided, grayish-green, borne in branching inflorescences ..... *Chenopodium album* (common lambsquarters) Plate 6-10

62. Leaves ovate, long petioled, edges smooth or wavy, veins conspicuous on lower surfaces; flowers round, green, borne in dense more or less unbranched spikes; pigweeds (*Amaranthus* spp.)

63. Upper portions of stems generally hairy; staminate flowers intermixed with pistillate flowers; sepals of pistillate flowers spathulate ..... *Amaranthus retroflexus* (redroot pigweed) Plates 6-5 and 6-6

63. Upper portions of stems without hairs; staminate and pistillate flowers borne on separate plants; sepals of pistillate flowers oblong to lanceolate ..... *Amaranthus palmeri* (Palmer amaranth) Plates 6-3 and 6-4

60. Stems not turning red nor dark lines apparent; fruit a small but conspicuously 3-lobed capsule splitting to release 3 seed; flowers either staminate or pistillate

64. Flowers without petals or sepals, borne in small cup-shaped structure bearing glands at top; pistillate flower solitary; sap usually milky ..... *Euphorbia heterophylla* (wild poinsettia)

64. Flowers with green sepals, separate, not arising from cup-shaped structure; glands absent; sap not milky

65. Stem and leaves covered with stellate hairs; flowers borne in clusters at top of stems; crotons (*Croton* spp.)

66. Edges of leaves toothed; hairs sparse and plant green; style branches 6 .... *Croton glandulosus* var. *septentrionalis* (tropic croton) Plate 6-33

66. Edges of leaves smooth; hairs dense and plant silvery gray; style branches 12 ..... *Croton capitatus* (woolly croton) Plate 6-34

65. Stem and leaves without hairs or hairs simple not stellate; flowers borne on stalks at tips of stems or in axils of upper leaves

67. Stalks bearing flowers at tips of stems; pistillate flowers surrounded by multilobed bract ..... *Acalypha ostryifolia* (hophornbeam copperleaf) Plates 6-31 and 6-32

67. Stalks bearing flowers in axils of leaves; pistillate flowers without surrounding bract ..... *Caperonia castaniifolia* (mexicanweed)

59. Petals showy, flowers conspicuous

68. Flowers of 2 types and tightly clustered in large heads 10-15 cm in diameter; flowers in center brown and tubular; flowers at edge yellow and strap-like; leaves ovate, long petioled; robust annual ..... *Helianthus annuus* (common sunflower) Plates 6-17 and 6-18

68. Flowers all similar and not clustered in large heads

69. Flowers small, 3-4 mm wide, clustered in dense spikes on stalks above the foliage; stipules forming a sheath about the stem; nodes generally swollen; fruit a black 3-sided achene ..... *Polygonum pensylvanicum* (Pennsylvania smartweed) Plate 6-65

69. Flowers large, 5-70 mm wide, solitary; stipules if present not sheathing stem; nodes not conspicuously swollen; fruit a capsule or berry

70. Stamens many and united by their filaments in a column about styles; leaves palmately net veined; fruit a capsule; mallows

71. Leaves deeply 3-lobed or 3-5 parted, 3-6 cm wide, lobes toothed or cut; flowers sulphur-yellow or whitish with a brown-purple center ..... *Hibiscus trionum* (Venice mallow) Plates 6-60 and 6-61

71. Leaves not deeply lobed nor parted; flowers purple or white or yellow

72. Leaves cordate to round, large, 9-20 cm wide; apex abruptly constricted to point; flowers yellow

73. Herbaceous annual; petals 6-10 mm long; lobes of capsule with short bristles; ring of bracts not present below sepals ..... *Abutilon theophrasti* (velvetleaf) Plate 6-59

73. Woody perennial; petals 50-70 mm long; lobes of capsule without bristles; ring of bracts below sepals ..... *Hibiscus tiliaceus* (sea hibiscus)

72. Leaves oblong to ovate to triangular, small, 1-5 cm wide; apex rounded or angled but not constricted; flowers purple or white or yellow

74. Leaves ovate to triangular, usually shallowly 3-lobed; calyx star-shaped; petals pale blue or lavender, 10-25 mm long; hairs simple, often golden and dense ..... *Anoda cristata* (spurred anoda) Plates 6-57 and 6-58

74. Leaves oblong or ovate-cordate, not lobed; calyx round or angular; petals yellow or white to cream, 5-15 mm long; hairs stellate

75. Foliage densely covered with stellate hairs; flowers white to cream; flower stalks slightly longer than petioles ..... *Sida hederacea* (alkali sida)

75. Foliage sparsely covered with stellate hairs; flowers yellow; flower stalks shorter than petioles ..... *Sida spinosa* (prickly sida) Plates 6-55 and 6-56

70. Stamens 5 and not united to each other; leaves pinnately net veined; fruit a berry

76. Flowers white; stamens clustered in center; anthers opening by terminal pores; calyx not inflated around mature berry; nightshades (*Solanum* spp.)

77. Stems distinctly hairy; ripe berries brownish-green; calyx covering ½ of mature berry ..... *Solanum sarrachoides* (hairy nightshade) Plates 6-75 and 6-76

77. Stems sparsely hairy; ripe berries black; calyx covering ¼ or only base of mature berry

78. Anthers 1.8-2.5 mm long; berries without white flakes; seed 15-60 per berry, 1.8-2.2 mm wide ..... *Solanum nigrum* (black nightshade) Plates 6-73 and 6-74

78. Anthers 1.3-1.8 mm long; berries with white flakes; seed 50-110 per berry, 1.4-1.8 mm wide ..... *Solanum americanum* (American black nightshade) Plates 6-77 and 6-78

76. Flowers yellow or white with yellow center; stamens not clustered; anthers splitting open by longitudinal slits; calyx inflated and loosely enclosing mature berry; groundcherries *(Physalis* spp.)

79. Flowers yellow

80. Flowers 10-15 mm wide; corolla with dark center; inflated calyx round, berry filling inside ..... *Physalis ixocarpa* (tomatillo groundcherry)

80. Flowers 4-12 mm wide; corolla without dark center; inflated calyx elongated, berry not filling inside

81. Leaves ovate-lanceolate; 6-10 mm long ..... *Physalis angulata* (cutleaf groundcherry) Plates 6-81 and 6-82

81. Leaves lanceolate to linear-lanceolate; 4-5 mm long ..... *Physalis lanceifolia* (lanceleaf groundcherry)

79. Flowers white with yellow center, 10-20 cm wide ..... *Physalis wrightii* (Wright groundcherry)

PHOTOGRAPHS OF WEEDS IN COTTON

The following pages contain photographs (alphabetically by families) of many of the most important weeds in cotton. All photographs are referenced in the classification key; however, the key does contain some species not represented by photographs. The common and scientific names of all weeds found here and in the key are from the "Composite List of Weeds" (Standardized Plant Names Subcommittee, Weed Sci. Soc. Am., 1984). Several other scientific names in current use have also been included in the key.

ACKNOWLEDGMENT

The authors of this chapter gratefully acknowledge and deeply appreciate the generosity of Arlyn W. Evans and the E. I. duPont de Nemours & Co., (Inc.) for supplying these photographs.

AIZOACEAE



Plate 6-1. Carpetweed (*Mollugo verticillata* L.)



Plate 6-2. Carpetweed (*Mollugo verticillata* L.)

AMARANTHACEAE

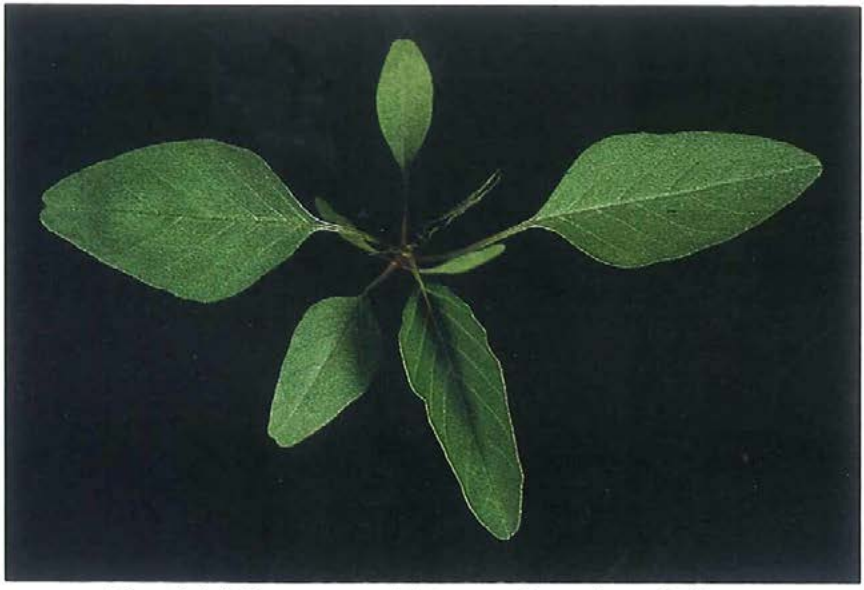


Plate 6-3. Palmer amaranth (*Amaranthus palmeri* S. Wats.)



Plate 6-4. Palmer amaranth (*Amaranthus palmeri* S. Wats.)

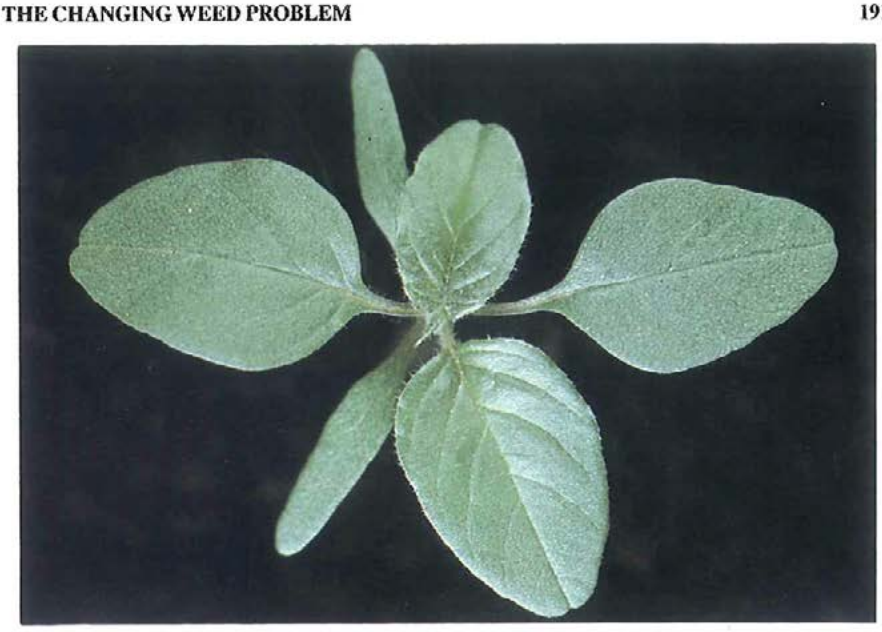


Plate 6-5. Redroot pigweed (*Amaranthus retroflexus* L.)



Plate 6-6. Redroot pigweed (*Amaranthus retroflexus* L.)

ASCLEPIADACEAE



Plate 6-7. Honeyvine milkweed [*Ampelamus albidus* (Nutt.) Britt.]

BIGNONIACEAE



Plate 6-8. Trumpetcreeper [*Campsis radicans* (L.) Seem. *ex* Bureau]



Plate 6-9. Trumpetcreeper [*Campsis radicans* (L.) Seem. *ex* Bureau]

CHENOPODIACEAE

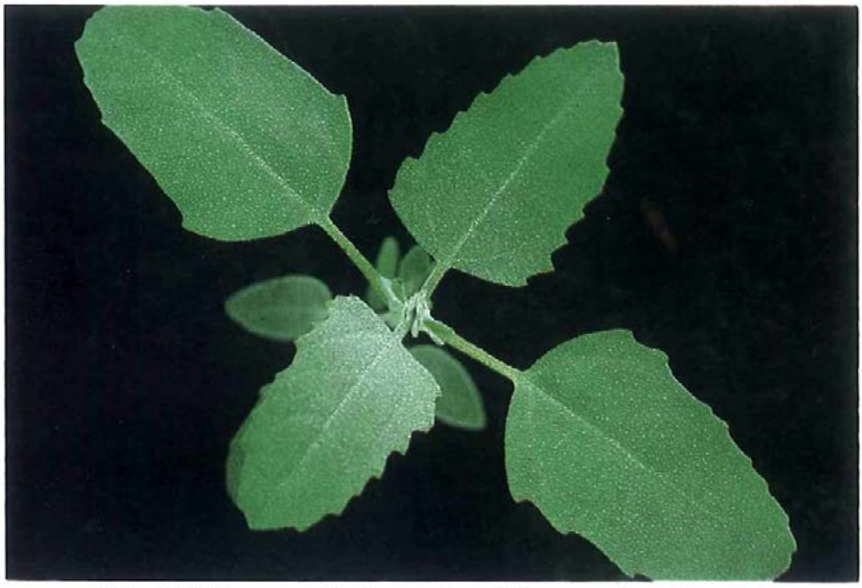


Plate 6-10. Common lambsquarters (*Chenopodium album* L.)

COMPOSITAE

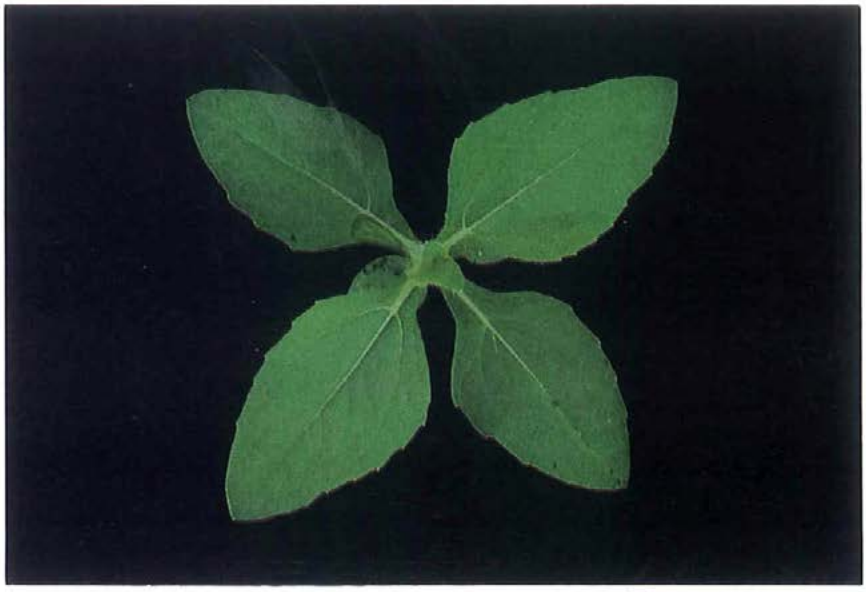


Plate 6-11. Bristly starbur (*Acanthospermum hispidum* DC.)

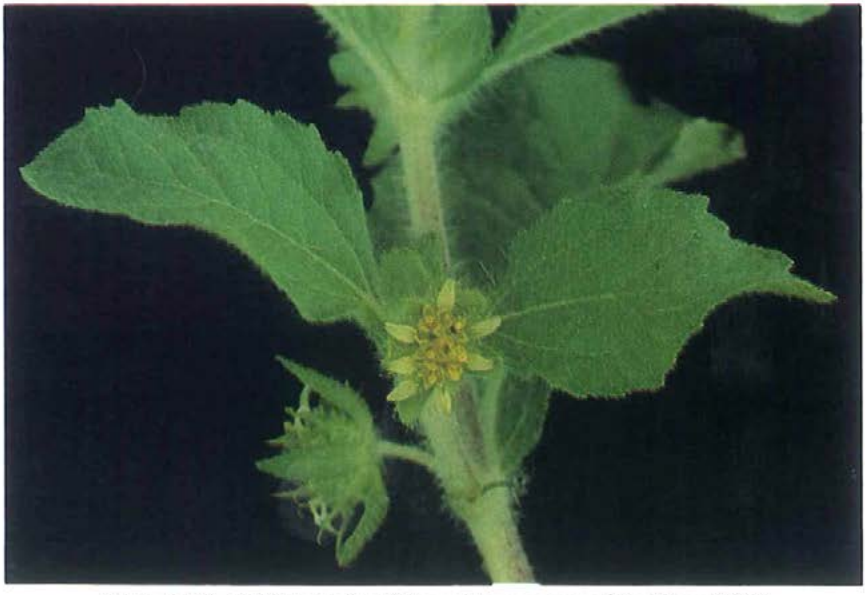


Plate 6-12. Bristly starbur (*Acanthospermum hispidum* DC.)



Plate 6-13. Common ragweed (*Ambrosia artemisiifolia* L.)



Plate 6-14. Common ragweed (*Ambrosia artemisiifolia* L.)



Plate 6-15. Common cocklebur (*Xanthium strumarium* L.)



Plate 6-16. Common cocklebur (*Xanthium strumarium* L.)

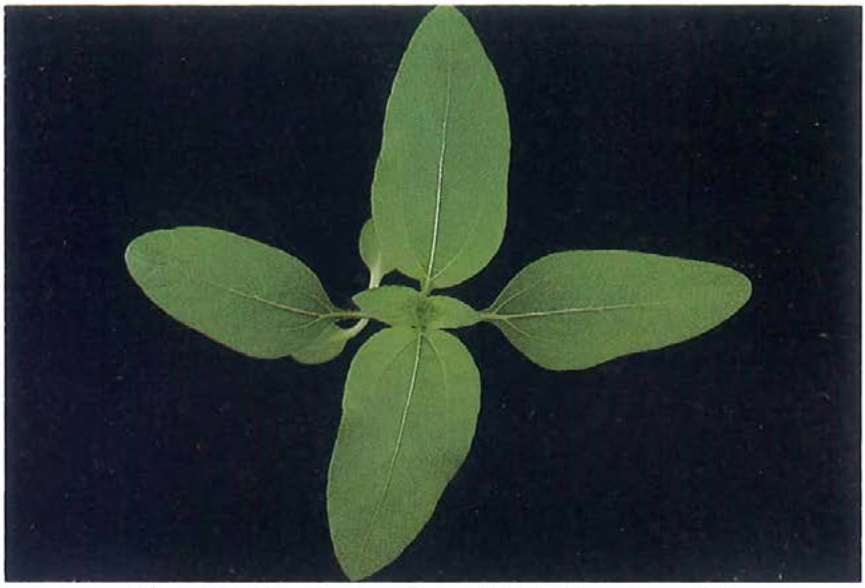


Plate 6-17. Common sunflower (*Helianthus annuus* L.)



Plate 6-18. Common sunflower (*Helianthus annuus* L.)

CONVOLVULACEAE



Plate 6-19. Field bindweed (*Convolvulus arvensis* L.)



Plate 6-20. Entireleaf morningglory
(*Ipomoea hederacea* var. *integriuscula* Gray)

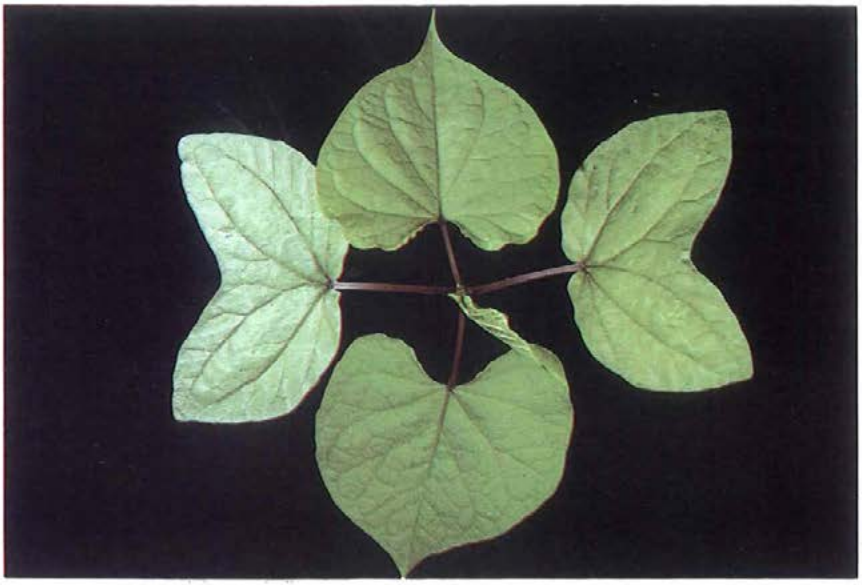


Plate 6-21. Purple morningglory (*Ipomoea turbinata* Lag.)

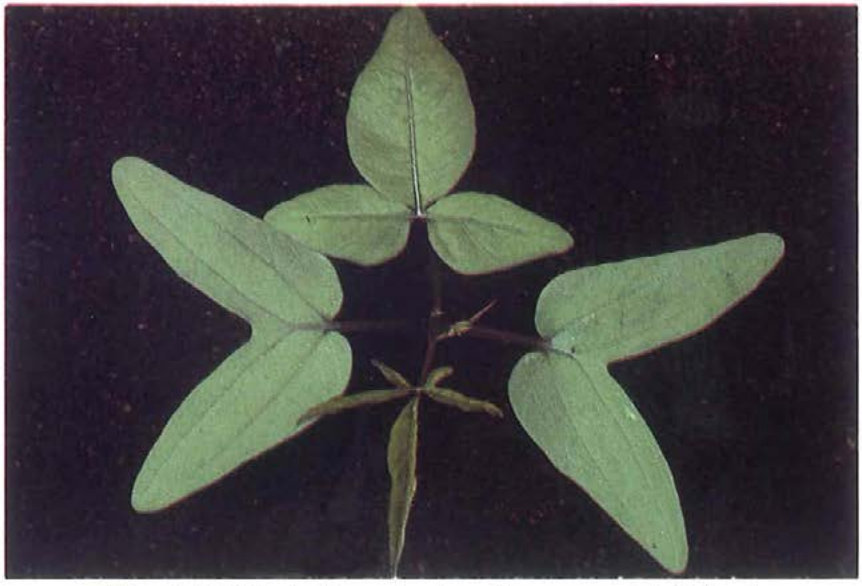


Plate 6-22. Palmleaf morningglory (*Ipomoea wrightii* Gray)

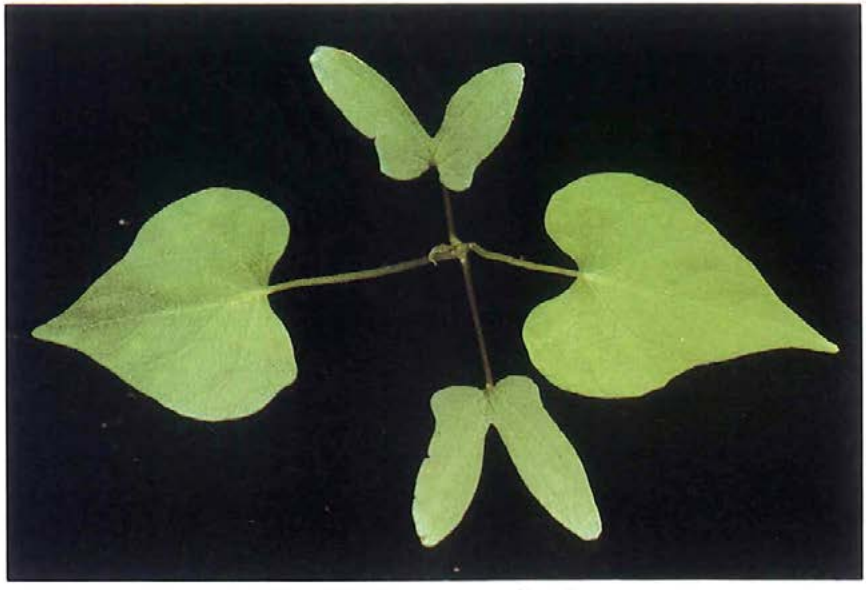


Plate 6-23. Cotton morningglory
[*Ipomoea trichocarpa* Ell. var. *torreyana* (Gray) Shinners]

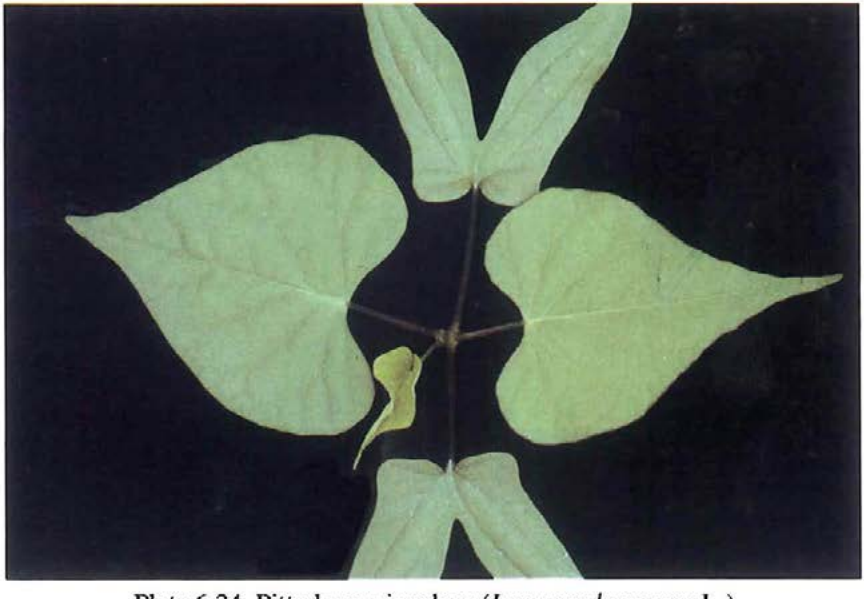


Plate 6-24. Pitted morningglory (*Ipomoea lacunosa* L.)

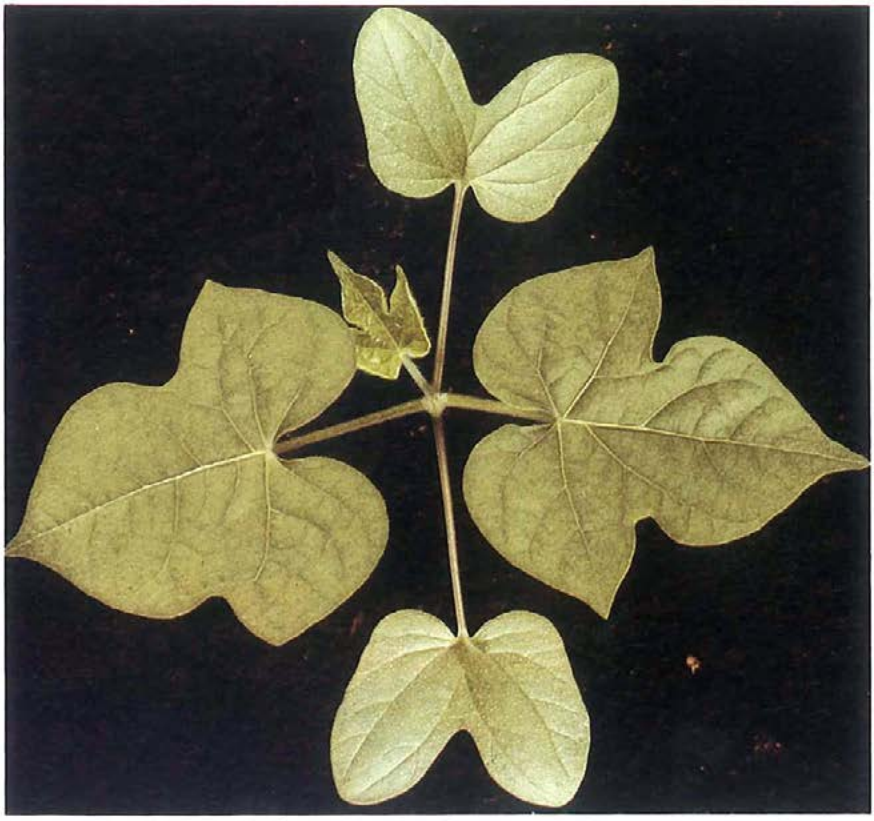


Plate 6-25. Ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.]

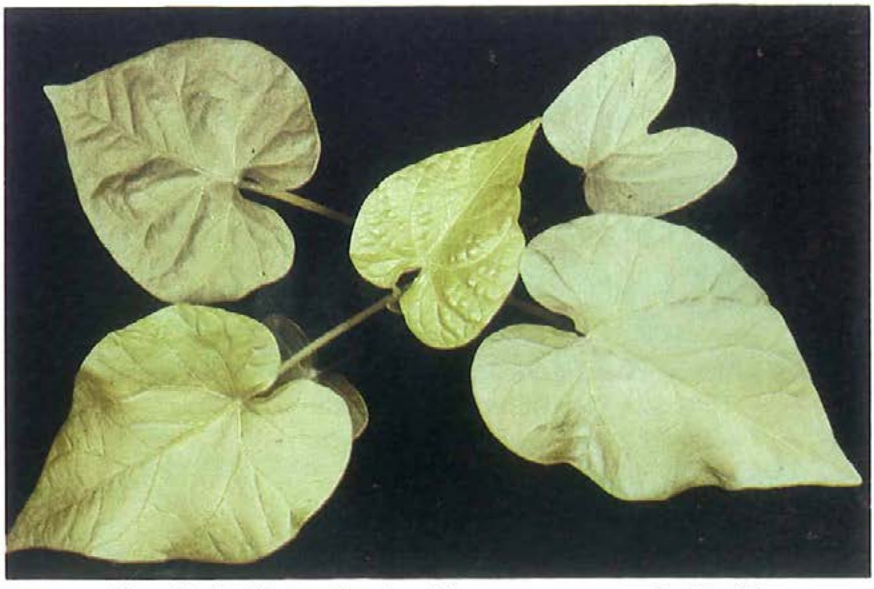


Plate 6-26. Tall morningglory [*Ipomoea purpurea* (L.) Roth]

CYPERACEAE

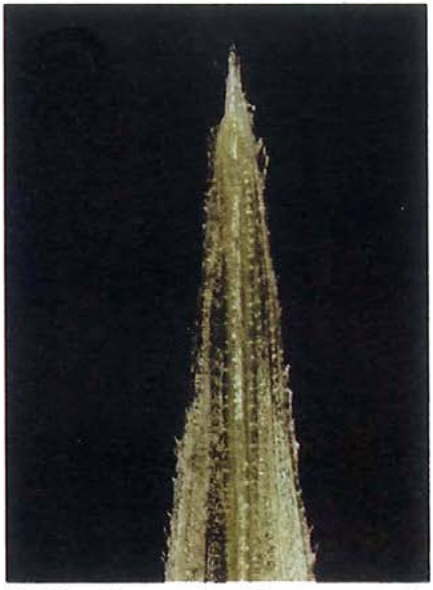


Plate 6-27. Purple nutsedge (*Cyperus rotundus* L.)



Plate 6-28. Purple nutsedge (*Cyperus rotundus* L.)



Plate 6-29. Yellow nutsedge (*Cyperus esculentus* L.)



Plate 6-30. Yellow nutsedge (*Cyperus esculentus* L.)

EUPHORBIACEAE



Plate 6-31. Hophornbeam copperleaf (*Acalypha ostryifolia* Riddell)

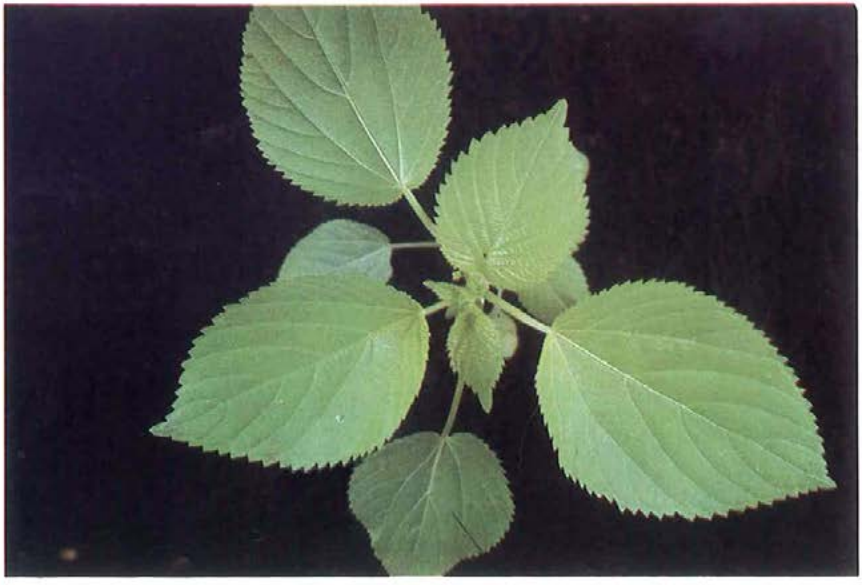


Plate 6-32. Hophornbeam copperleaf (*Acalypha ostryifolia* Riddell)



Plate 6-33. Tropic croton
(*Croton glandulosus* var. *septentrionalis* Muell.-Arg.)



Plate 6-34. Woolly croton (*Croton capitatus* Michx.)



Plate 6-35. Spotted spurge (*Euphorbia maculata* L.)



Plate 6-36. Hyssop spurge (*Euphorbia hyssopifolia* L.)

GRAMINEAE

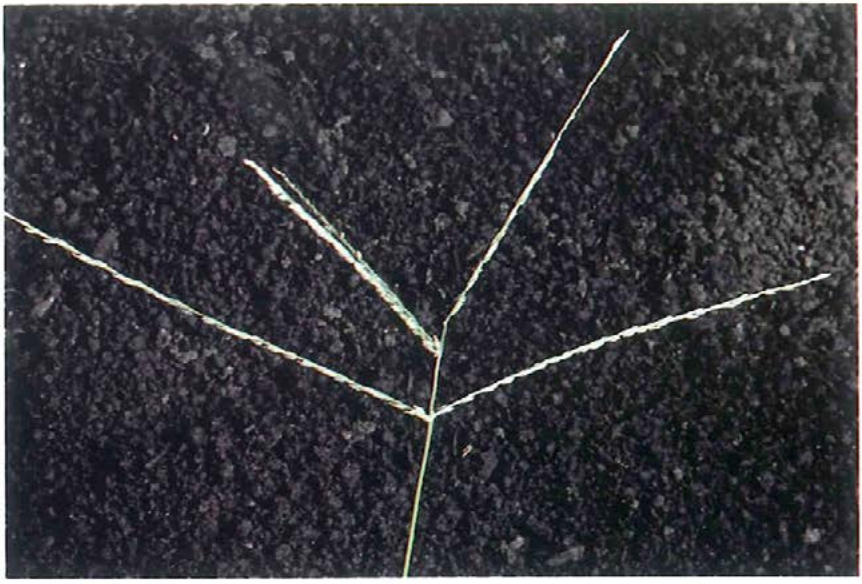


Plate 6-37. Large crabgrass [*Digitaria sanguinalis* (L.) Scop.]

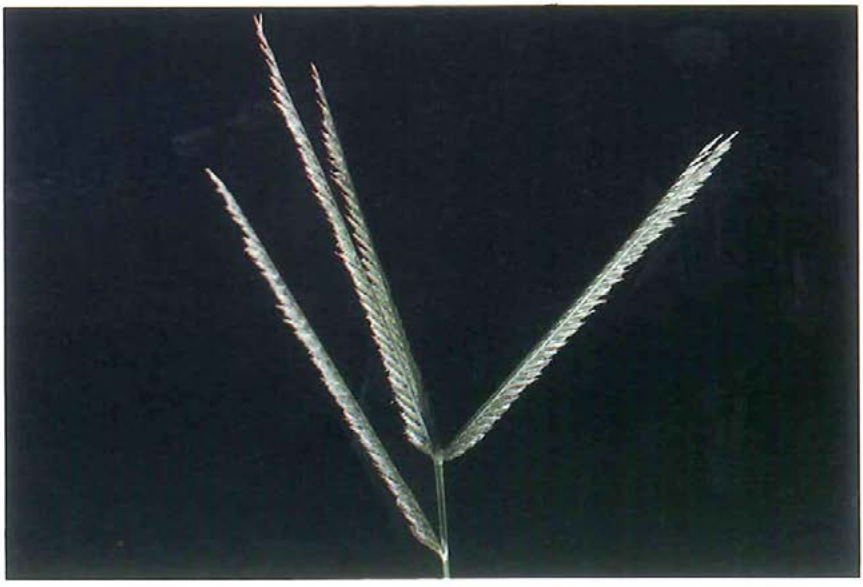


Plate 6-38. Goosegrass [*Eleusine indica* (L.) Gaertn.]



Plate 6-39. Johnsongrass [*Sorghum halepense* (L.) Pers.]



Plate 6-40. Broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash]



Plate 6-41. Junglerice [*Echinochloa colonum* (L.) Link]



Plate 6-42. Barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]

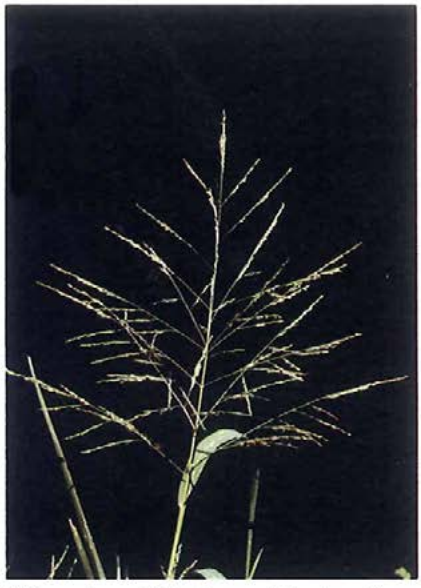


Plate 6-43. Fall panicum (*Panicum dichotomiflorum* Michx.)

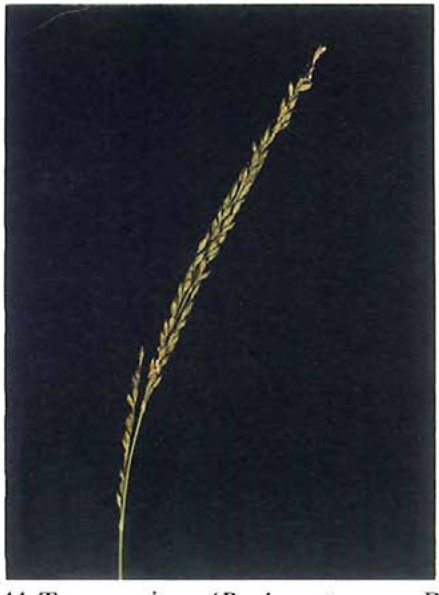


Plate 6-44. Texas panicum (*Panicum texanum* Buckl.)



Plate 6-45. Browntop panicum (*Panicum fasciculatum* Sw.)



Plate 6-46. Bermudagrass [*Cynodon dactylon* (L.) Pers.]



Plate 6-47. Field sandbur (*Cenchrus incertus* M. A. Curtis)

LEGUMINOSAE



Plate 6-48. Sicklepod (*Cassia obtusifolia* L.)



Plate 6-49. Sicklepod (*Cassia obtusifolia* L.)

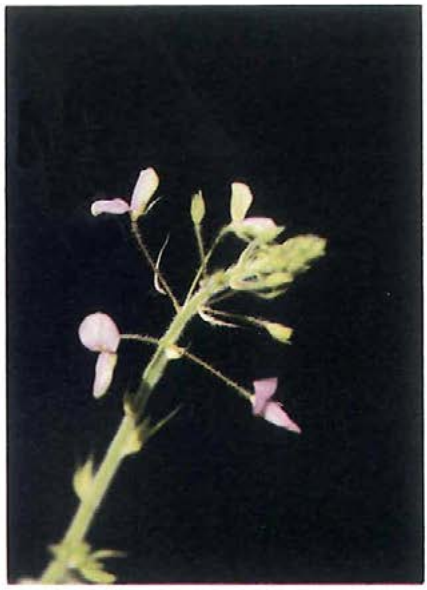


Plate 6-50. Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.]

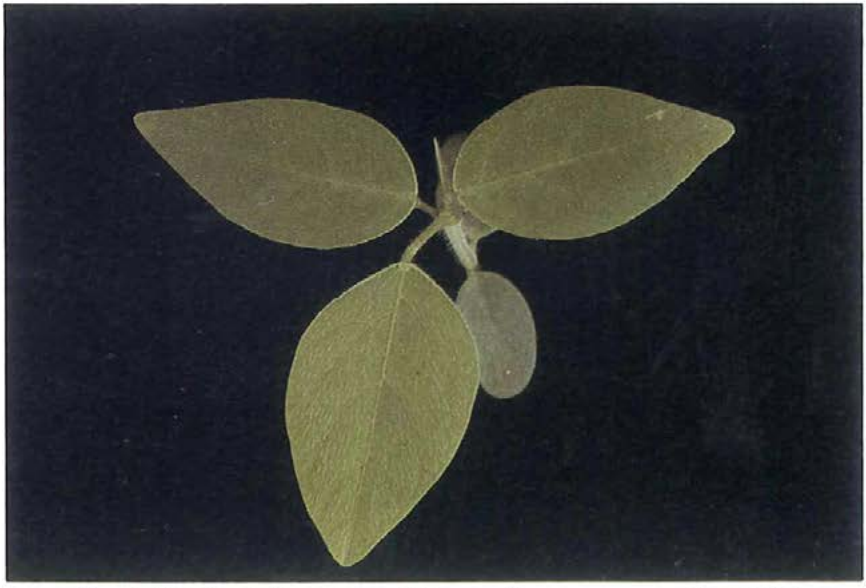


Plate 6-51. Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.]



Plate 6-52. Hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. *ex* A. W. Hill]



Plate 6-53. Hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. *ex* A. W. Hill]



Plate 6-54. Coffee senna (*Cassia occidentalis* L.)

MALVACEAE



Plate 6-55. Prickly sida (*Sida spinosa* L.)



Plate 6-56. Prickly sida (*Sida spinosa* L.)



Plate 6-57. Spurred anoda [*Anoda cristata* (L.) Schlecht.]



Plate 6-58. Spurred anoda [*Anoda cristata* (L.) Schlecht.]



Plate 6-59. Velvetleaf (*Abutilon theophrasti* Medik.)



Plate 6-60. Venice mallow (*Hibiscus trionum* L.)



Plate 6-61. Venice mallow (*Hibiscus trionum* L.)

MARTYNIACEAE



Plate 6-62. Devil's-claw (unicorn-plant)
[*Proboscidea louisianica* (Mill.) Thellung]

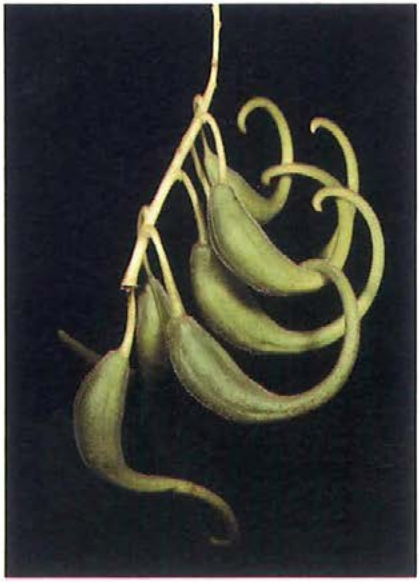


Plate 6-63. Devil's-claw (unicorn-plant)
[*Proboscidea louisianica* (Mill.) Thellung]

POLYGONACEAE

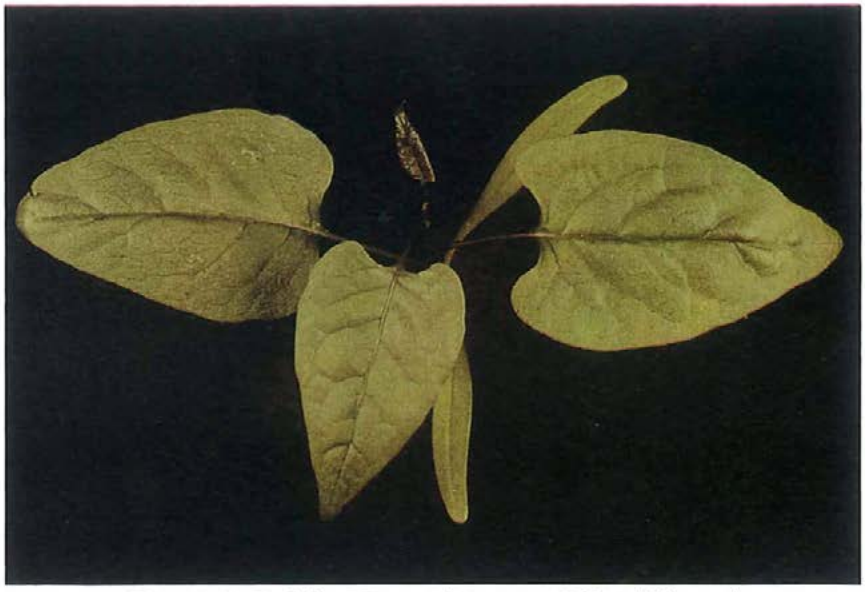


Plate 6-64. Redvine [*Brunnichia ovata* (Walt.) Shinners]

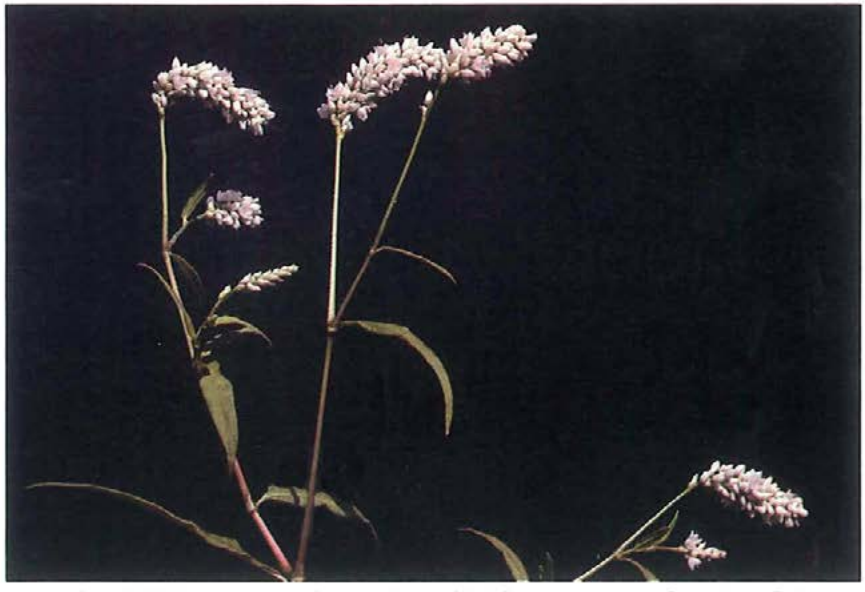


Plate 6-65. Pennsylvania smartweed (*Polygonum pensylvanicum* L.)

PORTULACACEAE



Plate 6-66. Common purslane (*Portulaca oleracea* L.)

RUBIACEAE

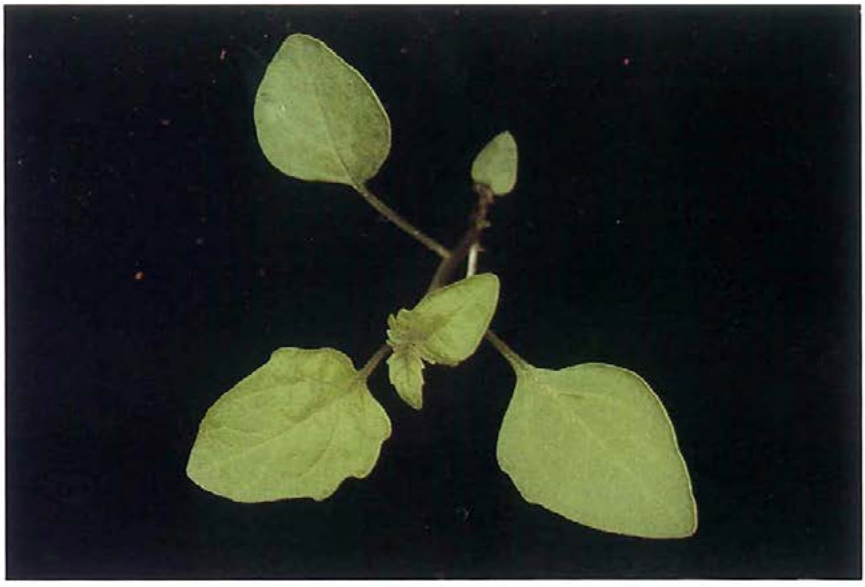


Plate 6-67. Florida pusley (*Richardia scabra* L.)



Plate 6-68. Florida pusley (*Richardia scabra* L.)

SOLANACEAE



Plate 6-69. Silverleaf nightshade (*Solanum elaeagnifolium* Cav.)



Plate 6-70. Silverleaf nightshade (*Solanum elaeagnifolium* Cav.)



Plate 6-71. Horsenettle (*Solanum carolinense* L.)



Plate 6-72. Buffalobur (*Solanum rostratum* Dun.)



Plate 6-73. Black nightshade (*Solanum nigrum* L.)



Plate 6-74. Black nightshade (*Solanum nigrum* L.)



Plate 6-75. Hairy nightshade (*Solanum sarrachoides* Sendtner)

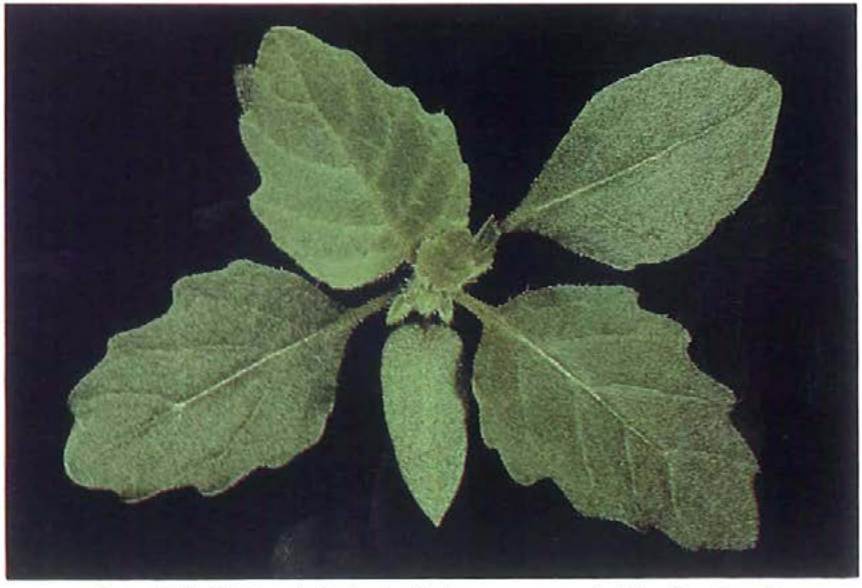


Plate 6-76. Hairy nightshade (*Solanum sarrachoides* Sendtner)



Plate 6-77. American black nightshade (*Solanum americanum* Mill.)



Plate 6-78. American black nightshade (*Solanum americanum* Mill.)



Plate 6-79. Jimsonweed (*Datura stramonium* L.)



Plate 6-80. Jimsonweed (*Datura stramonium* L.)



Plate 6-81. Cutleaf groundcherry (*Physalis angulata* L.)



Plate 6-82. Cutleaf groundcherry (*Physalis angulata* L.)

Chapter 7

HERBICIDE USE TRENDS IN COTTON

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INTRODUCTION

Historically, weeds have been a major deterent to profitable production of cotton *(Gossypium hirsutum* L.) in the United States. Prior to the development of selective herbicides, weeds were controlled with row-middle cultivation and hand hoeing. Hand hoeing was generally effective, but the labor needed from year-to-year fluctuated widely and could exceed 100 hours per acre (Porter *et al.*, 1957). At current prices for hand labor, it would not be unusual for weed control costs to be $200 to $300 per acre if hand hoeing was the only method of weed control available today.

Herbicides are used more intensively to control weeds in cotton than in any other major crop in the United States. When first used in the 1950s, herbicides were not necessarily intended to reduce the cost of weed control in cotton, but rather to minimize the large amounts of hand labor needed from year-to-year (Porter *et al.*, 1957). Weeds are particularly troublesome and competitive because cotton is a warm-season perennial that grows slowly in the spring. Young cotton plants compete very poorly with weeds, especially when cool temperatures prevail.

Cotton is often planted in early spring when the soil is relatively cool (55 to 65F). Since the optimum temperature for cottonseed germination is 80 to 90F, germination and seedling growth generally is slow for several weeks. During this period weeds often grow much faster than cotton. In addition, young cotton is plagued by diseases, insects and adverse weather. These factors relate to weed control in cotton, often directly, which contributes to the complexity of cotton production and the role that herbicides play in permitting more economical production of cotton in the United States.

Weeds compete with cotton, as with other field crops, for moisture, sunlight,

nutrients and space; but in addition, weed infestations later in the season interfere with defoliation, reduce harvesting efficiency, and lower the grade of harvested lint. Traditionally, farmers have attempted to maintain a high level of weed control throughout the entire growing season not only to increase yields, but also to avoid reducing harvesting efficiency and lint grades due to stained lint. This chapter will discuss how cotton farmers took a very cautious approach to the use of herbicides in the 1950s but then quickly adopted multiple applications of herbicides in the 1960s.

The prices paid for hand labor in the 1950s and early 1960s increased three- to four-fold partially because of the migration of vast numbers of farm workers from southern to northern states (Mayo, 1965). Several individual southern states experienced a net loss of 200,000 to 300,000 farm workers within a decade. In addition, many workers moved from farms to cities to work in factories and other non-agricultural industries. This dramatic loss of farm labor caused the price of hoe labor to increase dramatically and, in localized situations, to be unavailable for use in cotton.

Labor shortages and the increased cost of hand hoeing caused cotton farmers to make widespread use of several weed control practices that were relatively unique to cotton production. These included flame cultivation, postemergence directed applications of herbicidal oil, and geese. These techniques were both effective and cost-efficient, but required a higher level of management than was often available at the time. A handicap to earlier adoption of herbicides occurred in 1952 when the first widely applied preemergence herbicide, dinoseb[1], killed or severely injured thousands of acres of cotton (Davis, 1964). The level of cotton injury obtained from dinoseb was so severe that most farmers became afraid to use herbicides and adopted a wait-and-see attitude. It was depressing to many weed scientists and extension specialists in the mid-1950s when they could not convince farmers of the potential value of herbicides for weed control in cotton. It would have been almost impossible to have convinced a weed scientist working in the mid-1950s that within the next decade practically the entire cotton acreage in many areas would be treated with herbicides, with much of the acreage receiving multiple applications. The purpose of this chapter is to discuss the extent of use of herbicides since the early 1950s and to summarize the various methods in which herbicides have been used.

[1]Common names for herbicides that have been approved by the Weed Science Society of America (WSSA) are used in this chapter except when other names that have been used in references or surveys are being discussed. For example, if a survey being discussed reported on the use of "Karmex®," we will discuss the use of Karmex® rather than using diuron, Dynex®, or Karmex®/Dynex®. This causes inconsistency in the use of herbicide names, but it increases the accuracy of this report.

USE TRENDS IN THE 1950s

HERBICIDAL OILS

The first herbicide treatment recommended for weed control in cotton was postemergence directed sprays of herbicidal oil in 1950 (Talley, 1950). Special non-fortified oils were recommended at the rate of five gallons per acre directed to the 8- or 10-inch drill area centered over the row. It was suggested that the oils should be directed laterally to the drill area at a height of less than one inch above the soil. It was further suggested that no more than three treatments be applied, with waiting periods of five to seven days between treatments. It was recommended that treatments begin when weeds first appeared in the drill when cotton was three inches tall, and that applications should not be made after cracks appeared in the bark on the cotton stalk.

The herbicidal oil that was first recommended for weed control in cotton (Talley, 1950) was highly effective and provided a significant breakthrough in weed control technology at the time. Unfortunately, the use of herbicidal oil required a very high level of management (Figures 1 and 2). It was specified that the drill area of cotton rows should be one inch higher than the row middle, and that soil in the drill area be pressed flat for at least seven inches on either side of the cotton plants and maintained in this condition for the duration of oil applications. Another disadvantage was that rainfall might delay application for a few days, greatly reducing the effectiveness of the herbicidal oil. Even though complicated to apply, herbicidal oils were highly successful for many producers and continued to be used for many years. Initially, herbicidal oil cost only about 20 to 25 cents per gallon, but the steady increase in cost of petroleum products and the availability of arsenical herbicides in the 1960s lead to the obsolescence of this practice.

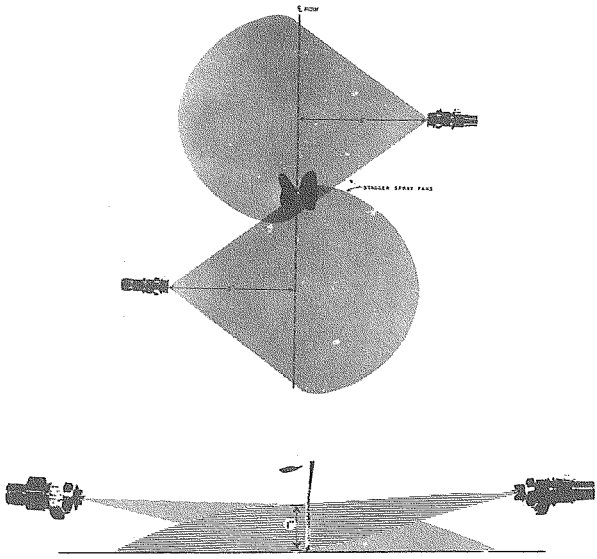


Figure 1. It was necessary to apply herbicidal oils very precisely within a few days after emergence of cotton and weeds for satisfactory results. The top photograph shows an overhead view and the lower photograph shows a side view of the recommended method of application. The high level of management required to achieve this precise method was a primary limiting factor in more widespread use of herbicidal oils.

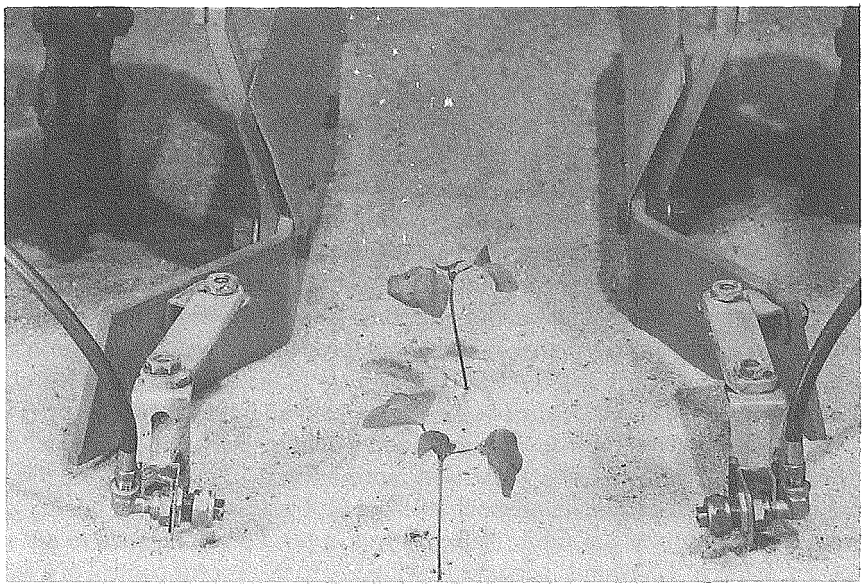


Figure 2. Spray nozzles mounted on the rear end of shielded applicators for applying herbicidal oil postemergence in cotton. The shields prevented movement of soil from the cultivated row middles into the cotton-drill area. It was necessary to keep the drill area flat and smooth to prevent herbicidal oil from being deflected onto cotton seedlings.

PREEMERGENCE HERBICIDES

Various salts of dinoseb were evaluated for preemergence weed control in cotton in the late 1940s (Cowart *et al.*, 1950; Harris *et al.*, 1950). Farmers commonly referred to dinoseb as dinitro, while scientists used the term, DNOSBP. Dinoseb was generally applied at four to eight pounds per acre. An alkanolamine salt of dinoseb was generally selected as the most promising material and it was widely tested in 1951. The most popular product was Premerge®. The earlier warnings of possible severe injury to cotton from dinoseb were ignored (Cowart *et al.*, 1950; Harris *et al.*, 1950) and dinoseb was applied to several thousand acres of cotton in several states in 1952. Treatments killed or severely injured much of the cotton treated in the Mid-South[2] when dinoseb vaporized as the young cotton seedlings emerged (Davis, 1964). It was later shown that a large number of variables affected the toxicity of dinoseb to cotton, including soil type, rainfall, soil pH and air temperatures. All of these variables affected vaporization

[2]States included in the four cotton producing regions are: Mid-South—AR, LA, MS, MO, TN; Southeast—AL, GA, NC, SC; Southwest—NM, OK, TX; West—AZ, CA. Many of the reports and surveys that we cite later used the same four regional names, but placed individual states in other regions other than that shown above. As a result, it will be necessary to refer to the appropriate table, or cited reference, to identify states within regions when reference is made to reports of others.

of dinoseb, and this quickly taught weed scientists the importance of vapor activity of herbicides (Shaw *et al.*, 1953).

Chlorpropham, commonly known as CIPC in the 1950s, had been introduced at about the same time as dinoseb, but generally did not receive as much interest until the injury problem with dinoseb occurred in 1952. Increased research showed that chlorpropham was much more selective to cotton than dinoseb and interest in its usage increased rapidly (Davis, 1964). Like dinoseb, it was usually applied preemergence at four to eight pounds per acre, dependent upon soil type. One of the more popular products was Chloro IPC. The primary disadvantages of chlorpropham was its low activity on certain broadleaf weeds and its relatively brief period of effective control, usually only three to four weeks. Monuron and diuron, known as CMU and DCMU respectively in the 1950s, were researched for preemergence weed control beginning in 1950 and 1951 respectively (Hill, 1980). Within the next few months monuron would be marketed as Telvar® and diuron as Karmex®. Initially, there was more interest in monuron, but diuron became the prime candidate in about 1953 because of lower water solubility and greater adsorption on soil (Hill, 1980). Diuron, applied preemergence to the soil surface at 0.5 to 1.5 pounds per acre provided 70 to 90 percent control of a large number of grasses and broadleaf weeds, and the results obtained were usually more consistent and longer lasting than with chlopropham or dinoseb (Figure 3). Diuron soon became the most commonly used herbicide for weed control in cotton and continued to be so until the mid-1960s.

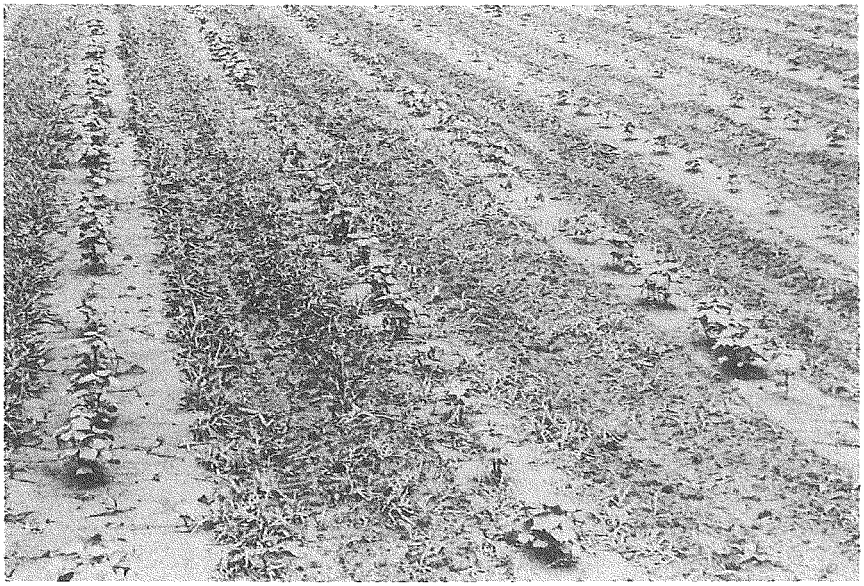


Figure 3. Preemergence weed control in cotton at Stoneville, MS in 1958 about three weeks after the application of Karmex® at 0.5 pounds per acre. Only a 12-inch band was treated with the herbicide after planting. Weeds in the untreated row middles would be removed by cultivation. Karmex® was the first herbicide available that would provide consistent control of the type shown above without excessive crop injury and was the most widely used herbicide in the late 1950s and 1960s.

SPOT TREATMENTS

A spot treatment involves the application of herbicide to a restricted area within a field, such as treatment of spots or patches of weeds. Herbicides that were most commonly used for spot treatment for both perennial and annual weeds in cotton in the 1950s were herbicidal oil, herbicidal oil fortified with one to two percent pentachlorophenol (PCP), sodium chlorate, sodium trichloroacetic acid (TCA) and, in the late 1950s, dalapon (Dowpon®). Initially sodium chlorate and TCA were used more frequently than others but these materials usually killed both cotton and weeds. Sodium chlorate, at one to two pounds per 100 square feet, and TCA at 0.05 to 0.1 pound per 100 square feet would often make the treated area unsuitable for cotton production in the subsequent year. Both were used throughout the Cotton Belt, but never gained a high level of popularity with farmers because of their lack of selectivity.

In the mid- to late-1950s, herbicidal oil used either alone or with PCP was more widely used than either sodium chlorate or TCA. Spot treatments with the oils were applied with a knapsack type sprayer so as to wet the weeds while keeping the oil away from cotton plants. The oils were used more widely for the control

of johnsongrass *[Sorghum halepense* (L.) Pers.] than for all other weeds combined.

Dalapon was introduced as Dowpon® in 1954 (Timmons, 1970) and was highly effective for spot treatment control of johnsongrass and other grasses. Treatments typically consisted of one to two pounds of Dowpon® in five gallons of water and the mixture applied with a knapsack sprayer to wet grass plants to runoff while minimizing contact with cotton. Spot treatment with Dowpon® retarded the growth of cotton, but the margin of selectivity between the weed and the crop was much better than other treatments that were available.

EXTENT OF HERBICIDE USE IN THE 1950s

Dinoseb applied preemergence was tested widely throughout the Cotton Belt in 1951, with widespread sales beginning in 1952. The acreage treated with dinoseb in 1952 has not been published, but it is likely less than 200,000 acres. The use of dinoseb declined after 1952 and it was initially replaced with chlorpropham applied preemergence. The first multi-state survey of cotton acreage treated with herbicides in 1955 showed that about 122,000 acres were treated with chlorpropham, 66,000 with diuron, and 115,000 acres with herbicidal oil, all in the Mid-South, Southeast and Southwest (Table 1[3]). Use of both herbicides was much greater in Mississippi than in other individual states. Preemergence use of dinoseb was not listed in the survey, although it is likely that a relatively small acreage was still being treated in the mid 1950s. Western states used very little herbicide during this period.

The 1955 survey indicated that a herbicidal oil was used to control weeds on about 115,000 acres in nine states (Table 1). The total acreage treated with all herbicides in the 1955 survey was about 302,000 acres, less than two percent of the total cotton acreage in that year.

The data in Table 2 on the extent of use of weed control practices in Texas indicate that the use of herbicidal oil did not exceed 22,000 acres in the 1950s, although the survey shown in Table 1 indicated that herbicidal oil could have been used on 75,000 acres in 1955.

Surveys in Mississippi showed that about 36,000 acres were treated with chlorpropham in 1953, as compared to only about 10,000 acres with dinoseb (Table 3). By 1955, the acreage treated with chlorpropham had increased to 50,000 acres, but it declined to 29,000 acres in 1956. The use of diuron for preemergence control first appeared in the Mississippi surveys in 1955 when 40,000 acres were treated and this increased to about 85,000 acres in 1956. Mullendore (1970) reported that about eight percent (96,000 acres) of the cotton acreage in Mississippi was treated with preemergence herbicides in 1957.

Spot treatments, in which individual weeds or clumps of weeds were treated by hand, began to be commonplace in the 1950s. The extent of usage is not documented, except in a Texas survey (Table 2). This survey showed that 74,000

[3]All tables in this chapter are found in an appendix at end of the chapter.

acres received spot treatments with a herbicidal oil in 1955 and this had increased to 151,000 acres by 1959. This survey also showed that dalapon began to be used as a spot treatment in Texas in 1958 when 40,000 acres were treated, and this had increased to 51,000 acres in 1959 (Table 2).

The extent of cotton acreage treated with herbicides began to increase rapidly in the late 1950s. A nation-wide survey by USDA (Saunders, 1962) showed that the acreage treated preemergence was about 1,000,000 acres in 1959. Three of the Mid-South States, Arkansas, Louisiana, and Mississippi, accounted for about 900,000 acres of the national total. The survey did not report that pre-emergence herbicides were used in the Western states. More than 500,000 acres were treated postemergence in 1959, but about 400,000 acres of the total was in only two states, Arkansas and Texas. The specific herbicides used for weed control in 1959 were not reported in the survey.

Seven of the states reporting in the 1959 survey listed the effectiveness of preemergence herbicides as "fair," while four states listed effectiveness as "good" (Saunders, 1962). Five states reported effectiveness of postemergence treatments as "good," and three reported "fair" control. Eleven states reported that the extent of herbicide usage was increasing, while two states, Virginia and Arizona, reported that usage was stationary. When questioned about the need for better herbicides, eleven states reported that there was "some" need and only two states reported an "urgent" need. The level of weed control that was being obtained in 1959 from both pre- and postemergence herbicides must have been much higher than farmers had expected to explain the relative lack of urgency for better weed control practices. If only the herbicides available in 1959 were presently available, their effectiveness would probably be rated "poor," based on present-day expectations.

USE TRENDS IN THE 1960s

The greatly expanded use of herbicides that began in 1958 or 1959 continued at an accelerated rate through the 1960s. The use of preemergence treatments increased from 6.6 percent of the total cotton acreage in the United States in 1959 to 48.6 percent in 1965 (Table 4). The use of postemergence treatments increased from 3.7 percent in 1959 to 43.1 percent in 1965. In 1959, only about 10 percent of the total crop acreage was treated with both pre- and postemergence herbicides but by 1968, 91 percent of the acreage was treated. The average cost of herbicides increased from about $3/A in 1959 to nearly $10/A in 1968 (Table 4). The total value of herbicides used in cotton increased from $4.7 million in 1959 to more than $89 million in 1968.

Many superlatives have been used to describe the importance of the 1960s in the development of weed control technology used in cotton. These have included "dynamic decade," "golden decade," and "the fabulous 60s." These terms were prompted by the introduction and sale of 10 important herbicides within about a

seven-year period (Timmons, 1970). These included Eptam® (EPTC), Dicryl® (dicryl), Lorox® (linuron), DSMA/MSMA, Herban® (norea), Treflan® (trifluralin), Caparol®, Cotoran® (fluometuron), Paraquat (paraquat) and Planavin® (nitralin). A few of these, such as Dicryl®, Herban®, and Planavin®, were available for only a few years but others, including DSMA/MSMA, Treflan®, Caparol® and Cotoran®, are as important in cotton production today as they were in the 1960s.

EXTENT OF USE OF PREEMERGENCE HERBICIDES IN THE 1960s

In Texas, the acreage treated with preemergence herbicides increased from 46,000 acres in 1962 to more than 2,000,000 in 1969 (Table 2). Unfortunately, the specific herbicides used were not listed in the survey.

In Mississippi, the acreage treated preemergence with Karmex® increased from about 85,000 acres in 1956 to nearly 900,000 acres in 1961 (Table 3). Karmex® continued to be the predominant preemergence herbicide used through the mid-60s but by 1969, the acreage treated with this herbicide had declined to about 82,000 acres. The reduced usage of Karmex® was caused primarily by the expanded use of Cotoran®, either alone or in combination, with other herbicides, but also by the greatly expanded usage of Treflan® and other herbicides (Table 3). By 1969, farmers in Mississippi were using more than 14 different herbicides or herbicide combinations for weed control in cotton.

Preemergence use of chlorpropham decreased after 1961 and was not listed in Mississippi surveys after 1963 (Table 3). Eptam® appeared in the Mississippi surveys only in 1969, when 2,000 acres were treated preemergence with injectors (Holstun *et al.*, 1963). Greatest use of Herban® applied preemergence was in 1969 when about 15,000 acres were treated; but usage declined thereafter. Use of Planavin® peaked in 1969, but decreased thereafter. In 1967, many producers in the Mid-South experienced the "cotton stunt" injury problem that was associated primarily with excessively deep incorporation of Treflan® and Planavin® (Mullendore, 1968). There were many contributing factors to the cotton injury problem, other than deep incorporation of herbicides, that included cold-wet weather, shallow planting, and injury from fertilizer and insects. Even so, many producers felt that cotton injury was more severe following use of Planavin® than with Treflan®. As a result, interest in Planavin® declined.

A significant change occurred in the use pattern in which preemergence herbicides were used in the Mississippi Delta in 1967. Previously, farmers had used either a soil surface applied herbicide or an incorporated dinitroaniline herbicide. But, in 1967, 85 to 90 percent of the cotton acreage was treated using two different preemergence herbicides (Mullendore, 1968). Originally the use of two preemergence herbicides was referred to as "double," "overlay," or "dual" treatment. These terms were used to indicate that a dinitroaniline herbicide was applied preplanting and soil incorporated followed by the application of another herbicide to the soil surface. During the next few years, "overlay" became a

more popular term. The extent of use of overlay treatments in Mississippi in the late 1960s is presented in Table 3.

The only other state survey showing the extent of usage of specific herbicides is for Tennessee in 1966, 1967, and 1968 (Table 5). In general, these surveys show a relatively rapid decline in usage of Karmex®, while the use of Cotoran® increased. The dinitroanilines, Treflan® and Planavin®, were not used as extensively in Tennessee as in Mississippi, nor is there evidence of extensive use of the overlay treatments as in Mississippi (Table 5).

In the 1960s, use of preemergence treatments were far more commonplace in Mid-South and southeastern states than in western states (Danielson *et al.*, 1965; Danielson *et al.*, 1968; and Jansen *et al.*, 1972). In 1968, almost half of the cotton (about 550,000 acres in Arizona, California, Nevada, and New Mexico) received preplant-incorporated (PPI) treatment or a combination of PPI plus postemergence treatment, while more than seven million acres received these treatments in the South and Southwest (Danielson *et al.*, 1972). Treflan® was the first widely accepted herbicide in western states because it provided control even when rainfall did not occur after planting.

EXTENT OF USE OF POSTEMERGENCE HERBICIDES IN THE 1960s

Use of herbicides applied postemergence increased dramatically in the 1960s (Table 4). In 1949, only 3.7 percent of the cotton acreage received postemergence treatment but, by 1968, 57 percent of the acreage was treated either postemergence alone or pre- and postemergence.

In Mississippi, the use of herbicidal oil increased from about 106,000 acres in 1961 to about 357,000 acres in 1963 (Table 3). Survey data that show the extent of use of herbicidal oil in Mississippi from 1964 through 1968 are not available but it is likely that this practice peaked in the mid-1960s. Unpublished surveys from Mississippi show that the number of sprayers to apply herbicidal oil increased from 715 to 1,738 from 1961 to 1962. The 1963 survey did not distinguish between sprayers to apply herbicidal oil *vs*. other herbicides but it did show a total of 4,123 postemergence herbicide sprayers in the state. The use of herbicidal oil was probably greatest in the Mid-South and in Texas, although it was used to some extent throughout the Cotton Belt. Surveys in Tennessee indicated that only 4,000 and 7,000 acres were treated in 1966 and 1968, respectively and this decreased to only 1,000 acres in 1970 (Table 5). In Texas, the number of acres treated with herbicidal oil increased from 86,000 to 283,000 from 1961 to 1962, but the number of treated acres declined thereafter. As discussed later, the use of herbicidal oil was largely replaced by the use of DSMA/MSMA applied alone or in combination with other herbicides.

The arsenicals, DSMA/MSMA, were introduced for postemergence weed control in the early- to mid-1960s and quickly became one of the most valuable weed control practices. Originally, the selectivity of the arsenicals for controlling grasses in cotton was not recognized and these materials were first suggested for

weed control in cotton when included in a tank mixture with Dicryl® (Thompson, 1961). Dicryl® was first made available for field evaluation in 1958 and Porter *et al.* (1960) were among the first to propose the use of Dicryl® for postemergence weed control in cotton. Other researchers began evaluating Dicryl® for selective weed control (Frans, 1962), but it was Thompson (1961) who first reported that the combination of Dicryl® + DSMA was highly effective. A product was quickly marketed that contained both Dicryl® and DSMA for use in tank mixtures. However, the product was on the market for only two or three years because it was quickly found that the arsenicals used alone or in combination with other herbicides were equally or more effective.

In 1960, it was found that Karmex® and other substituted ureas were highly effective for postemergence weed control when applied with surfactant (McWhorter and Sheets, 1961). By 1962, 562,000 acres of cotton in Mississippi were treated with Karmex® applied postemergence (Table 3). Postemergence use of the arsenicals (DSMA/MSMA) in Mississippi was first reported in a 1963 survey when about 72,000 acres were treated. By 1969, nearly 1.5 million acres were treated with an arsenical herbicide applied alone or in combination with Caparol®, Cotoran®, dinoseb, Herban®, Karmex® or Lorox® (Table 3). Similar use patterns for the herbicides were developing in adjacent Mid-South states.

In Tennessee, the acreage treated with the DSMA/MSMA alone or in combination increased from 107,000 acres in 1966 to nearly 300,000 acres in 1970 (Table 5). By 1970, most of the treated acreage was either with DSMA/MSMA applied alone or in tank mix with Caparol®, Cotoran®, Herban®, or Karmex®.

DSMA was first reported to be used in Texas in a 1963 survey when 100,000 acres were treated (Table 2). The arsenicals continued to be used on about 600,000 to 800,000 acres in Texas from 1965 to 1970. The Texas survey reports only on the use of DSMA but it is likely that this also included the use of MSMA.

Layby treatments became increasingly popular in the 1960s. Layby treatments are postemergence directed spray applications of herbicides at about the time of the last cultivation. In Mississippi, nearly 350,000 acres were treated with Karmex® applied layby in 1963. By 1970, the acreage treated with Karmex® decreased to 244,000 acres, but about 56,000 acres were treated with Cotoran® and 143,000 acres with Lorox® (Table 3).

Layby treatments were more widely used in the Mid-South states than in any other southern states. In Tennessee, only 14- to 26,000 acres were treated with herbicides applied layby in the late 1960s (Table 5). Karmex® was the most commonly used herbicide for layby treatment in Tennessee in 1968 but by 1970, Cotoran® and Karmex® were used equally.

EXTENT OF USE OF SPOT-TREATMENT HERBICIDES IN THE 1960s

Spot spraying continued to be a frequently used practice to control persistent weeds after the general weed infestation had been treated with other methods (Buchanan and McWhorter, 1970). Spot spraying was expensive because it re-

quired hand labor, but it was usually more economical than hand hoeing (Rea *et al.*, 1955; Rea, 1958). Most spot treatments were used to control perennial weeds. In the early 1960s, herbicidal oil, either used alone or fortified with TCA ester, was more widely used, but spot treatment of grasses with Dowpon® became increasingly popular in the mid- and late 1960s. These treatments continued to be applied by individuals walking through the field with hand sprayers or with two or more men riding through the field on a tractor equipped with seats and a hand-held spray system.

The extent of usage of spot treatments is poorly documented, and only a survey in Texas provides an indication on the number of acres treated. Up to 277,000 acres were spot treated with herbicidal oil in the early 1960s, but this level declined to only about 105,000 acres in 1969 (Table 2). Similarly, there were 137,000 acres spot treated with dalapon at the beginning of the 1960s and only 45,000 acreas were treated in 1969 (Table 2).

There are no surveys to indicate the extent of sodium chlorate or the arsenical herbicides used as spot treatments in the 1960s, but they were widely used. DSMA/MSMA was applied in the same manner as spot treatments with Dowpon® by mixing about one pound of active herbicide in five gallons of water and spraying this solution to thoroughly "wet" weeds. Sodium chlorate was applied either in solid form by hand or in liquid sprays to "wet" weeds. Eichers (1980a) reported that 1.5 million pounds of sodium chlorate were used in cotton in 1966. This represented 23 percent of the total herbicide used on a weight basis in cotton production that year. It is likely that much of this was used as a cotton desiccant/defoliant instead of as a herbicide. Use of sodium chlorate was exceeded only by the use of 2.6 million pounds of trifluralin. Eichers (1980a) also reported that 0.9 million pounds of diuron and 0.4 million pounds of MSMA were used in 1966. These four herbicides, trifluralin, sodium chlorate, diuron and MSMA, represented 83 percent of the total herbicide used in cotton production that year.

The three nationwide surveys conducted by USDA, ARS in 1962 (Danielson *et al.*, 1965), 1965 (Danielson *et al.*, 1968), and 1968 (Danielson *et al.*, 1972) showed that herbicides were used extensively for both pre- and postemergence treatments in Mid-South and southeastern states, but was far less frequently used in the West. In 1968 only about 750,000 acres of cotton received treatment with herbicides in the West and nearly two thirds of this, 450,000 acres, was in California (Jansen *et al.*, 1972). These surveys do not list the specific herbicides used, but they do provide estimates of usage on a state-by-state basis. The surveys also showed that the preemergence treatments used in 1968 had about the same level of effectiveness as those used in 1965, but that postemergence treatments were more effective in 1968 than in 1965. Combinations of preemergence and postemergence treatments were rated "good" in 12 states, "fair" in two states, and no state rated treatments as "poor" (Jansen *et al.*, 1972). Also, no state reported an "urgent" need for better herbicides. The herbicide-use trend was listed as up in 13 states, stationary in five states, and down in no states.

Problems with herbicide soil persistence appeared to be lower in 1968 than in 1965. In 1968, seven states reported problems with persistence, but 11 reported no major problems with persistence. Persistence problems affected about five percent of the treated acreage and were more severe in the West (Jansen *et al.*, 1972) due to a slower rate of herbicide decomposition.

USE TRENDS IN THE 1970s

At the beginning of the 1970s, practically all of the cotton acreage in the Southeast and Mid-South were treated both pre- and postemergence (Table 6). A large percentage of the cotton acreage in the Southwest and the West was also treated, but states in these areas made significantly less usage of both pre- and postemergence treatments than in eastern portions of the Cotton Belt. Less frequent rainfall reduced the effectiveness of preemergence herbicides in the western Cotton Belt, causing significantly reduced usage of soil surface-applied materials, such as Cotoran® and Karmex.® The lower frequency of rainfall, both before and immediately after emergence of cotton in western states, also resulted in lower weed infestations than in eastern states, thus reducing the need for many of the postemergence treatments that were used in the Mid-South and Southeast.

The decade of the 70s was a period of adjustment for many cotton producers who were still attempting to develop best management practices for the large number of highly effective herbicides that were introduced in the 1960s. In addition, they were confronted, and often confused, by a vast array of new herbicides that were introduced in the 1970s. These included five new dinitroaniline compounds, two additional triazines, and three other herbicides that would eventually be widely used. With the vast array of herbicides that had become available in both the 1960s and the 1970s, farmers now had literally hundreds of different possible weed control programs to select from. This often caused both anxiety and confusion because very active competition for sales occurred during the 1970s.

HERBICIDES FOR PREEMERGENCE CONTROL IN THE 1970s

During the early to mid-1970s the five newly introduced dinitroaniline herbicides that competed with Treflan® and Planavin® were Amex® (butralin), Basalin® (fluchloralin), Cobex® (dinitramine), Prowl® (pendimethalin) and Tolban® (profluralin). Within individual experiments or farm trials, there were often subtle differences among the dinitroaniline herbicides in terms of which had greatest cotton tolerance or which persisted the longest in the soil, but as summarized by Talbert (1978), "there is little indication of any consistent differences of the effect of these herbicides" at "reasonable rates." Also, there were no distinct advantages in which any of these products provided a consistently higher level of weed control that could be exploited for sales purposes.

The two new triazines that were introduced in the 70s were Bladex® (cyana-

zine) and Sancap® (dipropetryn). Bladex® would later find a widespread market throughout much of the Cotton Belt for postemergence weed control, but Sancap® was developed for preemergence control in the more arid cotton producing areas of Arizona, New Mexico, Texas, and Oklahoma (LeBaron, 1979). Greatest use of Sancap® was in Texas. LeBaron (1979) provided an excellent review on the history and development of triazine herbicides for use in cotton.

Other new herbicide introductions in the 1970s were Probe® (methazole), Roundup® (glyphosate) and Zorial® (norflurazon). Roundup® and Zorial® would later play a significant role in cotton production.

HERBICIDES FOR POSTEMERGENCE WEED CONTROL IN THE 1970s

Roundup® was introduced in 1971 and quickly became the most effective material available for spot treatment of johnsongrass and other weeds that escaped pre- and postemergence treatments. In the late 1970s, it also achieved significant use when applied in a rope-wick applicator for control of johnsongrass and other weeds that grew taller than cotton. Probe® was introduced for postemergence weed control in the mid 1970s. It gained popularity, especially in the Mid-South, for control of many broadleaf weeds when either applied alone or in combination with MSMA.

In the 1970s the arsenicals, DSMA/MSMA, continued to be the most widely used herbicides for postemergence weed control in cotton. These herbicides were economical as compared to alternatives. They were selective for use in cotton when properly applied, and they effectively controlled several weeds that were either impossible- or difficult-to-control with other herbicides, including the nutsedges, johnsongrass, and cocklebur. The relative importance of the arsenical herbicides is demonstrated in a review by Miller (1977a), who reported that he found 125 papers dealing with the arsenical herbicides in the Proceedings of the Southern Weed Science Society from 1967 to 1976. He concluded from his study that: (a) DSMA caused less cotton injury than MSMA; (b) injury from both herbicides was worse at low temperatures than at high temperatures; (c) directed sprays were much safer to cotton than over-the-top sprays; and (d) treatment should be terminated before the first flower appeared on cotton plants.

EXTENT OF HERBICIDE USE IN THE 1970s

Surveys are available from only two states that show the percentage of acreage treated with different herbicide practices in the early 1970s. In Mississippi, Treflan® continued to be the most widely used soil-incorporated herbicide (Table 3). The use of Planavin® decreased more than two-fold in the early 1970s when the most widely used preemergence practices were overlay treatments of Cotoran® or Karmex® after soil incorporation of Treflan® (Table 3). Cotoran® continued to be more widely used than Karmex.® Caparol®, Herban®, and Telvar® were used on far less acreage than the herbicides previously mentioned.

The use of herbicidal oil continued to decline in Mississippi in the early 1970s,

although Mobilnix,® an emulsifiable herbicidal oil, was used for four or five years in addition to conventional herbicidal oil (Table 3). The most widely used postemergence treatments in Mississippi in 1972 were MSMA alone or MSMA tank-mixed with Cotoran® or Karmex.® Cotoran® continued to be the most widely used herbicide for layby weed control, although Lorox® was commonly used (Table 3).

In Texas, the acreage treated with preemergence herbicides increased from about 2.2 million acres in 1970 to nearly 3.5 million acres in 1973 (Table 2). The extent of use of the arsenical herbicides also continued to increase during that period. Conversely, the use of herbicidal oil decreased dramatically during the period 1970 to 1973 as compared to earlier usage. The use of herbicidal oil or dalapon as a spot treatment was relatively stable in Texas during the early 1970s (Table 2).

Weaver (1983) conducted a series of surveys in Texas from 1973 through 1981 that provided estimates on the acreage treated with specific herbicides. The use of Treflan® represented 80 percent or more of the total acreage treated with the six dinitroaniline herbicides (Table 7). The use of all dinitroaniline herbicides varied from 52 percent of the Texas acreage in 1973 to nearly 87 percent in 1980. Use of the soil surface-applied preemergence herbicides varied from about 14 to 17 percent of the total cotton acreage. Throughout the survey, Caparol® was used on more acres in Texas than all other soil surface-applied herbicides combined (Table 7).

Postemergence herbicides were not used in Texas as extensively from 1973 through 1980 as they were in the Mid-South states (Table 7). Usage of herbicides applied postemergence declined from about 18 percent of the total cotton acreage in 1973 to 11 percent in 1980. The arsenicals were the most commonly used postemergence herbicides, but their use also declined from about 13 percent of the cotton acreage in 1973 to only about 7 percent in 1980 (Table 7).

Eichers (1980b) reported that herbicide use in cotton increased from 6.5 million pounds in 1966 to 18.3 million pounds in 1976 (Table 8). Trifluralin was the most commonly used herbicide overall in both years of the report and represented 38 to 40 percent of all herbicides used. Use of the arsenicals increased from 0.4 million pounds in 1966 to 3.3 million pounds in 1976. Eichers (1980a) did not report the use of fluometuron (Cotoran®) in 1966, but by 1976, 5.3 million pounds were used in cotton, 29 percent of all herbicides used.

In 1976, three herbicides comprised 81 percent of all the herbicides used in cotton. These were trifluralin (38 percent), fluometuron (22 percent), and the arsenicals (21 percent) (Table 9).

The extent of herbicide usage in different regions of the Cotton Belt in 1976 is summarized in Table 10. This summary shows that nearly all of the cotton acreage east of Texas was treated with herbicides in 1976. Only 68 percent of the acreage in Texas and Oklahoma was treated and more than 90 percent was treated in California. Herbicide usage per acre was highest in the Delta states

(3.47 lb/A) and in the Mountain states (3.26 lb/A) and lowest in California (0.84 lb/A).

The time and manner in which herbicides were applied in various states in 1976 are summarized in Table 11. Foliar application of herbicides to weeds before planting was the least used method. The use of soil incorporated treatments for preemergence control was the most extensively used of all methods of application (Table 11). Use of soil surface-applied preemergence treatments was also consistently high in all states, except Arizona, California, New Mexico, Oklahoma and portions of Texas. Greater usage was made of directed sprays than over-the-top sprays in most states, but this survey showed greater use of over-the-top treatments than any other published survey. The use of herbicides applied at layby varied widely from state to state, but in general, layby treatments are used far less frequently than directed sprays (Table 11).

In 1976, the most commonly used foliar-applied herbicides prior to planting were MSMA, paraquat, or mixtures of the two (Table 12), but only seven states reported this type of treatment. As verified in other surveys, Treflan® was the most widely used herbicide in 1976, although this survey suggests that use of Cotoran®/Lanex® was nearly as widespread as Treflan® (Table 12). Karmex® was used for preemergence control in as many states as was Cotoran®/Lanex®, but only about 25 percent as much acreage was treated with Karmex® as with Cotoran®/Lanex®. The use of these substituted urea herbicides, either alone or in combination with MSMA, probably represented 90 percent of all of the post-emergence directed sprays in 1976 (Table 13). The only herbicides applied over-the-top were Cotoran® and the arsenicals. Use of Karmex® and Lorox® accounted for about 80 percent of all herbicides applied at layby (Table 13), but Lorox® was not used in western states.

By 1979, herbicides were applied to more acres of cotton than insecticides and fungicides combined (Table 14). Herbicides were applied about three times more frequently to cotton growing in the southeastern and Mississippi Valley states than in southwestern or western states. Insecticides were applied more frequently on the acres that were treated than herbicides in all four regions of the country (Table 14).

In the mid-1970s, control of johnsongrass and other tall growing weeds in cotton was frequently accomplished with applications of Roundup® in recirculating sprayers (Larsen, 1987). These sprayers reached maximum usage in 1978 when this method began to be replaced by applications of Roundup® with the rope wick applicator. The extent to which these practices were used in cotton is not documented, but they were probably used on 10 to 20 percent of the cotton acreage in most southern and southwestern states over a three- to four-year period. Weaver (1983) estimated that rope-wick applicators were used on 22 and 38 percent of the cotton acreage in Texas in 1980 and 1981, respectively.

Roundup® probably became the most frequently used herbicide for spot treatment in the 1970s, but the extent of this usage is unknown. We estimate that

between 10 to 30 percent of the cotton acreage in each state may have received spot treatments with Roundup.® Dalapon continued to be used for spot treatments also as were the arsenical herbicides, but there are no surveys to indicate the extent to which these were used. In western states, Roundup® quickly replaced Dowpon® for spot treatment of perennial grasses, and was applied with a hooded sprayer at layby for control of field bindweed *(Convolvulus arvensis* L.).

As indicated earlier, considerable attention was devoted in the 1970s to the development of systems or programs to provide seasonal weed control in cotton with combinations of specific weeds. Examples of typical programs for different weed problems in the 1970s were provided by Buchanan and McWhorter (1970). Miller (1977b) provided a summary of weed control practices commonly used in the West in the 1970s.

Several reports were published by USDA in the 1970s that document the manufacture and use of herbicides and other pesticides. These include "The Pesticide Review in 1974" (Fowler and Mahan, 1975) and "The Pesticide Review in 1976" (Fowler and Mahan, 1977); "Farmers Use of Pesticides, 1971" (Andrilenas, 1975); "Farmers Use of Pesticides, 1976" (Eichers *et al.*, 1978); "The Farm Pesticide Industry" (Eichers, 1980a); and "Farmers Expenditures for Custom Pesticide Services, 1971" (Ferguson, 1975).

HERBICIDE USE IN THE 1980s

The 1980s was a period in which cotton producers were confronted with greater economic pressure than they had experienced since the Depression of the 1930s. Adverse weather led to reduced yields and reduced profits in much of the Cotton Belt. In addition, the profitability of cotton production decreased because of increased foreign competition. Many farmers were forced out of cotton production and others were forced to reduce the scope of their operations but, even so, the use of herbicides increased. Ecological shifts of weeds and increased infestations of weeds that were resistant to control with herbicides probably contributed to the increased use of herbicides along with the desire of the farmer to increase both yields and quality.

The 1980s were a contrast from previous decades because as many herbicides were lost as were gained for use in cotton. Use of Basalin®, Cobex®, dinoseb, Probe®, Sancap® and Tolban® was discontinued, although Probe® would be marketed again in 1987. Dual® (metolachlor), Goal® (oxyfluorfen), Poast® (sethoxydim), and Fusilade® (fluazifop) became available in the 1980s, although the extent to which these would be used would not equal the acreage treated with the herbicides that were discontinued.

HERBICIDES FOR PREEMERGENCE CONTROL IN THE 1980s

Loss of three dinitroaniline herbicides, Cobex,® Basalin,® and Tolban,® did not create direct hardships for farmers but only resulted in increased use of Treflan®

and Prowl®. Cobex® had been used in only a few states in the early 1980s as existing supplies were exhausted. Basalin® and Tolban® were used in practically all cotton producing states but their loss did not adversely affect weed control. Probably the greatest impact of their loss was the loss in competition from a marketing standpoint. One of the preemergence herbicides gained in the late 1970s was Destun® (perfluidone), but it was used in the 1980s in only two states for a brief period on a very limited acreage. Dual® has been used more frequently in recent years, but only on limited acreage in about five states. The gain and loss of the preemergence materials had comparatively little impact on cotton production and caused only slight rearrangements within the market place.

HERBICIDES FOR POSTEMERGENCE CONTROL IN THE 1980s

Herbicidal oil was rarely, if ever, used in the 1980s. The use of this practice never appeared in herbicide-use surveys after the mid-1970s.

Use of Probe® applied in directed sprays to control broadleaf weeds began in the late 1970s but use ceased in the early 1980s after existing supplies were sold. Manufacture of Probe® was resumed in 1987 and the product became available again. Probe® was never used on an extensive acreage, but it was used in southeastern states and in most Mid-South states (Tables 15 to 29). Dinoseb was also used for broadleaf weed control when applied in directed sprays but its usage was discontinued in 1987 because its registration was suspended by the Environmental Protection Agency (EPA). Use of dinoseb was highly economical as compared to many other postemergence herbicides, but it was used primarily only in those areas where producers made intensive use of postemergence-directed sprays (Tables 15 to 29). It was used on limited acreage in North Carolina, South Carolina and Tennessee but was more widely used in the four Mid-South states and in Texas.

Goal® became available in the mid-1980s and was used primarily for control of broadleaf weeds. Its use has been limited to relatively small acreages in a few Mid-South and Western states as a preplanting or layby treatment (Tables 15 to 29).

Use of Poast® and Fusilade® began in 1983 but the extent of their use has never achieved the levels that many weed scientists had expected. These herbicides are highly selective for the control of both annual and perennial grasses in cotton but most farmers have apparently been able to continue to achieve satisfactory control with the dinitroanilines applied preplanting and with the arsenicals applied postemergence at a lower price than they could achieve with Poast® or Fusilade®. The exact manner in which producers have applied Poast® and Fusilade® is unknown, but it is likely that most treatments have been with hand sprayers or with tractor spray rigs with the spray boom being turned on and off to spray only heavy infestations of grass. Broadcast over-the-top applications to entire fields with these herbicides have not been common. Treatments with the herbicides have largely replaced the use of Roundup in the rope-wick applicator.

Rope-wick applicators were still being used by some farmers in the mid-1980s but their use has diminished. In the West, Poast® and Fusilade® are used on heavy infestations of johnsongrass and bermudagrass, but results are often erratic when weeds are under drought stress.

ESTIMATES ON THE EXTENT OF HERBICIDE USE IN INDIVIDUAL STATES IN THE 1980s

The only published surveys that document herbicide use in the 1980s are in the "Reports of the Cotton Weed Loss Committee" in the Proceedings of the Cotton Weed Science Research Conference that are included in the annual proceedings of the Beltwide Cotton Production Research Conferences. These surveys are based on estimates made in individual states by extension and research personnel. The eight published reports of this survey have been assembled on a state-by-state basis and these summaries are presented in Tables 15 to 29.

The data in Tables 15 through 29 are so extensive that we will not discuss results on a state-by-state basis. These surveys are valuable for showing general trends in herbicide use, but we feel that some of the estimates are too high based on the totals obtained for some herbicides when data from all states are combined. We cannot predict which state estimates would be too high or too low. Estimates for any one state may be slightly too high or too low, but when the estimates listed in the Appendix Tables are consolidated into a single table representing herbicide usage for the entire country, the combined annual estimates in some cases exceeded the amount of herbicide that would have been available or else exceeded estimates provided by manufacturers and other sources. It seems likely that the total of the annual estimates may be 20 to 30 percent too high for some herbicides applied preemergence to the soil surface or postemergence and possibly 10 to 20 percent too low for herbicides applied preplanting and soil-incorporated. As a result, we have adjusted the values obtained from totaling data from all states (Tables 15 to 29) to provide what we feel are more realistic estimates on the extent of use of individual herbicides (Table 30).

EXTENT OF USE OF INDIVIDUAL HERBICIDES IN THE 1980s

The data summarized in Table 30 provide a list of 33 herbicides and herbicide combinations presented in the annual surveys published in the Cotton Weed Science Research Conference Proceedings. As discussed below, there are about that many additional treatments that are in use that are not listed in the survey. With more than 60 herbicides and herbicide combinations to select from, it is not surprising that any single herbicide or herbicide combination is used on a relatively small percentage of the total cotton acreage. Even so, more than 80 percent of the total acreage treated in the1980s was with Treflan®, Prowl®, Cotoran®/ Lanex® and DSMA/MSMA. Many surveys, such as that by the Cotton Weed

Loss Committee, may report on only one of the arsenicals, MSMA, but it is usually understood that actual usage could be either with DSMA or MSMA. Comparatively large acreages are listed as being treated with Poast®/Fusilade® or Roundup.® It is difficult to gauge the actual scope of use of these materials because their usage to treat one or two spots of weeds per acre might result in this usage being included in the survey as "an acre treated."

Herbicides that showed the most obvious decline in use in the 1980s were those that were discontinued, Basalin®, Cobex®, Destun®, Probe® and Tolban® (Table 30). Herbicides that were used at a relatively low, but constant use-rate, were Dowpon®, Paraquat® and Sancap.® Registration of Sancap® was discontinued in 1988. Those used at a steady intermediate level, from a few hundred thousand to several hundred thousand acres each year, were Bladex®, Caparol®, dinoseb, Karmex®/Dynex® and Lorox®/Linex®. Herbicides that remained at a relatively constant high level from several hundred thousand acres or more, were Cotoran®/Lanex®, DSMA/MSMA, Roundup® and Treflan®.

Use of Dual® and Goal® increased in the mid-1980s but comparatively few acres were treated with them. There were relatively large increases in the acreage treated with Poast®/Fusilade®, Prowl® and Zorial® (Table 30).

Decreased use was made of Cotoran® + Tolban® and MSMA + Probe®, because one of the herbicides in these combinations was discontinued. In 1980, a very limited acreage was treated in two states with Caparol® + Bladex®, but this was discontinued at about the time that Caparol® + Prowl® and Caparol® + Treflan® came into more common usage (Table 30). Cotoran® + Treflan® has continued to be used in seven states on a consistent but low acreage, usually less than 80,000 acres per year. Use of MSMA applied postemergence in tank mixtures with Bladex®, Caparol®, Cotoran®/Lanex® and Karmex®/Dynex® has been commonplace in 10 to 13 states at a relatively constant rate of several hundred thousand acres per year.

Several herbicides and herbicide combinations that were used for preemergence weed control are not reported in Table 30. These include Lasso®, Basalin® + Caparol®, Basalin® + Zorial®, Bladex® + Zorial®, Caparol® + Dual®, Cotoran® + Lasso®, Cotoran® + Prowl®, Cotoran® + Zorial®, Prowl® + Treflan® and Treflan® + Zorial®. There probably are others, but they would not have been used to any appreciable extent. Postemergence treatments that have been used that are not reported in Table 30 include Caparol® + dinoseb, Cotoran® + DSMA, Bladex® + DSMA, dinoseb + Karmex®/Dynex®, dinoseb + Lorox®, Bladex® + dinoseb, MSMA + dinoseb, Bladex® + dinoseb and Bladex® + dinoseb + MSMA. Each of the last three tank mixes listed could have been used on 100 to 200 hundred thousand acres of cotton in any single year in the 1980s. There are probably other tank mixes used for postemergence weed control that are not listed but their use would have been limited.

EXTENT OF HERBICIDE USE IN THE 1980s BASED ON TIME OF APPLICATION

Herbicides are applied as preplanting-foliar applications only infrequently (Table 31). The total of these on a national basis is only a small fraction of total herbicide use. Greater use is made of these treatments in the Mid-South than in all other states combined. Greatest use in the Mid-South is probably in years with high rainfall in March and April when producers are unable to use timely tillage prior to planting. In the West, use is on clay soils where preplanting irrigations are made in November and February or when winter rains are frequent.

The most commonly used preemergence practice on a nationwide basis throughout the 1980s was with soil incorporated herbicides for preemergence control (Table 31). Use of this practice on a national basis increased from 68 percent of the cotton acreage in 1980 to 83 percent in 1986. The second most frequently used practice was the application of herbicides postemergence, which increased from 49 percent of the cotton acreage in 1980 to 84 percent in 1986. Herbicides applied preemergence to the soil surface increased from 28 percent in 1980 to 54 percent in 1986. The use of spot treatments also increased from 36 percent in 1980 to 41 percent in 1986. The use of herbicides applied layby varied from 12 to 20 percent during the period (Table 31).

As in previous decades, greatest use of herbicides on a per-acre basis continued in the Mid-South which averaged 5.7 herbicide treatments per acre each year (Table 31). This large number of applications could be accounted for by: (a) a herbicide applied preplanting; (b) a herbicide applied to the soil surface after planting; (c) herbicides applied post-directed two-to-three times; and (d) a spot treatment and/or a layby application. This sequence is not uncommon in the Mid-South.

The Southeast received the second most frequent use of herbicides in the 1980s, followed by the Southwest and the West (Table 31). Nationally, the number of herbicide applications annually in cotton varied from a low of 1.95 per acre in 1980 to a high of 2.86 herbicide applications per acre in 1986. There is no evidence available to indicate that the extent of usage of herbicides in cotton will decline in the near future.

Herbicides are used intensively in cotton production, but in 1980 they accounted for only seven percent of the total herbicide sales in the United States (Table 32). Sixty-nine percent of the herbicides sold in 1980 were used on the more widely planted corn and soybeans. The value of herbicides sold for use in cotton in the United States was $142 million as compared to the value of herbicides used in cotton in the rest of the world of $179 million (Table 32).

SUPPLY AND COST OF HERBICIDES

There have been few shortages of herbicides registered for weed control in cotton. Economic Research Service, USDA, began publication of evaluation reports on pesticide supply and demand in 1975, and some of these reports include Andrilenas (1975) and Eichers (1976), Eichers and Andrilenas (1978), Eichers and Andrilenas (1979) and Eichers (1980b). Other useful information concerning the availability of herbicides is included in Fowler and Mahan (1975, 1977), Eichers (1980a and 1980b), Eichers (1981) and Eichers and Serletis (1982).

There are few published reports on the prices of specific herbicides over a period of several years, but Eichers (1980b) reported that the price increase for pesticides from 1970 to 1979 was only 53 percent. By comparison, the price of fertilizer increased 123 percent, tractors 147 percent, fuel and energy 165 percent and seed 155 percent. In 1982, Eichers and Serletis (1982) reported that pesticide prices had increased 78 percent from 1971 to 1981. During this same period, the cost of fertilizer increased 186 percent, machinery 207 percent, fuel and oil 302 percent and seed 204 percent.

The average price of nine selected herbicides commonly used in cotton in the Delta of Mississippi increased in price by 66 percent from 1969 to 1987 (Table 33). During this period, the price of some herbicides doubled (Cotoran® and Lorox®) or tripled (dalapon and MSMA), but others (Karmex® and Treflan®) did not increase in price (Table 33). The prices paid for herbicides usually do not vary dramatically throughout the Cotton Belt, so these prices might be representative of increases in other regions.

CUSTOM APPLICATION OF HERBICIDES

Traditionally, cotton producers make less use of custom applicators than producers of many other crops. In 1959, 94 percent of the acres treated with herbicides was by farmers and only 6 percent was by custom applicators (Saunders *et al.*, 1962). Some states in the Mid-South and Southwest did not report any use of custom applicators. In the West, 53 percent of the acres treated was by custom operators in 1959. In both 1962 and 1965, farmers in both the Mid-South and Southwest were still applying their own herbicides to 92 percent of the treated acreage (Danielson *et al.*, 1962 and Danielson *et al.*, 1965). In the West, 28 and 31 percent of the treated acreage was by custom applicators in 1962 and 1965, respectively. Greatest use of custom applicators to apply herbicides in 1962 was in New Mexico (50 percent) and in 1965 in California (40 percent).

In 1968, only Texas reported that more than 25 percent of the acreage treated with herbicides was with custom applicators (Jansen *et al.*, 1972). The limited use of custom applicators to apply herbicides has probably been due to: (a) preemergence herbicides are usually applied only on a band basis; and (b) most postemergence herbicides are applied on a band basis as directed sprays. Both

of these practices preclude use of aircraft or large ground devices commonly used by custom applicators.

FUTURE HERBICIDE USE

It is unlikely that there will be any substantial increase in the use of herbicides in cotton production in the United States in the next few years. Most of the herbicides marketed have now been available for many years and any changes in the total use will likely be dependent upon the number of acres of cotton planted each year. Some herbicides will be lost, especially in the western states, due to regulatory restrictions. Others will be lost due to the costs for registration, so this will especially be true where market shares are low and/or proprietary rights no longer exist.

New herbicides will probably continue to be provided at the rate of one every second or third year over the next several years. There are several new herbicides that are undergoing preliminary testing and some of these will likely be registered within the next three to ten years. Some of the new herbicides being developed include the sulfonyl chemistries that are effective at only a few grams per acre. This will be highly beneficial in reducing the total weight of herbicides applied annually in addition to providing improved control of broadleaf weeds.

One or two biological weed control agents, probably fungi, will likely be introduced for weed control in cotton within the next few years. The impact of these will be relatively minor on a national basis because the spectrum of weed control with pathogens is very narrow, often limited to one or two specific weeds.

Ecological shifts of weeds will probably continue, especially as greater usage is made of conservation tillage. A series of major ecological shifts could greatly increase herbicide usage within specific geographical areas.

Some weeds that are now adequately controlled could develop resistance to herbicides within the next 10 to 20 years. During the past 10 years, resistance or tolerance has been reported to such herbicides as atrazine, trifluralin, 2,4-D, bentazon, diuron, dicamba, paraquat, and others (LeBaron and Gressel, 1982). As of 1981, triazine-resistant weeds had been confirmed in 23 states of the United States, in four provinces of Canada and in a total of seven countries. The possibility of tolerance or resistance to herbicides increases in the Cotton Belt as individual herbicides (or chemistries) are used on a repetitive basis over a period of years.

The primary herbicide needs in cotton have been shown in recent surveys (Patterson and Monks, 1986; Weaver, 1986; Sanders, 1986). The major desire of most producers is for herbicides to provide more effective control of broadleaf weeds without injury to cotton or rotational crops. Most farmers prefer a herbicide that can be applied broadcast over-the-top. Morninglories (*Ipomoea* sp.) are the major problem weeds throughout much of the Cotton Belt and a survey in Louisiana in 1985 showed that farmers are now paying as much as $56 per acre

to control this weed (Sanders, 1986). Other problem weeds include cocklebur (*Xanthium strumarium* L.), sicklepod (*Cassia obtusifolia* L.), nutsedges (*Cyperus esculentus* L. and *Cyperus rotundus* L.), tropic croton (*Croton glandulosus* var. *Septentrionalis* Muell.-Arg.), bermudagrass [*Cynodon dactylon* (L.) Pers.], spurred anoda [*Anoda cristata* (L.) Schlecht.], wild poinsettia (*Euphorbia heterophylla*), velvetleaf (*Abutilon theophrasti* Medik.), nightshades (*Solanum* sp.), horsenettle (*Solanum* sp.) and unicorn-plant [*Proboscidea louisianica* (Mill.) Thellung].

As more use is made of alternative agriculture and conservation tillage, more cost-effective control measures will be needed for many winter weeds and for horseweed [*Conyza canadensis* (L.) Cronq.]. Many of the newer herbicides are so specific for control of only a few weeds that it seems likely that several different new herbicide chemistries will be needed for use in cotton to control the complex of weeds mentioned above.

The continued safe use of herbicides is essential to the cotton industry. The pesticide industry will continue to discover, develop and market more effective, safe and selective herbicides. These are needed to: (a) conserve energy in cotton production; (b) permit wider use of conservation tillage; (c) keep the price of fiber and food from increasing; (d) provide freedom from the drudgery of controlling weeds by hand; and (e) to permit producers in the United States to remain competitive with foreign producers.

Most producers feel that the "ultimate" herbicides are those that are sufficiently selective to cotton to permit over-the-top postemergence applications. Cotton is the only major crop produced in the United States that does not have one or more herbicides registered for over-the-top application for the control of broadleaf weeds. Both industry and producers are anxious for the development of herbicides to fill this void. The availability of such herbicides will provide considerable impetus to the increased use of conservation tillage. Herbicides of this type are now in development programs, but sales will not likely occur until the mid to late 1990s.

Herbicides developed during the next decade will be more selective to cotton and more toxic to weeds, on a per-unit basis, than present herbicides. Herbicides will continue to be an essential element in the management of weeds in cotton and their efficient use in integrated production management systems will be mandatory for economical production. The frequency of herbicide applications will not be reduced to any appreciable extent by the year 2000, but the total amount of herbicides used will likely decrease by one-to-two percent per year. Even so, essentially all of the cotton acreage in the United States will continue to receive annual herbicide treatments.

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Chapter 7

APPENDIX

Table 1. Estimates of herbicides used in cotton in 1955[1].

State	Preemergence		
	Chlorpropham	Diuron	Herbicidal oil
		(acres x 1000)	
Alabama	5.0	2.5	little
Arkansas	15.0	3.0	9.0
Georgia	5.5	—[2]	—
Louisiana	19.1	11.8	10.0
Mississippi	50.0	40.0	20.0
North Carolina	2.0	1.5	—
South Carolina	4.0	4.0	little
Tennessee	12.0	2.0	0.5
Texas	5.0	0.5	75.0
Missouri, Oklahoma	4.0	0.3	0.5
TOTAL	121.6	65.6	115.0
Grand Total = 302.2			

[1]From a summary by Dr. W. B. Ennis, Jr., ARS/USDA, Mississippi State, MS in a memo dated Sept. 29, 1955.

[2]Dash indicates that no data were provided.

Table 2. Extent and use of weed control practices in Texas from 1952 to 1973[1].

Year	Herbicide application				
	Pre-emergence[2]	Post-emergence	Directed herbicidal oil	Spot treated with oil	Spot treated with dalapon
	(number of acres x 1000)				
1952	8	—[3]	2	—	—
1953	—	—	7	—	—
1954	—	—	13	—	—
1955	—	—	15	74	—
1956	—	—	20	89	—
1957	—	—	13	88	—
1958	—	—	17	135	40
1959	—	—	22	151	51
1960	—	—	71	194	70
1961	—	—	86	219	137
1962	46	—	283	255	122
1963	174	100	181	277	131
1964	407	273	223	273	92
1965	495	506	208	211	70
1966	1,109	617	119	158	58
1967	1,397	768	107	140	52
1968	1,864	686	81	90	43
1969	2,155	788	53	105	45
1970	2,185	687	45	123	48
1971	2,638	682	44	76	60
1972	3,218	874	31	101	57
1973	3,476	813	30	114	71

[1]Data compiled by Cotton Specialist Fred C. Elliott, Texas Agricultural Extension Service, Texas A&M University from County Agent's annual reports.

[2]Includes herbicides applied to soil surface and soil incorporated after 1962.

[3]Dash indicates information not provided.

Table 3. Extent of use of herbicides in Mississippi.[1]

Herbicide	Year									
	1953	1955	1956	1961	1962	1963	1969	1970	1971	1972
	(Acres X 1000)									
State cotton acreage	2554	1745	1641	1665	1636	1485	1225	1235	1355	1664
Preemergence										
Chlorpropham	36.4	50.0	29.1	14.0	11.9	11.7	—	—	—	—
Dinoseb	9.6	—	—	—	—	—	—	—	—	—
Caparol®	—	—	—	—	—	—	2.2	3.3	1.3	1.6
Cotoran®	—	—	—	—	—	—	189.2	263.9	196.9	176.4
Karmex®	—	40.0	84.9	873.9	998.4	982.0	82.2	111.1	78.8	96.2
Eptam®	—	—	—	—	—	—	2.0	0	0	—
Herban®	—	—	—	—	—	1.3	14.8	8.3	6.6	4.8
Planavin®	—	—	—	—	—	—	143.9	94.5	52.5	64.1
Telvar®	—	—	—	—	—	59.6	27.1	31.3	39.4	16.0
Treflan®	—	—	—	—	—	1.2	508.9	452.2	170.6	192.4
Caparol® + DNA	—	—	—	—	—	—	1.5	1.1	13.1	8.0
Cotoran® + DNA	—	—	—	—	—	—	409.3	284.6	459.4	721.6
Herban® + DNA	—	—	—	—	—	—	17.6	4.4	6.6	16.0
Karmex® + DNA	—	—	—	—	—	—	125.2	67.9	144.4	224.5
Telvar® + DNA	—	—	—	—	—	—	23.2	11.5	39.4	80.2
Others	—	—	—	—	—	0.5	1.2	1.5	1.3	—
Subtotal	46.0	90.0	114.0	887.9	1010.3	1056.3	1548.3	1335.6	1210.3	1600.8
Postemergence										
Herbicidal oil	7.0	20.0	—	105.6	222.1	356.7	68.0	75.5	78.8	64.1
Mobilnix®	—	—	—	—	—	—	—	36.0	39.4	32.1
Dicryl® + DSMA	—	—	—	—	—	39.9	—	—	—	—
Dinoseb	—	—	—	—	—	—	102.6	49.8	78.8	48.1
Karmex®	—	—	—	264.9	562.1	248.7	—	—	—	—
MSMA	—	—	—	—	—	71.6	60.0	392.2	735.1	641.4
MSMA + Caparol®	—	—	—	—	—	—	129.8	55.2	170.6	160.4
MSMA + Cotoran®	—	—	—	—	—	—	314.9	454.6	472.5	1106.5
MSMA + Dinoseb	—	—	—	—	—	—	—	99.0	210.1	481.1
MSMA + Herban®	—	—	—	—	—	—	197.7	99.1	262.5	96.2
MSMA + Karmex®	—	—	—	—	—	52.4	356.9	333.6	498.8	833.9
MSMA + Lorox®	—	—	—	—	—	—	207.9	80.8	131.3	160.4
Others	—	—	—	—	—	—	8.0	—	6.6	80.2
Subtotal	7.0	20.0	0	370.5	784.2	769.3	1445.8	1675.8	2684.5	3704.4
Layby										
Cotoran®	—	—	—	—	—	—	60.3	55.8	65.6	48.1
Karmex®	—	—	—	—	—	348.8	195.2	244.2	249.4	368.8
Lorox®	—	—	—	—	—	—	153.4	143.0	157.5	176.4
Others	—	—	—	—	—	—	2.9	9.2	1.3	1.6
Subtotal	0	0	0	0	0	348.8	411.8	452.2	473.8	594.9
TOTAL	53.0	110.0	114.0	1258.4	1794.5	2174.4	3405.9	3463.6	4368.6	5901.1

[1]Estimates from 1956 through 1972 were by County Agents and summarized by Cooperative Extension Specialists, Mississippi State University, Mississippi State, MS. The 1953 survey was conducted by J. T. Holstun, Jr., ARS/USDA, Stoneville, MS and the 1955 survey was by W. B. Ennis, previously cited in Table 1.

[2]DNA = dinitroaniline herbicides (either Treflan or Planavin).

Table 4. Extent of usage and cost of weed control practices in cotton in the USA from 1959 to 1968. (Adapted from Danielson *et al.*, 1965; Danielson *et al.*, 1968; and Jansen *et al.*, 1972.)

Method of weed control or cost	Year			
	1959	1962	1965	1968
		(% of acreage)		
Preemergence	6.6	21.6	48.6	34.0
Postemergence	3.7	13.3	43.1	11.6
Preemergence + Postemergence	—	—	—	45.4
		($ x 1,000)		
Total herbicide cost	4,709	16,805	59,678	89,342
		($)		
Average cost/A	3.03	3.09	4.78	9.66

Table 5. Extent of cotton treated with herbicides in Tennessee in 1966, 1968 and 1970[1].

Method applied and herbicide	Year 1966	1968	1970
		(Acres x 1000)	
State cotton acreage	410	392	425
Preemergence:			
Caparol®	4	—	8
Chloro IPC®	4	—	—
Cotoran®	46	116	145
Dachthal®	3	—	—
Karmex®	158	70	63
Herban®	—	14	—
Planavin®	0	35	48
Treflan®	105	92	130
Subtotal	320	327	394
Postemergence:			
Herbicidal oil	4	7	1
DSMA/MSMA	74	94	155
DSMA/MSMA + Caparol®	2	3	46
DSMA/MSMA + Cotoran®	7	18	32
DSMA/MSMA + Herban®	—	7	2
DSMA/MSMA + Karmex®	24	28	63
Subtotal	111	157	299
Layby:			
Cotoran®	—	6	6
Lorox®	—	5	2
Karmex®	—	15	6
Subtotal	0	26	14

[1]Estimates provided by Extension Leaders and summarized by Dave Weaver, Extension Agronomist, University of Tennessee, Knoxville, TN.

Table 6. Estimates of cotton acreage treated with herbicides in 1971. (Adapted from the Farm Journal, Southern Edition, pages 8, 9 and 12, January 1972.)

Region and state	Acres of cotton harvested	Acres treated	
		Preemergence	Postemergence
		(A x 1000)	
Southeast:			
Alabama	550	475	223
Georgia	385	408	264
North Carolina	167	175	110
South Carolina	335	335	300
Tennessee	425	412	318
Subtotal	1,862	1,805	1,215
Mid-South:			
Arkansas	1,135	1,000	1,100
Louisiana	505	477	455
Mississippi	1,350	1,350	1,300
Missouri	300	315	290
Subtotal	3,290	3,242	3,145
Southwest:			
Oklahoma	396	100	60
Texas	4,885	2,500	1,000
Subtotal	5,281	2,600	1,060
West:			
Arizona	278	140	150
California	702	490	140
New Mexico	145	60	80
Subtotal	1,125	690	370
TOTAL	11,558	8,337	5,790

Table 7. Extent of use of herbicides in cotton in Texas from 1973 through 1981. (Adapted from Weaver, 1983.)

Herbicide and method applied	Year				
	1973	1975	1977	1980	1981
Total cotton acreage (X 1000)	5231	3900	6450	7873	7477
			(% of acres treated)		
Preplanting incorporated					
Basalin®	—[1]	—	0.1	1.0	0.8
Cobex®	0.1	1.5	1.5	—	—
Planavin®	6.2	—	—	—	—
Prowl®	—	—	7.7	15.8	13.6
Tolban®	—	1.8	2.8	5.4	3.9
Treflan®	45.5	54.7	54.7	64.7	58.4
Subtotal	51.8	58.0	66.8	86.9	76.7
Preemergence					
Bladex®	—	—	—	0.0	0.2
Caparol®	12.1	11.1	9.3	8.0	7.9
Cotoran®/Lanex®	0.8	0.6	1.0	0.9	0.5
Dacthal®	0.2	0.2	0.3	0.1	0.1
Karmex®	1.5	0.8	1.2	0.9	0.7
Lasso®	1.5	0.7	0.6	0.5	0.5
Sancap®	1.2	3.0	2.8	3.8	4.6
Surflan®	—	—	0.3	0.2	0.2
Subtotal	17.3	16.4	15.5	14.4	14.7
Postemergence					
Caparol®	2.9	2.4	1.4	2.9	2.1
Cotoran®/Lanex®	0.4	0.2	0.3	0.9	1.5
Karmex®	0.9	0.5	0.4	0.6	0.7
MSMA/DSMA	10.8	9.5	9.1	5.5	5.1
MSMA/DSMA Plus	2.9	1.3	2.1	1.3	1.4
Probe® + MSMA	—	—	0.2	—	—
Subtotal	17.9	13.9	13.5	11.2	10.8

[1]A dash indicates that data were not provided.

Table 8. Major herbicides used in cotton in 1966 and 1976. (Adapted from Eichers, 1980a.)

Herbicide	1966		1976	
	Amount	Percent of total	Amount	Percent of total
	(lb X 1 mil.)	(%)	(lb X 1 mil.)	(%)
Trifluralin	2.6	40	7.0	38
Sodium chlorate	1.5	23	—[1]	—
Diuron	0.9	14	—	—
MSMA/DSMA	0.4	6	3.3	18
Fluometuron	—	—	5.3	29
Others	1.1	17	2.7	15
TOTAL	6.5	100	18.3	100

[1]A dash indicates that data were not provided.

Table 9. Herbicides used in cotton in 1976. (Adapted from Eichers *et al.*, 1978.)

Herbicide	Land area treated	Percent of total herbicides used
	(Acres X 1000)	(%)
Arsenicals		
Sodium cacodylate + cacodylic acid	1,384	5.8
DSMA	1,183	5.0
MSMA	2,460	10.3
Phenyl ureas		
Diuron	1,074	4.5
Fluometuron	5,161	21.7
Linuron	913	3.8
Amides		
Alachlor	10	< 0.1
Triazines		
Prometryn	908	3.8
Other	87	0.4
Dinitroanilines		
Dinitramine	708	3.0
Pendimethalin	15	< 0.1
Profluralin	2	< 0.1
Trifluralin	9,086	38.2
Others		
Dinoseb	240	1.0
Paraquat	519	2.2
Other	24	0.1
TOTAL	23,774	

Table 10. Herbicide usage in cotton in 1976. (Adapted from Eichers *et al.*, 1978.)

Region	Land area in cotton	Level of land area treated with herbicides	Total herbicide usage	Average amount of herbicide used per treated area
	(A X 1000)	(%)	(lb X 1000)	(lb/A)
Appalachian (TN, NC, VA)	509	100	750	1.48
Southeast (SC, GA, AL, FL)	936	98	1,083	1.13
Delta States (LA, MS, AR)	3,338	100	11,561	3.47
Southern Plains (TX, OK)	5,293	68	2,761	0.77
Mountain (NM, AZ)	473	92	1,302	3.26
Pacific (CA)	1,160	92	891	0.84
TOTAL	11,709	—	18,348	—
Average	—	84	—	1.83

Table 11. Percentage of the cotton acreage in 1976 in various states treated with different herbicide practices. (Adapted from DeBord, 1977.)

State	Region	Preplanting		Pre-emergence	Postemergence		
		Foliar to weeds	Soil incorporated		Directed sprays	Over the top	Layby
				(%)			
Alabama	1	—	90	95	90	30	20
	2	—	90	80	50	35	10
	3	—	90	85	60	35	10
	4	—	90	90	75	55	50
	5	—	90	90	70	40	10
	6	—	90	85	70	40	10
Arkansas		5	70	95	100	30	20
California	1	10	85	0	5	0	10
	2	0	85	10	20	0	70
Georgia		—	99	35	40	50	10
Louisiana		2	75	99	100	20	30
Mississippi		5	88	85	175	35	40
Missouri		10	50	80	25	50	15
New Mexico		—	75	5	20	—	40
North Carolina	1	—	100	90	—	60	10
	2	—	100	90	—	70	10
	3	—	100	80	—	40	10
Oklahoma	1	0	70	10	20	10	0
	2	0	75	10	5	10	—
	3	0	85	—	—	—	—
South Carolina		0	100	50	80	45	35
Tennessee		2	80	95	20	40	1
Texas	1	10	60	15	20	20	< 1
	2	20	40	45	52	3	< 1

Table 12. Percent of acres in various states receiving preplanting and preemergence treatments and the percentage distribution of herbicides used on the treated acres in 1976. For example, five percent of the cotton acreage in Arkansas received foliar-applied preplanting treatments and 80 percent of these acres were with MSMA and 20 percent with paraquat. (Adapted from DeBord, 1977.)

Time of application and herbicide use	Region and state												
	Southeast					Mid-South			Southwest			West	
	AL	GA	NC	SC	TN	AR	LA	MS	MO	TX	OK	CA	NM
Preplanting foliar trts.													
Percent acres receiving	0	0	0	0	2	5	2	5	10	15	0	5	0
	(% of herbicides used on treated acreage)												
Arsenic acid	—	—	—	—	—	—	—	10	—	—	—	—	—
Dinoseb	—	—	—	—	—	—	—	30	10	—	—	3	—
MSMA	—	—	—	—	—	80	—	50	40	100	—	—	—
Paraquat	—	—	—	—	100	20	—	20	50	—	—	45	—
Paraquat or MSMA	—	—	—	—	—	—	100	—	—	—	—	—	—
2,4-D	—	—	—	—	—	—	—	—	—	—	—	3	—
Preplanting soil inc.													
Percent acres receiving	90	99	100	100	80	70	75	88	50	50	77	85	75
	(% of herbicides used on treated acreage)												
Amex®	—	—	—	—	3	—	—	—	—	—	—	—	—
Basalin®	—	—	—	—	6	—	—	—	1	—	—	—	—
Caparol®	—	—	—	—	—	—	—	—	—	—	—	33	5
Cobex®	15	14	20	10	—	15	10	15	5	4	3	3	—
Dacthal®	—	—	—	—	—	—	—	—	—	—	—	25	—
Planavin®	—	—	—	—	—	—	—	10	—	—	—	—	—
Prowl®	10	—	—	5	—	25	5	—	—	2	3	3	—
Tolban®	5	2		5	10	20	5		4	2	5	4	—
Treflan®	70	55	80	75	80	50	80	75	90	91	83	65	70
Preemergence													
Percent acres receiving	90	35	87	40-60	95	95	99	85	80	30	7	5	5
	(% of herbicides used on treated acreage)												
Bladex®	1	—	—	—	5	9	—	45	—	—	—	—	—
Caparol®	4	—	—	—	—	—	2	—	—	73	27	—	—
Cotoran®/Lanex®	80	80	70	85	70	70	80	72	95	5	2	—	—
Dacthal®	—	—	—	—	—	—	—	—	—	—	—	50	—
Karmex®	15	20	17	15	25	20	18	22	5	5	5	—	—
Lasso®	—	—	—	—	—	—	—	—	30	5	—	—	—
Sancap®	—	—	—	—	—	—	—	—	—	20	—	—	—
Zorial®	—	—	—	—	—	1	—	1	—	10	—	—	—

Table 13. Percent of acres in various state receiving directed postemergence, postemergence over-the-top, and layby treatments and the percentage distribution of herbicides used on the treated acres in 1976. For example, 40 percent of the cotton acreage in Georgia received treatments with postemergence-directed sprays and 60 per cent of these acres were with Cotoran® + MSMA, 20 percent with Karmex® + MSMA, and 20 percent with Probe® + MSMA. (Adapted from DeBord, 1977.)

Time of application and herbicide use	Region and state												
	Southeast					Mid-South				Southwest		West	
	AL	GA	NC	SC	TN	AR	LA	MS	MO	TX	OK	CA	NM
Directed postemerg. trts.													
Percent acres receiving	70	40		70-90	20	100	100	175	25	36	8	5	20
	(% of herbicides used on treated acreage)												
Caporal®	—	—	—	—	—	—	—	—	—	5	—	50	15
Caparol® + DSMA	—	—	—	—	—	—	—	—	—	—	10	—	—
Caporal® + MSMA	10	—	—	5	10	—	25	—	—	—	—	—	—
Cotoran®	—	—	—	—	—	80	—	75	—	—	—	—	—
Cotoran® + MSMA	60	60	—	25	40	—	60	—	30	—	—	—	—
Dinoseb	—	—	—	—	—	50	—	60	—	—	—	—	—
DSMA/MSMA	—	—	—	70	25	100	—	100	70	70	53	50	3
Karmex®	—	—	—	—	15	80	—	30	—	5	3	—	—
Karmex® + MSMA	20	20	—	—	—	—	25	—	—	—	—	—	—
Probe®	—	—	—	—	—	—	—	—	—	—	—	—	2
Probe® + MSMA	10	20	—	—	—	—	5	—	—	—	—	—	—
MSMA/DSMA + Karmex®/Cotoran®	—	—	—	—	—	—	—	—	—	20	—	—	—
Post—Over the Top													
Percent acres receiving	40	50	57	40-50	40	30	20	35	50	2.5	7		
	(% of herbicides used on treated acreage)												
Ansar®	—	—	57	—	—	—	—	—	—	—	33	—	—
Cotoran®	5	—	—	—	—	—	—	10	—	—	—	—	—
Cotoran® + MSMA	—	—	—	10	—	—	50	—	—	5	—	—	—
DSMA/MSMA	95	65	—	90	95	100	50	100	100	95	33	—	—
Layby													
Percent acres receiving	10	10	10	30-40	1	20	30	40	15		0		40
	(% of herbicides used on treated acreage)												
Caparol®	—	—	—	—	—	—	—	—	—	40	—	100	28
Cotoran®	10	—	1	25	35	—	10	—	—	—	—	—	—
Dinoseb	—	—	—	—	—	—	—	25	—	—	—	—	10
Karmex®	30	50	—	50	40	60	90	50	—	40	—	—	—
Lorox®	60	50	9	25	25	40	—	50	100	20	—	—	—
MSMA	—	—	—	—	—	—	—	20	—	—	—	—	—
Probe®	—	—	—	—	—	—	—	—	—	—	—	—	2
Treflan®	—	—	—	—	—	—	—	—	—	—	—	35	—

Table 14. Percent of cotton acreage treated with herbicides and other pesticides and average number of applications per acre in 1979. (Adapted from Sugiyama and Carlson, 1985.)

	Region			
Pest treated	Southeast (AL, GA, SC)	Mississippi Valley (AR, LA, MS, MO, TN)	Southwest (OK, TX)	West (AZ, CA, NM)
		(% of acres treated)		
Diseases	2	7	0	3
Insects	82	80	28	76
Weeds	94	99	86	81
Other pests	6	1	1	2
		(No. of applications/A)		
Diseases	1.0	1.3	0	1.0
Insects	9.6	5.5	4.6	2.3
Weeds	3.7	4.5	1.4	1.4
Other pests	1.0	1.3	1.0	1.3
Farmers surveyed	246	734	670	377

Table 15. Percentage of cotton acreage in Alabama treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	320	325	377	287	195	305	293	313
				(% of acres treated)				
Preplanting, Foliar								
Paraquat	—[1]	—	—	—	—	1	1	1
Subtotal	—	—	—	—	—	1	1	1
Preplanting, Soil Incorp.								
Basalin®	6	6	9	9	7	7	7	—
Prowl®	10	10	8	8	10	10	10	38
Tolban®	4	4	3	1	1	—	—	—
Treflan®	79	75	80	80	80	76	76	71
Subtotal	99	95	100	98	98	93	93	109
Preemergence								
Bladex®	4	4	9	6	2	2	3	2
Caparol® + Bladex®	3	3	3	3	—	—	—	—
Cotoran®/Lanex®	71	42	39	39	41	41	41	84
Karmex®/Dynex®	4	4	5	5	5	5	5	7
Zorial®	12	13	16	16	19	19	25	54
Subtotal	94	66	72	69	67	67	74	147
Postemergence								
Bladex®	—	—	—	—	—	—	—	37
Bladex® + MSMA	5	5	5	5	8	9	9	25
Caparol® + MSMA	5	5	5	5	5	5	5	6
Cotoran®/Lanex®	—	—	—	—	—	—	—	20
Cotoran® + MSMA	13	13	13	13	13	13	13	40
Dinoseb	—	—	—	—	—	—	1	2
Karmex®/Dynex® + MSMA	2	2	2	2	2	2	2	3
MSMA/DSMA	86	86	86	75	80	80	80	64
Poast®/Fusilade®	—	—	—	8	5	5	8	15
Subtotal	111	111	111	108	113	114	118	212
Spot Treatment								
MSMA	14	14	14	14	14	14	14	12
Poast®/Fusilade®	—	—	—	3	5	5	5	10
Roundup®	—	6	6	6	4	4	4	4
Subtotal	14	20	20	23	23	23	23	26
Layby								
Bladex®	1	2	1	1	1	1	1	1
Karmex®/Dynex®	2	3	3	3	3	3	3	3
Lorox®	5	5	5	5	4	4	4	4
Subtotal	8	10	9	9	8	8	8	8
TOTAL	326	302	312	307	309	306	317	503

[1]A dash indicates that no data were provided.

Table 16. Percentage of cotton acreage in Arizona treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	623	592	634	507	350	490	390	370
	(% of acres treated)							
Preplanting, Soil Incorp.								
Basalin®	0	—[1]	1	1	3	0	0	0
Caparol®	18	23	—	—	—	—	—	—
Prowl®	20	19	30	30	30	40	40	35
Prowl® + Caparol®	9	11	12	12	12	15	15	15
Tolban®	2	2	2	2	0	—	—	—
Treflan®	33	30	30	30	30	40	40	35
Treflan® + Caparol®	0	—	20	20	20	20	20	20
Subtotal	82	85	95	95	95	115	115	105
Preemergence								
Bladex®	—	—	—	—	—	—	—	—
Caparol® + Bladex®	—	—	—	—	—	—	—	—
Cotoran®/Lanex®	—	—	—	—	—	—	—	—
Karmex®/Dynex®	—	—	—	—	—	—	—	—
Zorial®	—	—	—	—	—	—	—	—
Subtotal	0	0	0	0	0	0	0	0
Postemergence								
Bladex®	—	—	—	—	—	—	—	10
Bladex® + MSMA	—	—	—	—	—	1	1	2
Caparol® + MSMA	1	1	3	4	15	20	20	10
Cotoran®/Lanex®	—	—	—	3	3	3	—	—
Cotoran® + MSMA	—	—	—	—	—	—	—	—
Dinoseb	—	—	1	1	1	2	2	2
Goal®	—	—	—	—	—	—	—	5
Karmex®/Dynex®	—	—	—	—	—	—	—	2
Karmex®/Dynex® + MSMA	< 1	< 1	2	3	5	5	5	2
MSMA/DSMA	9	9	—	—	3	3	3	3
Poast®/Fusilade®	—	—	—	—	8	1	1	1
Subtotal	10	10	6	11	35	35	32	37
Spot Treatment								
Dalapon	1	1	—	—	—	—	—	—
MSMA	15	13	10	10	5	5	—	5
Poast®/Fusilade®	—	—	—	—	—	15	—	25
Roundup®	39	24	40	35	30	30	—	20
Subtotal	55	38	50	45	35	50	—	50
Layby								
Bladex®	—	—	10	10	10	10	10	15
Caparol®	59	54	30	30	30	50	50	50
Karmex®/Dynex®	8	8	10	10	10	8	8	8
Subtotal	67	62	50	50	50	68	68	73
TOTAL	214	195	201	201	215	268	215	265

[1]A dash indicates that no data were provided.

Table 17. Percentage of cotton acreage in Arkansas treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

	Year							
Herbicide	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	610	700	610	410	330	430	440	480
			(% of acres treated)					
Preplanting, Foliar								
Dalapon	1	1	1	1	1	1	1	1
MSMA	1	1	1	1	1	1	1	1
Paraquat	1	1	1	1	1	1	1	1
Roundup®	1	1	1	1	1	1	1	1
Subtotal	4	4	4	4	4	4	4	4
Preplanting, Soil Incorp.								
Basalin®	5	5	5	5	5	5	5	—[1]
Prowl®	20	20	20	20	20	25	40	40
Tolban®	5	5	5	5	5	—	—	—
Tolban® + Cotoran®	2	2	2	2	2	—	—	—
Treflan®	50	50	50	50	50	50	45	45
Treflan® + Cotoran®	2	2	2	2	2	4	4	4
Zorial®	—	—	—	—	—	—	6	6
Subtotal	84	84	84	84	84	84	100	95
Preemergence								
Bladex®	5	5	5	5	5	5	5	5
Cotoran®/Lanex®	80	80	80	70	70	70	60	60
Karmex®/Dynex®	10	10	10	10	10	10	10	10
Zorial®	5	10	10	20	20	20	40	40
Subtotal	100	105	105	105	105	105	115	115
Postemergence								
Bladex®	5	5	5	5	5	5	5	5
Bladex® + MSMA	20	20	20	20	35	35	35	35
Caparol®	1	1	1	1	1	1	1	1
Caparol® + MSMA	1	1	1	1	1	1	40	40
Cotoran®/Lanex®	5	5	5	5	5	5	5	5
Cotoran® + MSMA	80	80	80	100	100	100	100	100
Dinoseb	20	20	20	20	20	20	20	20
Karmex®/Dynex®	1	1	1	1	1	1	1	1
Karmex®/Dynex® + MSMA	60	60	60	60	60	60	60	60
MSMA/DSMA	100	100	100	100	100	100	100	100
Poast®/Fusilade®	—	—	—	—	30	30	5	5
Subtotal	293	293	293	313	358	358	372	372
Spot Treatment								
Dalapon	5	5	5	5	5	5	5	5
MSMA	5	5	1	1	1	1	1	1
Poast®/Fusilade®	—	—	—	—	—	—	30	30
Roundup®	25	25	25	25	25	25	25	25
Subtotal	35	35	31	31	31	31	61	61
Layby								
Bladex®	—	—	—	—	—	—	10	10
Karmex®/Dynex®	30	30	30	30	30	30	30	30
Lorox®	60	60	60	60	60	60	40	40
Subtotal	90	90	90	90	90	90	80	80
TOTAL	606	611	607	627	672	672	732	727

[1]A dash indicates that no data were provided.

Table 18. Percentage of cotton acreage in California treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

	Year							
Herbicide	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	1650	1550	1540	1380	980	1400	1340	1010
				(% of acres treated)				
Preplanting, Foliar								
Caparol®	—[1]	<1	<1	—	—	—	—	—
Dalapon	—	—	—	—	—	—	—	1
Dinoseb	1	—	—	—	—	—	—	—
MSMA	—	—	1	5	—	—	—	—
Paraquat	1	1	0	0	2	2	2	1
Roundup®	—	—	—	—	1	1	1	1
Others	—	—	—	1	3	3	3	3
Subtotal	2	1	1	6	7	6	6	6
Preplanting, Soil Incorp.								
Basalin®	—	—	3	3	1	1	1	—
Caparol®	48	45	48	—	—	—	—	—
Cobex®	—	1	—	—	—	—	—	—
Dacthal®	13	3	—	—	—	—	—	—
Prowl®	10	10	15	15	18	18	18	28
Prowl® + Caparol®	—	—	—	4	5	5	5	1
Tolban®	1	1	3	—	—	—	—	—
Tolban® + Cotoran®	—	—	1	—	—	—	—	—
Treflan®	55	55	60	20	18	18	18	18
Treflan® + Caparol®				8	5	5	5	1
Treflan® + Cotoran®	1	<1	1	—	—	—	—	—
Subtotal	128	115	131	50	47	47	47	48
Preemergence								
Dacthal®	13	13	13	—	—	—	—	—
Subtotal	13	13	13	—	—	—	—	—
Postemergence								
Bladex®	—	—	—	—	5	—	—	—
Bladex® + MSMA	—	—	—	—	1	1	1	1
Caparol®	—	—	—	11	1	1	1	—
Caparol® + MSMA	—	—	—	—	—	1	1	1
Cotoran® + MSMA	—	—	—	—	—	—	—	1
Goal®	—	—	—	—	—	—	—	1
MSMA/DSMA	3	3	3	5	2	3	3	3
Poast®/Fusilade®	—	—	—	—	1	1	1	—
Subtotal	3	3	3	16	10	7	7	7
Spot Treatment								
MSMA	1	1	1	2	—	—	—	—
Poast®/Fusilade®	—	—	—	—	1	1	1	1
Roundup®	2	2	2	2	—	1	1	1
Subtotal	3	3	3	4	1	2	2	2
TOTAL	149	135	151	76	65	62	62	63

[1]A dash indicates that no data were provided.

Table 19. Percentage of cotton acreage in Florida treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	3.4	6.0	18.0	16.0	9.5	11.0	14.0	12.0
	(% of acres treated)							
Preplanting, Soil Incorp.								
Prowl®	8	30	40	40	40	50	50	50
Treflan®	75	50	50	50	50	40	40	40
Subtotal	83	80	90	90	90	90	90	90
Preemergence								
Bladex®	5	20	10	—[1]	10	5	3	3
Cotoran®/Lanex®	10	20	10	—	10	15	20	25
Zorial®	5	—	2	—	2	5	7	7
Subtotal	20	40	22	0	22	25	30	35
Postemergence								
Bladex® + MSMA	—	—	2	2	2	10	15	15
Caparol® + MSMA	—	—	—	—	—	—	3	2
Cotoran® + MSMA	5	—	2	2	2	5	5	5
Karmex®/Dynex®	—	—	1	—	—	—	—	—
Karmex®/Dynex® + MSMA	—	—	—	—	—	2	5	5
MSMA/DSMA	70	9	75	75	75	75	75	75
Poast®/Fusilade®	—	—	—	—	—	2	2	2
Subtotal	75	9	80	79	79	94	105	104
TOTAL	178	129	192	169	191	209	225	229

[1]A dash indicates that no data were provided.

Table 20. Percentage of cotton acreage in Georgia treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	155	170	180	163	120	180	260	210
				(% of acres treated)				
Preplanting, Foliar								
MSMA	1	1	1	1	1	1	1	1
Paraquat	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Roundup®	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Subtotal	1	1	1	1	1	1	1	1
Preplanting, Soil Incorp.								
Basalin®	8	8	8	8	8	2	2	2
Prowl®	7	7	7	7	22	37	37	37
Tolban®	9	9	9	9	9	—[1]	—	—
Tolban® + Cotoran®	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Treflan®	75	75	75	75	60	60	60	60
Treflan® + Cotoran®	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Subtotal	99	99	99	99	99	99	99	99
Preemergence								
Bladex®	1	1	1	1	1	1	1	1
Cotoran®/Lanex®	74	73	73	60	50	50	50	50
Destun®	1	—	—	—	—	—	—	—
Karmex®/Dynex®	18	18	18	22	20	20	20	20
Zorial®	6	8	8	12	20	20	20	20
Subtotal	100	100	100	95	91	91	91	91
Postemergence								
Bladex®	1	3	3	3	3	3	3	3
Bladex® + MSMA	8	20	50	50	50	50	50	50
Caparol® + MSMA	1	1	1	1	1	1	1	1
Cotoran®/Lanex®	1	1	1	1	1	1	1	1
Cotoran® + MSMA	15	15	15	15	15	15	15	15
Dinoseb	2	2	2	2	2	2	2	2
Karmex®/Dynex® + MSMA	5	5	5	5	5	5	5	5
MSMA/DSMA	35	35	35	35	35	35	35	35
Probe® + MSMA	5	2	1	—	—	—	—	—
Subtotal	73	84	113	112	112	112	112	112
Spot Treatment								
Dalapon	1	1	1	1	1	1	1	1
MSMA	2	2	2	2	2	2	2	2
Roundup®	7	7	7	7	7	5	5	5
Subtotal	10	10	10	10	10	8	8	8
Layby								
Bladex®	1	3	3	10	15	15	15	15
Karmex®/Dynex®	2	2	3	3	3	3	3	3
Lorox®	5	5	5	5	10	10	10	10
Subtotal	8	10	11	18	28	28	28	28
TOTAL	291	304	334	335	341	339	339	339

[1]A dash indicates that no data were provided.

Table 21. Percentage of cotton acreage in Louisiana treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	470	570	700	605	410	645	630	570
			(% of acres treated)					
Preplanting, Foliar								
Dalapon	3	3	3	3	3	3	3	1
MSMA	7	6	6	6	6	6	6	6
Paraquat	1	1	1	1	5	5	5	5
Roundup®	10	10	10	10	15	15	15	20
Subtotal	21	20	20	20	29	29	29	32
Preplanting, Soil Incorp.								
Basalin®	8	8	8	13	21	21	21	15
Cobex®	2	2	—[1]	—	—	—	—	—
Prowl®	9	9	9	14	20	20	20	30
Tolban®	6	5	5	5	—	—	—	—
Treflan®	53	53	53	43	35	35	35	40
Treflan® + Cotoran®	3	3	3	3	3	3	3	3
Zorial®	—	—	—	5	10	10	10	10
Subtotal	81	80	78	83	89	89	89	98
Preemergence								
Bladex®	6	8	6	6	6	6	6	6
Caparol®	1	—	1	—	—	—	—	—
Cotoran®/Lanex®	74	55	73	73	66	66	66	66
Dual®	—	—	—	—	2	2	2	2
Karmex®/Dynex®	14	5	15	15	15	15	15	15
Zorial®	3	3	3	10	15	20	20	30
Subtotal	98	71	98	104	104	109	109	119
Postemergence								
Bladex®	6	5	5	5	5	5	5	5
Bladex® + MSMA	12	10	10	10	10	10	10	10
Caparol®	5	4	4	4	4	4	4	4
Caparol® + MSMA	2	2	2	2	2	10	10	10
Cotoran®/Lanex®	50	41	41	41	20	20	20	20
Cotoran® + MSMA	21	18	18	18	25	25	25	25
Dinoseb	18	18	18	18	20	20	20	20
Goal®	—	—	—	—	—	5	5	15
Karmex®/Dynex®	22	17	17	17	5	5	5	5
Karmex®/Dynex® + MSMA	21	17	17	17	17	10	10	10
MSMA/DSMA	76	63	63	63	63	63	63	63
Poast®/Fusilade®	—	—	—	15	20	30	30	30
Probe®	3	2	—	—	—	—	—	—
Probe® + MSMA	5	3	—	—	—	—	—	—
Subtotal	241	200	195	210	191	207	207	217

Table 21. Continued.

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	470	570	700	605	410	645	630	570
	(% of acres treated)							
Spot Treatment								
Dalapon	1	1	1	1	1	1	1	1
MSMA	3	2	2	2	2	2	2	2
Poast®/Fusilade®	—	—	—	—	20	20	20	20
Roundup®	2	6	6	6	6	6	6	6
Subtotal	6	9	9	9	29	29	29	29
Layby								
Bladex®	—	10	—	—	—	—	—	10
Karmex®/Dynex®	28	10	20	20	20	20	20	20
Lorox®	40	20	30	30	30	30	30	20
Subtotal	68	40	50	50	50	50	50	50
TOTAL	515	420	450	476	492	513	513	545

[1]A dash indicates that no data were provided.

Table 22. Percentage of cotton acreage in Mississippi treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	1050	1150	1230	1000	750	1040	1040	975
	(% of acres treated)							
Preplanting, Foliar								
Dalapon	1	0	1	<1	1	1	0	0
MSMA	1	1	1	1	1	1	1	1
Paraquat	1	<1	<1	<1	1	1	1	1
Roundup®	1	<1	1	<1	1	1	1	1
Subtotal	4	1	3	1	4	4	3	2
Preplanting, Soil Incorp.								
Basalin®	8	5	12	20	5	5	0	0
Cobex®	1	1	0	0	0	0	0	0
Prowl®	38	28	29	35	35	36	35	40
Tolban®	5	5	1	1	1	0	0	0
Treflan®	38	48	57	25	35	35	35	35
Treflan® + Cotoran®	1	1	0	0	0	0	0	0
Zorial®	—[1]	—	—	—	15	15	20	25
Subtotal	91	88	99	81	91	91	90	100
Preemergence								
Bladex®	13	8	2	2	2	2	3	10
Cotoran®/Lanex®	63	55	62	40	46	46	60	70
Dual®	—	—	—	—	—	—	—	5
Karmex®/Dynex®	10	5	2	2	6	6	4	4
Zorial®	10	30	29	50	66	66	50	60
Subtotal	96	98	95	94	120	120	117	149
Postemergence								
Bladex®	3	1	—	—	—	—	—	5
Bladex® + MSMA	20	20	16	16	20	20	20	30
Caparol®	1	—	—	2	12	12	8	6
Caparol® + MSMA	5	10	16	16	16	16	15	8
Cotoran®/Lanex®	10	5	5	5	5	5	7	5
Cotoran® + MSMA	50	80	75	65	65	65	40	35
Dinoseb	20	40	61	50	61	61	20	18
Karmex®/Dynex®	8	2	—	—	—	—	15	10
Karmex®/Dynex® + MSMA	14	15	14	14	14	14	40	20
MSMA/DSMA	60	40	19	19	19	19	19	20
Poast®/Fusilade®	—	—	—	—	5	5	5	2
Probe®	1	—	—	—	—	—	—	—
Probe® + MSMA	3	—	—	—	—	—	—	—
Subtotal	195	213	206	187	217	217	189	159

Table 22. Continued.

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	1050	1150	1230	1000	750	1040	1040	975
	(% of acres treated)							
Spot Treatment								
Dalapon	1	1	1	2	2	2	1	1
MSMA	5	1	1	1	1	1	1	5
Poast®/Fusilade®	—	—	—	10	30	30	30	50
Roundup®	35	60	67	30	15	15	10	15
Subtotal	41	62	69	43	48	48	42	71
Layby								
Bladex®	10	—	9	12	15	15	15	30
Cotoran®	—	—	—	—	5	5	5	2
Karmex®/Dynex®	10	10	8	8	8	8	8	9
Lorox®	20	20	19	15	10	10	8	20
Subtotal	40	30	36	35	38	38	36	61
TOTAL	467	492	508	441	518	518	477	542

[1]A dash indicates that no data were provided.

Table 23. Percentage of cotton acreage in Missouri treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	157	245	242	154	93	160	152	167
	(% of acres treated)							
Preplanting, Foliar								
Dalapon	—[1]	—	1	—	—	—	—	—
MSMA	1	1	1	1	1	1	1	1
Paraquat	2	2	—	2	2	2	2	2
Roundup®	—	—	1	—	1	1	1	1
Subtotal	3	3	3	3	4	4	4	4
Preplanting, Soil Incorp								
Basalin®	5	5	12	5	5	1	—	—
Prowl®	15	15	29	15	15	25	25	25
Tolban®	5	5	1	5	—	—	—	—
Tolban® + Cotoran®	1	1	—	1	1	—	—	—
Treflan®	50	50	57	50	50	50	50	50
Treflan® + Cotoran®	1	1	—	1	1	—	1	5
Subtotal	77	77	99	77	72	76	76	80
Preemergence								
Bladex®	—	—	2	—	5	5	5	5
Cotoran®/Lanex®	60	60	62	60	60	60	60	60
Karmex®/Dynex®	25	25	2	25	25	10	10	10
Lasso® + Cotoran®	10	8	10	10	10	—	—	—
Zorial®	1	1	29	1	20	20	20	20
Others	—	—	—	—	—	4	—	—
Subtotal	96	94	105	96	120	99	95	95
Postemergence								
Bladex®	—	—	—	—	2	2	2	2
Bladex® + MSMA	—	—	—	—	5	10	20	20
Caparol®	—	—	—	—	—	—	8	—
Caparol® + MSMA	5	5	—	—	—	—	15	20
Cotoran®/Lanex®	—	—	—	—	3	3	3	3
Cotoran® + MSMA	25	25	25	25	25	40	40	40
Dinoseb	—	—	—	—	2	5	20	20
Goal®	—	—	—	—	—	—	—	3
Karmex®/Dynex®	—	—	—	—	—	—	15	—
Karmex®/Dynex® + MSMA	10	10	10	10	10	10	40	10
MSMA/DSMA	50	50	50	50	50	50	50	50
Poast®/Fusilade®	—	—	—	—	2	5	5	10
Probe® + MSMA	—	—	5	5	—	—	—	—
Subtotal	90	90	90	90	99	125	218	178

Table 23. Continued

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	157	245	242	154	93	160	152	167
	(% of acres treated)							
Spot Treatment								
MSMA	—	—	—	—	5	5	—	—
Poast®/Fusilade®	—	—	—	—	5	5	10	10
Roundup®	5	5	5	5	—	—	10	10
Subtotal	5	5	5	5	10	10	20	20
Layby								
Bladex®	—	—	—	—	—	5	5	5
Karmex®/Dynex®	—	—	—	—	—	5	5	5
Lorox®	10	10	10	10	10	10	10	10
Subtotal	10	10	10	10	10	20	20	20
TOTAL	281	279	312	281	315	334	433	397

[1]A dash indicates that no data were provided.

Table 24. Percentage of cotton acreage in New Mexico treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	170	158	143	88	57	72	55	42
	(% of acres treated)							
Preplanting, Soil Incorp.								
Basalin®	1	1	1	1	1	—[1]	—	—
Caparol®	1	1	15	—	—	27	27	27
Prowl®	1	3	3	3	3	4	4	4
Tolban®	20	30	30	30	30	—	—	—
Tolban® + Cotoran®	30	20	20	20	20	—	—	—
Treflan®	5	10	10	10	10	44	44	44
Others	—	—	—	15	15	3	3	3
Subtotal	58	65	79	79	79	78	78	78
Preemergence								
Dual®	—	—	—	—	—	8	8	8
Subtotal	—	—	—	—	—	8	8	8
Postemergence								
Caparol®	5	5	5	5	5	5	5	5
Caparol® + MSMA	1	1	1	1	1	1	1	1
Karmex®/Dynex®	1	5	5	5	5	5	5	5
MSMA/DSMA	5	10	10	10	10	10	10	10
Poast®/Fusilade®	—	—	—	—	—	—	1	1
Probe®	1	—	—	—	—	—	—	—
Subtotal	13	21	21	21	21	21	22	22
Spot Treatment								
Dalapon	1	1	1	1	1	1	1	1
MSMA	3	3	3	3	3	3	3	3
Roundup®	5	25	25	25	25	25	25	25
Subtotal	9	29	29	29	29	29	29	29
Layby								
Caparol®	50	50	50	50	50	50	50	50
Karmex®/Dynex®	5	5	5	5	5	5	5	5
Subtotal	55	55	55	55	55	55	55	55
TOTAL	135	170	184	184	184	191	192	192

[1]A dash indicates that no data were provided.

Table 25. Percentage of cotton acreage in North Carolina treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	46	66	83	71	59	94	92	79
			(% of acres treated)					
Preplanting, Soil Incorp.								
Basalin®	2	2	2	2	5	5	5	—[1]
Prowl®	8	8	8	8	32	32	40	42
Tolban®	15	15	15	15	—	—	—	—
Tolban® + Cotoran®	1	1	1	—	—	—	—	—
Treflan®	63	63	63	63	63	63	55	55
Treflan® + Cotoran®	5	5	5	5	—	—	—	—
Zorial®	—	—	—	—	—	—	20	2
Subtotal	94	94	94	93	100	100	120	99
Preemergence								
Bladex®	2	2	2	2	1	1	1	—
Cotoran®/Lanex®	83	82	82	83	99	99	98	99
Karmex®/Dynex®	6	6	6	6	—	—	—	—
Zorial®	< 1	< 1	< 1	< 1	—	—	1	1
Subtotal	91	90	90	91	99	99	100	100
Postemergence								
Bladex®	3	3	3	3	3	3	—	—
Bladex® + MSMA	—	—	—	—	—	—	10	10
Caparol®	—	—	—	—	7	7	—	—
Cotoran®/Lanex®	12	12	12	12	3	3	—	—
Cotoran® + MSMA	10	10	10	10	—	< 1	20	20
Dinoseb	1	1	1	1	3	3	5	5
MSMA/DSMA	48	48	48	48	50	50	75	75
Poast®/Fusilade®	—	—	—	—	10	10	15	15
Probe®	1	1	—	—	—	—	—	—
Probe® + MSMA	4	4	—	—	—	—	—	—
Subtotal	79	79	74	74	76	76	125	125
Spot Treatment								
Poast®/Fusilade®	—	—	—	—	—	—	5	5
Roundup®	1	1	1	1	—	—	—	—
Subtotal	1	1	1	1	—	—	5	5
Layby								
Lorox®	12	12	12	12	—	—	2	2
Subtotal	12	12	12	12	—	—	2	2
TOTAL	277	276	271	271	275	275	352	331

[1]A dash indicates that no data were provided.

Table 26. Percentage of cotton acreage in Oklahoma treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	600	715	650	480	309	414	355	350
	(% of acres treated)							
Preplanting, Foliar								
MSMA	1	1	1	1	2	2	2	2
Roundup®	1	1	1	1	1	1	1	1
Subtotal	2	2	2	2	3	3	3	3
Preplanting, Soil Incorp.								
Basalin®	—[1]	—	—	—	3	3	3	—
Prowl®	3	3	3	3	15	17	17	20
Tolban®	10	10	10	10	—	—	—	—
Treflan®	72	72	72	72	75	73	73	70
Subtotal	85	85	85	85	93	93	93	90
Preemergence								
Caparol®	5	5	5	5	12	12	12	12
Cotoran®/Lanex®	1	1	1	1	2	2	2	2
Sancap®	7	8	10	10	8	8	8	8
Subtotal	13	14	16	16	22	22	22	22
Postemergence								
Caparol® + MSMA	3	3	3	3	5	5	5	5
MSMA/DSMA	16	16	16	16	20	18	18	18
Poast®/Fusilade®	—	—	—	—	—	—	—	3
Subtotal	19	19	19	19	25	23	23	26
Spot Treatment								
Poast®/Fusilade®	—	—	—	—	3	3	3	2
Roundup®	15	15	15	15	25	27	27	20
Subtotal	15	15	15	15	28	30	30	22
TOTAL	134	135	137	137	171	171	171	163

[1]A dash indicates that no data were provided.

Table 27. Percentage of cotton acreage in South Carolina treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	110	122	119	97	69	105	124	115
	(% of acres treated)							
Preplanting, Soil Incorp.								
Basalin®	5	8	8	8	8	8	2	—[1]
Prowl®	2	15	18	18	19	32	34	40
Tolban®	18	7	4	4	—	—	—	—
Treflan®	75	70	70	70	73	60	64	58
Other	—	—	—	—	—	—	—	2
Subtotal	100	100	100	100	100	100	100	100
Preemergence								
Bladex®	3	15	15	8	5	—	—	
Cotoran®/Lanex®	70	58	58	65	68	70	70	70
Karmex®/Dynex®	5	5	5	5	5	3	3	3
Zorial®	4	4	4	2	4	6	8	8
Subtotal	82	82	82	80	82	79	81	81
Postemergence								
Bladex®	—	—	—	15	15	15	15	15
Bladex® + MSMA	1	18	20	20	20	25	25	25
Caparol®	—	—	—	—	—	2	2	2
Caparol® + MSMA	1	1	—	—	—	—	—	—
Cotoran® + MSMA	90	90	75	75	75	65	65	65
Dinoseb	0	2	5	5	5	5	5	5
Karmex®/Dynex® + MSMA	3	3	—	—	—	—	—	—
MSMA/DSMA	50	50	60	60	60	70	70	70
Poast®/Fusilade®	0	0	0	0	1	1	1	1
Probe® + MSMA	2	—	—	—	—	—	—	—
Subtotal	147	164	160	175	176	183	183	183
Spot Treatment								
MSMA	3	3	3	3	3	3	3	3
Poast®/Fusilade®	0	0	0	0	2	2	2	2
Roundup®	1	1	1	1	1	1	1	1
Subtotal	4	4	4	4	6	6	6	6
Layby								
Bladex®	2	—	—	15	—	20	20	25
Caparol®	—	10	10	—	—	—	—	50
Karmex®/Dynex®	10	10	10	6	10	5	5	5
Lorox®	28	23	23	15	23	20	20	15
Other	—	—	—	—	10	—	—	—
Subtotal	40	43	43	36	43	45	45	95
TOTAL	373	393	389	395	407	413	415	465

[1]A dash indicates that no data were provided.

Table 28. Percentage of cotton acreage in Tennessee treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	250	290	325	260	150	320	330	320
			(% of acres treated)					
Preplanting, Soil Incorp.								
Basalin®	5	15	15	23	15	—[1]	—	—
Prowl®	10	15	15	23	15	30	30	30
Tolban®	5	5	5	3	3	—	—	—
Treflan®	78	63	63	48	63	50	50	50
Treflan® + Cotoran®	3	3	3	3	—	—	—	—
Zorial®	—	—	—	8	5	—	—	—
Other	—	—	—	—	—	—	—	5
Subtotal	101	101	101	108	101	80	80	85
Preemergence								
Bladex®	3	3	3	3	3	1	1	1
Cotoran®/Lanex®	88	88	88	80	88	78	78	83
Dual®	—	—	—	—	—	1	1	1
Karmex®/Dynex®	8	8	8	8	5	5	5	5
Prowl®	—	—	—	—	—	5	5	5
Zorial®	3	3	3	10	5	18	18	16
Subtotal	102	102	102	101	101	108	108	111
Postemergence								
Bladex®	—	—	—	—	1	1	1	1
Bladex® + MSMA	1	1	1	1	1	1	1	1
Caparol®	1	1	1	1	1	—	—	1
Caparol® + MSMA	3	3	3	3	3	3	3	3
Cotoran®/Lanex®	1	1	1	1	1	1	1	1
Cotoran® + MSMA	7	7	7	7	7	7	7	7
Dinoseb	1	1	1	1	1	1	1	1
Karmex®/Dynex® + MSMA	1	1	1	1	1	1	1	1
MSMA/DSMA	13	13	13	13	13	17	17	17
Poast®/Fusilade®	—	—	—	—	50	50	50	55
Probe®	1	—	—	—	—	—	—	—
Subtotal	29	28	28	28	79	82	82	88
Spot Treatment								
Dalapon	1	1	1	1	1	1	1	1
MSMA	1	1	1	1	1	1	1	1
Poast®/Fusilade®	—	—	—	—	4	4	4	8
Roundup®	4	10	10	10	10	10	10	1
Subtotal	6	12	12	12	16	16	16	11
TOTAL	238	243	243	249	297	286	286	295

[1]A dash indicates that no data were provided.

Table 29. Percentage of cotton acreage in Texas treated with herbicides from 1979 through 1986. (Adapted from the Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Beltwide Cotton Production Research Conferences.)

Herbicide	Year							
	1979	1980	1981	1982	1983	1984	1985	1986
Acres of cotton (X 1000)	7731	7873	7477	5819	3500	4600	4700	3700
				(% of acres treated)				
Preplanting, Soil Incorp.								
Basalin®	<1	<1	<1	4	4	3	3	—[1]
Prowl®	4	9	13	13	20	23	23	23
Tolban®	1	2	2	0	<1	0	0	—
Tolban® + Cotoran®	<1	—	—	—	—	—	—	—
Treflan®	27	39	50	48	50	55	55	55
Subtotal	32	50	65	65	74	81	81	78
Preemergence								
Caparol®	5	3	5	7	7	7	7	7
Cotoran®/Lanex®	<1	<1	—	—	3	3	—	—
Dacthal®	—	—	3	—	—	—	—	—
Dual®	—	—	—	—	1	1	3	2
Karmex®/Dynex®	<1	<1	—	—	—	—	—	—
Prowl®	—	—	—	—	—	—	—	3
Sancap®	—	3	—	4	4	4	4	5
Surflan®	<1	<1	<1	<1	<1	<1	<1	<1
Zorial®	—	—	<1	<1	<1	<1	<1	<1
Subtotal	5	6	8	11	15	15	14	17
Postemergence								
Caparol®	<1	<1	<1	<1	<1	<1	<1	<1
Cotoran®/Lanex®	<1	<1	<1	<1	<1	<1	<1	<1
Dinoseb	—	—	<1	<1	<1	10	—	—
Karmex®/Dynex®	<	<1	<1	<1	<1	<1	—	—
MSMA/DSMA	5	2	2	2	2	2	2	2
Poast®/Fusilade®	—	—	—	—	8	—	12	15
Probe® + MSMA	<1	—	—	—	—	—	—	—
Subtotal	5	2	2	2	10	12	14	17
Spot Treatment								
Poast®/Fusilade®	—	—	—	—	—	8	15	15
Roundup®	25	46	46	35	33	35	35	35
Subtotal	25	46	46	35	33	43	50	50
Layby								
Caparol®	<1	<1	<1	<1	<1	<1	<1	<1
Karmex®/Dynex®	<1	<1	<1	<1	<1	<1	<1	<1
Lorox®	<1	—	—	—	—	—	—	—
Subtotal	0	0	0	0	0	0	0	0
TOTAL	67	104	121	113	132	151	159	162

[1]A dash indicates that no data were provided.

Table 30. Estimates of the percentage of acres of cotton treated with various herbicides in the United States. Estimates were made by the authors using base information obtained from Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Proceedings of the Beltwide Cotton Production Research Conferences, and adjusting these estimates based on contacts with herbicide manufacturers, wholesalers, extension personnel and others.

Herbicide	States reporting usage[1]	Year						
		1980	1981	1982	1983	1984	1985	1986
Acres in cotton (X 1000)	(No.)	14532	14328	11340	7382	10266	10215	8713
		(% of acres treated)						
Basalin®	14	1.7	3.0	6.8	4.3	4.9	2.3	0.2
Bladex®	12	2.5	3.0	2.4	5.8	4.4	4.4	3.9
Cobex®	3	0.3	0	0	0	0	0	0
Caparol®	12	10.7	10.4	8.6	6.4	6.6	9.7	7.9
Cotoran®/Lanex®	13	16.1	17.4	15.5	16.3	19.5	18.6	20.1
Dacthal®	2	2.0	3.0	0	0	0	0	0
Dalapon	9	0.3	0.4	0.3	0.3	0.5	0.3	0.3
Destun®	2	0	0	0	0.1	0.1	0.1	0.1
Dinoseb	12	1.7	2.4	1.8	1.1	2.3	3.4	1.8
Dual®	5	0	0	0.3	0.3	0.1	0.5	0.2
Goal®	4	0	0	0	0	0.1	0.6	0.4
Karmex®/Dynex®	13	2.9	2.9	2.6	1.9	2.5	1.9	2.0
Lorox®	9	0.7	0.7	0.4	0.7	1.0	1.0	1.1
MSMA/DSMA	15	9.6	9.1	8.8	9.5	10.7	9.8	11.5
Paraquat	7	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poast®/Fusilade®	14	0	0	0.4	4.1	3.9	4.4	6.3
Probe®	5	0.1	0	0	0	0	0	0
Prowl®	15	10.3	11.9	32.6	14.9	17.5	18.6	19.5
Roundup®	14	11.7	12.6	8.8	10.8	8.8	6.9	5.7
Sancap®	2	0.4	0.1	0.6	0.9	1.7	0.6	0.5
Tolban®	14	2.8	2.4	1.7	0.3	0	0	0
Treflan®	15	48.2	60.0	51.1	61.0	59.4	56.8	63.1
Zorial®	12	2.1	2.8	5.9	6.1	6.3	4.4	7.5
Caparol® + Bladex®	2	0.1	0.1	0	0	0	0	0
Caparol® + Prowl®	2	0.3	0.3	0.5	0.5	0.5	1.0	1.0
Caparol® + Treflan®	2	0	0.9	2.6	1.9	1.6	2.0	2.1
Cotoran® + Tolban®	7	0.4	0.5	0.3	0.1	0	0	0
Cotoran® + Treflan®	7	0.3	0.3	0.3	1.1	1.2	1.5	0.6
MSMA + Bladex®	12	2.2	2.1	2.2	1.4	1.5	2.4	2.3
MSMA + Caparol®	13	0.7	1.0	1.1	1.4	1.8	1.1	0.9
MSMA + Cotoran®	12	4.1	4.2	4.4	2.7	3.4	3.4	3.1
MSMA + Karmex®/ Dynex®	10	0.7	0.6	0.7	0.4	0.4	0.7	0.6
MSMA + Probe®	7	0.2	0	0	0	0	0	0
All Others		20.6	20.9	17.6	13.5	14.6	17.6	13.8

[1]Number of states reporting use in the Reports of the Cotton Weed Loss Committee mentioned above.

Table 31. A comparison of timing of herbicide applications for weed control in cotton in the United States on a regional basis. A value of 200 percent indicates that each acre in the region was treated two times.

Year	Region[1]	Acres in cotton	Time of application: Pre-plant foliar	Pre-plant soil incorp.	Pre-emergence	Post-emergence	Spot treatment	Lay-by	Accumulative regional percentages
			(% of acres[2])						
1980	Southeast	979	< 1	98	86	85	12	11	293
	Mid-South	2665	6	84	94	220	38	46	489
	Southwest	8588	< 1	53	7	3	43	0	107
	West	2300	< 1	94	9	6	14	20	143
	Weighted totals	14532	1	68	28	49	36	12	195
1981	Southeast	1102	< 1	99	87	89	13	10	298
	Mid-South	2782	8	90	99	220	40	49	506
	Southwest	8127	< 1	67	9	3	44	0	122
	West	2317	< 1	118	9	5	17	17	167
	Weighted totals	14328	2	82	32	52	36	13	218
1982	Southeast	897	< 1	97	82	84	13	10	287
	Mid-South	2169	7	82	99	210	24	48	470
	Southwest	6299	< 1	67	11	3	33	0	115
	West	1975	4	63	< 1	15	16	15	113
	Weighted totals	11340	2	71	32	51	27	13	196
1983	Southeast	603	< 1	108	92	125	15	17	357
	Mid-South	1583	10	88	113	232	37	50	532
	Southwest	3809	< 1	66	16	11	33	0	126
	West	1387	4	60	0	17	11	15	108
	Weighted totals	7382	3	73	40	69	28	15	228
1984	Southeast	1015	< 1	91	88	107	14	12	313
	Mid-South	2275	11	88	113	234	37	50	533
	Southwest	5014	< 1	82	16	13	42	0	153
	West	1962	4	65	< 1	15	15	19	118
	Weighted totals	10266	3	81	41	72	33	16	246
1985	Southeast	2262	11	91	113	232	41	45	531
	Mid-South	1113	< 1	94	90	114	14	14	326
	Southwest	5055	< 1	82	15	15	49	0	160
	West	1785	4	63	< 1	13	2	17	99
	Weighted totals	10215	3	82	42	73	35	14	250
1986	Southeast	1049	< 1	98	113	143	14	19	387
	Mid-South	2192	10	97	130	222	54	57	570
	Southwest	4050	< 1	79	118	18	48	0	162
	West	1422	4	64	< 1	15	21	21	125
	Weighted totals	81713	4	83	54	84	41	20	286

[1]Southeast includes the states of: AL, FL, GA, NC, SC, and TN; Mid-South states are: AR, MS, and MO; Southwest states are: OK and TX; West includes the states of: AZ, CA, and NM.

[2]Values on acres treated were determined by multiplying the cotton acreage in each state by the percentage of acreage treated with various practices in Reports of the Cotton Weed Loss Committee, Cotton Weed Science Research Conference, Proceedings of the Beltwide Cotton Production Research Conferences.

Table 32. Value of herbicides used in cotton in 1980 as compared to other major crops. (Adapted from Eikers and Serletis, 1982.)

	United States		Rest of the World	
	Costs	Percent of total	Costs	Percent of total
	($ X 1,000,000)	(%)	($ X 1,000,000)	(%)
Corn	754	35	323	12
Soybeans	749	34	164	6
Cotton	142	7	179	7
Wheat	97	5	525	19
Rice	53	2	376	14
Others	376	17	1153	42
Total	2171	100	2720	100

Table 33. Average price of selected herbicides in the Delta of Mississippi. Prices are expressed on the basis of one pound of active herbicide[1].

Herbicide (and formulation)	Year				
	1969	1973	1976	1980	1987
			($/lb)		
Bladex® (80 wp)	—[2]	3.56	5.06	3.56	4.13
Caparol® (80 wp)	4.00	3.38	4.50	6.19	5.38
Cotoran® (80 wp)	5.00	4.67	6.68	6.87	10.50
Dalapon (75 wp)	1.00	1.22	1.66	1.90	3.10
Dinoseb (3 ppg)	1.20	1.36	1.98	2.86	2.13
Karmex® (80 wp)	3.75	3.06	3.88	3.69	3.69
Lorox® (50 wp)	5.70	6.40	7.10	9.00	11.10
MSMA (6.67 ppg)	.45	.49	1.21	1.49	1.61
Paraquat (2 ppg)	15.00	15.00	19.39	20.75	20.60
Probe® (75 wp)	—	5.53	8.47	—	—
Roundup® (3 ppg)	—	—	—	20.97	19.50
Surflan® (75 wp)	—	—	—	10.40	12.70
Treflan® (4 ppg)	5.88	5.40	6.93	6.35	5.49
Zorial® (80 wp)	—	—	—	8.69	11.76
Avg. price of the 9 herbicides that are listed each year	4.66	4.55	5.93	6.57	7.07

[1]Prices are average prices of dealers in the Greenville/Greenwood, MS area.
[2]Prices not available.

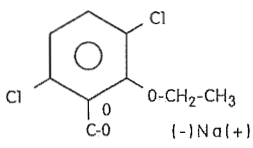
Chapter 8

HERBICIDE CHEMISTRY

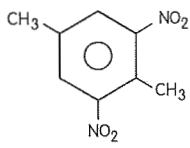
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INTRODUCTION

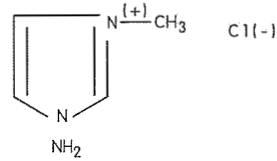
Organization facilitates the mastery of any scientific discipline and the communication among workers within the discipline. Consequently, weed scientists have organized herbicides into various groupings. For example, herbicides are organized by time of application (preplant, postermergence, etc.), by mode of action (hormone-like, photosynthesis inhibitors, etc.), or by chemical families (substituted ureas, phenoxy acids, etc.). In this chapter chemical families will be emphasized because chemical structure frequently provides clues as to mode of action, time of application, or other properties of a herbicide (Table 1). For example, assume nothing is known of the herbicidal properties of the following chemicals:



"A"



"B"



"C"

Though observations of the structures one could predict that compound "C" would be applied postemergence because if applied to the soil, the positive charge on the chemical would result in deactivation via adsorption to the negatively charged clay particles. One could not predict the time of application for compounds "A" or "B" since anionic and nonionic herbicides may be applied

Table 1. Properties of herbicides used for cotton production.

Herbicide	Formulations[3]			Common use rates	Water solubility @ 25C[1]
				lb ai/a	
Alachlor	G	FC		2.5-4.0	242 ppm
Cyanazine	WP	FC	DG	1.5-2.0	171 ppm
Dipropetryn	WP			1.2-2.0	16 ppm
Diuron	WP			.05-1.6	42 ppm
DSMA	SL			3.0	very soluble
Fluazifop	EC			.06-.25	2 ppm
Fluometuron	WP	FC		1.0-2.0	90 ppm
Glyphosate	SL			—[2]	1.2%
Linuron	WP	DG	FC	0.5-.75	75 ppm
Methazole	WP			1.0-2.5	1.5 ppm
Metolachlor	EC			1.5-2.0	530 ppm
MSMA	SL			2.0	very soluble
Norflurazon	WP	G		1.0-2.0	28 ppm
Oryzalin	EC			1.0-1.5	24 ppm
Oxyfluorfen	EC			.25-0.5	0.1 ppm
Pendimethalin	EC			0.5-1.0	0.5 ppm
Prometryn	WP	FC		1.2-2.4	48 ppm
Sethoxydim	EC			.187-.374	48 ppm
Trifluralin	EC	G		0.5-1.0	<1.0 ppm

[1]Obtained from the Herbicide Handbook of the Weed Science Society of America, 5th Edition, 1983.

[2]10-30% solution depending on special equipment used.

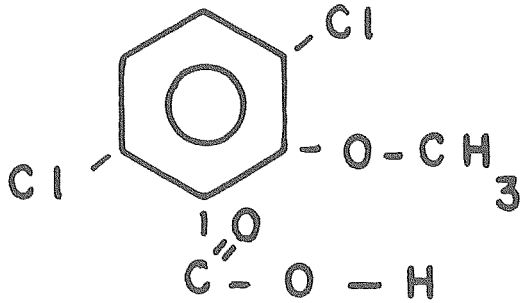
[3]DG = Dispersable granules EC = Emulsifiable concentrate
FC = Flowable concentrates G = Granules
SL = Solutions WP = Wettable powders

either preplant, preemergence, or postemergence. One could also predict that the compounds "A" and "C" would readily dissolve in water because they are highlypolar but an emulsifier would be necessary if compound "B" was to be applied in water. Likewise, one could predict that compound "A" likely would leach readily in soil because it is water soluble and negatively charged while compound "B" would not leach as readily because of low water solubility and "C" would not leach because of the positive charge.

One could predict that the persistence of compound "B" would be greatly reduced in flooded soils because under anaerobic conditions, microorganisms likely would reduce the nitro groups to amino groups The effect of soil moisture on "A" and "C" is less apparent. Finally, one could predict that volatility would

not be a problem with compounds "A" or "C" because of their ionic character but may be a problem with compound "B" because of its low molecular weight and nonionic character.

While a great deal of useful information can be obtained by simply observing chemical structure, some herbicidal properties cannot be predicted unless the chemical fits into a known herbicidal family. Whether "B" would control pigweed (*Amaranthus spp.*) more effectively than it would control large crabgrass (*Digitaria sanguinalis* [L.] Scop.) cannot be predicted because there are no known herbicides of similar structure to serve as a "family" representative. Conversely, one would predict that "A" would effectively control pigweed because of the similarity of its structure with dicamba (Figure 1).



Dicamba (2-methoxy-3,6-dichlorobenzoic acid)

Figure 1. Dicamba (2-methoxy-3,6-dichlorobenzoic acid).

In summary, there are certain herbicidal properties which can be predicted by observing the chemistry of the herbicide. Among these are:

Volatility—This will increase as the polarity and molecular weight of the herbicide decrease. Polarity is generally more important than molecular weight, i.e. a salt is much less volatile than an ester but a hexyl ester is less volatile than a propyl ester.

Leachability—Water insoluble herbicides will not readily leach. Water soluble herbicides may or may not leach depending on attraction to the soil. Positively charged herbicides do not generally leach but negatively charged ones may.

Photodecomposition—To have color, a compound must absorb light

and, thus, colored compounds must be susceptible to photodegradation. Colorless compounds may be susceptible because of absorption of ultraviolet light.

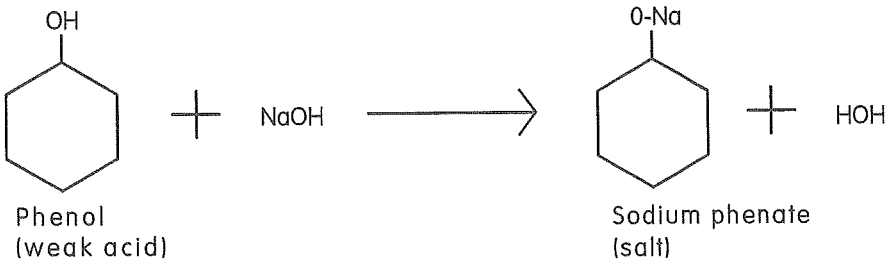
Time of Application—Positively charged herbicides will be applied postemergence. Application time of nonionic or negatively charged herbicides cannot be predicted.

FAMILIES OF HERBICIDES USED IN COTTON

The use of herbicides developed perhaps more slowly in cotton than in corn and small grain because 2,4-D and the other phenoxy acids, the first major group of selective herbicides, were extremely phytotoxic to cotton. However, experiments were underway prior to 1950 in Louisiana to evaluate a dozen chemicals as preemergence or directed postemergence herbicides in cotton (Cowart *et al.*, 1949).

DINITROPHENOLS

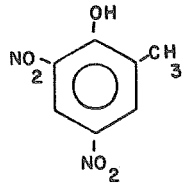
A history of chemical weed control in cotton most appropriately begins with the substituted phenols since they were some of the first selective herbicides used in cotton. Phenol is a weak acid and forms a salt in the presence of a strong base i.e.:



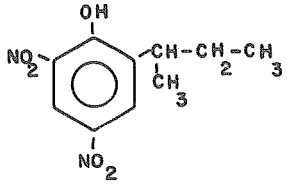
This reaction is reversible in that the salt reverts to the phenol in the presence of an acid.

The above reaction explains many of the properties of the phenolic herbicides. For example, the phenols are water soluble at a high pH but oil soluble at a low pH. Consequently, phenols should be able to penetrate a waxy leaf effectively at a low pH thereby increasing postemergence activity. They should volatilize more readily from acid soils than alkaline soils but should leach readily in alkaline soils. Phenols used as herbicides contained either chloro or nitro substitutuions. The nitrophenols were the first patented organic selective herbicides (Kaufman, 1976). The sodium salt of 2-methyl-4,6 dinitrophenol (DNOC) was used to con-

trol weeds in small grain in France about 1933 (Kingman and Ashton, 1975). Although DNOC (Sinox®) was the first dinitrophenol used for weed control, Crafts (1945) reported that lengthening the carbon chain in the ortho position increased phototoxicity of the compound by increasing oil solubility and, therefore, the penetration through the cuticle of the leaves (Figure 2). Thus, dinoseb (Premerge® and other tradenames) became the most widely used herbicide of this family and in the early 1950s the salts of dinoseb were the most widely used preemergence herbicides in cotton.



Sinox [(2-methyl-4, 6-dinitrophenol)]



Dinoseb [2-(1-methylpropyl)-4,6-dinitrophenol]

Figure 2. Chemical structures of dinitrophenols used for weed control.

In 1952, a number of reports of injury to cotton following preemergence applications of the salts of dinoseb were received from producers. Apparently, the injury was magnified by unusually high temperatures and light rains that occurred as the cotton seedlings were emerging from the soil. On acid soils, the salts were converted to the phenol and the vapors caused severe burn of the tender seedlings. The injury caused by dinoseb undoubtedly discouraged the use of herbicides by farmers for the next decade. However, the injury provided a valuble lesson to researchers and stimulated research into the mode of action and importance of selectivity of herbicides. Until recently, salts of dinoseb were used successfully as postemergence directed herbicides in cotton for control of small weeds. Presently, the U.S. Environmental Protection Agency (EPA) has suspended the use of dinoseb and its salts because of toxicological problems (EPA, 1986).

Although the chlorinated phenols were used in early tests, and pentachlorophenol in diesel fuel was widely used as a spot treatment for control of johnson-

grass (*Sorghum halepense* [L.] Pers.) and other weeds, frequent crop injury prevented their widespread use in cotton.

CHLORINATED CARBOXYLIC ACIDS

Along with the phenols, the chlorinated carboxylic acids (Figure 3) were among the earliest chemicals evaluated for their potential use in cotton. Trichloroacetic acid (TCA) at 20 lbs/A applied as bands on both sides of the row was suggested as one of the treatments to be included in a "standard" preemergence herbicide experiment in 1949 (Anonymous, 1949). Since TCA is a stronger acid than the dinitrophenols, TCA was applied as a salt to reduce corrosion of equipment and injury to the applicator. Although TCA was not widely used in cotton, a related chemical, dalapon (various tradenames) achieved wide acceptance as a spot treatment for johnsongrass control. Dalapon is a weaker acid than TCA but also is formulated as water soluble salts. The first formulations were sodium salts but later mixtures of sodium and magnesium salts were produced which reduced the tendency to harden when stored under moist conditions. Ester formulations of dalapon also were evaluated. However, these volatile, oil-soluble products tended to produce a rapid "burn" of the leaves that resulted in less control of underground vegetative organs of perennial grasses than did the salt formulations.

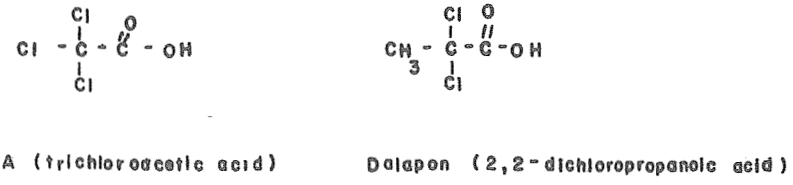


Figure 3. Examples of aliphatic acids used as herbicides.

CARBAMATES

The carbamates possess a wide range of biological activity and have been used

to control weeds, insects and diseases. Chemically, the carbamates may be considered as derivatives of carbamic acid but in this instance, the parent acid is unstable (Figure 4). Conversion of the hydroxyl group (OH) to an ester increases the chemical stability of the molecule and decreases its water solubility. Replacement of one oxygen with sulfur results in a thiocarbamate and replacement of both oxygens results in a dithiocarbamate. The carbamates, thiocarbamates (carbamothioates), and dithiocarbamates (Figure 5) are all useful herbicides but their uses are quite different. As a rule, the carbamate herbicides retain a hydrogen on the nitrogen while with the thio- and dithiocarbamates, both hydrogens are replaced by carbon chains of varying lengths.

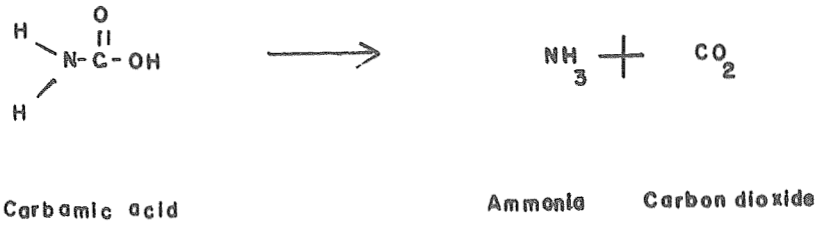


Figure 4. Chemical decomposition of carbamic acid.

It was soon apparent that the chlorination of the phenyl ring of propham (Chem-Hoe®) increased the herbicidal effectiveness of the herbicide. By 1951, researchers in Mississippi concluded that chloropropham (Furloe® and other tradenames) (Figure 6) was "equal to or superior to" the dinitrophenols for controlling crabgrass in cotton (Leonard *et al.*, 1952). Although the carbamates played a significant role in the advancement of chemical weed control in cotton, they are no longer extensively used in the production of this crop.

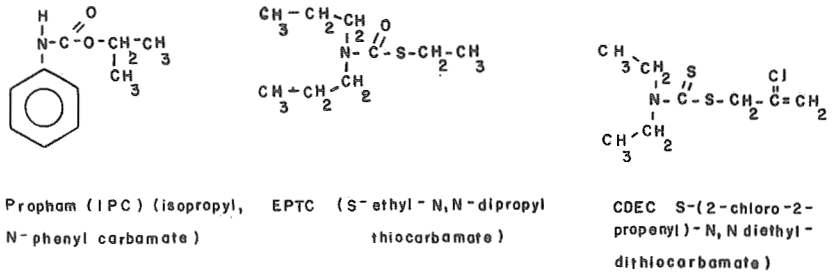


Figure 5. Representative carbamate, thiocarbamate, and dithiocarbamate herbicides.

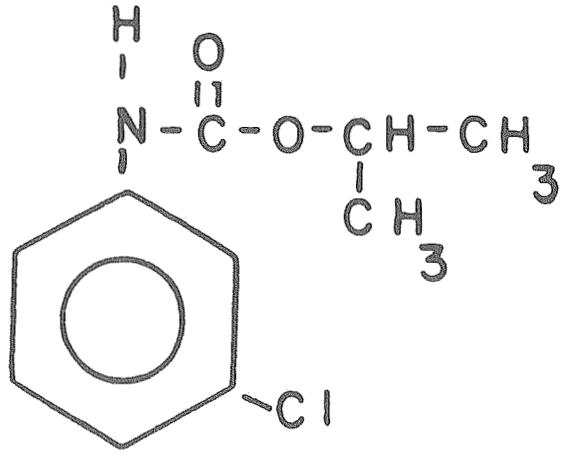


Figure 6. Chemical structure of chloroprophlam (1-methylethyl 3-chlorophenyl carbamate).

SUBSTITUTED UREAS

The development of the substituted ureas (Figure 7) as herbicides closely parallels that of the carbamates. Unlike the carbamates, however, the ureas are still widely used for weed control in cotton. As with the carbamates, one unsubstituted hydrogen in the urea molecule is necessary for maximum herbicidal activity. Fenuron (Dybar® and other tradenames) is highly water soluble and tends to leach readily in the soil. Thus, it was useful for control of certain deep rooted species of brush but lacked crop safety in cotton. By chlorinating the ring, water solubility and leachability were reduced and crop safety was improved. For example, monuron (Telvar® and other tradenames) was used for preemergence weed control on extremely heavy clay soil such as those found in the Blacklands of Texas while diuron (Karmex® and other tradenames) had utility over a wide range of soil types and climatic conditions (Figure 8). Monuron is no longer registered by the EPA for use in cotton and diuron is not recommended for preemergence use if cotton is grown on sandy soils or soils with less than 1 percent organic matter.

In addition to preemergence use, diuron has found wide application as a postdirected spray in cotton as has linuron (Lorox®), a chemical related to diuron except that a methoxy group replaces one of the methyl substitutions (Figure 8). The methoxy substitution gives linuron a shorter residual in the soil and slightly higher water solubility than diuron. These characteristics limit linuron's usefulness as preemergence herbicide in certain soils. However, linuron has excellent postemergence activity when used as a directed spray and its short residual in the soil is an advantage if applied as a "layby" treatment. The other substituted urea widely used in cotton is fluometuron (Cotoran® and other tradenames). Chemically, fluometuron differs from diuron in that a trifluoromethyl group replaces the dichloro substitutions of diuron (Figure 8). Fluometuron is used extensively in the Mississippi Delta and the southeastern United States for preemergence control of prickly sida (*Sida spinosa* L.) and other broadleaf weeds. It has an advantage over the other urea herbicides in that it is labeled for over-the-top application when the cotton is 3 to 6 inches tall. However, applications of fluometuron should be directed when possible to minimize phytotoxicity to the cotton.

A discussion of the substituted ureas should include a mention of methazole (Probe®) (Figure 9) since it can be considered as a cyclic urea and information indicates that it is metabolized to a substituted urea in plants, animals and soils (5). Because there are no hydrogens present on the nitrogens of methazole, one would speculate that its herbicidal activity would be low if its primary mode of action is inhibition of the Hill reaction as is the other urea herbicides. The metabolite should be active, however. The lack of N-H bonds in methazole should reduce hydrogen bonding thereby decreasing water solubility and increasing solubility in oil as compared to the other urea herbicides. The increased oil solubility may contribute to increased foliar absorption and the excellent postemergence

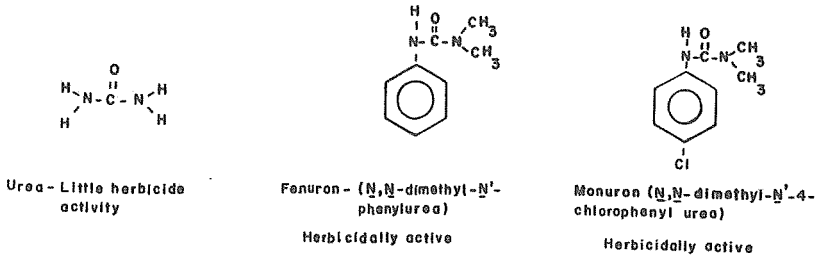


Figure 7. Effect of substitutions on the herbicidal activity of urea.

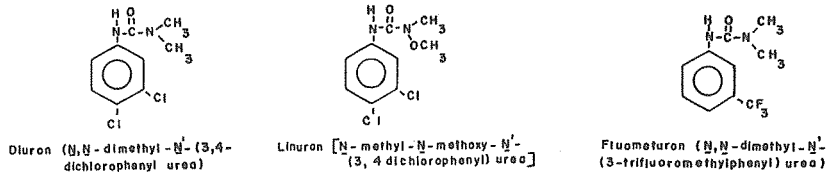


Figure 8. Chemical similarities of urea herbicides.

activity observed with this compound. Methazole recently has been reintroduced into the market, and presently has been registered by the EPA for use throughout the Cotton Belt.

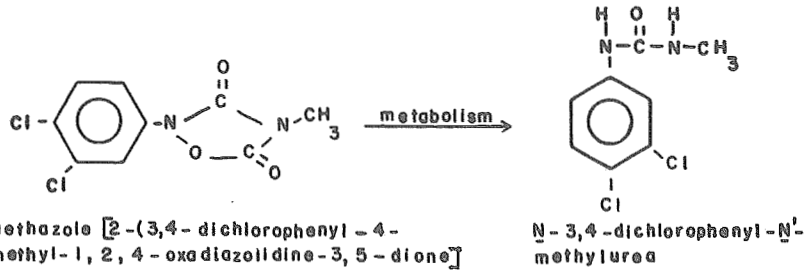


Figure 9. Relationship of methazole to the urea herbicides.

Finally, a new group of urea herbicides, the sulfonylureas, has been approved for use in wheat and other small grains (Figure 10). Another compound in this group also has been registered by the EPA for use in soybeans. The ingenuity of the herbicide industry will undoubtedly lead to sulfonylurea compounds that are useful in cotton. The sulfonylurea herbicides are characterized by activity against broadleaf weeds and grasses at rates as low as 0.01 kg/ha (lbs/A). They are generally more water soluble at a high pH than at a low pH because of their ability to form an anion in the presence of a base.

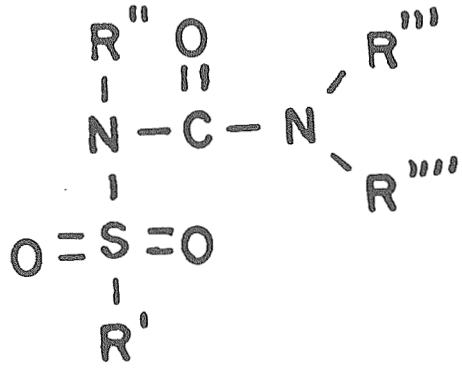


Figure 10. General formula for a sulfonyl urea. The R^{I} groups vary among herbicides but it is likely that either R^{II} or R^{III} will be a hydrogen atom.

ARSENIC COMPOUNDS

Inorganic forms of arsenic have been used as pesticides for more than a century. A lack of selectivity and high mammalian toxicity limited their usefulness for weed control in cotton. Arsenic acid has been widely used as a cotton disiccant in areas where harvesting is done by stripping rather than picking. The salts of organic arsenic effectively control small annual grasses and common cocklebur in cotton but their principal use has been for the control of johnsongrass. From a chemical viewpoint, arsenic may be trivalent or pentavalent in its bonding with other atoms. The trivalent compounds are often more toxic to mammals than are the pentavalent compounds. Salts of trivalent arsenic are designated arsenites while the pentavalent salts are termed arsenates (Figure 11).

By replacing one or more of the hydroxyl groups with carbon groups (Figure 12), organic compounds are produced which are generally much lower in mammalian toxicity than are their inorganic counterparts. However, the organic compounds may be toxic to ruminating animals perhaps via conversion to inorganic arsenic by microorganisms in the rumen. Salts of arsenic acid containing one carbon chain are designated arsonates while those with two carbon chains are termed arsinates. MSMA (various tradenames) and DSMA (various tradenames) are examples of organic arsonates used as herbicides.

Since MSMA and DSMA are extremely polar, they are highly water soluble and they do not volatilize following application. Also, since they are water solu-



Figure 11. Examples of inorganic compounds which contain arsenic.

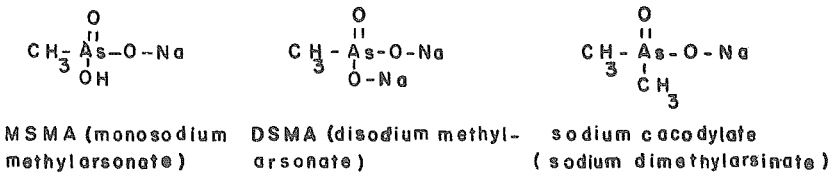


Figure 12. Examples of organic compounds which contain arsenic.

ble and the herbicidal moiety is negatively charged, one would predict that MSMA and DSMA would readily leach in soil. However, due to the complexes

formed between arsenic and iron or aluminum found in the lattice structure of clays, leaching is usually minimal in most soils. Thus, their principal activity has been postemergence to the weed.

To avoid arsenic residues in the cotton seed, they should not be applied to cotton foliage after formation of the first flower bud.

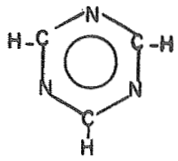
SYMETRICAL TRIAZINES

Chemically the term "triazine" indicates a compound with three nitrogen atoms in a six-membered ring. While a "triazole" also has 3 nitrogen atoms, the atoms are contained in a five-membered ring (Figure 13). A "symetrical" triazine has the nitrogens evenly spaced within the ring. In numbering the atoms in a heterocyclic ring, one usually begins with a non-carbon atom. Since all three of the nitrogen's bonds are required to form the aromatic ring, substitutions can occur only at the 2, 4, and 6 positions occupied by the carbons in the triazine ring.

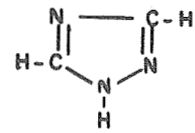
Triazine herbicides generally have amino groups substituted at two of the carbons. Thus, there is only one substitution remaining to form the major subgroups within the family. This substitution is either a chloro, mercapto or alkyloxy group. To assist in identifying these substitution, the chloro substituted herbicides end with "-zine" *i.e.* atrazine (AAtrex® and other tradenames), the mercapto herbicicdes end with "-tryn" *i.e.* prometryn (Caparol®) and the alkyloxy herbicides end with "-ton" *i.e.* prometon (Pramitol®) (Figure 14). Herbicides with these subgroups vary by the length of the carbon groups attached to the nitrogen, oxygen or sulfur. Since there are no acid groups present in the triazine molecules, their solubility in water or oil cannot be changed by formulating them as salts or esters. Thus, they are usually marketed as wettable powders, dispersable granules or flowable concentrates.

In general, the alkyloxy triazines such as prometon have low selectivity among plants and, thus, are used as soil sterilants rather than in crop production. While the chlorotriazines such as atrazine have excellent selectivity among plants, they usually are most effective against broadleaved plants and thus are used in grass crops such as corn or grain sorghum. However, cyanazine (Bladex®) is labeled for early preplant weed control in cotton in California, for preemergence weed control in some states of the Mid-South, and for post-directed application throughout the cotton growing areas. Cyanazine sometimes has been mixed with MSMA or dinoseb for increased postemergence activity but dinoseb is no longer approved for use in cotton.

The mercaptotriazines, prometryn and dipropetryn (Sancap®), (6, ethylthio-*N*,*N*'-bis-(1-methylehtyl)-1,3,5-triazine-2,4-diamine), have been used in cotton for a number of years. Prometryn is most popular in areas with neutral to alkaline soils. It is less effective on the acid soils of the Southeast where the substituted ureas such as diuron and fluometuron are more popular. Chemically, dipropetryn varies from prometryn only in that the methylthio group of prometryn is replaced



1, 3, 5-triazine



1, 2,4-triazole

Figure 13. Comparison of triazine and triazole compounds.

by an ethylthio group. Lengthening the carbon chain, decreases the water solubility slightly which reduces the leachability of dipropetryn. This reduced leaching plus an apparent inherent tolerance make dipropetryn somewhat safer to use on sandy soils than is prometryn. However, the registration of dipropetryn for cotton has been voluntarily cancelled by its manufacturer.

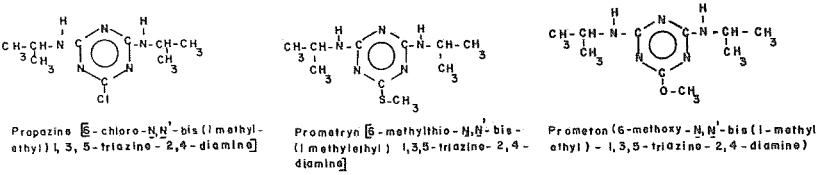
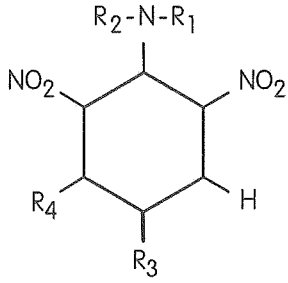


Figure 14. Examples of commonly used triazine herbicides.

DINITROANILINES

This family of herbicides provides reliable control of annual grasses and certain broadleaved weeds and is more widely used in cotton than other herbicide families throughout the Cotton Belt. All members of the family contain the following basic structure:



By varying the "R" groups of the above molecule, a number of useful herbicides have been synthesized (Figure 15). For example, trifluralin (Treflan® and other tradenames), benefin (Balan®), fluchloralin (Basalin®), profluralin (Tolban®) and ethalfluralin (Sonalan®) vary from each other only by substitutions on the nitrogen (R_1 and R_2). These herbicides are all essentially nonpolar and may volatilize from a moist soil if not incorporated. They are yellow-to-orange in color which indicates they absorb light in the visible spectrum and thus would be sus-

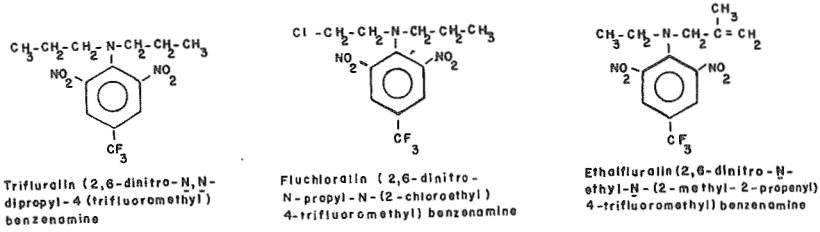
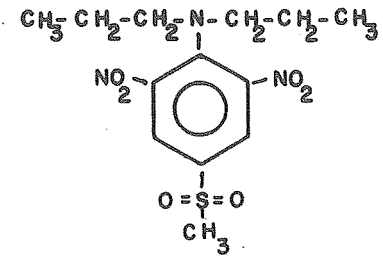


Figure 15. Examples of dinitroaniline herbicides which vary only by substitution on the nitrogen atom.

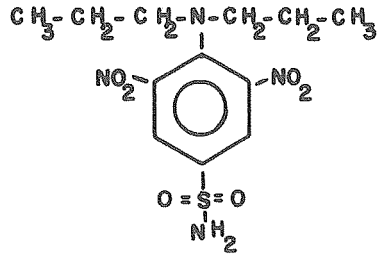
ceptible to photodegradation by sunlight. They are highly oil soluble and can be emulsified with water. Their leachability is extremely low because of their low water solubility. Their persistence in flooded soil may be only a few days because of the ability of certin microorganisms to reduce the NO_2 groups to NH_2 groups under anaerobic conditions.

Attempts to reduce the volatility, and thus the need for soil incorporation, have been most successful by replacing the trifluoromethyl group with a polar substitution such as a sulfonamide group (Figure 16). Herbicides such as oryzalin (Surflan®) have been most popular in areas with heavy clays where thorough soil incorporation is difficult to achieve or in minimum tillage systems of production. Because of increased polarity, these compounds are less oil soluble than other members of the dinitroaniline family and consequently are not as easily emulsified with water.

Finally, there are members of the family such as pendimethalin (Prowl®), dinitramine (Cobex®) and prodiamine (Rydex®) which have substitutions at the 3-position on the ring (Figure 17). These compounds are less volatile and more water soluble than trifluralin but more volatile than oryzalin. The persistence of prodiamine is frequently longer than for other members of the family and, under dry conditions, may injure susceptible crops rotated with cotton. Indeed, under cold dry conditions which sometimes occur in cotton producing areas, other herbicides of this family may cause injury to grain sorghum planted in rotation with cotton.

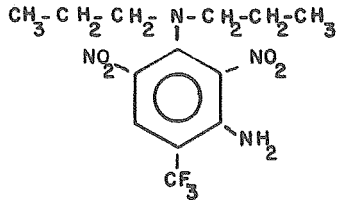


Nitralin (2,6-dinitro-N,N-dipropyl-4-methylsulfonyl benzenamine)

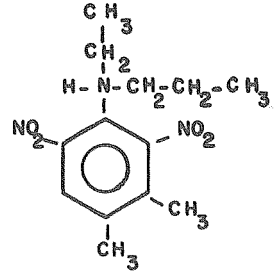


Oryzalin (2,6-dinitro-N,N-dipropyl-4-aminosulfonyl benzenamine)

Figure 16. Examples of dinitroaniline herbicides which vary by substitution at the para position of the ring.



Prodiamine (2,6-dinitro-N,N-dipropyl-3-amino-4-trifluoro methyl benzenamine

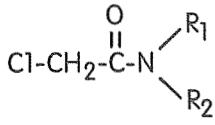


Pendimethalin (2,6-dinitro-N-(1-ethylpropyl)-3,4-dimethyl benzenamine

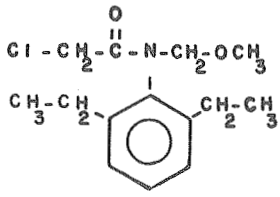
Figure 17. Examples of dinitroaniline herbicides which have substitutions at the meta position of the ring.

CHLOROACETAMIDES

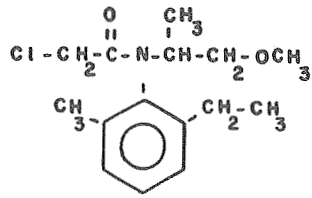
In addition to cotton, these herbicides are useful in a wide array of crops including corn, soybeans and peanuts. All herbicides in this family contain the following base structure but they vary in the substitutions at R_1 and R_2:



Presently, alachlor (Lasso®) and metolachlor (Dual®) are the most widely used herbicides in this family (Figure 18) but there are other experimental compounds which have a potential use in cotton. At the present time, neither herbicide can be used in sands or sandy loam soils due to the potential for crop injury. Also, cotton planted in a furrow may be injured if heavy rains occur before the cotton emerges. The effectiveness of the chloroacetamides against yellow nutsedge (*Cyperus esculentus* L.) is of particular benefit to the cotton producer. Nusedge control is enhanced by incorporating the herbicide into the soil but cotton should be planted below the zone-of-incorporation to minimize injury. Alachlor and metolachlor have sufficient oil solubility so that they may be formulated as emulsifiable concentrates. Other members of the family such as propachlor are not easily emulsified and have been marketed as wettable powders, flowables, or granules.



Alachlor [2-chloro-N-(2,6 diethyl phenyl)-N-(methoxymethyl) acetamide]



Metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide]

Figure 18. Chemical structure of commonly used chloroacetamide herbicides.

ORGANIC PHOSPHORUS COMPOUNDS

In many respects, the chemistry of the phosphates is related to the chemistry of the arsenates because both have five electrons in their bonding orbitals (Figure 19). As with the arsenic compounds, the most useful phosphorus herbicides have been the phosphonates. The isopropylamine salt of glyphosate [*N*(phosphonomethyl) glycine] (Roundup® and other tradenames) has been highly effective for control of perennial weeds such as johnsongrass in cotton (Figure 20). Because of lack of selectivity, glyphosate must be applied with a rope wick, recirculating sprayer, or other selective application equipment which will prevent the herbicide from contacting the cotton foliage.

Glyphosate readily translocates in plants but, as with the arsenic compounds, has little soil activity. Lack of preemergence activity apparently is caused by complexing of the phosphorus with soil minerals. Some preemergence activity has been reported when glyphosate is applied to organic material such as thatch and the herbicide does not contact mineral soil. The salts of glyphosate are not volatile.

Sulfosate (Trimethylsulfonium, carboxymethylaminomethylphosphonate) (Touchdown®) also has shown promise for weed control in cotton, but it also must be applied with equipment which prevents the chemical from contacting the cotton. Sulfosate presently is not labeled by the EPA for use in cotton.

The activity of the phosphonate herbicides can be increased against certain grasses including johnsongrass by the addition of "activators" such as ammonium sulfate. The ammonium sulfate usually is added at a rate of 1 to 2 percent of

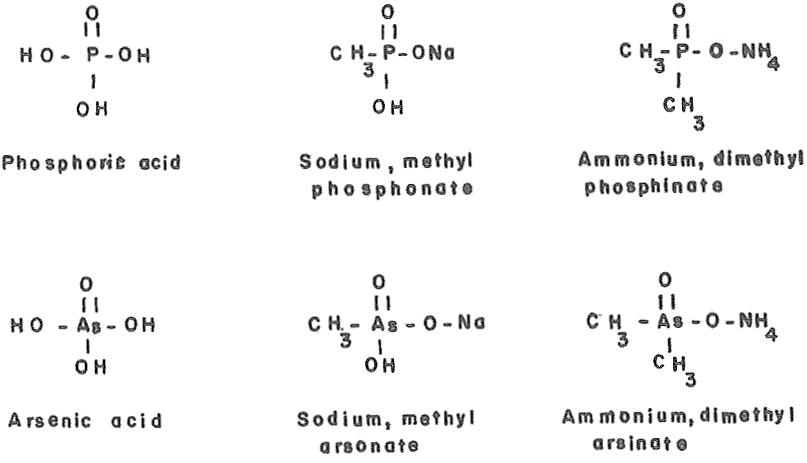


Figure 19. Relationship of phosphorus and aresenic as acids and organic salts.

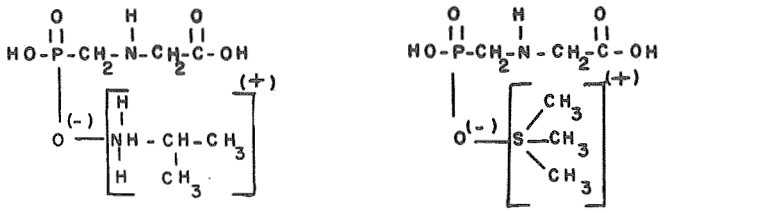


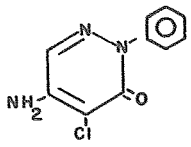
Figure 20. Examples of phosphate salts which have herbicidal activity.

the spray solution and it seems to enhance activity against weeds grown under environmental stress. The mode of action of the "activators" is not clear but they may stabilize the degree on ionization of the herbicide. The phytotoxicity of the phosphonate compounds apparently is somewhat dependent on the cation since the isopropyl amine salt is a highly effective herbicide while the sodium sesqui salt has been used to hasten ripening and increase the yields of sugarcane.

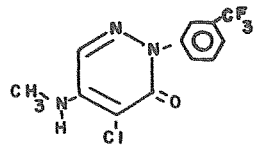
SUBSTITUTUED PYRIDAZINONES

Although several herbicides belong to the pyridazinone family (Figure 21), only norflurazon (Zorial®) is widely used in cotton. Also, the weeds controlled and mode of action vary among these chemically related compounds. The water solubility of norflurazon is low due to high molecular weight and a lack of polarity. Since it can not be readily formulated as a salt to increase water solubility or as an ester to increase solubility in an emulsifiable oil, norflurazon has been marketed either as a wettable powder or as granules.

Although norflurazon controls prickly sida and other troublesome weeds, its activity against yellow nutsedge, especially when incorporated into the soil, make it of interest to cotton producers in the Southeast and Mid-South. Soil persistence is of concern in the dry portions of the Cotton Belt.



Pyrazon [4-chloro-5-amino-2-phenyl-3-(2H)pyridazinone]



Norflurazon [4-chloro-5-(methylamino)-2-(3-(trifluoromethyl)phenyl)-3-(2H)-pyridazinone]

Figure 21. Examples of pyridazinone herbicides.

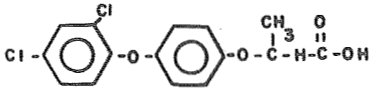
ARYLOXYPHENOXY ALKANOIC ACIDS

Although diclofop (Hoelon®) has been more widely used in wheat than in cotton, from a chemical viewpoint it can be considered as the forerunner of an important group of cotton herbicides (Figure 22). By replacing one of the phenyl rings of diclofop with a heterocyclic ring, the activity against many grassy weeds increased. However, the selectivity between grasses is generally lower among the heterocyclic compounds than it is with diclofop. Fluazifop (Fusilade®) was the first heterocyclic member of this family registered by the EPA for use in cotton. However, other members of the family have provided excellent control.

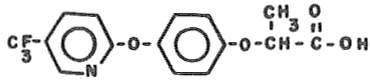
All herbicides in this family are formulated as esters and thus are highly oil soluble and emulsifiable in water. Their high molecular weight makes them less volatile than are equivalent esters of 2,4-D. As esters they would leach very little but they are apparently rapidly hydrolyzed to the corresponding acid in soil and should be then somewhat leachable in alkaline soils.

Because of the second carbon of the propanoic acid in all compounds is asymmetric (it is joined to four nonequivalent atoms or groups), the herbicides exist as optical isomers (mirror images). In biological systems, one of the optical isomers usually has much higher activity than the other. Manufacturers, in some instances, have developed formulations containing essentially only the most active isomer, thereby providing effective control of grasses with low rates of application. Thus, fluazifop-P(Fusilade-2000®) contains the purified active isomer of fluazifop.

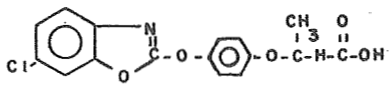
High crop tolerance and activity against both annual and perennial grasses make the aryloxyphenoxy alkanoic acids useful herbicides to the cotton producer.



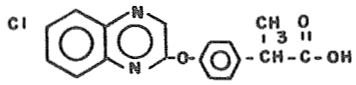
Diclofop [(±)-2-[4-(2,4-dichloro phenoxy) phenoxy] propanoic acid]



Fluazifop [(±)-2-[4-[[5-(trifluoro methyl)-2-pyridinyl] oxy] phenoxy] propanoic acid]



Fenoxaprop [(±)-2-[4-[(6-chloro-2-benzoxazolyl) oxy] phenoxy] propanoic acid



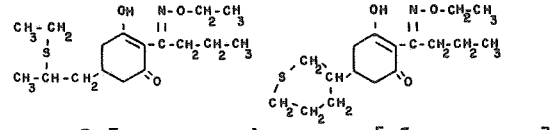
Xylofop [(±)-2-[4-[(6-chloro-2 quinoxalinyl) oxy] phenoxy] propanoic acid]

Figure 22. Examples of aryloxphenoxy herbicides.

CYCLOHEXENONES

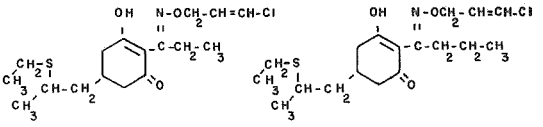
Although chemically unrelated, the cyclohexenones and the aryloxyphenoxy alkanoic acids are quite similar in crop tolerance and spectrum of weed control. Presently, sethoxydim (Poast®) is the only cyclohexenone labeled for use in cotton but there are several experimental compounds which also effectively control grasses (Figure 23). To date, herbicides in this family have been oil-soluble and emulsifiable in water. Since these herbicides do not possess an acid moiety, their solubility in oil or water can not be altered by formulating as a salt or as an ester.

Like the aryloxphenoxy alkanoic acids, many of the cyclohexenones exist as optical isomers because one of the carbons attached to the sulfur group is asymmetric. However, chemical companies have not marketed formulations containing a single isomer. Unlike the aryloxphenoxy alkanoic acids, the cyclohexenones also should exist as sterioisomers around the oxime moiety. Again, isomers have not been separated in commercial formulations.



Sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthiobutyl)propyl]-3-hydroxy-2-cyclohexene-1-one]

Cycloxydim [2-[1-(ethoxyimino)butyl]-5-(2H-tetrahydrothiopyran-3-yl)-3-hydroxy-2-cyclohexen-1-one]



Cloproxydim [2-[1-(3-chloro-2-propenyloxy)propyl] - 5-(2-ethyl thiopropyl)-3-hydroxy-2-cyclohexen-1-one]

RE-36290 [2-[1-(3-chloro-2-propenyloxy)-butyl]-5-(2-ethyl thiopropyl)-3-hydroxy-2-cyclohexen-1-one]

Figure 23. Examples of cyclohexenone herbicides.

DIPHENYLETHERS

The diphenylethers are probably most widely used in soybeans but at least one herbicide, oxyfluorfen (Goal®), is used as a post-directed herbicide in cotton (Figure 24). Chemically, oxyfluorfen is related to nitrofen, a herbicide once widely used in many vegetable crops. Because of phytotoxicity to cotton, oxyfluorfen is applied as a directed spray. It is of interest to the cotton producers because of its activity against morningglory and other troublesome weeds.

Oxyfluorfen also is related to bifenox (Modown®) and acifluorfen (Blazer® and

Tackle®) but lacks the carboxyl moiety that these herbicides possess. Thus, the water solubility of oxyfluorfen can not be altered by changes in formulation. It is soluble in oil and marketed as an emulsifiable concentrate. Its low solubility in water suggests that it would not leach in the soil. Although oxyfluorfen is essentially nonpolar, its volatility is relatively low because of its high molecular weight.

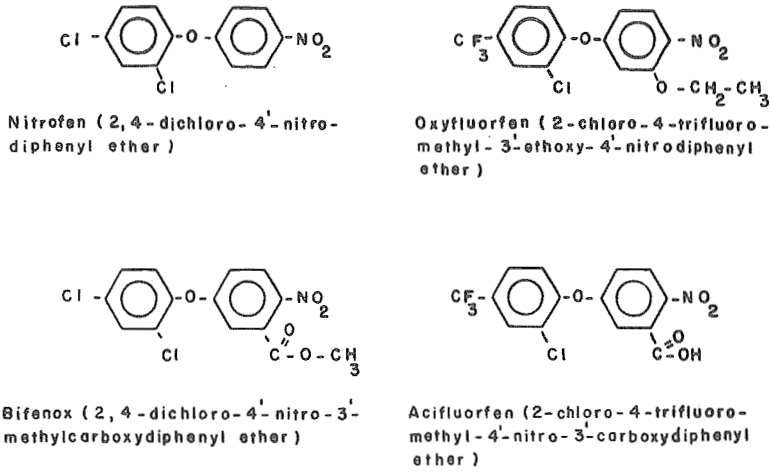


Figure 24. Examples of diphenylether herbicides.

CINMETHYLIN

Presently only one herbicide, cinmethylin (Cinch®), in this family has been available for experimental testing (Figure 25). The chemistry is unique among herbicides used in cotton in that it consists only of carbon, hydrogen and oxygen. It is relatively nonpolar and therefore low in water solubility and leachability. It is amber in color and thus must absorb sunlight and may be susceptible to photodecomposition. Since it is essentially nonpolar, one would expect it to be volatile from a moist soil. However, its high molecular weight somewhat compensates for its lack of polarity and the resultant volatility approximates that of trifluralin. The presence of asymmetric carbon atoms indicate that cinmethylin should exist in isomeric forms. According to the technical manual provided by its producers, the isomers have varying effectiveness as herbicides.

Cinmethylin controls most annual grasses when applied either preemergence or preplant-incorporated into the soil. Control of broadleaved weeds is less dependable and is quite dependent on rainfall soon after application. Cinmethylin probably will be most widely used as a mixture with another herbicide which effectively controls broadleaved weeds.

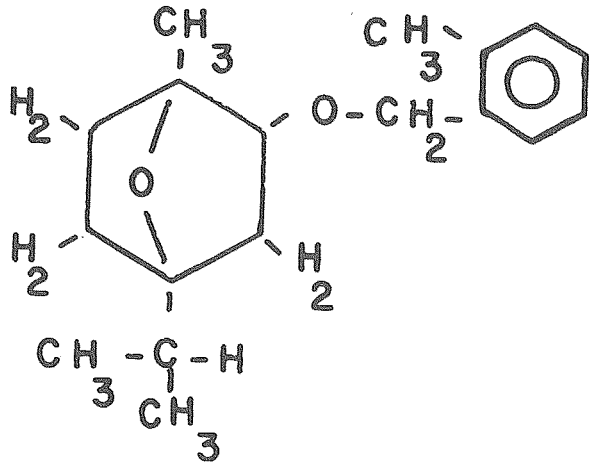


Figure 25. Chemical structure of cinmethylin [1-methyl-4(1-methyl ethyl)2-(2-methylphenyl)methoxy-7-oxabicyclo-2,2,1-heptane].

HERBICIDES FOR THE FUTURE

Many of the weeds once troublesome to cotton producers can now be effectively controlled with available herbicides. When a wide variety of species of weeds is present, combinations of herbicides are available to attack the problem. However, certain perennial weeds such as field bindweed (*Convolvulus arvensis* L.) and silverleaf nightshade (*Solanum elaeagnifolium* Cav.) are not readily controlled with herbicides presently available to the cotton producer. Some annual broadleaved weeds, especially those genetically related to cotton such as spurred anoda (*Anoda Cristata* (L.) Schlecht) and velvetleaf (*Abutilon theophrasti* Medic.), may also escape our presently available herbicides. Thus, there is a definite need for new herbicides which can be applied over-the-top of cotton for controlling broadleaved weeds.

The success of recently introduced herbicides for controlling broadleaved weeds in soybeans gives encouragement that similar progress can be made in cotton. Also, the use of safeners in corn and sorghum gives hope that this approach may eventually be useful in cotton. However, to date no safeners are commercially available for any dicotyledonous crop.

Plant breeders and genetic engineers may eventually develop cotton varieties which can tolerate herbicides that control their weedy relatives. However, for the near future, improved weed control will probably result from the synthesis and testing of new chemicals or from improved application techniques.

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Chapter 9

REDUCED-TILLAGE SYSTEMS

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and
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INTRODUCTION

Tillage has been one of the most important production tools available to cotton (*Gossypium hirsutum* L.) producers in the United States. The average annual number of tillage operations varies from state to state but generally involves 8 to 12 tillage operations (Reeves, 1975). At least half of these are specifically for the control of weeds.

In cotton production, a number of terms describe tillage operations and the interchangeable use of many of these has been confusing. In this report, "no-till" is defined as tillage restricted to the immediate seed zone (Figure 1). "Minimum-tillage" and "reduced-tillage" implies that the entire surface is tilled, but that there are fewer tillage operations per year than when compared to conventional tillage systems. "Conservation-tillage" is defined as reduced-tillage or minimum-tillage systems in which 30 percent or more of the previous crop residue remains on the surface as a cover after planting.

Despite the success utilizing reduced-tillage systems in cotton production, such systems have not been as readily adopted for cotton as for other crops. Young (1982) reported that technology for reduced-tillage systems of cotton is presently at about the level of soybeans in the early 1970s. McWhorter and Barrentine (1988) reported that more members in the Weed Science Society of America survey, regardless of region or type of employment, ranked conservation tillage the most important crop or situation that needed new and improved weed technology. With the development of needed technology, cotton grown on erodible soils will probably be cultured with some form of conservation tillage involving a reduced number of tillage operations.



Figure 1. Cotton seedlings four days after emergence in no-tillage production research at Stoneville, Mississippi. (Photo by C. T. Bryson.)

HISTORY OF TILLAGE IN COTTON

Weeds have been a major problem in cotton production. In early cotton production, human energy, hand-hoeing and animal power were used to control weeds. Animal power was replaced by tractors in the 1930s and 1940s. Since the 1950s, herbicides have been used to supplement mechanical tillage and hand-hoeing.

In 1983 Block (1984) estimated the American farmer had tripled his use of conservation tillage during the last decade to one of every three acres planted. He also projected that, by the year 2010, conservation-tillage would be utilized on more than 90 percent of the land planted. King and Holcomb (1985) predicted that conservation-tillage will be used on 50, 80 and 95 percent of planted land in 1990, 2000 and 2010, respectively. This prediction of greater use of conservation-tillage indicates that reduced tillage practices are expected to increase greatly for all crops, including cotton.

Historically, mechanical tillage has been the most important tool for weed control in cotton production. Mechanical tillage in cotton can be categorized as preplant tillage and postplant tillage. Wiese and Chandler (1979) estimated that 50 percent of all preplant tillage is for weed control. Tillage, in addition to controlling weeds at preplanting, is helpful in forming planting beds which promote uniform stands of cotton and provide a smooth surface for postemergence weed control (Kempen, 1987). Postplant tillage is used extensively to control weeds

growing between the rows. These cultivations alone are inadequate to control weeds along the rows and are performed simultaneously with postemergence, directed, herbicide sprays to control weeds within the row (Foy, 1959; Holstun, 1963; Upchurch and Selman, 1968).

The moldboard plow, one of the primary tillage tools used in the United States, is an efficient tool for burying weeds and crop residues (Raney and Cooper, 1968; Kempen and Greil, 1985; King and Holcomb, 1985). However, burial of plant residues, once believed to be a beneficial practice, leaves the soil surface unprotected resulting in loss of soil from wind and water erosion (Kaddah, 1977; King and Holcomb, 1985; Unger *et al.*, 1977; Webb *et al.*, 1986). The loss of soil due to water erosion for different crops and regions is summarized in Tables 1 and 2[1].

Webb *et al.* (1986) reported that about 47 million acres of major cropland, including summer fallow and hay, are highly erodible and fragile land (sheet and rill erosion only) (Table 1). On highly erodible acres, those planted to soybeans and corn have the highest erosion rate, with 29 tons per acre per year (TAY) for soybeans and 23 TAY for corn. Although 13 million acres of hayland are potentially highly erodible and fragile, the relatively low erosion rate of hayland (3.2 TAY) indicates that soil erosion is low as long as the land remains covered and is not tilled. Cotton has the smallest percentage (three percent) of highly erodible and fragile land among the seven major crops corn, soybeans, sorghum, cotton, wheat, oats and barley, and about 13 percent of the total erosion from cotton production comes from this three percent of the land. Cotton is grown on about 383,000 acres of fragile land and 170,000 acres of highly erodible land (Table 2).

Most of the highly erodible and fragile land is in the Southwest with the rest in the Mid-South, Appalachian, and Southeast regions[2] (Tables 1 and 2; Webb *et al.*, 1986). Hanson (1982) reported that wind erosion is also wreaking havoc, as five TAY of cropland are lost annually in the 10 Great Plain states. Three states, Colorado, New Mexico, and Texas, each have annual wind erosion rates above eight TAY.

When fully implemented, the conservation compliance provisions of the 1985 Farm Bill should drastically increase the number of cotton acres in reduced-tillage production systems especially on sandy or highly erodible soils. This bill states that producers must have an acceptable conservation plan in place by 1990 which must be fully implemented by 1995. Full compliance is required for producers to qualify for future federal farm payments or loans.

Historically, the total number of cotton acres planted no-till has been low. Lessiter (1988) reports that 1710 acres of cotton were planted no-till in 1972. He predicted that no-till cotton acreage will increase by three percent during 1988

[1]All of the tables in this chapter are in the Appendix at the end of the chapter.

[2]In this Chapter Regions in the Cotton Belt and states within each region will be as follows: Southeast—Alabama, Georgia, Florida, North Carolina and South Carolina; Mid-South—Arkansas, Louisiana, Mississippi, Missouri and Tennessee; Southwest—Oklahoma and Texas; and West—Arizona, California and New Mexico.

from the 13,464 acres in 1987, but the total no-till cotton acres across the Cotton Belt are down by 2,000 acres from a high in 1983.

Vast losses of soil from water and wind erosion, and the need to reduce production costs, are causing producers and researchers to reevaluate previous tillage practices. Leaving crop and weed residues on the soil surface (including crop/weed stubble) reduces raindrop impact and velocity of runoff water, thus limiting the detachability of soil particles (King and Holcomb, 1985). Surface residue also reduces wind erosion as it absorbs wind energy. Thus, tillage equipment, such as chisel plows, disks, etc., which leave much plant residues on the soil surface are used more frequently, and a trend exists to limit tillage to essential operations only. The basic tillage systems and other operations evaluated for establishing cotton stands are shown in Table 3. Tillage system "E" represents the most frequently used conventional tillage system in cotton production. Today's conventional tillage system in cotton consists of between 11 to 15 trips across the field (Reeves, 1975). This is very similar to the nine operations that are commonly used preplanting in California (Carter and Colwick, 1971). An addition of three to four postplanting cultivations brings the total to 13 or 14 operations per year.

Some of the earliest reduced-tillage research in cotton was conducted by Harris (1964) from 1950 to 1963 in Mississippi (Figure 2). He successfully eliminated postemergence cultivations and increased yields and profits by utilizing herbicides instead of tillage to control weeds. In addition to hand hoeing, Harris used broadcast preemergence applications and postemergence directed and spot sprays of herbicides to control weeds. Usually, neither multiple applications of spot spraying nor hand hoeing are profitable for today's cotton farmer.

Other early research from 1954 to 1957 was conducted in Arizona by Kaddah (1977). He reported that minimum-tillage treatments produced higher yields than conventional treatments in cotton. The increased profit from additional yield and the reduced-tillage indicated that not all conventional tillage practices were essential.

Success with early minimum-tillage systems for cotton production encouraged additional research to determine which tillage practices were essential for weed control, yet would conserve the soil and reduce crop production costs.

Each basic tillage system (Table 3), which will be discussed in detail later, seems to fill a need for a certain region or local/national problems. From our literature search, the concentration of past research efforts in the Southwest (31 percent), Mid-South (22 percent), Southeast (36 percent) and West ($\leq$ 11 percent) is probably directly related to erodible and fragile land in these regions. If suitable reduced-tillage practices are developed which reduce production costs of crops, this should also increase incentives for adopting reduced-tillage practices on non-erodible land. From a practical standpoint, conservation-, reduced-, or no-tillage systems usually are not adopted in a locality unless there is an economic advantage over conventional tillage (Wiese and Chandler, 1987).

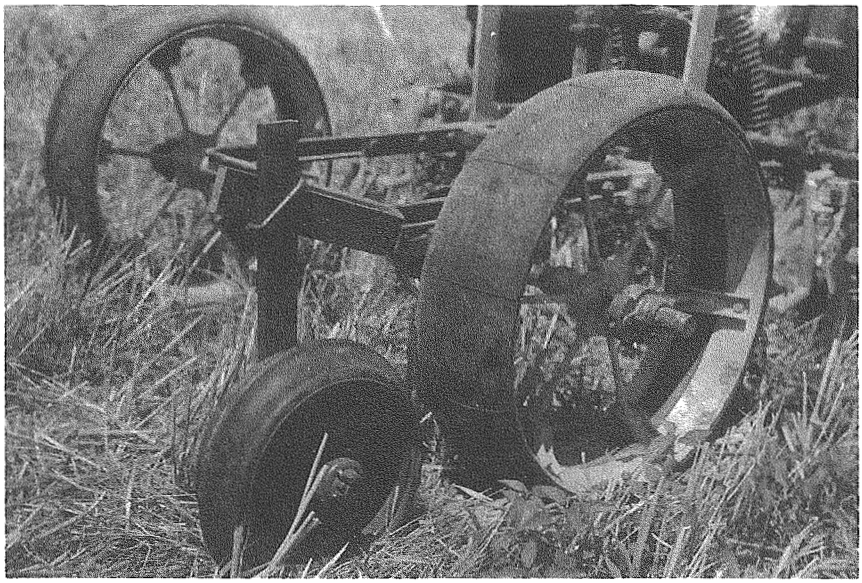


Figure 2. Cotton planted no-till in research experiments at Stoneville, Mississippi in the 1950s. (Photo by anonymous.)

ADVANTAGES AND DISADVANTAGES OF REDUCED- AND NO-TILLAGE COTTON PRODUCTION

In addition to reviewing the literature on reduced tillage systems of cotton, we conducted a survey in early 1987 among extension and research scientists in most of the cotton producing states to determine the most important advantages and disadvantages of reduced-tillage production systems in cotton in the United States. Reduced soil erosion was the most important advantage listed in the survey (Table 4). Soil residues of the previous crop and weeds (stubble and surface residues) remaining on the soil as a mulch should reduce wind and water erosion in cotton production as in other crops. These effects have been reported for other crops by Harrold (1972), Larson *et al.* (1970), Phillips and Young (1973), Triplett *et al.* (1973) and Woodruff (1972). McWhorter and Jordan (1985) stated that the crop residue in cotton would also provide protection for the seedling crop from wind and sand damage. Losses of soil through erosion in cotton have been estimated to range from seven to eight tons per acre per year (TAY) in Mississippi (Brandon, 1978) to over 40 in Texas (McWhorter and Jordan, 1985). Losses in minimum-tillage in Mississippi averaged four tons per acre per year of soil when compared to average losses of seven to eight in conventional tillage systems of cotton production.

Hanson (1982) reported that the tolerance level of soil erosion (the rate that soil may be replaced) ranges from two to five tons per acre per year, indicating

that the soil lost by water erosion under minimum-tillage in the above study was within the acceptable range. King and Holcomb (1985) reported for the Soil Conservation Service that conservation-tillage reduces soil erosion 50 to 90 percent compared with conventional tillage, with the percentage of surface covered by residue being the most important factor in determining the amount of the reduction. Mutchler *et al.* (1985) reported acceptable soil losses of 0.5 tons per acre per year with no-till cotton following no-till soybeans and wheat compared to less than 20 tons per acre per year with conventional tillage.

A number of advantages in reduced tillage systems in cotton production in our survey are closely related. Reduced production costs, including less labor and tractor time, with reduced equipment horsepower, reduced energy inputs, and lower capital investment in equipment are all expected from reduced tillage. These advantages are very similar to those given by Spurgeon *et al.* (1974) for limiting the number of operations in preparing a seedbed. These advantages include: (a) reduced cost for labor and equipment, (b) reduced fuel usage, (c) easier timing of operations since seedbed preparation is faster and simpler, (d) increased yield and return per acre (probably the most important advantage), (e) less soil erosion during winter and early spring rains which results in reduced soil compaction from tractor implements, (f) earlier harvest of cotton which usually brings increased prices and (g) fewer tractors required for a given size of farm.

Actual monetary savings reported from the use of reduced- or no-tillage *vs.* conventional tillage ranged from $37 to $135 per acre (Brandon, 1978; Carter and Colwick, 1971; Reeves, 1975; Wiese and Harman, 1982; Wiese *et al.*, 1988; Worsham, 1977; Wuertz, 1975). This does not include additional profit if yields were greater with reduced tillage. These profits are considered to be conservative estimates; profits in the 1970s have not been adjusted for inflation that has occurred in the last 10 or more years. Although the savings seem somewhat insignificant, one cotton producer (Wuertz, 1975), who farmed 15,800 acres in Arizona, indicated that a savings of $74 per acre could amount to the price of one or two new tractors each year. Based on production costs projected for cotton in California (Zelinski, 1987), tillage costs can represent as much as 15 percent of the total production costs. If total tillage costs could be reduced by 50 percent (from $120 to $60 per acre), as much as $60 per acre could be saved by reducing tillage practices in California.

Improved soil moisture, another advantage with reduced tillage, is especially important in the dryland cotton production area of the Southwest (Hanson, 1982; Keeling and Abernathy 1988; Wiese and Harman 1982; Waddle, 1984). Waddle (1984) reported that 20 inches of precipitation is needed to mature a cotton crop at yields of 0.75 bales per acre. This amount of precipitation approaches that of some areas of the High Plains of Texas and Oklahoma. Therefore, a small improvement of soil water storage in those areas could improve yields more than in areas of the Mid-South and Southeast that receive 47 to 60 inches of precipitation and areas of the West that have to be irrigated to produce crops. Wiese and

Harman (1982) reported that when wheat stubble contributed about 2007 pounds per acre of residue, there was about 1.2 inches more available stored moisture in the upper 2.6 feet of the soil profile at planting; and cotton yielded up to 90 pounds per acre more lint under no-tillage than under conventionally tilled practices (Figure 3). In another study, Unger *et al.* (1977), reported that many crops in the Southwest produce residues of less than 4000 pounds per acre, which is considered the amount of residue needed to contribute substantially to storage of soil moisture. According to Mutchler *et al.* (1985), the residue cover of cotton is less than that of soybeans and corn, and the tap root system of the cotton plant contributes little to holding soil in place.

Improved soil fertility resulting from reduced tillage is probably due to increased organic matter and available nutrients from surface plant residues and cover crops (Hanson, 1982; King and Holcomb, 1985; Waddle, 1984). Also, Hanson (1982) reported that some soil scientists estimate that it takes more than $6 worth of fertilizer to replace nutrients lost in a ton per acre of eroded topsoil.

Improved cotton yields, along with several other advantages shown in Table 4, ranked lower in importance in our survey than advantages discussed above. Yields are not necessarily greater with reduced- or no-tillage practices when compared to conventionally tilled cotton. However, as shown in Table 5, over twice as many research studies reported higher yields than reported lower yields. Difficulty in establishing cotton (or poor crop growth in cover crops) and inadequate weed control were most frequently cited as limiting causes for poor cotton yields in reduced-tillage. Since the majority of studies (85 percent) reported equal or higher yields under reduced-tillage of cotton, reduced-tillage, particularly where soil is conserved and production costs are reduced, holds considerable promise for the future in cotton production.

The two most frequently cited disadvantages for reduced-tillage in cotton production in our survey were the increased cost for weed control and weed control difficulties (Table 6). Knake *et al.* (1965) indicated herbicides can replace much of the tillage carried out for many agronomic crops including cotton. In many cases, herbicides are more expensive than tillage operations. Worsham (1977) stated that successful weed control holds the key to the success or failure of reducing tillage. He emphasized that reducing tillage should not be attempted on land where perennial weeds are troublesome. He also pointed out that ecological shifts in weed populations can appear quickly with continuous use of reduced-tillage production. Frans (1977) and Abernathy *et al.* (1984) emphasized that adequate weed control must be achieved to obtain good yields of cotton. This research indicated that postemergence cultivation was needed regardless of the method of seedbed preparation (either no-, reduced-, or conventional tillage) and cotton yields were reduced with poor weed control.

Another disadvantage to no-till or reduced-tillage cotton production is soil compaction by machinery required for herbicide and/or insecticide application, planting, harvesting and stalk removal. In the Delta Region, soil compaction is a



Figure 3. Cotton planted no-till in wheat stubble in the Southern Plains of Texas. (Photo by A. F. Wiese.)

cotton yield limiting condition that requires subsoiling to disrupt a hard pan zone of soil. McConnell *et al.*(1989) report that subsoiling increases lint yield between 12 and 41 percent. They also indicate that shallow tillage pans of select soil types are more detrimental to cotton development than deeper tillage pans.

Herbicide application errors can be more costly to the producer in reduced tillage production than in conventionally planted crops since backup cultivation may be more difficult or impossible. Errors frequently cited include the failure to use preplant foliar herbicides and/or a surfactant, poor spray coverage, and spray volumes which are too low.

In general, present research results indicate weed control can be obtained under reduced-tillage systems (as evidenced by equal or better yields), although better management may be required under reduced-tillage than under conventional tillage systems.

The lack of good seedbed preparation and difficulty of obtaining good cotton stands were mentioned in our survey as primary concerns associated with reduced-tillage culture of cotton. Results of research do not indicate that poor stands were a common problem in reduced-tillage production systems; however, in no-till systems, cotton stands may be affected by environmental conditions and by hard or crusty soils. Mullins *et al.* (1977) observed that no-tillage planters left depressions over the cotton seed allowing water and herbicides to concentrate in the seed area interfering with the emergence and growth of cotton. Al-

though they observed that crusting of the soil also interfered with cotton emergence, they found that the crust-resistance strength of no-tillage soils was about twice that of conventional-tillage soils.

High salt concentrations also contribute to stand and cotton growth problems in the Southwest (McWhorter and Jordan, 1985), and subsoiling has been shown to be beneficial in breaking soil pans and reducing salinity problems (Waddle, 1984; Kaddah, 1977). The possibility of stand problems occurring with reduced-tillage production means that good management will be required to obtain an adequate seedbed for the emergence and growth of cotton.

One disadvantage cited in our survey was the increase in insect and disease problems which might occur in reduced-tillage cotton production systems. Crop diseases and other pest problems in soybeans and corn are sometimes more severe in no-tillage or reduced-tillage systems than in conventional production systems (Larson *et al.*, 1970; Lessiter, 1974; Shear, 1968; Wiese, 1977). As early as 1879, Comstock reported fall plowing, especially in the northern part of the cotton producing areas of the Southeast, aided in the destruction of bollworms (*Heliothis* spp.) by bringing them to the soil surface where they are killed by cold temperatures during the winter months (Comstock, 1879). Fall stalk destruction, the shredding and incorporation of cotton stalks into the soil, is a sanitary measure required by law in the Southwest to control cotton pink bollworm [*Pectinophora gossypiella* (Saunders)] (Anonymous, 1984). A key management strategy for boll weevil [*Anthonomus grandis* (Boheman)] is also the reduction of overwintering populations by early harvest and prompt shredding and plowdown of cotton residues (Anonymous, 1984; Kaddah, 1977; Ridgway, 1984). Similarly, tillage is performed to manage certain diseases of cotton. McWhorter and Jordan (1985) point out that there has been little research on cotton diseases in cotton grown with reduced-tillage systems. Clean tillage practices that completely bury cotton debris as soon as possible after harvest are important for preventing buildup of inoculum and early-season infections by some seedling pathogens, foliar pathogens and viruses (Bell, 1984). Although unknown, it would appear that many insect and disease problems would be difficult to manage if tillage was drastically reduced.

In some areas, continuous use of reduced-tillage in cotton may not be possible because of the lack of technology to control weeds. It then becomes important to control weeds by rotating tillage systems or rotating crops which permit the use of a wider range of herbicides than in a monoculture system. A crop rotation of soybeans for three consecutive years following cotton has been shown to reduce bermudagrass [*Cynodon dactylon* (L.) Pers.] populations by as much as 70 to 90 percent in three Mississippi Delta fields (Bryson, 1985). Usually crop rotation practices are determined by commodity prices and maximum production rather than weed control problems or soil conservation efforts, although these are often interrelated.

REDUCED-TILLAGE/CROPPING SYSTEMS FOR COTTON PRODUCTION

Basic types of tillage systems and types of planting evaluated for establishing cotton stands are summarized in Table 3. Unlike system "E," systems "A" to "C" contain relatively few operations. Although all of these systems are shown as following a cotton crop, they could follow other crops and planting would be accomplished with either a conventional planter after some tillage or with a no-till planter into the previous crop stubble/residue. System "A," the ratooning of cotton, which was practiced on a small scale in some areas of Arizona at one time, may involve the fewest operations of all systems. However, even with this system, herbicides were usually incorporated into the planting beds after stalks were shredded. This system was reevaluated in 1978 to 1980 as a potential practice for Arizona. Although occasional yield advantages were observed, the increased insect (especially the boll weevil in Arizona and California), disease and weed problems appeared too difficult to manage with present technology (Van Brackle, 1979, 1980a, 1980b).

Without the bedding operation, system "B" would be considered no-tillage culture (only tillage at planting in the drill row). Apparently some growers prefer to keep the same planting beds for more than one year (Fields, 1982). But even with rehipping, the same beds (including the desired firmness of beds) could be maintained. Also herbicides could be incorporated into beds as beds are made before planting (Wiese and Chandler, 1987). Hamilton (1987)[3] reported that this method is sometimes used in Arizona to incorporate herbicides, but poor weed control and excessive crop injury may occur.

System "C" would be a better choice for a tillage system when little tillage is desired and subsoiling is needed to reduce soil compaction and salinity problems (Carter *et al.*, 1965; Carter and Tavernetti, 1968; Carter and Colwick, 1971; Kaddah, 1977; Waddle, 1984; Stockton *et al.*, 1964). Since subsoiling is beneficial to many types of cotton soils, it appears that system "B" would only be used in instances where soil compaction and/or water infiltration were not problems. Fall tillage (plowing or disking) needed for destroying winter annual weeds, or for other reasons, could be substituted for or used in addition to subsoiling in system "C."

System "D" would be especially suited for areas where a cover crop is needed during fallow periods to prevent water and wind erosion (Brown *et al.*, 1985; Hardin, 1984; Hurst, 1983; Touchton *et al.*, 1984; White *et al.*,1986; White and Worsham 1990). When following a legume or cereal crop, cotton could be seeded, without tillage, with a no-till planter directly into the stubble/residue of the legume or cereal crop. If a legume or cereal crop is planted as a special need for cover, some light disking might be needed as shown in establishing the cover

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crop, and a herbicide plus shredding would probably be needed to kill the cover crop before no-till planting of cotton. It appears that several legumes have been successful in serving the dual purpose of supplying nitrogen and providing cover. One study showed it was advantageous to plant the legume in the standing cotton stalks (rather than after shredding as shown in Table 3) after defoliation and before harvesting. Earlier warm temperatures in the fall and longer growing periods in the spring resulted in the earlier reseeding of the legume. Early cover crop reseeding was considered essential because the legumes did not have to be planted each year and cotton planting was not delayed (Touchton *et al.*, 1984).

Cover crops and crop rotation systems in cotton present unique possibilities for protection of soil movement as well as potential problems as weeds. Hairy vetch and crimson clover (White and Worsham, 1990) were successfully utilized for winter cover, but additional herbicide inputs are required to burn down these plants prior to cotton planting. Double cropping with sorghum (Keeling and Abernathy, 1989) and barley (Wiese *et al.*, 1988) may require herbicide inputs to control unwanted volunteer crops in cotton, but Wiese *et al.* (1988) reported that although costs were higher, increased yield and reduced machinery depreciation made no-tillage over $40 per acre more profitable than conventional tillage in no-till cotton after irrigated barley production systems.

The additional operations and kinds of tillage tools shown for tillage system "E" would be beneficial in incorporating crop debris into the soil, a practice required by regulation in the Southwest (Kaddah, 1977). Both the deep burial of weeds by plowing and the extra tillage, if timely, are useful in destroying weeds. Other methods of tillage, such as landplaning, are especially required periodically where furrow irrigation is practiced. In general, conventional tillage systems vary depending on the particular year or needs of the land. Research indicates some operations commonly used in conventional tillage systems are not essential for the successful culture of cotton.

Regardless of the tillage system used (Table 3), herbicides could be applied as preplanting, preemergence and postemergence treatments as needed. Also, post-planting cultivations can usually be conducted as needed. However, cultivations are more difficult in fields with high levels of crop residues (surface residues/stubble). Other tillage systems than those listed in Table 3 are possible, but these represent the basic systems evaluated and reported. Specialized systems for specific soil types, such as the one presented by Morris *et al.* (1990) for clay soils may require a more timely use of limited-tillage and herbicide inputs because of environmental conditions and soil texture. Weed control problems ranked first as the most important limiting factor of reduced-tillage systems in cotton production in the United States (Table 7).

MOST TROUBLESOME WEEDS

The ranking of troublesome weeds in cotton by research and extension personnel is shown in Tables 8, 9 and 10. Cotton losses due to weeds are shown in Table 11. The herbicides used to control weeds in cotton are shown in Table 12. Although herbicides are used in combination with an average of two to four postemergence cultivations, weeds still reduce cotton yields six percent or more in most regions (Chandler *et al.*, 1984; Chandler, 1984; and Table 10). Cotton losses reported in Table 11, where state losses were averaged by regions, do not vary greatly (six to eight percent). Chandler *et al.* (1984) reported losses ranging from a low of 8 percent for the Southwest to a high of 16 percent for the Southern Plains. Estimated losses for the Southeast and Mid-South were 11 and 15 percent, respectively.

McWhorter and Jordan (1985) state nearly 66 percent of all cotton losses due to weeds have been caused by five species: johnsongrass [*Sorghum halepense* (L.) Pers.], cocklebur (*Xanthium strumarium* L.), prickly sida (*Sida spinosa* L.), morningglory (*Ipomoea* spp.) and nutsedge (*Cyperus* spp.). In our 1987 survey of research and extension personnel, these five weed species ranked at the top of the list in conventional-tillage and herbicide systems being utilized in the cotton producing belt (Table 8). Johnsongrass, morningglories, cocklebur, prickly sida, yellow nutsedge (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.) (Figure 4) were placed in the top ten most troublesome weeds by 94, 82, 71, 66 and 35 percent of the research and extension personnel responding to our 1987 survey. Bermudagrass (Figure 5) and pigweeds (*Amaranthus* spp.) were also placed in the top ten most troublesome weeds in conventional tillage systems by greater than 50 percent of the researchers and extension personnel. Our results are similar to estimated reduction in percent cotton yields by weeds and estimated cotton acreage infested by weeds reported by Whitwell and Higgins (1986) and in a list of the most troublesome weeds in cotton by states in the Southeast (Elmore, 1986).

When research and extension personnel were requested to project the 15 most troublesome weeds in reduced-tillage systems in cotton production systems nationwide, johnsongrass ranked number one and was placed in the top ten most troublesome weeds in the reduced-tillage cotton systems by all individuals responding (Table 9). From research in conservation tillage and tillage rotation systems including cotton in the Blacklands of Texas, Brown *et al.* (1987) found that the predominant weeds were johnsongrass and brown-top panicum (*Panicum fasciculatum* Sw.). Yellow nutsedge, bermudagrass, morningglories, purple nutsedge, prickly sida and cocklebur ranked as the top ten most troublesome weeds in reduced tillage systems as they had been ranked for conventional tillage systems. However, trumpetcreeper [*Campsis radicans* (L.) Seem. ex Bureau] and horseweed [*Conyza canadensis* (L.) Cronq.] (Figure 6) ranked in the top ten most troublesome weeds of cotton in reduced-tillage systems. Both these weeds,



Figure 4. Difficult-to-control perennial weeds such as purple nutsedge are often well established in no-till cotton productions systems. (Photo by C. T. Bryson.)



Figure 5. At harvest, bermudagrass causes reduction in lint grades in addition to reductions in yield due to competition. (Photo by C. T. Bryson.)



Figure 6. Comparison of (a) no-till *versus* (b) conventional-tillage cotton production systems at Stoneville, Mississippi where horseweed, trumpet creeper, and honeyvine milkweed were weed problems at the time of crop establishment. (Photo by C. T. Bryson.)

as well as perennials and winter annuals, are currently controlled by preplanting tillage operations. Reduction of tillage would require additional preplant-foliar herbicide applications to control these and other weeds as has been demonstrated in reduced-tillage cotton production by Brown and Whitwell (1987) and in no-till corn by Wilson *et al.* (1985).

A number of weed species ranked in the top ten regionally as the most troublesome weeds in reduced tillage cotton production systems in the United States but were not listed among the top ten nationwide (Table 8). For example, giant foxtail (*Setaria faberi* Herm.) ranked as the fifth most troublesome weed in Missouri. Silverleaf nightshade (*Solanum elaegnifolium* Cav.) and buffalobur (*Solanum rostratum* Dun.) were important weeds in Oklahoma and northern Texas. Devil's claw (*Proboscidea louisianica* (Mill.) Thuellung) which is highly competitive with cotton is an important weed of Texas. In the West, black nightshade (*Solanum nigrum* L.) and hairy nightshades (*Solanum sarrachoides* Send.) are important in cotton production in California. Lambsquarter (*Chenopodium album* L.) is important in the Southeast and the Tennessee River Valley in Alabama. In the Southeast and Mid-South, a number of scientists expressed concern about the importance of honeyvine milkweed [*Ampelamus albidus* (Nutt.) Britt.] and jimsonweed (*Datura stramonium* L.) in reduced-tillage cotton production.

Sicklepod (*Cassia obtusifolia* L.) ranked number ten as the most troublesome

weed presently occurring and projected for reduced-tillage cotton production systems. Although this weed does not occur nationwide, the importance placed on it in the Southeast ranked sicklepod among the top ten weeds. Sicklepod is a major weed problem in the Southeast and is moving north and west in its distribution. In contrast, velvetleaf (*Abutilon theophrasti* Medik.) and giant foxtail, which are important weeds in soybean in the Midwest, are moving toward the Southeast and may become major cotton weeds further south and eastward.

In general, the data presented in Tables 10 and 11 complement one another, *i.e.*, the most common weeds reported in Table 11 account for the majority of the losses reported in Table 10, and data in both tables agree with the general ranking of weeds for the total Cotton Belt in Table 8. The weed genus *Echinochloa* was about the only genus infesting large acreages that was not listed as one of the top ten troublesome weeds. Other weeds ranked in the top ten, either in our survey or those reducing yields, were also the same weeds infesting the greatest acreage of cotton land. For additional information see Chapters 4, 5 and 6.

WEED CONTROL

Supplementing mechanical cultivation with applications of herbicides has been the accepted practice for managing weeds in cotton (Holstun and Wooten, 1968; Kempen and Greil, 1985). Although cultivation is helpful in the Southwest for establishing planting beds and furrows for carrying irrigation water, the primary role of cultivation is for weed control, as demonstrated by Buchanan and Hiltbold (1977). They reported, over a three- to five-year period with two different soil types, cotton yields did not vary with different cultivation practices. Cultivation resulted in cotton yields equivalent to but no greater than those for chemical or hand removal of weeds when cotton was grown without cultivation. Cotton yield reductions were reported to be 90 to 95 percent at two locations when weeds were not controlled.

Herbicides are especially useful for controlling weeds in the drill row of crops where weeds escape because of improper cultivation or where size prohibits their coverage with soil during cultivation (Kempen, 1987; Chandler, 1984). Yield losses due to weeds are indicative of the severe weed problems that occur throughout cotton producing areas, and indicate the reason for high herbicide usage reported in Table 12 (See also Chapters 5 and 7). As shown in Table 12, six methods of herbicide application are used in conventional tillage systems in current cotton production. These include: (a) preplanting foliar applied, (b) preplanting soil incorporated, (c) preemergence, (d) postemergence, (e) spot treatment and (f) layby. Based on the estimates provided in Table 12, 80 to 90 percent of cotton acres are treated with a preplant soil incorporated herbicide(s). Also, since sufficient and timely rainfall usually occurs in the Mid-South and Southeast to incorporate surface-applied herbicides, 80 to 90 percent of cotton acres in those two regions receive a preemergence application of one or more herbicides.

The higher annual rainfall, previously reported, in cotton producing areas of these two regions probably increases weed problems and accounts for the greater use of postemergence treatments in these regions as well. However, many acres are also treated in the West and Southwest with postemergence herbicides (directed or spot sprays) before or at cotton layby.

In no-tillage production, preplant incorporated herbicide treatments would be eliminated. The predominant use of preplant incorporated herbicides in the West and Southwest would appear to preclude the use of this tillage system (Weaver, 1986; Table 12). In situations where preplant incorporated herbicides are necessary, a reduced-tillage system may be required, especially where grasses and small seeded annuals are a problem. Also, where no-tillage cotton production is desired and preplant incorporated and preemergence herbicide treatments cannot be used, control of grasses could be accomplished with postemergence applications of Fusilade® (fluazifop), Poast® (sethoxydim) or Whip® (fenoxaprop). However, where broadleaf weeds are a serious problem, adequate or economical control may not be possible without additional new herbicides.

The herbicides listed in Table 12 include most of the herbicides that are registered for use in cotton and are the most common applied for the management of weeds in cotton (Kempen, 1987; Whitwell and Higgins, 1986). When weed control practices are compared between conventional and reduced-tillage systems, the increased use of herbicides to replace tillage previously used in conventional systems represents the greatest change in managing weeds in reduced-tillage systems (Tables 13 and 14). Some reports indicate reduced-tillage systems would be less economical than conventional tillage because of increased herbicide costs (Frans, 1977; Harman and Wiese, 1985; Worsham, 1977).

In reduced- or no-tillage production of cotton, a preplant foliar application of a herbicide(s), usually Gramoxone® (paraquat), MSMA or Roundup® (glyphosate), almost always is needed to control emerged weeds (McWhorter and Jordan, 1985) (Table 13). Effectiveness and the cost of a herbicide used at a rate high enough to control weeds preplanting is somewhat dependent on weed size, but costs may be more expensive than preplant tillage (Frans, 1977; Harman and Wiese, 1985; Worsham, 1977). Although these treatments are used to a limited extent in all regions, preplant foliar applications are not a common practice (Table 12).

Other herbicide treatments—preplant incorporated, preemergence and postemergence—will continue to be used in reduced tillage as they have been in conventional systems (Table 13), but preemergence treatments will be used only in areas that have adequate rainfall or are equipped to incorporate herbicides with sprinkler irrigation. Also, when preplant incorporated treatments are used in reduced-tillage systems, it will be necessary to incorporate the herbicides when planting beds are formed with listers, disk bedders, or other equipment (Wiese and Chandler, 1987; Tables 15 and 16). McWhorter and Jordan (1985) suggested that the preplant incorporated herbicides could be applied immedi-

ately after hipping over old beds. This would be accomplished about two weeks before planting with the use of a rolling cultivator or a Do-all on sandy or silt loam soils where the soil is well pulverized after hipping or rehipping operations. Since preemergence herbicides must be activated through rainfall, and rainfall is not always timely, cotton producers may place more dependence on effective postemergence herbicides for weed control. Postemergence herbicides that could be used either selectively over-the-top or as directed sprays are shown in Table 12.

Previous research indicates that good weed control usually can be obtained now in reduced-tillage systems of cotton (Table 13). Adequate weed control was obtained in reduced-tillage systems of cotton in about 80 percent of the experiments covered in our review. Some effective herbicide treatments used in reduced-tillage are shown in Table 13 and are discussed below. As expected, since relatively few good foliar herbicides are available, Gramoxone®, MSMA and Roundup® were the three herbicides applied most frequently for killing established weeds during a fallow period after a crop was harvested or sometime before planting when tillage was not used. Another frequent use of these herbicides was to kill a cover crop just before cotton planting. Many herbicides, such as Cotoran® (fluometuron), Caparol® (prometryn) or one of the dinitroanilines [Prowl® (Pendimethalin) or Treflan® (trifluralin)], were combined with the above foliar herbicides to provide residual control until crop planting or even extending until crop harvest. Prowl® and Treflan® were commonly used as soil incorporated treatments, whereas Cotoran®, Caparol®, Bladex® (cyanazine), Zorial® (norflurazon) or others were applied at planting as overlay treatments. Most of the herbicides shown in Table 12 as postemergence treatments were applied in one or more studies as directed sprays either early in the growing season or up to layby time of cotton. MSMA, Fusilade® or Poast® were applied either as broadcast over-the-top treatments or as spot sprays. When Roundup® was applied as a broadcast treatment, it was applied with a special applicator.

Although there have been more successes than failures, weed control problems have occurred in reduced-tillage systems of cotton. Most failures have occurred because perennial weeds were not controlled adequately (Hamilton[3]; Lyon, 1975; Triplett *et al.*, 1983; Van Brackle, 1980; Worsham, 1977). Herbicide treatments have failed to control annual weeds as well in some reduced-tillage cotton production systems (Brown and Whitwell, 1985; Brown and Whitwell, 1988; Unger *et al.*, 1977). Reports indicate that horseweed increased without fall or late winter tillage (Brown and Whitwell, 1988) and additional herbicide inputs are required to control this weed (Hayes *et al.*, 1988; Keeling *et al.*, 1989). Since winter annuals may begin germinating in early to late fall, they can become rather large by early spring making control of these large plants difficult with foliar sprays before or at the time of cotton planting.

Whether reduced- or no-tillage production of crops will have a significant influ-

[3]Ibid.

ence on the difficulty of control of winter annuals is not known, but there are probably many winter annuals presently controlled by tillage which would present a problem if they are not controlled by tillage. Hamilton[3] reported that control of the perennial silverleaf nightshade, is easier to obtain in tillage systems where moldboard plowing is used. Plowing in general has been helpful in managing weeds, especially perennials (Raney and Cooper, 1968; McWhorter and Jordan, 1985). The success shown by the selective grass herbicides, Fusilade®, Poast® and Whip® in controlling annual and perennial grasses in cotton in conventional tillage systems indicates that they will be useful in managing both annual and perennial grasses in reduced-tillage systems of cotton. Similar herbicides with selectivity on cotton and activity on broadleaf weeds would be extremely helpful in the successful management of these weeds in reduced- or no-tillage systems of cotton.

Regardless of the herbicides utilized for weed control in cotton production, reduced- or no-tillage systems are probably more effective in Texas and Oklahoma because the state had less severe weed infestations than in the Mid-South or Southeast. One of the last regions to possibly adopt minimum- and reduced-tillage cotton production systems is the Mid-South due to the highly fertile alluvial soils and high rainfall in addition to the high growth rate and reproductive capability of weeds in this region. Research, previously discussed in this chapter, has demonstrated that reduced-tillage can be utilized in the Mid-South. The lack of reduced- and no-till cotton production systems now being utilized in the Mid-South is due in part to the development and registration of new highly selective herbicides.

The number of acres of cotton irrigated in the Southeast and Mid-South has increased over the past decade. This has increased the possibility to utilize chemigation for weed control; however, this technology has not been widely used. Commonly utilized methods of irrigation include over-the-top sprinkler, furrow irrigation and trickle irrigation. Some of these irrigation systems may not be compatible in reduced-tillage cotton production because one or more additional cultivations are required to properly shape cotton beds for furrow irrigation or drainage of excess water. Barney and Whitmore (1989) reported that Prowl® applied preplant and incorporated with irrigation water applied immediately after application proved to be effective in controlling weeds common to west Texas without injuring cotton. Peacock and Goldhamer (1984) reported cotton yields were reduced in the West when weed control traffic occurs with furrow irrigation practicies. They reported that cotton yields were lower in rows (beds) with adjacent wheel traffic than in rows without traffic.

[3]Ibid.

SUMMARY

The increased stored soil moisture created by reduced-till production and the reduction in water and wind erosion of soils will be highly advantageous in cotton production throughout the United States. However, it has been demonstrated that no-tillage and reduced-tillage systems are most useful on well-drained and sloping soils which are highly susceptible to water erosion. Yields may be greater with conventional cultivation systems than with no-till or reduced-till on poorly drained soils.

Trumpetcreeper, honeyvine milkweed, nightshades, nutsedge, bermudagrass, and johnsongrass are perennials that often increase in severity in reduced-tillage systems. In addition, annual weeds such as velvetleaf, jimsonweed, hemp sesbania, and sicklepod may increase in other regions of the Cotton Belt. Many of these weeds are now causing yield losses of 5 to 10 percent within specific states or regions. Often these weeds are among the most difficult to control. In no-till and reduced-till systems, these weeds frequently necessitate preplant applications of herbicides for adequate control. Regardless of the tillage system, the single most important need today in cotton production is a selective herbicide that can be applied broadcast over-the-top for control of a wide spectrum of broadleaf weeds.

The usage of no-till or reduced-tillage offers the producer a management tool for solving cotton production problems that include moisture conservation, and wind and water erosion. Because weed control has been obtained without adversely affecting cotton yields, the total acreage of reduced-tillage in the Cotton Belt is expected to increase in the future.

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Chapter 9

APPENDIX

This appendix contains all of the tables referred to in Chapter 9. For Tables 8, 10, 11 and 12 the regions are as follows: West–Arizona, California and New Mexico; Southwest–Oklahoma and Texas; Mid-South–Arkansas, Louisiana, Mississippi, Missouri and Tennessee; and Southeast–Alabama, Georgia, Florida, North Carolina and South Carolina.

Table 1. Crops and their acreage of highly erodible and fragile land excluding wind erosion). (Adapted from Webb *et at.*, 1968).

Crops	Area	Proportion of cropland	Annual erosion rate	Percent of total erosion from erodible acres
	(Mil. acres)	(%)	(Tons/A)	(%)
Row crops				
Corn	13.3	14.6	23.0	51.1
Soybean	7.2	10.8	28.6	43.6
Sorghum	1.5	8.7	15.9	31.0
Cotton	0.6	3.6	14.1	13.0
Subtotal	22.6	11.8	24.1	45.0
Small grains				
Wheat	7.2	8.2	12.7	32.3
Oats	1.4	15.4	10.3	38.5
Barley	0.7	8.8	9.6	30.5
Subtotal	9.3	8.9	12.0	32.9
7 major crops	31.9	10.8	20.6	42.6
Summer fallow	2.1	7.6	8.8	24.3
Hay	12.8	25.2	3.2	63.6
Subtotal	46.8	12.5	15.3	41.1

Table 2. Cotton cropland, highly erodible land, and fragile land, by regions. (Adapted from Webb et al., 1986.)

Region[2]	Total cotton	Highly erodible and fragile lands				Percent of region's cotton cropland
		LG4[1]	LG5[1]	LG6[1]	Total	
		(Acres x 1,000)				(%)
Northeast	2	0	0	0	0	0
Appalachian	367	44	17	11	72	19.6
Southeast	767	23	6	11	40	5.2
Delta States	2,662	57	12	21	90	3.4
Corn Belt	315	0	0	0	0	0
Lake States	0	0	0	0	0	0
Northern Plains	3	0	0	0	0	0
Southern Plains	10,198	12	0	328	340	3.3
Mountain	590	0	0	8	8	1.4
Pacific	1,599	0	0	4	4	.3
U.S. total	16,502	136	35	383	554	3.4

[1]LG4 and LG5: land groups with high erosion potential; LG6: land group with fragile land.
[2]Regions with cotton production are Southeast; Delta States = Mid-South; Southern Plains = Southwest; Pacific = Western.

Table 3. Operations [least (A) to greatest (E)] in establishing a cotton stand.

A	B	C	D	E
1. Shred stalks	1. Shred stalks	1. Shred stalks	1. Shred stalks	1. Shred stalks
2. Grow ratooned ("stub") cotton from previous crop	2. Bed (1 or more)	2. Chisel (subsoiling) or precision till in fall or spring	2. Plant covercrop	2. Disk (1 or more)
	3. Plant conventionally	3. Bed (1 or more)	3. Light disking	3. Chisel (subsoil) if needed
	could omit bedding and apply herbicides if needed	4. Plant conventionally	4. Apply herbicide to kill covercrop	4. Disk (1 or more) with 2nd at angle
		could subsitute or include as extra operation sweep or moldboard plowing or disking for step 2.	5. Shred covercrop if needed	5. Bed (1 or more)
			6. Plant with No-Til planter	6. Condintion bed
			could plant in previous years crop stubble/residue with No-Till planter	7. Plant conventionally
				Moldboard plowing could be an additional operation between steps 3 and 4. Land planing could be additional operations between steps 4 and 5

All systems could have postemergence (early and/or late, preplant, and preemergence herbicides applied if needed. Nematocides, if needed, could be applied after bedding. In systems B and C, cotton could be planted on old or new cotton bed. Bed conditioning might also be needed for systems B, C, and D. An additional bedding might be done for fertilization. Postplanting cultivations could be conducted if needed.

Table 4. The 15 most important advantages of reduced-tillage systems in cotton production in the United States as ranked by 29 research and extension agronomy, crop science, and weed scientists from AL, AR, AZ, CA, GA, LA, MO, MS, NC, NM, OK, TN and TX in 1987.

Advantage	Weighted[1]
1. Reduce soil erosion	100
2. Reduce total production costs	90
3. Reduce labor and tractor time	55
4. Saves soil moisture	50
5. Saves time	40
6. Lower horsepower equipment required	30
7. Reduce energy inputs	30
8. Reduce soil compaction	30
9. Improves soil fertility	25
10. Improves yields	20
11. Lowers capital investment in equipment	20
12. Presents double cropping opportunities	20
13. Easier crop establishment on clay soils	20
14. Improves yields on clay soils	10
15. Better field access (on wet soils)	10

[1]Average rank on a scale of 0 (least important)—100 (most important) as to most important advantages listed.

Table 5. A summary of literature citations on cotton yield responses as a result of practicing reduced- or no-tillage culture of cotton.

Poorer yields than conventional-tillage	Equal yields to conventional-tillage	Better yields conventional-tillage
Brown and Whitwell (1984)	Alston *et al.* (1976)	Harmon and Wiese (1985)
Bryson (1988)	Brandon (1978)	Kaddah (1977)
Grisso *et al.* (1984)	Brown *et al.* (1985)	Mutchler *et al.* (1985)
McConnell *et al.* (1989)	Brown and Whitwell (1985)	Touchton *et al.* (1986)
Morrison *et al.* (1990)	Bryson (1988)	Van Brackle (1980b)
Roach and Culp (1984)	Dale (1987a)	Wiese and Harman (1983)
Whitwell and Brown (1981)	Dale (1987b)	Wiese *et al.* (1987)
	Derting (1990)	Williford and Fulgham (1973)
	Frans (1977)	
	Grisso *et al.* (1984)	
	Harman and Wiese (1985)	
	Hoskinson and Hayes (1984)	
	Hurst (1983)	
	Lloyd *et al.* (1987)	
	Lyon (1975)	
	Phillips (1968)	
	Roach (1981)	
	Roach and Culp (1984)	
	Spurgeon *et al.* (1974)	
	Stevens *et al.* (1986)	
	Stibbe and Hadas (1974)	
	Touchton *et al.* (1984)	
	Touchton *et al.* (1986)	
	Van Brackle (1980b)	
	White *et al.* (1986)	
	White and Worsham (1990)	
	Whitwell and Brown (1981)	
	Wiese and Harman (1982)	
	Wiese *et al.* (1988)	
	Williford and Fulgham (1973)	
	Worsham (1977)	
	Wuertz (1975)	

Table 6. The 15 most important disadvantages of reduced-tillage systems in cotton production in the United States ranked by 29 research and extension agronomy, crop science, and weed scientists from AL, AR, AZ, CA, GA, LA, MO, MS, NC, NM, OK, TN and TX in 1987.

Disadvantage	Weighted[1]
1. Increased costs—weed control	100
2. Weed control difficult	85
3. Increased perennial weeds	65
4. Higher management levels required	65
5. Problems with stand establishment	45
6. Increased insect problems	45
7. Increased disease problems	35
8. Lack of good seedbed preparation	30
9. Technology lacking	15
10. Inability to incorporate herbicide	15
11. Annual weeds more difficult to control	15
12. Weed ecology shifts	15
13. Reduced cotton grades (trash due to weeds)	15
14. Old stalk removal	15
15. Poor cotton production/yields	15

[1]Average rank on a scale of 0 (least important)—100 (most important) as to the most important disadvantages.

Table 7. The 15 most important limiting factors of reduced-tillage systems in cotton production in the United States as ranked by 29 research and extension agronomy, crop science, and weed scientists from AL, AR, AZ, CA, GA, LA, MO, MS, NC, NM, OK, TN and TX in 1987.

Limiting factor	Weighted[1]
1. Weed problems	100
2. Technology/know how	40
3. Attitude of farmers	40
4. Stand establishment	35
5. Economics (cost more)	35
6. Reduces yields	32
7. Management problems	32
8. Increased diseases	20
9. Lack of properly designed machinery	19
10. Perennial weeds	19
11. Drainage of flatlands	19
12. Need to deep till (subsoil)	19
13. Requirement to cut/destroy stalks	19
14. Increased insects	16
15. Soil salinity	16

[1]Average rank on a scale of 0 (least important)—100 (most important) as to the most important limiting factors.

Table 8. The most troublesome weeds in cotton in the United States as ranked by research and extension agronomy, crop science, and weed scientists from AL, AR, AZ, CA, GA, LA, MO, MS, NC NM, OK, TN and TX in 1987.

	Region				
Rank	West	Southwest	Mid-South	Southeast	Beltwide
1.	Morningglories	Johnsongrass	Morningglories	Cocklebur	Morningglories
2.	Nightshades	Nightshades	Prickly sida	Sicklepod	Cocklebur
3.	Johnsongrass	Pigweed	Johnsongrass	Nutsedges	Johnsongrass
4.	Nutsedges	Nutsedges	Cocklebur	Prickly sida	Purple nutsedge
5.	Pigweed	Morningglories	Nutsedges	Bermudagrass	Prickly sida
6.	Groundcherries	Unicorn plant	Bermudagrass	Morningglories	Yellow nutsedge
7.	Bermudagrass	Bermudagrass	Spurges	Pigweed	Pigweed
8.	Barnyardgrass	Sidas	Hemp sesbania	Johnsongrass	Spurges
9.	Field bindweed	Texas panicum	Broadleaf signalgrass	Spurges	Bermudagrass
10.	Lambsquarter	Spurges	Barnyardgrass	Goosegrass	Sicklepod

Table 9. The projected 15 most troublesome weeds in reduced tillage systems of cotton production in the United States as ranked by 29 research and extension agronomy, crop science, and weed scientists from AL, AR, AZ, CA, GA, LA, MO, MS, NC, NM, OK, TN and TX in 1987.

Weed(s)	Weighted[1]	Placed in top 10 most troublesome
		(%)
1. Johnsongrass	100	100
2. Yellow nutsedge	75	83
3. Bermudagrass	55	83
4. Morninglories (annual)	50	75
5. Purple nutsedge	45	42
6. Trumpet creeper	42	58
7. Prickly sida	35	67
8. Horseweed	32	50
9. Cocklebur	30	42
10. Sicklepod	28	33
11. Spurges	25	42
12. Pigweeds	25	42
13. Redvine	24	33
14. Texas panicum	20	25
15. Bigroot morningglory	25	17

[1]Average rank on a scale of 0 (least important)—100 (most important) as to the most troublesome weeds.

Table 10. Estimated cotton acreage infested by weeds in regions in 1985. (Adapted from Whitwell and Higgins, 1986.)

Weed genera	Regions			
	West	Southwest	Mid-South	Southeast
	(Acres X 1000)			
Grass Weeds				
Brachiaria	—	—	610	17
Cynodon	91	10	474	57
Cyperus	254	550	413	154
Digitaria	—	650	905	273
Echinochloa	610	1180	480	20
Eleusine	—	—	662	94
Panicum	19	910	188	92
Sorghum	175	2075	1048	166
Other	279[b]	—	—	1[b]
Broadleaf Weeds				
Abutilon	—	—	35	10
Acanthospermum	—	—	—	66
Amaranthus	1401	4175	742	356
Ambrosia	—	—	110	51
Anoda	7	50	35	15
Cassia	—	—	34	259
Chenopodium	42	—	51	50
Convolvulus	65	27	—	—
Croton	—	—	—	160
Euphorbia	35	8	1167	185
Franseria	—	300	—	—
Helianthus	22	65	—	—
Ipomoea	205	520	1420	355
Melochia	—	—	—	5
Physalis	386	500	2	—
Polygonum	—	—	35	6
Portulaca	300	—	186	—
Proboscidea	—	3040	—	—
Salsola	34	1000	—	—
Sesbania	40	—	215	12
Sida	—	—	742	349
Solanum	565	2660	119	—
Sonchus	40	—	—	—
Xanthium	92	510	1185	442
Other	902[c]	100	742[eg]	47[adf]
Total cotton acres (X 1,000)	1785	5055	2262	1160

[a]Vines; [b]*Setaria* sp.; [c]*Brassica* sp., *Sisymbrium, Capsella,* Volunteer Cereals; [d]*Desmodium* sp.; [e]*Hibiscus* sp.; [f]*Abutilon, Amaranthus, Ambroais, Anoda, Polygonum* sp.; [g]*Brunnichia, Cyananchum,* and *Campsis.*

Table 11. Estimated reduction in percentage of cotton yields by weeds (weed genera) in 1985. (Adapted from Whitwell and Higgins, 1986.)

Weed genera	Regions			
	West	Southwest	Mid-South	Southeast
			(%)	
Grass weeds				
Brachiaria	—	—	2	1
Cynodon	4	1	3	4
Cyperus	13	1	5	8
Digitaria	—	1	5	2
Echinochloa	5	1	2	—
Eleusine	—	—	3	3
Panicum	1	3	1	2
Sorghum	8	11	7	6
Other	4	—	1	—
Broadleaf Weeds				
Abutilon	—	—	1	1
Acanthospermum	—	—	—	1
Amaranthus	10	30	4	5
Ambrosia	—	—	—	1
Anoda	4	1	2	1
Cassia		—	—	9
Chenopodium	1	—	—	1
Convolvulus	1	1	—	—
Croton	—	—	—	7
Euphorbia	—	—	9	2
Franseria	—	3	—	—
Helianthus	1	3	—	—
Ipomoea	15	7	18	15
Melochia	—	—	—	1
Physalis	6	1	—	—
Polygonum	—	—	1	—
Portulaca	—	—	1	—
Proboscidea	—	5	—	—
Salsola	—	2	—	—
Salvia	—	2	—	—
Sesbania	1	—	2	1
Sida	—	1	12	7
Solanum	14	20	1	—
Xanthium	1	4	18	19
Other	2	2	3	4
Total % crop lost	6	6	7	8
Total bales (X 1,000)	4870	4560	3339	1542
Bales lost (X 1,000)	138	274	179	125

Table 12. Estimated herbicide use (X acres treated) in cotton by regions in 1985. (Adapted from Whitwell and Higgins, 1986.)

Herbicide treatement	Regions			
	West	Southwest	Mid-South	Southeast
	(Acres X 1000)			
Preplant-Foliage				
MSMA	0	1	2	1
Paraquat	1	0	2	1
Roundup®	1	1	5	1
Other	2	0	0	0
Preplant-Soil-Incorporated				
Treflan®	40	64	41	58
Prowl®	26	20	35	34
Caparol®	9	0	2	0
Treflan® + Caparol®	10	0	0	0
Prowl® + Caparol®	8	0	0	0
Other		4[b]	9[abf]	1[abf]
Preemergence				
Bladex®	0	0	5	1
Cotoran®	0	1	62	60
Karmex®/Dynex®	0	0	10	6
Zorial®	0	0	33	13
Other	3	21[bdeh]	1[g]	1[g]
Postemergence				
MSMA/DSMA	5	11	58	59
Bladex® ± MSMA	1	0	24	22
Cotoran® ± MSMA	0	0	60	21
Caparol® ± MSMA	9	3	20	2
Karmex®/Dynex® ± MSMA	3	0	35	1
Dinitro	1	0	20	3
Poast®/Fusilade®	1	12	13	13
Goal®	0	0	2	0
Spot Treatment				
Dowpon®	1	0	2	1
Roundup®	9	31	13	3
MSMA	1	0	1	3
Poast®/Fusilade®	1	9	23	3
Layby				
Karmex®/Dynex®	5	1	16	2
Lorox®	0	0	22	6
Bladex®	7	0	8	7
Other	38[c]	1[c]	1[g]	1

a = Treflan® + Cotoran®; b = Basalin®; c = Caparol®; d = Sancap®; e = Surflan®; f = Zorial®; g = Cotoran®; h = Dual.®

Table 13. Weed control literature references on studies of reduced- or no-tillage *vs*. conventional tillage production systems of cotton, and some common herbicide systems used for weed control.

References reporting adequate weed control in reduced-tillage systems of cotton	References reporting poor weed control in reduced-tillage systems of cotton	Most common herbicides used in reduced-tillage systems of cotton
Abernathy *et al.* (1985) Alston *et al.* (1976) Barnes and Whitmore (1989) Brandon (1978) Brown and Whitwell (1984a,b) Brown *et al.* (1987) Brown & Whitwell (1985) Bryson (1988) Dale (1987a) Derting (1990) Fields (1982) Frans (1977) Grisso *et al.* (1984) Hardin (1984) Hayes *et al.* (1988) Hoskinson & Hayes (1984) Hurst (1983) Kurtz & Hurst (1982) Keeling and Abernathy (1988) Keeling and Abernathy (1989) Keeling *et al.* (1989) Lloyd *et al.* (1987) Stevens *et al.* (1986) Van Brackle (1979) White *et al.* (1986) Whitwell & Brown (1981) Wiese & Harman (1982) Wiese & Harman (1983) Wiese & Harman (1985) Wiese (1987) Wiese *et al.* (1987) Wiese *et al.* (1988) Williford & Fulgham (1973) Worsham (1977) York & Byrd (1986) Young (1982)	Alston *et al.* (1976) Brown & Whitwell (1985) Bryson (1988) Lyon (1975) Triplett *et al.* (1983) Unger *et al.* (1977) Van Brackle (1980a) Worsham (1977) Young (1982)	Preplant foliar/residual Gramoxone®, Roundup®, Cotoran®, Caparol®, Karmex®, Zorial®, Prowl®, Treflan® Preplant Prowl®, Treflan®, Bladex®, Zorial®, Caparol®, Cotoran® Preemergence Bladex®, Cotoran®, Karmex®, Zorial®, Caparol® Postemergence MSMA/DSMA ± Bladex®, Cotoran®, Caparol®, Karmex®, Roundup®, Fusilade®, Poast®, or others

Table 14. Definition of terms relating to basic conservation tillage systems.

1. No-till	Sometimes called zero tillage, chemical tillage, or slot planting and is the ultimate conservation-tillage system. The seedbed is prepared and crop is planted in a single trip (Wiese and Harman, 1985).
2. Ridge-plant	Sometimes called till-plant (ridge), this system entails planting the crop with little or no preliminary tillage on ridges formed or built up during the preceding crop season (Wiese and Harman, 1985; Young, 1982).
3. Disk/Chisel-plant	This system differs from no-till in that you disk or chisel either in the fall or spring, or both in fall and spring. The equipment is designed and adjusted to leave most residue on the soil surface. You also may harrow the land to break up clods before planting row crops (Wiese and Harman, 1985; Young, 1982).
4. Strip-till	Sometimes called till-plant (flat). A specialized planter is used, equipped to incorporate or push aside residue to form clean narrow strips for planting (residue incorporated or tilled with sweeps, disk blades, or tillers) (Wiese and Harman, 1985; Young, 1982).
5. Eco-fallow Chemical-fallow	An improved method of stubble-mulch tillage. A system commonly used on the Great Plains and western regions where wheat is the primary crop and fallowing—leaving the ground idle a season—is common practice. The followup crop is planted into the stubble by no-till planting or some other form of reduced tillage (Wiese and Harman, 1985).
6. Sod-planting	Sod-planting is really a variety of no-till. A no-till planter in a single operation either plants grass seed to renovate pasture or plants row crops or forage in pasture or meadow sod (Wiese and Harman, 1985).
7. Precision	A western cotton production practice that involves shredding the cotton stalks in the fall, subsoiling and bedding in the spring, and planting with precision directly over the subsoiled slot. It is a strip-tillage system where the wheel never runs over the subsoiled slot (Carter *et al.*, 1965; Carter and Tavernetti, 1968; Carter and Colwick, 1971; Elliot *et al.*, 1966).

Table 15. Tillage implements and their primary use.

Tillage implements	Primary use of tillage implements
Moldboard plow	Used for covering crop and weed debris in primary tillage. (Wiese and Harman, 1982; Wiese and Harman, 1985). They have a higher power requirement than the disk or harrow and are more expensive to operate. The most common primary tillage tool used in the U.S. regardless of row crop. (Elliot *et al.*, 1966)
Disk harrow	Used for land preparation and herbicide incorporation (Wiese and Harman, 1982). The offset disk is the most commonly used disk in irrigated agriculture for primary tillage. The tandem disk is widely used on loam soils and is usually a lighter-duty disk for secondary tillage. Now second only to the moldboard plow in use in the U.S. (Elliot *et al.*, 1966).
Disk plows (vertical and tilted)	Use similar to moldboard plow, but leaves the soil surface rougher than a modlboard plow (Elliot *et al.*, 1966). This is advantageous in increasing water infiltration and retarding wind erosion.
Chisel plow	Used as the moldboard plow for primary tillage but leaves the soil surface rough and covers only about 20-75 percent of crop/weed residue per trip over the field (coverage of residue depends somewhat on type of shank—twisted/straight—used).
Spring-tooth harrow	May substitute for disk harrow in land preparation and herbicide incorporation. Secondary tillage (Wiese and Harman, 1982).
Powered rotary tillers	Increasing in use for preparing cotton land. Useful for pulverizing clay loam of cloddy soils for rowcrop seedbed preparation. Till soils from two- to five-inch depths and are often combined with bed shapers to give a precise row-crop bed. Power requirements are high (Elliot *et al.*, 1966; Wiese and Harman, 1982).

Table 15. Continued

Lister	Throws soil to both sides, leaving a furrow where lister runs (Elliot *et al.*, 1966).
Subsoilers & chisels	Operate in soil 18-30-inches to shatter compacted soil (Elliot *et al.*, 1966).
Sweeps	Used where shallow-tillage will suffice for cotton land preparation and surface trash is not a problem (Elliot *et al.*, 1966).

Table 16. Methods of reduced-tillage that have been used or are now being used in grain-producing areas of the world.

1. Plow-plant in one operation: In earlier years of the trend to reduced tillage, this method was used on a number of farms in several areas of the country.
2. Plowing and planting, in two operations: Provided the same benefits and suffered about the same disadvantages as plow-plant techniques. Required one additional trip over the field after plowing.
3. Wheeltrack planting in plowed, or plowed and harrowed soil: This method allows the farmer to attain a slightly better degree of timeliness than with plow and plant or plow-plant methods. Moisture conditions at planting are slightly less critical than for the two previously listed methods.
4. Lister planting, or modified lister planting: This method is practiced in drier areas used for row-cropping. Since ridging is a major characteristic of this method, it may not be as suitable for use in crop rotation as other methods. More power is required than for no-tillage.
5. Strip-till planting: This method differs from most no-tillage planting techniques according to the width and depth of the strip of soil that is manipulated. Strip-till planting may be accomplished by commercially available till planters, modified lister planters or rotary strip-till planters.
6. Field-cultivator planting: This method does not eliminate the plow, but it may eliminate the soil compacting problems found with disking/harrowing.
7. Chisel-plow planting: This method is gaining popularity even though it is second only to conventional-tillage in operation costs, number of soil manipulations, machinery investment, horsepower requirements and labor needs. Some farmers chisel-plot in the fall and then chisel-plow-plant in the spring. Others precede the planting operations with a field cultivator. Crop residues must be chopped to permit efficient operation of chisel plows and field cultivators. Slow seedling emergence and poor stands are likely if the surface of chiseled fields are left too loose or too rough. Soils warm up in the spring slower than with conventional tillage.
8. Aerial seeding: Rice, corn, soybeans, grain sorghum, pastures and small grains have been successfully seeded by aircraft, although some tillage may be performed after the seeding.

Table 16. Continued.

9. Stubble-mulch planting: Typical stubble-mulch systems make almost full use of crop residues and sharply reduce wind and water erosion, and are adapted mostly to the drier areas of the Corn and Wheat Belts in North America.

10. Non-inversion tillage: Includes disk-tillage, chisel-tillage, rotary-tillage, and sweep tillage (as it sounds, tillage that does not invert the soil).

Definition of reduced-tillage proposed by Young (1982) = reducing tillage to only those operations that are timely and essential to producing the crop and avoiding damage to the soil and growing crops (another minimum-tillage system by Hayes) (49).

Chapter 10

EFFECT OF SOIL PROPERTIES AND PROCESSES ON HERBICIDE PERFORMANCE AND PERSISTENCE

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INTRODUCTION

Soil-applied herbicides are designed to achieve continuous weed control over periods of time ranging from a few weeks to several months. Effective herbicides should persist in soil at concentrations that will provide weed control but should not persist long enough for carryover to injure following crops. Increased persistence also increases the opportunity for movement of herbicide into surface or groundwater. Herbicide performance and persistence are determined by the properties of the herbicide, the soil and climatic factors and the physical, chemical and biological processes to which these chemicals are subject. Understanding these factors and processes can result in improved and more effective methods of herbicide use, and aid in the development of new herbicides while minimizing undesirable contamination of soils and waters.

Knowledge of herbicide-soil interactions is needed at several different levels. Cotton farmers seek to match weed control needs with effective chemicals on a field-specific basis. Equally specific knowledge of the soils and a reasonable anticipation of weather are taken into account in the selection of herbicides. Weed scientists seek to integrate knowledge of herbicide chemistry, soil interactions and environmental effects to develop new application techniques and to identify herbicides that will provide effective weed control over broad regions. Scientists concerned with meeting or developing regulations that protect the environment require both broad knowledge of these interactions and specialized knowledge, including herbicide persistence and movement at trace concentrations, mechanisms of degradation and the identity and toxicological properties of herbicide metabolites.

ENVIRONMENTAL FACTORS AFFECTING HERBICIDES IN COTTON SOILS

The environmental factors of climate and soil primarily affect the retention, transformation and transport processes that control herbicide behavior in soil. The climatic factors include temperature, moisture, air movement, humidity and solar radiation; soil factors include organic matter and clay content, pH and salinity. Due to the interactions between climatic and soil factors and the processes affecting herbicides, it is often difficult to isolate the effect of any one factor on a given process. Therefore, only generalities concerning environmental factors based on a number of review articles will be discussed here (Guenzi, 1974; Hance, 1980b). More specific details will be discussed later in this chapter.

CLIMATE

Cotton is grown in the United States south of 37° latitude due to a direct relationship between potential yield and growing days. The crop requires at least 160 days above 60F in order to obtain maximum yields. A second limiting factor for cotton yield is the total amount and distribution of rainfall and irrigation during the growing season. Cotton is grown in areas of the United States with rainfall ranging from 6 inches in the West to 60 inches in the Southeast (Waddle, 1984). The cotton grown in low rainfall (6-inch) areas is irrigated. These variations in temperature and moisture regimes also affect performance and persistence of herbicides over the Cotton Belt.

The herbicide properties of solubility and vapor pressure and the processes of degradation and volatilization are dependent on temperature with both properties and processes increasing as temperature increases. High temperatures can lead to increased herbicide losses through increased degradation and volatilization. Low humidity and high temperatures dry out soils which may decrease plant uptake of herbicides by reducing movement of herbicide to plant roots and increasing loss of herbicide by increasing volatility.

The amount, intensity and frequency of rainfall or irrigation water controls the movement of pesticides to and away from target plants and the ability of the pesticide to go into solution. Under dry conditions, some precipitation is necessary to move soil-applied herbicides to the rooting zone where uptake can occur. Heavy rains immediately after herbicide application can lead to surface runoff of the herbicide. A large quantity of rainfall at low intensities can move some herbicides past the rooting zone and decrease herbicide effectiveness.

Degradation is also primarily dependent on temperature and moisture conditions, thereby affecting the persistence of a herbicide. Degradation tends to increase under warm, moist conditions while decreasing under dry and cold conditions. For instance, Burnside *et al.* (1963, 1969) showed that triazine, *i.e.* atrazine (AAtrex®), and substituted-urea, *i.e.* monuron (Telvar®), herbicides' persistence in the wetter eastern part of Nebraska was less than in the drier

western part. Various studies have shown that herbicides are more persistent in the cooler northern and drier western states than in the warmer wetter southeastern states. Under normal conditions there is sufficient oxygen in the soil for aerobic degradation to take place. However, under extremely wet conditions where there is no oxygen, anaerobic degradation may replace aerobic degradation, depending on the presence and ability of anaerobic organisms to degrade a herbicide.

SOIL

Cotton can be grown on any soil used to grow crops in the United States below 37° N latitude that is subject to the aforementioned temperature and moisture regimes. Cotton is grown on seven major soil orders and 20 subgroups. These soils have as wide a range in properties—organic matter contents, pH levels, salinity levels and clay contents—as do soils used for other row crops. In general, the soils used for cotton production have a lower organic matter content than soils with other crops primarily due to the environmental conditions of the cotton growing areas. High soil temperatures and moisture contents, combined with intensive tillage, accelerate organic matter decomposition.

There have been numerous attempts to correlate herbicide performance and persistence to soil type (*i.e.* as a function of soil texture, organic matter content, pH). However, the reports in the literature are conflicting. Herbicide persistence, for instance, has been reported to increase, decrease or remain the same in soils with increasing soil organic matter content (Hurle and Walker, 1980). The reasons for the conflicting reports could be the differences in physical and chemical properties among the soils, differences in herbicide chemistries used in the studies, and differences in mechanisms of herbicide degradation.

Soil organic matter and clay content are probably the most important soil factors that affect herbicide performance and persistence. They indirectly influence all the processes affecting herbicides. As a rule, the greater the organic matter and clay contents, the greater the adsorption of the herbicide to the soil particles. Adsorption removes the herbicide from solution or air, thereby making less chemical available for movement in water and air, decomposition by microorganisms and absorption by plants. In essence, it lowers the amount of herbicide that is actively available and hence lowers its performance. Crop residues on the soil surface in reduced tillage systems can also adsorb herbicides—as much as 50 percent of the total amount applied in some cases (Banks and Robinson, 1984). Also, in soils with higher organic matter contents, microbial populations are usually greater which in turn may lead to greater rates of degradation of the herbicide.

Soil pH can affect both the physical and chemical properties of some herbicides and some processes. Increased solubility occurs at solution pH values where *s*-triazine herbicides are protonated (positively charged cation) or weak acid herbicides are dissociated (negatively charged anion). Soil pH also affects

the decomposition and movement of different herbicides. For example, hydrolysis (one form of chemical decomposition) of chlorsulfuron (Glean®) is more rapid in acidic soils (pH < 7) (Joshi *et al.*, 1985). Acidic herbicides are more mobile at pH values where the molecule exists as the anion.

SOIL PROCESSES AFFECTING HERBICIDE ACTIVITY IN SOIL

For successful weed control using soil-applied herbicides, levels of herbicide must remain available in the soil long enough for the seedling to absorb toxic levels of the chemical. Once applied to soil, three processes reduce the availability of the herbicide to the target plant: retention, transformation and transport. These processes are affected by the pesticide properties, by the soil and by environmental factors (Figure 1) acting in concert to control the amount of available chemical in solution at a given time.

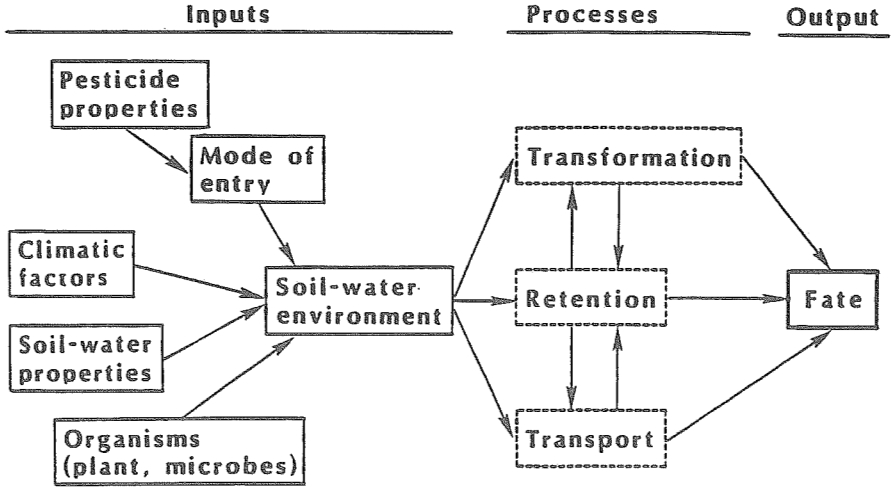


Figure 1. Interaction of the factors and processes affecting the rate of pesticides in the soil environment. (From Cheng and Koskinen, 1986.)

HERBICIDE RETENTION PROCESSES

Retention is a primary factor affecting the efficacy of soil-applied herbicides. The retention process refers to the ability of the soil to hold a herbicide and prevent the chemical from moving. Retention also controls the amount of herbicide available for transformation processes. Retention primarily refers to the adsorption process, but also includes the absorption of herbicides by the soil

particles, plants, and microorganisms. The literature abounds with references on the retention of pesticides in soils (*e.g.*, Hamaker and Thompson, 1972; Green, 1974; Weed and Weber, 1974; Calvet, 1980; and references cited therein). This section will present some of the main features and generalizations concerning the adsorption-desorption process.

Herbicides can be adsorbed to soil by a number of mechanisms including physical bonding such as van der Waals forces, hydrogen bonding and dipole-dipole interactions, chemical bonding such as ion exchange, covalent bonding, protonation, ligand exchange, cation bridging and water bridging with varying degrees of strengths of interactions. For hydrophobic, nonpolar compounds with low water solubilities, adsorption also has been described as a hydrophobic partitioning process between soil water and a soil organic matter phase (Table 1).

Adsorption of nonionic, nonpolar hydrophobic herbicides is due to weak attractive interaction such as van der Waals forces. Electrostatic interactions can also be important, especially when a herbicide molecule is polar in nature. Attraction potential can develop between polar molecules and the heterogeneous soil surface that has ionic and polar sites, resulting in stronger bonding. For any given herbicide or family of chemicals, there is likely a continuum of mechanisms responsible for adsorption onto soil particles. For instance, within the triazine herbicide family, it has been suggested that mechanisms involving van der Waals forces, charge transfer, hydrophobic bonds, cation exchange and cation bridging are responsible for bonding to soil surfaces (Hayes, 1970).

Adsorption of phenyl- and other substituted-urea herbicides to soil or soil components also has been attributed to a variety of mechanisms depending on the adsorbent. The mechanisms have included hydrophobic bonding (Carringer *et al.*, 1975), cation bridging (Hance, 1971; Gaillardon *et al.*, 1980), van der Waals forces (Hance, 1969; Senesi and Testini, 1980) and charge-transfer (Hance, 1969; Senesi and Testini, 1980). Even cation exchange has been reported for the substituted-urea tebuthiuron (Spike®) (Weber, 1980).

The degree of herbicide adsorption is controlled by a number of factors including amounts and types of soil organic matter and clays, herbicide properties and the amount of moisture in the soil, as well as soil pH, surface area and cation exchange capacity. Soil organic matter is the principal adsorbent for many nonionic organic compounds (Hamaker and Thompson, 1972). However, there are many nonionic organic chemicals that adsorb extensively on the clay mineral fraction of soil (Yaron *et al.*, 1967). Herbicides such as glyphosate (Roundup®) can be adsorbed through formation of complexes with metal ions such as iron and aluminum. Herbicide application rates are often increased in high organic matter soils or high clay soils, or both, and decreased in sandy soils so that an effective, but safe, concentration is maintained in the soil solution.

The bonding energy between herbicides and soils is related to the type of adsorption mechanism (*e.g.* cation exchange, formation of complexes, hydrophobic interactions). As a rule, nonpolar, nonionic herbicides are adsorbed by low

Table 1. Intramolecular forces that can attract herbicides to and retain them on soil surfaces.

London-van der Waals forces:	short range bonds between the herbicide and soil that are the result of dispersion forces.
Hydrogen bonds:	bonds produced from the electrostatic attraction between an electropositive H nucleus and exposed electron pairs on electronegative atoms such as O and N.
Cation bridging:	formation of a complex between an exchangeable cation on the soil and an anionic or polar organic functional group on the herbicide.
Water bridging:	interaction between an H on an hydrating water molecule on a cation on the soil and an organic functional group on the herbicide.
Anion exchange:	electrostatic attraction of an anionic herbicide to a positively charged site on the soil surface, involving the exchange of one anion or another at the binding site.
Ligand exchange:	complex formed when a functional group on the herbicide such as carboxylate or hydroxyl displaces an inorganic hydroxyl or water molecule of a metal ion (Fe or Al) at the surface of a soil mineral.
Protonation:	Protonation of a herbicide, or formation of charge transfer complexes, at a mineral surface occurs when an organic functional group of the herbicide forms a complex with a surface proton (H).
Cation exchange:	electrostatic attraction of cationic (positively charged) organic functional groups such as amines and heterocyclic N by a negatively charged site at the soil surface.
Covalent bonding:	formation of covalent bonds between functional groups of the herbicide and the soil organic matter.

energy bonds. Adsorption of a few herbicides, such as the bipyridylium cations diquat and paraquat, involve higher energy bond formation. These herbicides are adsorbed primarily through cation exchange. However, adsorption also can involve charge transfer interactions (Kahn, 1974), hydrogen bonding and van der Waals forces (Burns *et al.*, 1973), which have progressively lower bonding energies, respectively than cation exchange. As bonding energy increases the amount of herbicide adsorbed generally increases, so that less herbicide is in solution for plant uptake.

The soil pH can affect adsorption and influence the type of physical bonding that occurs. For instance, triazines and pyridinones are weakly basic chemicals that easily can be protonated at low soil pH levels. The pKa values (the pH at which half the molecules are protonated) for these herbicides range from about 1.7 for atrazine (AAtrex®) and fluridone (Sonar®) to 4.3 for prometon (Pramitol®). At soil pH levels less than 2 pH units above the pKa of the herbicide, adsorption is greater than in higher pH soils and there is abundant evidence for cation exchange as the bonding mechanism for triazines to soil (Carringer *et al.*, 1975; Senesi and Testini, 1980). On the other hand, at soil pH values greater than two pH units above the pKa, more than 99 percent of the molecules of atrazine (AAtrex®) and fluridone (Sonar®) are not protonated and other mechanisms such as hydrophobic attractions, charge-transfer bonds, hydrogen bonding and van der Waals forces become more important (Hance, 1969; Hayes, 1970; Weber, 1980; Bouchard and Lavy, 1985; Weber *et al.*, 1986). As the soil pH increases these herbicides become progressively less adsorbed to soil.

Weakly acidic herbicides such as the phenoxyacetic acids exist either as the undissociated molecule or the corresponding anion depending on the pH of the system. Adsorption of weakly acidic herbicides probably involves physical adsorption of the undissociated molecule and is not site specific. Numerous studies have shown that adsorption increases with a decrease in pH provided there is a decrease in the percent of the dissociated acid (Cheng, 1971; Koskinen *et al.*, 1979). Other adsorption mechanisms such as charge-transfer and hydrogen honding are also possible for weakly acidic herbicides.

Observed differences in adsorption between herbicides within the same class of compounds (*i.e.*, substituted-ureas, sulfonylureas) in the same soil are due to differences in the chemical characteristics of the herbicides. As with the soil surfaces, functional groups on an organic molecule influence the strength and mechanism of chemical retention. For example, the adsorption of phenylurea herbicides on soil increases with halogen (Cl^- or Br^-) or chlorophenoxy substitution in the phenyl ring as opposed to alkyl groups. Increasing chain length of the dialkyls or substituting the dialkyl with the corresponding alkyloxy derivative also increases adsorption (Hance, 1965; Grover, 1975).

Very little research has been conducted on adsorption of herbicide metabolites on soil. There are reports that adsorptions of some metabolites on soil can be equal to or greater than the parent herbicide (Koskinen,1984; Clay and Koskinen, 1990).

For most herbicides, a rapid, reversible equilibrium initially is established between the chemical in solution and the chemical adsorbed onto the soil surface initially. The adsorption is due to the previously described physicochemical and electrostatic forces or hydrophobic partitioning. However, once adsorbed the chemical is subject to other processes that can affect retention. Some chemicals may further react to become covalently and irreversibly bound (*i.e.*, become

"bound residues") and some herbicides may become physically trapped within the soil particles.

Bound residue formation is a detoxification process catalyzed by soil microorganisms. Bound residues are typically defined as that portion of the residue which is not extractable with aqueous solutions or organic solvents due to incorporation of the residue into soil organic matter. Typically, radioactive carbon (^{14}C)-labeled herbicides are used in studies to quantify the nonextractable material; ^{14}C budget studies indicate that significant portions of the total applied ^{14}C-herbicide is ultimately converted to bound residue. For instance, microbial laccase and peroxidase enzymes act in coupling and polymerization reactions to bind pesticide metabolites to soil organic matter (Bollag and Loll, 1983). Chemical reactions also are important in the formation of bound residues. The binding of *s*-triazine residues is primarily chemical; microorganisms act only in the production of various metabolites (Bollag and Loll, 1983). Bound residues may also be formed through the uptake of herbicides or metabolites and the subsequent release of these materials through decomposition of the crop residues in the soil.

Aromatic amines (including dinitroaniline herbicide such as trifluralin [Treflan®] metabolites) can form covalent bonds with soil organic matter. Both biological and nonbiological mechanisms seem to be involved including oxidative coupling reactions of anilines to phenols and formation of anilinoquinone linkages (Hsu and Bartha, 1974a; Parris, 1980). Graveel *et al.* (1985) reported an initial rapid adsorption of aromatic amines, with a sharp decrease in the amount of extractable amine after 24 hours, followed by a gradual decrease over the next several weeks of incubation. This would suggest formation of covalent bonds with the soil organic matter.

There is evidence suggesting that bound or trapped forms of herbicide or metabolites may be released from organic matter. Small amounts of bound prometryn (Caparol®) and two of its metabolites were recovered from the humic and fulvic acid fractions of prometryn (Caparol®) treated soils (Khan, 1982). Helling and Krivonak (1978) found that ^{14}C-labelled bound residues of dinitroaniline herbicides were taken up by soybeans and that some of these residues were mildly phytotoxic. Dichloroaniline (DCA)-humic acid complexes (Hsu and Bartha, 1974b) and bound prometryn (Caparol®) residues (Khan and Ivarson, 1982) were degraded by microorganisms. Saxena and Bartha (1983) determined that DCA-humus complexes had faster turnover rates in soil than soil humic acid fractions, and concluded that the accumulation of DCA bound residues was unlikely. Although the release of bound residues are not expected to have economically important effects in most situations, their potential availability should not go unrecognized. The release of bound residues may be important when sensitive crops are planted after cotton.

Decreased extractability of organic chemicals with increased incubation time at times may be due to physical trapping of the herbicide within the soil particle. Decreased extractability of fluridone (Sonar®) after equilibration for 7 to 28 days

compared to one day was attributed in part to the herbicide penetrating deeper into the soil micropores and adsorbing on the interlayer surfaces of montmorillonite (Weber *et al.*, 1986). The herbicide prometon (Pramitol®) has also been shown to adsorb on the interlayer of montmorillonite (Weber *et al.*, 1965). Hydrophobic interactions and trapping of molecules in a molecular sieve formed by humic materials has been hypothesized as a retention mechanism for the incorporation of ^{14}C-prometryn into humus (Khan, 1974).

TRANSFORMATION PROCESSES

Transformation processes are those processes that actually reduce or totally eliminate the amount of herbicide present and available for plant uptake, transport and, ultimately, weed control. Herbicides are degraded by both biological and nonbiological means. Physical and chemical processes—including photodecomposition, hydrolysis, oxidation and reduction and polymerization reactions—degrade most herbicides to some extent, although the rates of these reactions in nature may be negligible for many herbicides. Nevertheless, the importance of certain physical reactions can necessitate different application strategies for specific herbicides.

The degradation of herbicides is accompanied by the formation of metabolites which, in most cases, are less toxic than the original chemicals. The metabolites of microbial degradation tend to have progressively simpler structures as herbicide degradation continues. In contrast, degradation in plants relies primarily on conjugation of residues with sugars or other compounds. The metabolites of chemical- or photo-degradation may be more novel in structure. In addition to the production of extractable metabolites, a portion of the herbicide is converted into bound residue. Bound residues typically account for a substantial portion of the applied herbicide and, as previously discussed, are formed through the chemical and enzymatic bonding of herbicides and metabolites to soil organic matter.

After reviewing reports of the degradation of sixteen herbicides in different soils, Guth (1980) suggested that most pesticides are degraded by the same pathway in different soils, although the pathways differ among pesticides. Guth also suggested that there were no differences in the pathways of degradation between laboratory and field experiments. Exceptions to this exist. For instance, long-term pesticide use may lead to the evolution of different metabolic pathways in soil microorganisms. Microorganisms which utilized *s*-triazines as nitrogen sources (Cook and Hutter, 1981) or carbon sources (Behki and Khan, 1986) were isolated from soils with histories of *s*-triazine use, but not from soils without this history. A change in the metabolic pathway of the insecticide parathion was observed in soil repeatedly treated with parathion (Sudhakar-Barik *et al.*, 1979). Additional research is needed to determine the significance of changes in microbial degradation pathways after repeated herbicide applications.

Differences in the kinetics of degradation can result in substantially different concentrations of metabolites in different soils at various times after application.

Laskowski *et al.* (1983) reviewed selected literature and determined that the variation in pesticide degradation rates in different soils was as little as 2-fold to as much as 36-fold. In all of these studies, degradation rates were measured under standard temperature and water potentials. Thus, the variation is due to the soils themselves. Although factors such as water availability, soil pH, organic matter content, microbial activity and soil aeration are known to influence each of the various degradation processes, accurate prediction of degradation rates solely from soil properties and environmental conditions is not yet possible. However, we can predict the persistence of most cotton herbicides within the degree of accuracy needed by producers for adequate weed control.

Chemical Decomposition—It has been extremely difficult to separate the individual contributions of chemical and biological processes. Experimentally, this is achieved by removing the biological component through autoclaving or by adding inhibitors of microorganisms to the soil. The risks of incomplete sterilization, contamination, or growth of resistant organisms remain as potential problems. Alternatively, chemical degradation can be demonstrated in soil-free systems where biological components can be excluded. Chemical degradation is a significant factor in the initial degradation of the chloro-*s*-triazines such as cyanazine (Bladex®) which, through hydrolysis, are converted to hydroxytriazines (Jordan *et al.*, 1970). Muir and Baker (1978) found both hydroxycyanazine and the cyanazine amide [2-chloro-4-(1-carbamoyl-1-methylethylamino)-6-ethylamino-1,3-5-triazine] in soil after cyanazine application. The cyanazine amide may be formed by nonbiological processes (Sirons *et al.*, 1973). Grayson (1986) demonstrated the potential for abiotic hydrolysis of cyanazine in weak acids. However, dipropetryn (Sancap®) and prometryn (Caparol®), both of which are methylthio-s-triazines used in cotton, are not converted to hydroxylated metabolites as are atrazine (AAtrex®) or cyanazine (Bladex®). These herbicides are initially converted to sulfoxides or sulfones in soil. The involvement of microorganisms in this process is unknown (Kaufman, 1974).

Photodecomposition—Photodecomposition (photolysis) is the decomposition of a herbicide induced directly by absorbing energy from light. Most herbicides have an absorption maxima in the region between 220 and 400 nm. However, only herbicides such as 2,4,5-T, chloramben (Amiben®), dinoseb and trifluralin (Treflan®) with significant absorption above 285 nm, are expected to undergo direct photolysis by sunlight. The atmosphere absorbs most UV radiation below 285 nm.

Photodecomposition of other herbicides occurs indirectly by reaction with another chemical which is activated by absorbed energy (sensitization). In experiments using artificial light at wavelengths near the herbicide's absorption maximum, a wide range of herbicides, including phenoxyalkanoic acid, *s*-triazine, substituted-urea and dinitroaniline herbicides, have been reported to

undergo photochemical reactions. These reactions have been the subject of various reviews (Plimmer, 1970; Crosby, 1976).

The contribution of photodecomposition to the persistence of many cotton herbicides is not well known. Trifluralin (Treflan®) and other dinitroanilines can be substantially decomposed by photolysis (Wright and Warren, 1966; Helling, 1976). The photocomposition of substituted-urea herbicides like diuron (Karmex®) in aqueous solutions has been observed (Hill *et al.*, 1955; Rosen *et al.*, 1969). In the latter studies, 69 percent of the added linuron (Lorox®) was recovered from solution following two months exposure to sunlight. The *s*-triazine herbicides are subject to photodecomposition under laboratory conditions (Jordan *et al.*, 1970). Atrazine (AAtrex®) and simazine (Princep®) applied to the soil surface were degraded extensively on the sun-lit surface in comparison to the surface kept in the dark (Comes and Timmons, 1965). Small amounts of water moved fluridone (Sonar®) into the soil sufficiently to reduce but not eliminate its photodegradation in water (Jordan *et al.*, 1970). These data suggest that fluridone may also be subject to photodegradation in soil (West *et al.*, 1979). In contrast, perfluridone (Destun® [no longer available]) applied to soil was not susceptible to photodegradation (Ketchersid and Merkle, 1975).

The amount of herbicide decomposition by photolysis reactions in field situations is often difficult to assess. Photodecomposition is only of importance while the herbicide remains on the soil surface. A herbicide is not expected to remain on the soil surface for long however, since incorporation by diffusion and rainfall will move the majority of a herbicide some distance into the soil. Diuron (Karmex®) was partially or completely inactivated after two weeks on dry or wet soil surfaces, respectively, but the relative contributions of biodegradation, volatilization and photodecomposition were not measured (Horwitz and Herzlinger, 1974). Incorporation by irrigation increased the level of activity in these studies. Similar results were obtained by Comes and Timmons (1965). Soil incorporation of the dinitroanilines by tillage reduces photodecomposition to minimal levels.

The presence of other compounds which interact with light and the herbicide to increase or decrease photodecomposition in soils and natural waters further complicates the assessment of photodegradation. Several studies indicate that the use of silica gels or glass plates in photolysis experiments overestimates the photodegradation in comparison to soil systems (Ketchersid and Merkle, 1975; Messersmith *et al.*, 1971; Miller and Zepp, 1983; Nilles and Zabik, 1975). Because of the complexity of natural soil systems and the lack of systematic research on many pesticides, Miller and Zepp (1983) concluded that current models of pesticide photochemistry could not predict the importance of these reactions in soil for most pesticides.

Biological Degradation—Biological degradation is the process controlling the persistence of most cotton herbicides in soils and water. Soil microorganisms reduce herbicides to nontoxic forms through a sequence of enzymatic actions on

the herbicides and their metabolites. The rates of microbial degradation are governed by biological, environmental and chemical factors. Generally, degradation results in herbicide metabolism to provide a source of carbon for microbial use. When compounds are altered but not used for growth, the process is termed cometabolism. Although initial steps in the metabolism often reduce the phytotoxicity of the herbicide, the subsequent degradation of metabolites is important also. Many herbicide metabolites are weakly phytotoxic and their accumulation in the soil could increase the risk of adverse effects to crops or the environment.

Although microorganisms which can degrade herbicides and use them as carbon sources have been isolated, other microorganisms only partially degrade herbicides. A *Bacillus sphaericus* strain degraded linuron (Lorox®), but concentrations of the metabolite, 3,4-dichloroaniline, in the culture medium increased correspondingly (Walnoffer, 1969). In soil, this metabolite would be available for degradation by other microorganisms. The $^{14}CO_2$ evolution from soil treated with [ring-^{14}C] propanil (Stam®) was increased dramatically by adding a bacterium which degraded 3,4-dichloroaniline, an initial degradation product of propanil (Zeyer and Kearney, 1982). The relative importance of such interspecies interactions is difficult to assess, but probably accounts for a significant amount of the degradation of many herbicides.

The activity of herbicide-degrading microorganisms is mediated by the soil environment and the soil physical and chemical properties. The most important of the environmental factors are soil water potential (available water content) and temperature. Decreased water availability usually results in increased persistence of the herbicide (Smith, 1985; Hitchings and Roberts, 1980; Walker, 1978). Anderson (1981) investigated the relationship between microbial biomass levels and degradation rates of diallate (Avadex®) and triallate (Far-Go®) in soils at different moisture contents. Degradation rates of both herbicides were reduced as water content decreased, but biomass levels did not decrease. Degradation rates were largely independent of biomass levels, indicating that microbial activity was reduced by the suboptimal soil water contents. Low water potentials slow the diffusion of herbicides and other substrates to the microorganisms, thereby reducing their activity (Papendick and Campbell, 1981). Bacterial activity is reduced in moderately dry soil, (water potential: -6 bars). Some fungi can remain active in extremely dry soil (water potentials as low as -30 bars) (Griffin, 1981). Even though soils may have equivalent moisture contents, differences in soil texture and microstructure may result in greatly differing levels of available water or water potentials.

Microbial activity is increased in warm soils and reduced in cold soils. In general, herbicide biodegradation also responds in this way provided that soils have adequate water content. Soil temperature effects in the field are often highly related to soil water availability. Evaporative losses tend to be greater under warmer temperatures. Temperature effects in dry soil are relatively small, due to the overriding effect of reduced soil water availability.

Other soil factors that indirectly regulate microbial degradation include soil texture, pH and organic matter levels. These factors primarily affect microorganism populations and their activities. Factors such as high nutrient availability, neutral pH, high cation exchange capacity and high organic matter levels tend to promote microbial growth and activity. Total microbial biomass or population size are only indicators of potential microbial degradation because herbicide-degrading microorganisms are only a small fraction of the total population in aerobic soils (Burge, 1969; Cullimore, 1981; Kunc and Rybarova, 1983; Loos, *et al.*, 1979). In nutrient-limited cultures, herbicides or their metabolites can be degraded to provide a source of nitrogen, sulfur or phosphorus for microorganisms (Cook *et al.*, 1978; Cook and Hutter, 1981, 1982), but the significance of these findings in the soil environment has not been established. Degradation pathways of this type might be expected in soil after addition of crop residues with high carbon to nitrogen or carbon to sulfur ratios.

Little systematic work on the effects of soil pH on herbicide degradation has been done, aside from that on the *s*-triazines (Hance, 1979). Hance (1979) found that linuron (Lorox®) degradation was increased in high pH soils, but Corbin and Upchurch (1967) found that the persistence of diuron (Karmex®) phytotoxicity was not affected by soil pH. Persistence of nitralin (Planavin®) and trifluralin (Treflan®) phytotoxicity, as determined by bioassay, was greater in acid soils than neutral soils, but quantification of the two herbicides by extraction and gas chromatography showed that only nitralin persistence was greater in acid soils (Savage, 1973). The reduced nitralin (Planavin®) degradation in acid soils was likely due to reduced microbial activity since acid hydrolysis reactions have not been reported for this herbicide in soil.

Soil aeration also greatly influences the biodegradation of herbicides. Oxygen diffuses at much greater rates in air-filled soil pores than in water-filled pores. High soil water content reduces the rate of oxygen diffusion and once the dissolved oxygen is depleted, anaerobic conditions begin to develop. Anaerobic conditions may be present in stream sediments, flooded soils, subsoils or, to a lesser extent, in microsites such as the interior of soil aggregates.

Trifluralin (Treflan®) degradation proceeded at a much greater rate in flooded soils than those kept at water contents below saturation (Probst *et al.*, 1967). Similar results were obtained in field studies with fluchloralin (Basalin®), pendimethalin (Prowl®), profluralin (Tolban®), and trifluralin (Treflan®) (Barrett and Lavy, 1983; Brewer *et al.*, 1982). The role of microorganisms as the principal agents of degradation under both aerobic and anaerobic conditions was established by comparing trifluralin degradation in autoclaved and nonautoclaved soil, and by the inhibition of trifluralin degradation by treatment with azide, a microbial inhibitor (Parr and Smith, 1973). Anaerobic dehalogenation reactions are due to microbial processes (Suflita *et al.*, 1982). Anaerobic incubations of diuron (Karmex®) and linuron (Lorox®) resulted in unusual dehalogenated metabolites (Stepp *et al.*, 1985). However, rates of herbicide degradation in the anaerobic

systems were not compared to an aerobic system in these studies. Knowledge of the pathways and relative rates of degradation for many compounds are incompletely determined or unknown.

Degradation progress curves in liquid culture and in soil are often marked by lag periods (periods of slow degradation) immediately after addition of the herbicide. Rapid degradation usually follows until the herbicide is nearly depleted. The initial lag phase is attributed to enzyme induction and synthesis or microbial adaption. Most evidence indicates that degradation enzymes are intracellular. However, acylanilide herbicides may be degraded by extracellular soil enzymes (Burns and Edwards, 1980). Several studies have shown that degradation enzymes can be induced by structurally related compounds. Walnoffer (1969) described a strain of *Bacillus sphaericus* which degraded monolinuron, linuron (Lorox®) and metobromuron, but not monuron (Telvar®), diuron (Karmex®) or fluometuron (Cotoran®). The specificity in degradation was attributed to the presence of the methoxy substituent common to monolinuron, linuron (Lorox®) and metobromuron. In later studies, the purified enzyme from this bacterium was found to degrade a wide variety of phenylamide fungicides and herbicides (Englehardt *et al.*, 1973). Chlorbromuron (Maloran®), monalide (Potablan®), propanil (Stam®), propham (IPC) and two other phenylamides induced the enzyme, but activity against linuron was less than when linuron acted as the inducer.

Other isolated enzymes also display wide ranges of specificities in their activity against structurally similar compounds. Isolated enzymes from *Pseudomonas striata* Chester, resembled those of the *Bacillus sphaericus* hydrolyzing a range of phenylcarbamate and phenylamide herbicides, respectively (Englehardt *et al.*, 1973; Kearney, 1965). The acylamidase enzymes from *Fusarium oxysporum* Schlect and *F. solani* had comparatively narrower ranges of substrates that were hydrolyzed (Blake and Kaufman, 1975; Lanzilotta and Pramer, 1970). The wide range of substrate specificities exhibited by some of these enzymes suggests that interactions between pesticides may be possible in the field. Application of herbicides with similar structures or the practice of split-applications may shorten the persistence of herbicides by reducing the lag period required for enzyme induction. The repeated application of thiocarbamate herbicides such as EPTC (Eptam®) has resulted in the accelerated biodegradation of these herbicides, and a resultant decrease in weed control. However, this phenomenon has not been demonstrated to occur with any herbicides used in cotton.

Specific structural components of the herbicide molecule can affect the enzymatic activity. The addition of sulfonate, amine or halogens to the aromatic ring tends to increase the persistence of the ring. Kearney (1967), using isolated enzyme from *Pseudomonas striata* and various phenylcarbamate substrates, found that the position and electron withdrawing potential of the ring substituents affected the rate of enzymatic hydrolysis. Strong electron withdrawing groups, such as NO_2, increased hydrolysis; the nitro group at the para position had more effect than at the meta position. Also, hydrolysis rates decreased as the size of

the side-chain increased; this was attributed to steric effects. However, with other enzymes and substrates, specific substituents may have somewhat different effects (Blake and Kaufman, 1975).

As stated earlier, persistence of herbicides is desirable while effective weed control is needed. The manipulation of persistence, either to increase or decrease the biodegradation of herbicides, is being developed to increase the effectiveness of herbicides. Application of PCMC (*p*-chlorophenyl methylcarbamate) with chlorpropham increased the duration of control of dodder by chlorpropham (Furloe®) (Dawson, 1969). The discovery that various carbamate and organophosphate insecticides inhibited the microbial degradation of several herbicides in soil and in pure culture led to increased interest in the manipulation of herbicide persistence (Kaufman, 1977). Dietholate, an organophosphate compound related to parathion, prolongs the persistence of several carbamothiate herbicides in soil. Further development of compounds that increase the persistence of short-lived compounds may have practical application.

HERBICIDE TRANSPORT PROCESSES

The movement of herbicides affects their potential effectiveness against weeds and the safety to crops. The performance of preemergence herbicides is often improved by the movement of the herbicide into the top few centimeters of soil. Rainfall or irrigation will accomplish this movement, or herbicide may diffuse into moist soil. Many of the dinitroaniline (Treflan®, Prowl®, others) and substituted-urea (Karmex®, Lorox®, others) herbicides used in cotton rely on retention in the surface layers of soil for selectivity with movement below this zone resulting in crop damage. Herbicide movement also is an important process in the contamination of surface and groundwater supplies. The potential contamination of groundwater and the improvements in the areas of analytical chemistry and computer modeling of chemical transport in soils are causing a reevaluation of herbicide transport in soils.

The mechanism of herbicide movement depends on the dominant exchange processes at the placement site and the physical and chemical properties of the herbicide. Herbicides in water or air will move within the medium primarily by convection in response to gravity or density. There is also short-range movement in response to concentration gradients or diffusion. The mechanism of movement also depends on the vapor pressure and water solubility of the herbicide. Soil-applied chemicals with a distribution ratio between water and air (weight/volume basis) under 10^4 (*e.g.*, EPTC [Eptam®], trifluralin [Treflan®]) will diffuse primarily in air while those over 3×10^4 will diffuse mainly in water (*e.g.*, diuron, *s*-triazines) (Goring, 1962).

Volatilization and subsequent transport of herbicides are important processes in the loss of several herbicides from soil surfaces and, in some cases, movement within the soil matrix. Vapor loss not only can reduce substantially the effective-

ness of the herbicide, but also may cause damage to cotton or non-target crops by drift. The volatility of herbicides in soil systems is related to their vapor pressures. The vapor pressures (v.p.) of herbicides range from 10^{1} to 10^{-7} Pa at 68F, with most being well below 10^{-1} Pa. The greatest potential for volatility losses are herbicides that have vapor pressures greater than 10^{-2} Pa. These include all the thiocarbamates, trifluralin (Treflan®), CDAA (Randox®), dinoseb, dichlobenil (Casoron®), and some organic acid esters, among others. Herbicides with vapor pressures $< 10^{-2}$ Pa also are subject to volatility losses but to a lesser extent. For instance, volatilization of prometryn (Caparol®) (v.p. 1.3×10^{-4} Pa, 68F) from soil damaged cotton under certain conditions (Talbert *et al.*, 1971).

The magnitude of the vapor loss depends not only on the vapor pressure of the herbicide, but also on the water solubility, formulation, adsorption-desorption characteristics of soil and plant surfaces, concentration, soil water content, air flow rate, humidity, temperature and diffusion (Guenzi and Beard, 1974; Plimmer, 1976; Hance, 1980a). In general, volatility tends to increase as soil moisture or atmospheric humidity and temperature increase. As soil moisture decreases, the potential for adsorption of the herbicide on the soil increases and, therefore, the tendency toward volatilization losses decreases. As temperature increases, the vapor pressure, and hence the volatility, of a herbicide increases. For instance, prometryn (Caparol®) volatilization from the soil surface increased with increasing soil temperature and moisture (Talbert *et al.*, 1971). However, these relationships can be complicated by the fact that soil moisture can decrease as temperature increases, leading to decreases in volatility due to increased adsorption, or increases in volatility due to co-vaporization of water and herbicide.

Some herbicides can have significant movement in soil through the diffusion of volatilized herbicide. Of the herbicides used in cotton, the dinitroanilines (Treflan®, Prowl®, others) have the greatest potential for diffusion. Dinitroanilines are inherently volatile due to their high vapor pressure (Helling, 1976). Vapor transport can be decreased by decreasing the air-filled porosity of the soil (Bode *et al.*, 1973). Thus, increasing the bulk density or the soil water content tended to reduce diffusion of volatilized herbicide. However, as vapor diffusion decreased, diffusion of trifluralin (Treflan®) in the soil water increased.

The movement of herbicides in soil water depends upon rainfall or irrigation water, the macroscopic and microscopic structure of the soil, and the adsorption-desorption characteristics of the herbicide on soil. Water moves through the soil under both saturated and unsaturated conditions. When the soil is saturated with water, the pores are filled with water and transport occurs at the maximal rate. Movement of water and herbicide occurs at much slower rates under unsaturated conditions (Weber and Whitacre, 1982) because only the smaller pores are filled and water moves in response to water potential gradients. Generally, coarse-textured soils will have greater rates of water movement than fine-textured soils when saturated. However, under unsaturated conditions fine-textured soils may have greater transport rates.

In water, herbicides are transported by mass flow. Highly soluble herbicides have a greater initial potential for movement than insoluble herbicides assuming adsorption of both chemicals to soil is similar. Simultaneously, the chemical process of diffusion affects the distribution of herbicide in the water. Dispersion due to differential flow rates within pores and adsorption to soil retards the movement of herbicides relative to that of water, or a noninteracting tracer such as bromide. Soil pores have a wide range of sizes and lengths, and are highly interconnected. A portion of the pore space usually is not part of the continuous flow path or flows at much slower than average rates. Herbicides can enter and exit these spaces through diffusion. Herbicide diffusion coefficients are inversely related to adsorption, except for herbicides such as trifluralin (Treflan®) which have a high degree of movement as a volatile compound through air-filled pore space(Scott and Phillips, 1972).

Since many herbicides used in cotton are applied to the soil surface, the transport of herbicide during water infiltration is important. Water infiltration is characterized by high initial infiltration rates which decrease rapidly to a nearly constant rate. Dry soils have greater rates of infiltration than wet soils during the initial application of water. Thus, perfluridone (Destun®) movement after application of 1.5 inches of water was considerably greater in soil at a water content of <1 percent of field capacity than at 50 percent of field capacity (Ketchersid and Merkle, 1975). Other studies showed that fluometuron (Cotoran®) moved deeper into the soil in response to greater rainfall intensity or after rainfall onto a dry rather than a moist soil (Baldwin *et al.*, 1975a). In contrast, initial soil water content had little effect on the infiltration and movement of fluometuron (Cotoran®) in a very sandy soil (Wood and Davidson, 1975). The greater movement of perfluidone (Destun®) may be due to greater water solubility than fluometuron and differences in adsorption.

Adsorbed herbicides are not available for transport, but if water with lower herbicide concentration moves through the soil layer, herbicide is desorbed from the soil surface until a new equilibrium is reached. Thus, the kinetics of adsorption and desorption relative to the water conductivity rates determine the actual rate of herbicide transport. At high rates of water flow, adsorption and desorption reactions may not reach equilibrium (Hornsby and Davidson, 1973). Nonequilibrium models may describe adsorption and desorption better under these circumstances. The prediction of herbicide concentration in the soil solution is further complicated by hysteresis in the adsorption-desorption isotherms. Both adsorption and dispersion contribute to the substantial retention of herbicide found behind the initial front in typical breakthrough curves and to the depth distribution of residues.

The potential for herbicide movement is often assessed experimentally using soil columns that are treated with herbicide and leached in different ways. The herbicide is measured in the water exiting from the column or in depth increments in the column after a specific time. Another commonly-used procedure is

soil thin-layer chromatography (Helling, 1971a), where radiolabelled herbicides are chromatographed on a glass plate covered with a thin layer of soil. While these methods provide comparative estimates of mobility and have the advantage of defined conditions, many studies indicate that movement of herbicides under field conditions differs substantially from movement in laboratory soil columns (Hance *et al.*, 1981). The potential for herbicide movement is also assessed using computer models to simulate herbicide transport as a result of specific conditions and processes.

Differences in results between laboratory and field experiments are due in part to the variabilities of rainfall, evaporation and temperature in the field. Increasing evidence also indicates that there is substantial variability within field soils (Nielson *et al.*, 1983). This variability is due to differing physical and chemical properties of the soil within a field. Geostatistical techniques can be used to map soil properties of interest such as infiltration rate (Viera *et al.*, 1981) or adsorption (Wood *et al.*, 1987),and to develop sampling strategies that take field variability into account. Another difference between laboratory and field assessments is the greater degree of layering and structural influences in field soils. Soil aggregate sizes affected the distribution of herbicide in laboratory profiles following leaching (Dekkers and Barbera, 1977). This effect probably is due to the diffusion of herbicide into soil aggregates as shown by Hance (1976), but the effects of aggregates on water flow could not be discounted. Thus, the well-defined soil column is only partially representative of the soil conditions present in the field. Movement in field soils occurs over a long period of time and some herbicide is degraded during the experimental period. Laboratory studies are often conducted in much shorter time which may minimize degradation.

Herbicides used in cotton differ in their potential for downward transport in soil. Among soil-applied herbicides, the dinitroanilines appear to have little potential for downward transport (Helling, 1976). Substituted-urea and *s*-triazine herbicides have moderate potentials for leaching as determined by comparative movement on soil thin-layer plates (Helling, 1971b). Mobility of cotton herbicides within this group was in the order of fluometuron (Cotoran®) > prometryn (Caparol®) = diuron (Karmex®) > trifluralin (Treflan®). Dalapon (Dowpon®) was classified as highly mobile in this study. Soil thin-layer techniques also showed prometryn (Caparol®) and dipropetryn (Sancap®) to be less mobile than fluometuron (Cotoran®) (Murray *et al.*, 1975).

Field studies with substituted-urea herbicides indicate that a small fraction of the applied herbicide moves into the subsoil. Small amounts (10-40 ppb) of diuron (Karmex®) were found at the 12-18 inch depth in cotton fields (Upchurch *et al.*, 1969). In contrast, 10-400 ppb were found in the 0-6 and 6-12 inch depth increments. Similar results were found after repeated diuron (Karmex®) use in vineyard (Dawson *et al.*, 1968) and orchard (Khan *et al.*, 1976) soils. Approximately 5 ppb of diuron (Karmex®) were found in the 20-24 inch depth of the orchard soil. Small concentrations of fluometuron (Cotoran®) have also been reported in sub-

soils below the 12-inch depth (Nicholls *et al.*, 1982; Rogers *et al.*, 1985) in subsoils of cotton fields. The herbicide residues in these subsoils were not phytotoxic except to very sensitive species.

One year after a field application, 3 percent of the cyanazine (Bladex®) and 8.6 percent as the cyanazine metabolite 2-hydroxy-(1-carboxy-1-methylethylamino)-6-ethylamino-1,3,5-triazine were found at the 8-16 inch soil depth (Muir and Baker, 1978). Greater quantities of these compounds were retained in the 0.5 to 4- and 4 to 8-inch soil depths. Muir and Baker also found that another cyanazine metabolite, [2-chloro-4-(1-carbomyl-1-methylethylamino)-6-ethylamino-*s*-triazine], leached into drainage tile water in greater quantities than cyanazine. On a monthly basis, the amounts leached into the drainage water were less than 0.5 percent of that applied on a monthly basis. These results indicate that metabolites may have increased rates of transport in soil relative to the parent compound.

There is increasing evidence that some herbicides are transported deep into soil profiles at relatively rapid rates. The preferential flow of water and herbicides through macropores in soil appear to provide avenues for the rapid infiltration to considerable depths, perhaps as far as to groundwater (Simpson and Cunningham, 1982; Thomas and Phillips, 1979). Processes other than preferential flow also may be involved. Field evidence of rapid napropamide (Devrinol®) and prometryn (Caparol®) transport (Figure 2) was provided by Jury *et al.* (1986). A small portion of the napropamide (Devrinol®) and prometryn (Caparol®) moved ahead of the main bulk of the chemical which was retained at the surface. In contrast, bromide and bromacil (Hyvar®) did not have a leading peak. The lack of macropores in the nearly structureless loamy sand soil led the authors to suggest that some other transport mechanism must be involved for the napropamide (Devrinol®) and prometryn (Caparol®). The increased solubility of some pesticides in solutions of dissolved organic matter has led to speculation that herbicide-organic matter complexes which lessen the adsorptive effects of the soil might be responsible for increased rates of transport (Ballard, 1971; Khan, 1973; Madhun *et al.*, 1986). However, evidence showing appreciable levels of herbicide transport in soil by this mechanism is still lacking.

Under the right conditions or in the right situations, pesticides can be transported through soil to groundwater. A variety of pesticides have been found in the groundwater of a number of states. In one monitoring study, 17 pesticides were found in the groundwater of 33 states with concentrations ranging up to 700 ppb (Table 2) (Cohen *et al.*, 1986). Only three of the pesticides reported were herbicides used in cotton production: cyanazine (Bladex®), dinoseb and metolachlor (Dual®). Since this report, additional states have reported finding these chemicals in groundwater. Although the concentrations found are small due to the dilution of these compounds in the aquifer, it essentially is impossible to assess the total amount leached in relation to that applied.

Potential contamination of groundwater by pesticides can result from both non-point and point sources of contaminants. Non-point source contamination

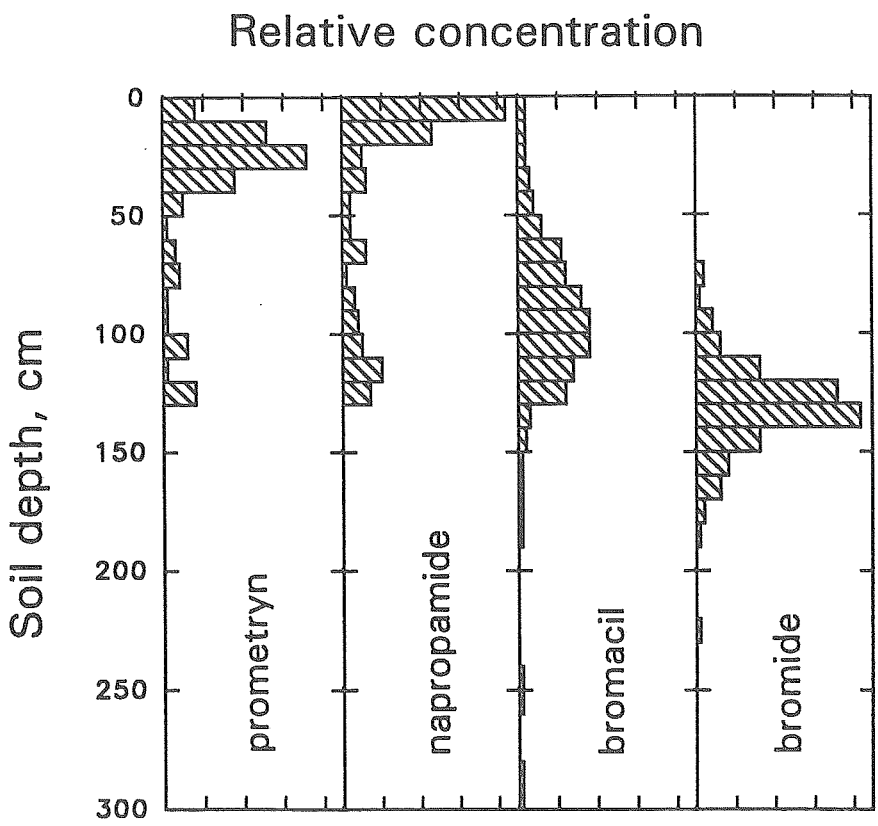


Figure 2. Average relative concentrations of herbicides and bromide tracer in loamy sand field soil after leaching with 10 cm of water. (from Jury *et al.*, 1986.)

would result from movement of the pesticide through soil and subsoil following field application. This may be the avenue of entry for mobile pesiticides that are not adsorbed and are relatively persistent. Point source contamination can result from movement of pesticides through soil at pesticide disposal or mixing sites, entry through uncased or abandoned wells, or entry in surface water through natural recharge sites. Non-point *versus* point source contamination cannot be distinguished after the fact. However, isolated instances of contamination most likely would be due to point source contamination. For instance, LaFleur *et al.* (1973) reported finding fluometuron (Cotoran®), a relatively immobile chemical, in the underlying groundwater within two months after application. They obtained their water samples through an uncased well. This would indicate that the

Table 2. Pesticides Found in Groundwater of Various States. (From Cohen *et al.*, 1986.)

Pesticide	Number of states	Concentration
		(ppb)
alachlor	4	0.1-10
aldicarb	15	1-50
atrazine	5	0.3-3
bromacil	1	300
carbofuran	3	1-50
cyanazine	2	0.1-1.0
DBCP	5	0.02-20
DCPA	1	50-700
1,2-dichloropropane	4	1-50
dinoseb	1	1-5
dyfonate	1	0.1
EDB	8	0.05-20
metolachlor	2	0.1-0.4
metribuzin	1	1.0-4.3
oxamyl	2	5-65
simazine	3	0.2-3.0
1,2,3-trichloropropane	2	0.1-5.0

contamination may have been from point source rather than from non-point source contamination.

The rate of herbicide degradation in the subsoil environment will have a significant effect on the transport of herbicide over long periods of time. Several studies indicate that the rate of degradation in subsoils is substantially less than that of surface soils (Bouchard *et al.*, 1982; Harris *et al.*, 1969; Kempson-Jones and Hance, 1979; Roeth *et al.*, 1969). Longer persistence in the subsoil environment would increase the opportunity to move deeper into the subsoil. Although microorganisms have been found in surprising quantities in deep soils and aquifers, their potential activity against most herbicides is largely unknown (Ventullo and Larson, 1985). The degradation rate of 2,4-D in groundwater samples was well below that of benzoate or sodium nitrilotriacetic acid (Ventullo and Larson, 1985).

In many soils, rainfall often exceeds the infiltration rate, and water runoff occurs. Total herbicide losses in runoff from cotton fields were usually less than one percent of the applied diuron (Karmex®), linuron (Lorox®), fluometuron (Cotoran®), prometryn (Caparol®) and trifluralin (Treflan®) (Baldwin *et al.*, 1975a, 1975b; Willis *et al.*, 1975). Concentrations of herbicide in runoff waters described

for these studies ranged from levels below detection to 920 ppb, but in most instances were below 500 ppb.

Wauchope (1978) reviewed the transport of herbicides in field drainage waters and concluded that pesticide losses of herbicides formulated as wettable powders were significantly greater than those of other formulations. Losses up to 40 percent could be expected in certain situations. The factors cited by Wauchope as most important in herbicide runoff were the intensity of rainfall, length of time since pesticide application and the slope of the field. Of course, incorporated herbicides are much less susceptible to loss in runoff than surface- or foliage-applied herbicides. The factors that control infiltration of water and herbicides into the soil (soil texture and structure, water content, herbicide adsorption) also govern how much herbicide is lost in runoff. High levels of soil moisture at rainfall reduce the infiltration and increase runoff, and increase the amount of herbicide transported from the field. Under these circumstances, the amount of prometryn (Caparol®) transported in runoff reached 3 percent of the applied herbicide compared to 0.4 percent in runoff from soil that was dry at rainfall (Baldwin *et al.*, 1975b). Herbicides in runoff are distributed in both the water and sediment according to the adsorptive capacity of the soil for the herbicide.

HERBICIDE PERSISTENCE AND ACTIVITY IN SOILS

Successful herbicide performance depends on the herbicide remaining available in sufficient quantities to be active against the weed. It has been shown that cotton produced maximum yield when kept weed-free for eight weeks after emergence (Buchanan and Burns, 1970). Therefore, to be successful, cotton herbicides must persist for this critical period, but not persist so long as to be harmful to the environment or succeeding crops. Persistence of herbicide is the net result of retention, transformation and transport processes acting in concert.

Residual levels of herbicides used in cotton may damage sensitive crops that follow cotton in the same field. The potential for damage is determined by the availability of herbicide in the soil and the sensitivity of the crop to the herbicide in question. Crops and weeds vary widely in their sensitivity to individual herbicides. In addition, prolonged periods of abnormal environmental influences may affect the microbial degradation and therefore increase or decrease herbicide persistence. The herbicide available for plant uptake is governed by the total residue concentration and the fraction adsorbed to the soil.

Organic matter is the principal soil component that must be considered in recommending herbicide application rates. In soils with a range of organic matter contents, between 0.5 and 3.0 lb. per acre of trifluralin (Treflan®) were required for 80 percent weed control four weeks after planting (Weber *et al.*, 1987). There was a high correlation between the amount of herbicide required for weed control and organic matter content. Similar results were obtained with metolachlor (Dual®). Increasing application rates above recommended levels increases the

risk of carryover, while decreasing herbicide rates may reduce the period of control obtained for some weeds.

Most herbicides used in cotton are dissipated by the previously mentioned degradation processes during the first year after application. Therefore, carryover and subsequent accumulation would be limited. If a herbicide were applied at 1.0 pound per acre and 10 percent of the chemical carried over, in the fifth year the maximum amount of chemical present would be 1.11 pounds per acre. At 20 percent carryover, there would be 1.25 pounds per acre the fifth year (Table 3).

Table 3. Accumulation of herbicide applied at 1.0 pound per acre with 10 and 20 percent carryover.

	10 percent carryover		20 percent carryover	
Year	Carryover	Total	Carryover	Total
		(lb/A)		
1	0	1.00	0	1.00
2	0.10	1.10	0.20	1.20
3	0.11	1.11	0.24	1.24
4	0.11	1.11	0.25	1.25
5	0.11	1.11	0.25	1.25

Parka and Tepe (1969) found that between 0.6 and 30 percent of the trifluralin (Treflan®) remained five to seven months after application, but in most soils the range was from 2-6 percent. After applications of 24 and 15 pounds of trifluralin over four- and three-year periods, respectively, herbicide levels were not over 4.1 percent (0.98 ppm), indicating that trifluralin does not accumulate in soils. Numerous other studies support the conclusion that trifluralin and other dinitroaniline herbicides do not accumulate in soils suitable for cotton (Miller *et al.*, 1975; Golab *et al.*, 1979; Brewer *et al.*, 1982). In soils of more northern areas, where cold temperatures slow degradation, trifluralin is more persistent, and significant amounts of herbicide can carry over at high rates of application (Solbakken, *et al.*, 1982; Smith and Muir, 1984).

Trifluralin (Treflan®) residues may affect the growth of rotational crops following cotton. Stoller and Wax (1977) found that dinitroaniline herbicides were sufficiently dissipated after 5 and 12 months to allow the normal growth of wheat and corn, respectively. Miller *et al.* (1975) found that trifluralin damaged grain sorghum and Japanese millet 15 months after application. The soil concentrations of trifluralin at 15 months were approximately 1 ppmw in the top 12 inches of soil. Similar effects were found with nitralin (Planavin®) and benefin (Balan®). In other studies, trifluralin damage to oats was dependent on the application rate (Schwiezer and Holstun, 1966). Little damage was observed at the 1 pound per

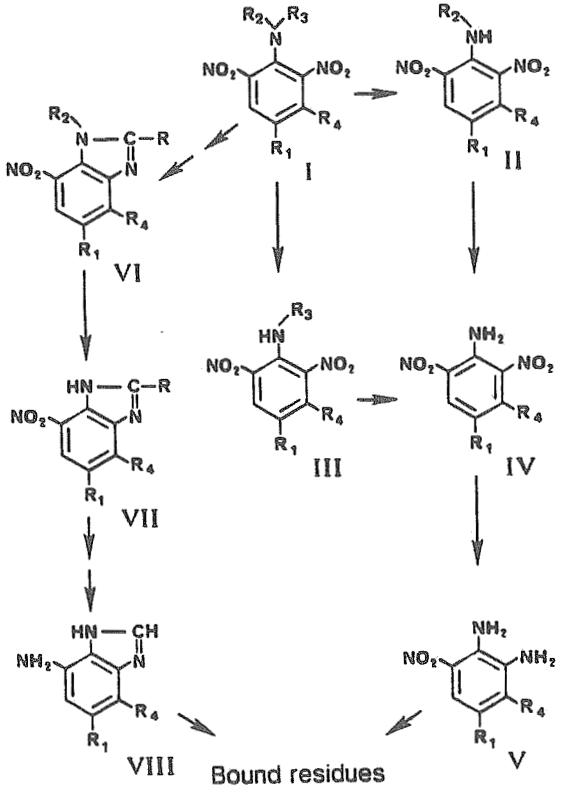
acre rate, but oats were damaged at the 2 and 4 pounds per acre rates 6 months after application.

The degradation of dinitroaniline herbicides results in a large number of metabolites similar in structure to the parent chemical (Probst *et al.*, 1967; Kearney *et al.*, 1976; Golab *et al.*, 1975). A simplified scheme for the degradation of the dinitroanilines is shown in Figure 3. Further details of the metabolism and fate of these herbicides can be found in previous reviews (Helling, 1976; Kaufman, 1974). Long term use of trifluralin (Treflan®) has the potential for accumulation of metabolites to levels that could have adverse effects on cotton production. The metabolites of trifluralin (Treflan®) have been shown, however, to be nonphytotoxic to cotton, even at relatively high concentrations (Koskinen *et al.*, 1984; Koskinen *et al.*, 1985; Vaughn and Koskinen, 1987). Boyette *et al.* (1988) found only small effects by trifluralin metabolites on microbial decomposition processes at rates of chemicals much higher than would be found in field situations.

Substituted-urea herbicide persistence has also been extensively studied. Typically between 75 and 90 percent of the applied diuron (Karmex®) or linuron (Lorox®) is dissipated in the first year after field application (Chandler and Savage, 1980; Hill *et al.*, 1955; Khan *et al.*, 1976; Upchurch *et al.*, 1969). Related studies showed that eight months after application diuron (Karmex®) was not present in high enough concentrations to damage cover crops (Hill *et al.*, 1955). Although small amounts of diuron (Karmex®) and the metabolite 3,4-dichloroaniline can carry over, there is no indication that the residues accumulate in soils repeatedly treated with diuron (Khan *et al.*, 1976). Fluometuron (Cotoran®) has the potential to carry over in sufficient quantities to damage some rotational crops after use in cotton, but does not accumulate in appreciable quantities (Chandler and Savage, 1980; Rogers *et al.*, 1985; Rogers *et al.*, 1986). Application of the insecticide aldicarb (Temik®) reduced the rate of degradation of fluometuron (Cotoran®) and dinitramine (Cobex®), but both herbicides had less than 5 percent of applied remaining after 120 days (Gomaa *et al.*, 1979).

The degradation of fluometuron (Cotoran®) and diuron (Karmex®) by several pathways leads to the formation of substituted aniline metabolites (Figure 4) similar in structure to the parent chemical. These metabolites have been shown not to affect growth and yield of cotton even at concentrations much higher than would be found in normal field situations (Moorman and Koskinen, 1990).

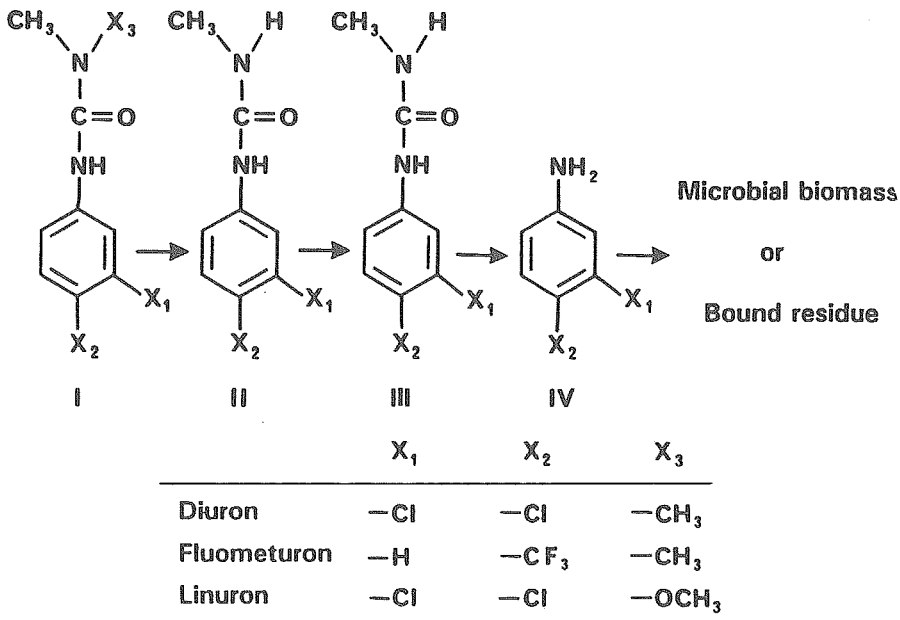
The *s*-triazines principally used in cotton (cyanazine [Bladex®], prometryn [Caparol®], dipropetryn [Sancap®]) are of short to moderate persistence in soil. Cyanazine (Bladex®) half-lives were estimated to be from 11 to 24 days over a 3-year field study (Muir and Baker, 1978). In another field study, only traces of cyanazine (Bladex®) remained after 5 months (Sirons *et al.*, 1973). From 2 to 23 percent of the applied prometryn (Caparol®) remained in soil 7 months after the last of three annual applications (Weber *et al.*, 1974). In this study, the greater



	R_1	R_2	R_3	R_4
Fluchloralin	$-CF_3$	$-CH_2CH_2CH_3$	$-CH_2CH_2Cl$	$-H$
Pendimethalin	$-CH_3$	$-H$	$-CH(CH_2CH_2CH_3)(CH_2CH_3)$	$-CH_3$
Profluralin	$-CF_3$	$-CH_2CH_2CH_3$	$-CH_2-\triangleleft$	$-H$
Nitralin	$-SO_2CH_3$	$-CH_2CH_2CH_3$	$-CH_2CH_2CH_3$	$-H$
Trifluralin	$-CF_3$	$-CH_2CH_2CH_3$	$-CH_2CH_2CH_3$	$-H$

Figure 3. Probable pathways of dinitroaniline degradation in aerobic soils. (From Golab *et al.*, 1975; Golab *et al.*, 1979; Kearney *et al.*, 1976; Laanio *et al.*, 1973; Stralka and Camper, 1981.)

residue levels were in the soils amended with massive amounts of clay or organic matter. Persistence or carryover problems with these herbicides applied in cotton are not anticipated.



	X_1	X_2	X_3
Diuron	—Cl	—Cl	$—CH_3$
Fluometuron	—H	$—CF_3$	$—CH_3$
Linuron	—Cl	—Cl	$—OCH_3$

Figure 4. Pathway of diuron, fluometuron, and linuron degradation in aerobic soils. (From Bozarth and Funderburk, 1971; Dalton *et al.*, 1966; Ross and Tweedy, 1970; Tweedy et al., 1970; Wallnofer, 1969.)

Some polycyclic phenoxyalkanoic acid (PCA) herbicides are used or have potential for use in cotton (*e.g.* fluazifop-butyl [Fusilade®], oxyfluorfen [Goal®], lactofen [Cobra®]). PCA herbicides are added to soil as esters that are rapidly hydrolyzed to herbicidally active acids (Martens, 1978; Bewick, 1986). The subsequent degradation of the acids occurs at slower rates, with the aliphatic side chains being degraded before the aromatic rings (Martens, 1978; Smith, 1985). The acids formed from these compounds are moderately persistent in soil, with 50 percent being degraded in 50 days or less. Limited evidence suggests that these herbicides persist longer in low pH soils (Hance, 1979). This would be consistent with the expected effect of low pH on the ester hydrolysis reaction.

Limited information is available on the field persistence of other herbicides that can be used in cotton. Norflurazon (Zorial®) was present in five field soils in quantities sufficient to injure grain sorghum (*Sorghum bicolor* L. Moench) one year after application (Schroeder and Banks, 1986a). Fluridone (Sonar®) persistence in these same soils was less than one year and injury to grain sorghum was not observed the year following application (Schroeder and Banks, 1986b). Methazole (Probe®) is rapidly degraded in soils to 1-(3,4-dichlorophenyl)-3-meth-

ylurea which is moderately persistent and contributes to the residual herbicidal activity of this compound (Walker, 1978).

INTERACTIONS OF SOIL FACTORS/PROCESSES AND CULTURAL PRACTICES AND HERBICIDE ACTIVITY

TILLAGE OPERATIONS

As previously discussed, herbicide persistence and efficacy in soil are controlled by various soil processes including adsorption, decomposition and movement. These processes are directly or indirectly affected by soil properties such as soil moisture, temperature, pH, organic matter and microbial populations. Tillage systems affect these same soil properties (Blevins *et al.*, 1983; Phillips and Phillips, 1984; Wiese, 1985; Koskinen and McWhorter, 1986).

Conventional tillage systems can decrease the soil moisture compared to conservation tillage systems. This is primarily due to increased runoff and decreased infiltration. The first-stage evaporation also increases (Phillips, 1984; Weber and Lowder, 1985). The decreased moisture in conventional tillage systems has the potential to decrease the degradation, volatilization and leaching of the herbicide.

Different tillage systems have different effects on soil temperature. In general, increased tillage increases the soil temperature in the spring and summer. The magnitude of the increase depends on the geographical location and the soil depth at which the temperature is measured. The rate of chemical reactions and microbial processes are temperature dependent, therefore, increases in soil temperature can lead to increased decomposition. Increased temperature also increases the volatilization of the herbicide.

In some situations, continuous application of ammonium fertilizer in conservation tillage systems decreases soil pH substantially compared to conventional tillage systems. Lack of tillage causes ammonium fertilizer to be nitrified near the soil surface. This lowers the soil pH in the vicinity of the fertilizer. With tillage, the fertilizer is mixed in the soil, diluting the pH effects. The low pH around the nitrifying fertilizer affects herbicide adsorption and chemical and microbial decomposition as previously discussed.

Tillage dramatically affects the organic matter content of soil. Once a soil is plowed for the first time, the organic matter begins to decrease. Each tillage operation accelerates the organic matter decomposition, particularly in warm moist climates. Finally, an equilibrium value is reached where the inputs equal the degradation. Most cotton producing areas are at this low equilibrium level.

Leaving residue on the surface, as in conservation tillage, or plowing under cover crops will start the process of restoring the organic matter content. With increased organic matter, there will be increased herbicide adsorption and de-

creased availability. Crop residues on the soil surface intercept and retain herbicides—in some cases more than 50 percent of that applied (Banks and Robinson, 1982).

Soil microbial populations can be substantially lower in soil under conventional tillage systems than under conservation tillage systems. The differences are primarily confined to the top three inches of soil (Doran, 1980; Dick, 1984). The differences in microbial populations, activities and ecology between tillage systems are primarily the result of differences in soil moisture, pH, temperature and organic matter content.

As discussed, tillage systems affect various soil properties which, in turn, can affect herbicide persistence. Many studies report greater persistence of triazine herbicides (AAtrex®, Caparol®, others) in soil under conventional tillage systems compared to no-till systems (Witt, 1984). However, if a residue does remain at the end of a growing season, there is more risk to the rotational crop planted with no-till practices rather than with conventional tillage because the herbicide residue is left in a shallow concentrated band.

Tillage and seedbed preparations can also affect the distribution of herbicides in soil. For instance, trifluralin (Treflan®) is preplant incorporated resulting in a uniform distribution of herbicide in the surface two to three inches of soil. In the bedding process, soil is removed and raised beds are constructed. Even after knocking down the beds, the depth of herbicide treated soil is greater in the row than in the furrow.

APPLICATION METHODS

For herbicides that are subject to losses due to volatilization and photodecomposition, or both, incorporation of the herbicide can increase its persistence. Soil incorporation has been shown to dramatically reduce the losses of trifluralin (Treflan®) and increase its efficacy. Increase in persistence has been found within the depth of incorporation (Savage and Barrentine, 1969; White *et al.*, 1977). However, incorporation must be as soon after application as possible, *e.g.*, within 24 hours for trifluralin (Treflan®). Increased persistence with soil incorporation has been demonstrated for prometryn (Caparol®) (Walker, 1976), diuron (Karmex®) and fluometuron (Cotoran®) (Horowitz and Herzlinger, 1974).

Another method for reducing volatilization, photodecomposition and even leaching losses is to formulate and apply herbicides as granules. Volatile herbicides such as triallate (Far-Go®), EPTC (Eptam®), dichlobenil (Casoron®) and propham (Chem-Hoe®) are normally incorporated into soil to avoid rapid loss. These herbicides have been shown to be more persistent when formulated as granules that could be surface-applied without incorporation, as opposed to other formulations (Parochetti *et al.*, 1971; Hance *et al.*, 1973; Siegman *et al.*, 1975; Schreiber, 1976; Spencer-Jones and Wilson, 1976). Prometryn (Caparol®) applied to soil as granules reduced volatilization and subsequent injury to cotton compared to prometryn applied as emulsifiable concentrate or wettable powder

formulations (Talbert *et al.*, 1971). Based on a literature review, it was concluded (Edwards, 1972) that for insecticides the relative order of persistence was granules > emulsions > miscible liquids > wettable powders. In general, granular herbicides are also more persistent than other formulations.

Herbicides have been applied through different irrigation systems (drip, furrow and sprinkler irrigation) with varying degrees of success. Herbicides with water solubilities greater than 0.1 mM have worked the best. Alachlor (Lasso®), atrazine (AAtrex®), metribuzin (Sencor,® Lexone®), napropamide (Devrinol®), and various thiocarbamates have all been used effectively in irrigation systems (Combellack, 1984). Trifluralin (Treflan®) has been reported to inadequately control weeds when applied and incorporated by high pressure sprinkler irrigation systems (Smith *et al.*, 1973; Ogg, 1980), apparently due to low solubility (< 1.0 μM) in water, strong adsorption to soil, volatilization losses or a combination of the three. However, new sprinkler systems with low pressure drop nozzles may give acceptable weed control with trifluralin (Treflan®) and pendimethalin (Prowl®).

Although good weed control has been reported using a center pivot sprinkler system to apply herbicides, the method has potential problems with certain types of herbicides. Volatilization losses during center pivot application can be large for herbicides with high vapor pressures and relatively low water solubilities. Also, herbicides formulated as wettable powders have not been applied through sprinklers because problems occur when they settle out of solution and clog sprinkler lines.

SUMMARY

The performance and persistence of cotton herbicides is not a fixed property of the herbicide. It is regulated by the interaction of pesticide, soil, plant and environmental factors with transformation, retention and transport processes. Pesticide factors include: chemical properties such as structure, solubility and volatility; application methods including formulation and rate; and decomposition characteristics such as mechanisms, kinetics and metabolite formulation. Important soil factors include organic matter and clay type and amount, pH, moisture, aeration, microbial activity, topography and depth to groundwater. The major plant factor is the species characteristics combined with stage of growth. Environmental factors include temperature, precipitation, air movement and solar radiation.

While many of these factors vary across the cotton producing regions and season, they can also vary substantially from field to field within a farm and from day to day. It would appear that only rare combinations of factors and their effects on processes would result in performance and persistence problems such as carryover, lack of weed control or environmental contamination. For instance, most of the herbicides applied for preemergence weed control in cotton

have created no particular carryover problems. In the West there have been some persistence problems where rainfall has been critically short. In the Mid-South and Southeast, some persistence problems have resulted from the use of herbicides such as diuron (Karmex®) and linuron (Lorox®) applied at layby, especially where rainfall was critcially short late in the growing season, thus delaying degradation of the herbicide.

Lack of weed control with repeated herbicide applications, similar to problems associated with thiocarbamate herbicides in corn, have not been observed in cotton production. It would also appear that groundwater contamination by herbicides would not be a problem in cotton production. No incidences of non-point pollution have been reported.

There are no apparent persistence problems with some of the new chemistries such as the monophenyl- and diphenyl-ether sethoxydin (Poast®) and fluazifop (Fusilade®) type herbicides that are applied broadcast over-the-top for selective control of grasses. However, as new chemicals are introduced and used for weed control in cotton production, knowledge of factors and processes and their interactions and how they affect herbicide persistence in soil will prevent future potential problems. The knowledge also will aid in the future development of crop rotation systems for cotton.

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Chapter 11

MODES OF ACTION OF HERBICIDES USED IN COTTON

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INTRODUCTION

WHY UNDERSTAND MODE OF ACTION?

Weed scientists, pesticide chemists and those interested in pest management have become increasingly interested in learning how herbicides kill target plants. Their reasons and motives for wanting this information are varied and sometimes overlap.

Scientists involved in herbicide discovery have made mode of action studies an integral part of several of their strategies for finding new herbicides. One approach involving mode of action is to design herbicides to inhibit particular biochemical processes. This is attractive to industry because molecular sites unique to higher plants can be chosen, thus reducing potential animal toxicological problems. Also, an inhibitor of a particular enzyme might be a good selective herbicide because it differs between target species and associated crops. Knowledge of structures of substrates, products, cofactors and already known inhibitors of the enzyme gives the chemist a start in the design of the herbicide.

Another use of mode of action information is in intelligently improving herbicides by structure-activity studies. Knowledge of the molecular site of action provides a primary assay for doing structure-activity studies. For example, to improve a herbicide that kills the plant by inhibiting a particular enzyme, a large number of analogues could be screened by simply determining their ability to inhibit the enzyme in a test tube. This method is generally much more rapid and less expensive than are bioassays.

The pesticide industry is also becoming more interested in knowing the molecular site of action of its herbicides. This information can be used to defend or challenge patents and to defend or challenge toxicological studies. A structural analogue that hits an entirely different molecular site for its herbicidal action than a somewhat similar molecule might have a better chance in court to be ruled a different and unique chemistry not covered by a competitor's patent. Also, a compound known to kill plants by inhibiting an enzyme found only in plants might have fewer problems in toxicological studies than a herbicide that kills

plants by inhibiting processes common to plants and animals such as mitochondrial respiration or potassium transport.

Knowing the mechanism of action of different herbicides is also useful in predicting possible herbicide interactions. For instance, a herbicide that causes rapid cellular collapse is likely to antagonize one that must be translocated to meristematic areas for activity. Thus, paraquat (Gramoxone®), a rapidly-acting contact herbicide that depends on photosynthesis, would be likely to antagonize glyphosate (Roundup®), a herbicide that must be translocated to meristems for maximal effect. However, bentazon (Basagran®), a photosynthesis inhibitor, will increase weed control by paraquat by giving paraquat time to translocate before it becomes lethal at the cellular level. In this manner, design of synergists or protectants can be based on knowledge of herbicide mode of action.

Absorption and translocation are parts of the mode of action of a herbicide. Understanding these processes for a particular herbicide is also important in predicting interaction of the herbicide with other pesticides, additives and adjuvants. Understanding the influence of the environment on herbicide efficacy is particularly dependent on knowing the entire mode of action of a herbicide, especially its absorption and translocation characteristics.

Determining the mechanisms of resistance of weeds to herbicides is becoming more important because the incidence of herbicide resistance is increasing geometrically (LeBaron and Gressel, 1982; Gressel, 1986). Understanding the nature of resistance is dependent on knowing the mode of action of the herbicide to which resistance has developed. This knowledge offers an opportunity to intelligently design an alternative herbicide that affects the same site or to take advantage of the genetic alteration in a way that might put the resistant mutant at a disadvantage. Additionally, the altered gene that confers resistance might be transferred to susceptible crops by new methods of genetic engineering (see next to last section).

LEVELS OF MODE OF ACTION

The mode of action of a herbicide is a complicated and multifaceted process, beginning with the interaction of the herbicide with the plant surface and ending with cellular death. The site at which the herbicide affects the plant can be considered on an organ (*e.g.*, root or leaf), tissue (*e.g.*, mesophyll or meristem), cellular, organelle (*e.g.*, mitochondria or chloroplast) or molecular basis. In addition, at each level there are secondary and tertiary effects. For example, secondary effects of blocking electron transport in photosynthesis are blocked ATP and NADPH synthesis, which in turn, halts carbon dioxide fixation. This results in reduced synthesis of sugars which ultimately reduce the synthesis of everything else in the plant. Simultaneous with the reduced synthetic capabilities caused by the photosynthetic inhibitor are destructive secondary and tertiary effects of unchannelled energy dissipation from light-energized chlorophyll molecules that cannot lose their energy through normal photosynthetic processes.

The effects of these secondary molecular processes can be examined and described at each level of action. Additionally, there are sometimes more than one direct molecular site of action of a herbicide, although the phytotoxicity is generally almost exclusively due to only one of the molecular sites of activity. For instance, a herbicide might inhibit several enzymes, but most of the herbicidal activity is usually associated with only one inhibitory activity. In cases where there are more than one direct or "primary" molecular site of action of a herbicide, the relative importance of the different primary sites may vary between species. Thus, a full and detailed description of how a herbicide kills a plant is enormously complex.

Furthermore, herbicides often have non-toxic effects at low dosages on target species or at low or high dosages on plant species that are resistant to them. For instance, low dosages of triazine herbicides (*e.g.*, Caparol®, AAtrex®) can enhance nitrogen metabolism in some species (Ries *et al.*, 1967) and sublethal levels of many herbicides can induce synthesis of certain secondary products (Duke, 1985b). Few of these effects have been well characterized.

The level at which the mechanism of action is most clear is usually at the primary molecular level. For clarity and brevity, this is the level at which emphasis will be placed in this chapter. Sources of more detailed information on the mechanisms of action of herbicides include Duke (1985a), Fedtke (1982), Moreland *et al.* (1982), and Ashton and Crafts (1981).

MODES OF ACTION OF HERBICIDE CLASSES

Only those herbicide classes that are currently being evaluated for use in cotton in the southern United States (York, 1987) or those that have been used over the past decade in the United States (McWhorter, 1988) are discussed.

ARSENICALS

Two arsenic compounds, DSMA (disodium methanearsonate) and MSMA (monosodium methanearsonate), are commonly used in cotton weed control. Other forms of arsenic such as arsenite, arsenate and cacodylate are more phytotoxic than methanearsonate (Sachs and Michaels, 1971); however, methanearsonate salts are superior herbicides because they give less contact damage and are rapidly translocated through the plant symplast (the living part of the plant) (Wauchope, 1983). Methanearsonate translocation is much like translocation of phosphate. Transport is toward growing areas or storage areas, making it effective against perennial weeds that have underground storage organs.

Since little or no carbon-arsenic bond breakage occurs in plants (Domir *et al.*, 1976), the methanearsonate ion is probably the toxic species of MSMA and DSMA. Its mode of action at the molecular level is not well understood. Effects on amino acid content, respiration and chlorophyll synthesis have been reported (Wauchope, 1983), however, none of these effects appear to be primary.

A primary effect that may well explain the herbicidal activity of methanearsonate was proposed by Knowles and Benson (1983). They demonstrated that methanearsonate can be photochemically reduced by photosystem I of photosynthesis to form sulfhydryl group reagents, including arsenomethane (Figure 1). Arsenomethane reacts with sulfhydryl groups of enzymes involved in carbon fixation and its regulation, inhibiting carbon fixation. This is especially apparent in the C4 plant johnsongrass. C4 plants like johnsongrass assimilate carbon (C) through the C4 pathway and are considered to be more efficient in photosynthesis than other plants. In johnsongrass methanearsonate causes rapid buildup of malic acid due to inhibition of $NADP^+$-malic enzyme, a C4 enzyme especially sensitive to reagents that react with sulfhydryl groups. The elimination of carbon fixation in bright light causes rapid photooxidative damage (leaf burning) due to uncontrolled dissipation of absorped light energy by several mechanisms (Halliwell, 1985).

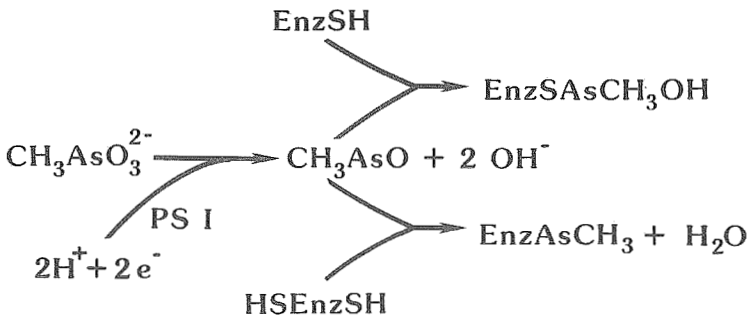


Figure 1. Proposed mode of action of arsenomethane herbicides. PSI = photosystem I; $CH_3AsO_3^{2-}$ = methanearsonate; CH_3AsO = arsenomethane; EnzSH = sulfhydryl-containing enzyme; HSEnzSH = enzyme with two adjacent sulfhydryl groups.

The basis of selectivity for the methanearsonates may be differential conjugation in some cases. Several studies have shown that MSMA is rapidly bound to sugars, amino acid and organic acids in plants. Sckerl and Frans (1969) found that methanearsonate was conjugated to a ninhydrin-positive molecule in sensitive johnsongrass but not in tolerant cotton. Thus, the molecule may be bioacti-

vated to a more toxic or more translocatable species in order to be herbicidally effective. In other cases, differential absorption appears to explain differences in susceptibility. For instance, Keeley and Thulen (1971) found good correlations between control of yellow and purple nutsedge with DSMA and MSMA and absorption of the herbicides.

ARYLOXYPHENOXY ALKANOIC ACIDS

The aryloxyphenoxy alkanoic acids are a new group of grass-killing herbicides characterized by an alkanoic acid (generally propanoic acid) with an aryloxyphenoxy group attached to an asymmetric carbon. They are members of a larger class of herbicides, the polycyclic alkanoic acids, which also includes the benzoyl-N-phenyl phenoxy alkanoic acids (Duke and Kenyon, 1988). The polycyclic alkanoic acids all appear to have the same mechanism of action; however, only the aryloxyphenoxy alkanoic acids of this group are utilized in cotton. All members of this group are sold as propanoic acid esters—usually methyl, ethyl, or butyl.

Commonly used members of this group that are used in cotton are fluazifop-butyl (Fusilade®) and haloxyfop-methyl (Verdict®). Although diclofop-methyl (Hoelon®) is not commonly used in cotton, virtually all studies of the mechanism of action of this group of herbicides have been conducted with diclofop. Since the symptomologies of all members of this herbicide group are the same, there is little reason to expect that there are any significant differences in the mechanisms of action of the members of this class of herbicides.

This group of herbicides is readily absorbed by plant leaf cuticles. The ester group apparently increases absorption by increasing lipophilicity. Thus, members of this herbicide group probably cross the plant cuticle by becoming incorporated into the waxy matrix of the cuticle and then diffusing into adjacent cells by movement into membranes. As a result of its ability to rapidly move into the lipophilic domains of the cuticle, this group of herbicides is relatively "rainfast." Soon after entry into the cell, or perhaps even in the cell wall, the ester linkage is broken by hydrolysis. Hydrolysis bioactivates the herbicide because the ester form of the herbicide is not active at the site of action.

Despite the efficient absorption of members of this herbicide group, they generally are translocated rather poorly (Duke and Kenyon, 1988). However, there are exceptions such as fluazifop-butyl which has been reported to translocate relatively well (translocation of 25 to 60 per cent of absorbed) (Kells *et al.*, 1984; Wills and McWhorter, 1983; Nalewaja *et al.*, 1986). The translocated form of the herbicide has been determined to be almost exclusively the de-esterified form (Carr *et al.*, 1986). Generally, the more lipophilic a compound, the less phloem-mobile it is.

Herbicidal injury by these herbicides usually follows the pattern of: (a) cessation of growth, (b) chlorosis, (c) meristematic necrosis and, ultimately, (d) death and necrosis of the remainder of the plant. Although many effects of this herbi-

cide group on leaf tissues have been described, the tissues that appear initially to be most drastically affected are meristems. Intercalary meristems, the basal meristems of grass leaves, are particulary vulnerable since these poorly translocated herbicides accumulate most rapidly at this meristem as they move basipetally from the leaf blade. No microscopic studies have been published on intercalary meristem effects of these herbicides; however, Vaughn [see Duke and Kenyon (1988)] showed that halxoyfop-methyl causes extensive vacuolization and vacuolar engulfment of cytoplasm in root meristems of grain sorghum [*Sorghum bicolor* (L.) Moench].

Some studies have indicated that this class of herbicides act as auxin antagonists because artificial auxins such as 2,4-D could reverse their effects. However, structure-activity studies (Taylor *et al.*, 1983) have indicated that the antagonism of phenoxy propanoic acid-type herbicides such as 2,4-D, and aryloxyphenoxy alkanoic acids is due to structural similarities and not to the auxin-like activity of the phenoxy propanoic acids.

The most definitive studies to determine the site of action of these compounds all indicate that the primary site of action is lipid synthesis. Hoppe (1985) found diclofop to inhibit fatty acid synthesis with an I_{50} of 0.1 μM after 0.5 to 4 hours of pretreatment in sensitive species, but not in insensitive (tolerant) species. Diclofop (Hoelon®) and other aryloxyphenoxy propanoic acid herbicides stopped fatty acid synthesis within one hour in isolated chloroplasts of sensitive maize, but not in insensitive bean (Hoppe and Zacher, 1985) (Figure 2). These studies were done with green chloroplasts because the proplastids of meristems are virtually impossible to isolate. However, the immature, rapidly metabolizing plastids of the intercalary meristem undoubtedly are sites of even more active lipid synthesis than mature chloroplasts. Thus, one might expect the cellular results of inhibition of lipid synthesis of the intercalary meristem, and cells rapidly proliferating from it, to be, as observed, general membrane disruption and cellular collapse.

More recent work from several laboratories has shown that the primary molecular site of action of this herbicide class is acetyl-CoA carboxylase, an enzyme required in lipid synthesis (Burton *et al.*, 1987; Secor and Cséke, 1988; Kobek *et al.*, 1988). The enzyme isolated from grass species such as barley is sensitive to these herbicides at very low levels.

There is no good evidence that the selectivity of this group of herbicides is based on differential absorption or translocation (Duke and Kenyon, 1988). From recent findings, one would predict that the mechanisms of tolerance or resistance to this group of herbicides resides at the site of action; however, Hoppe (1985) and others (Shimabukuro, 1985) have evidence that metabolic degradation may play a role in the tolerance of some species to these herbicides.

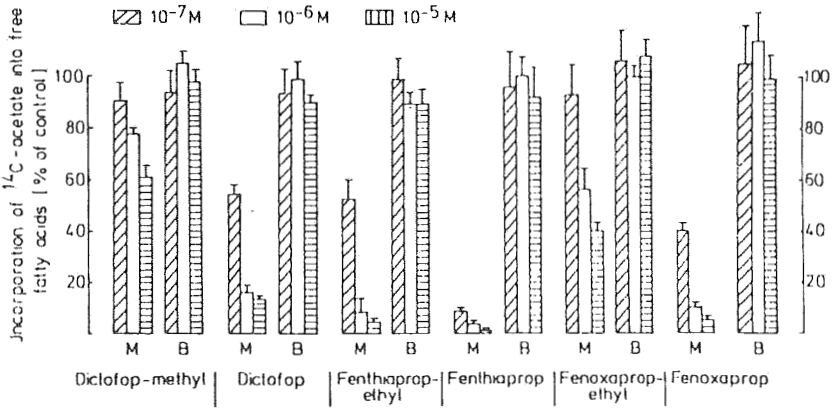


Figure 2. Effect of polycyclic alkanoic acid herbicides on the incorporation of ^{14}C-acetate into free fatty acids by isolated sensitive maize (M) and insensitive bean (B) chloroplasts. Incubation was terminated after 1 hour by lipid extraction. (Hoppe and Zacher, 1985.)

CHLORINATED ALIPHATIC ACIDS

There are two commonly used chlorinated aliphatic acid herbicides, TCA (trichloroacetic acid) and dalapon (2,2-dichloropropionic acid). Of these, only dalapon (Dowpon®) is currently used in cotton. Dalapon is a postemergence herbicide and symptoms of herbicide injury with this herbicide are growth inhibition, chlorosis and distortion of growth patterns. It is readily absorbed by foliage and is translocated both apoplastically (outside of the cytoplasm) and symplastically (from cell to cell, within the cytoplasm) (Ashton and Crafts, 1981). Dalapon is not readily metabolized in plants, but is readily degraded in the soil (Foy, 1975). Even in cotton, only about 10 per cent of dalapon applied to the plant was degraded during a 10-week period after treatment (Foy, 1961).

The mechanism of action of dalapon at a fundamental level is unknown. It has been reported to be an inhibitor of lipid synthesis, a disrupter of nitrogen metabolism and an inducer of phenolic metabolism (Ashton and Crafts, 1981). There is no good evidence that any of these are primary effects and in some cases conflicting results have been obtained.

Anderson *et al.* (1962) hypothesized that dalapon acts by disrupting nitrogen metabolism, causing toxic levels of ammonia to build up. Later work demonstrated that dalapon altered free amino acid levels in susceptible varieties of plants with no effects on levels in dalapon-resistant varieties. This led to the

hypothesis that dalapon inhibits aminating enzymes involved in amino acid biosynthesis (detailed by Ashton and Crafts, 1981). However, the symptoms of dalapon injury do not resemble those of herbicides such as glufosinate (Ignite®) which have been proven to kill by causing massive ammonia buildup by inhibiting the aminating enzyme, glutamate synthetase (Wild *et al.*, 1987).

The only proven primary site of action is the effect of dalapon on the synthesis of pantothenic acid in microorganisms (Hilton *et al.*, 1959; Van Oorschot and Hilton, 1963). Pantothenic acid is required for synthesis of coenzyme A which is required for many metabolic and biosynthetic functions. Hilton *et al.* (1959) found that dalapon competes with pantenoate for a site on the pantothenic acid-synthesizing enzyme. If the herbicide effectively inhibits the same enzyme in plants, this one effect could account for many of the observed secondary effects. Pantothenate fed to dalapon-affected barley plants will partially overcome the effects on abnormal tillering, however, little or no reversal of growth effects is seen (Hilton *et al.*, 1959). Since these findings, little support has been garnered for the hypothesis that inhibition of pantothenic acid is the primary mechanism of action of dalapon. In fact, the literature is filled with conflicting evidence. No clear picture emerges.

Dalapon will inhibit mineral absorption by excised roots within 20 minutes at only 0.1 mM (Ferrari *et al.*, 1981). Furthermore, there is a good correlation between the magnitude of this effect and the phytotoxicity of dalapon to the tested species. The only other physiological parameter that has been correlated with susceptibility to dalapon is higher levels of the amino acid asparagine in tolerant genotypes of bermudagrass (Sistrunk, 1969).

CHLOROACETAMIDES

The chloroacetamides are represented by the herbicides alachlor (Lasso®) and metolachlor (Dual®). The mechanism of action of this group of herbicides is still unknown. Both alachlor (Sharp, 1988) and metolachlor (LeBaron *et al.*, 1988) have recently been reviewed. These compounds are generally absorbed readily and apoplastically translocated (translocated outside of the cytoplasm). At the whole plant level, chloroacetamides are growth inhibitors, greatly inhibiting both germination and growth.

Many secondary effects of these compounds have been found. Although many studies have shown that protein synthesis is inhibited by chloroacetamides, *in vitro* studies demonstrated that there is no direct effect on plant protein synthesis (Deal *et al.*, 1980). Only a few distinct effects that may be closely related to the primary mechanism of action have been described. These compounds are known to alkylate proteins (McFarland and Hess, 1986). The alkylation varies with the specific protein and generally herbicidal activity correlates with alkylation potential. Their herbicidal activities may be associated with alkylation of specific proteins. Weisshaar and Böger (1987) have shown that metalachlor has a very pronounced and rapid inhibition (76 per cent in 4 hours) of ^{14}C-acetate incorpo-

ration into certain acyl lipids (monogalactosyl diacylglycerol) in the green alga *Scenedesmus acutus*. This process and others greatly inhibited by chloroacetamides, such as anthocyanin synthesis (Molin *et al.*, 1986), require coenzyme A. Chloroacetamides can alkylate coenzyme A *in vitro* (Leavitt and Penner, 1979). Thus, although these herbicides may inhibit several enzymes by alkylation, those processes dependent on coenzyme A may be the most sensitive.

Rapid effects of this herbicide group on membrane leakage, mineral ion uptake and amino acid uptake have also been reported (Balke, 1985). However, the symptomology of phytotoxicity at the whole plant level (severe growth inhibition) is not characteristic of compounds that rapidly destroy membrane function.

CINEOLE DERIVATIVES

Cinmethylin (Cinch®) is a preemergence, cineole-based herbicide that is registered for control of grasses in cotton. This herbicide is closely related to 1,8-cineole, a sesquiterpenoid allelochemical produced by many species, including those of the genera *Salvia* and *Artemisia*. Very little is known of its mechanism of action.

The only symptomology for this herbicide is inhibition of growth. In the only published paper on the mechanism of action of cinmethylin, El-Deek and Hess (1986) reported that there was no effect of the herbicide on cell elongation of oat coleoptiles. They did find, however, that cell division was inhibited, although all stages of mitosis were similarly affected. They theorized that the herbicide prevents entry into mitosis rather than being a mitotic disrupter. Growth inhibition by cinmethylin could not be reversed by root-feeding affected plants with supplemental amino acids, suggesting that the herbicide does not affect amino acid synthesis.

CYCLOHEXANEDIONES

This herbicide group is used postemergence in much the same way that the aryloxyphenoxy propanoic acids (see above) are used. Examples of cyclohexanediones that are used in cotton are sethoxydim (Poast®) and clethodim (Select®). The etiology and symptomology of herbicidal damage caused by this group is virtually identical to that caused by the aryloxyphenoxy propanoic acids; that is, the compound is absorbed by the leaf and translocated to the intercalary meristem where it disrupts meristematic cell plastid development and cellular integrity (Ishikawa *et al.*, 1980; Lichtenthaler and Meier, 1984). As with the aryloxyphenoxy propanoic acids, the primary site of action appears to be inhibition of lipid synthesis. Ishihara *et al.* (1987) reported that sethoxydim inhibits polar lipid synthesis in corn root tips within 15 minutes after treatment. No significant effects on synthesis of proteins, nucleic acids or sugars were measured within two hours. Lichtenthaler *et al.* (1987) and Kobek *et al.* (1988) found cyclohexanediones to strongly inhibit lipid synthesis in the chloroplasts of sensitive

species within 20 minutes, however, no inhibition was detected in chloroplasts of insensitive species (Figure 3).

As with the aryloxyphenoxy propanoic acids such as diclofop (Hoelon®), several laboratories have recently provided good evidence that this herbicide class inhibits lipid synthesis by inhibiting acetyl-CoA carboxylase activity (Burton *et al.*, 1987; Focke and Lichtenthaler, 1987; Rendina and Felts, 1988; Secor and Cséke, 1988). Acetyl-CoA carboxylase activity of insensitive plant species was affected very little at concentrations that severely inhibited the enzyme from susceptible grasses (Burton *et al.*, 1987; Rendina and Felts, 1988).

The mechanism of resistance to cyclohexanediones appears to be at the sight of action. Careful studies (Struve *et al.*, 1987) have found no differences in absorption of sethyoxydim by sensitive [Kentucky bluegrass (*Poa pratensis*) and sheep fescue (*Festuca ovina*)] and resistant [annual bluegrass (*Poa annua*) and red fescue (*Festuca rubra*)] grasses. As mentioned above, lipid synthesis and acetyl-CoA activity of sensitive species, but not insensitive species, are inhibited by this family of herbicides.

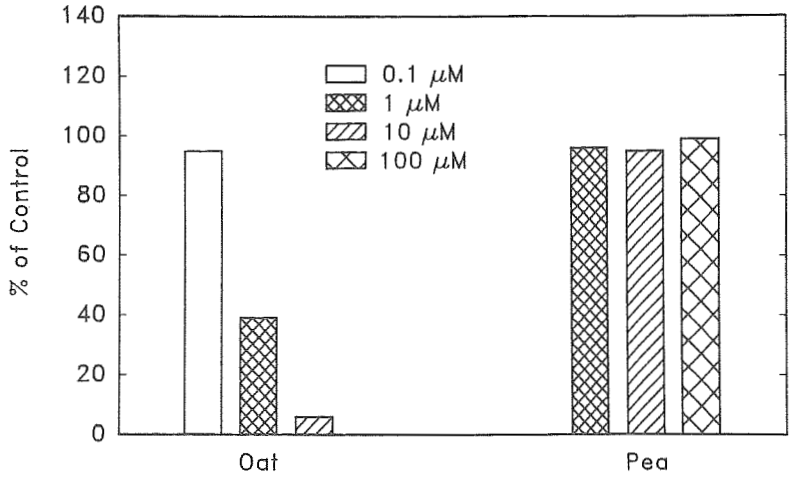


Figure 3. Effects of sethoxydim on incorporation of ^{14}C-acetate into free fatty acids by isolated chloroplasts of oat (sensitive) and pea (insensitive) over a 20 minute period. (Redrawn from Lichtenthaler *et al.*, 1987.)

DCPA

Dimethyl tetrachloroterepthalate (DCPA) is a preplant herbicide that is not absorbed readily by leaves. It neither is translocated well nor is it known to be metabolized by plants. DCPA (Dacthal®) is a growth inhibitor and differentiation

disruptor. It stops cell division in root tips (Bingham, 1968; Chang and Smith, 1972). Cell division is arrested in prophase and aberrant cell nuclei are common in DCPA-affected cells (Holmsen and Hess, 1984). Concomitant with arrested cell division, researchers have observed abnormal cell nuclei, abnormal cell differentiation, and altered cell wall formation (Nishimoto and Warren, 1971; Anderson and Shaybany, 1972; Holmsen and Hess, 1985; Shaybany and Anderson, 1972). As observed by Holmsen and Hess (1984), these are effects that might be expected from a microtuble disrupter. Holmsen and Hess (1985) found DCPA to have effects similar to both colchicine and propham (Chem-Hoe®), both disruptors of mitotic spindle structure and function. Robinson and Herzog (1977) found that DCPA inhibited the polymerization of pig brain tubulin in a test tube, although it had little effect on cell wall organization in the alga *Oocytis solitaria*. Vaughn *et al.* (1987) found DCPA causes loss of spindle and cortical microtubules in both trifluralin-sensitive goosegrass and a trifluralin-resistant goosegrass with altered microtubles (see below). Apparently, if DCPA intereacts directly with tubulin, the protein from which microtubules are constructed, the site of interaction of DCPA differs from that of the dinitroanilines.

DINITROANILINES

A large number of dinitroaniline herbicides, including dinitramine (Cobex®), oryzalin (Surflan®), trifluralin (Treflan®), profluralin (Tolban®), pendimethalin (Prowl®) and fluchoralin (Basalin®) are used in cotton. They are all growth inhibitors used as preplant-incorporated herbicides much like DCPA (see above). Like most preplant herbicides, the dinitroanilines are taken up primarily by roots; however, other subterranean parts of seedlings can be important in uptake. Translocation from roots to shoots or vice versa is generally negligible. The dinitroanilines are extensively metabolized by both microorganisms and higher plants; however, few studies have been designed to differentiate between microbial degradation of the herbicide before it entered the plant and degradation by the plant. Ashton and Crafts (1981) provide a detailed literature review of uptake, translocation and metabolism of dinitroaniline herbicides.

Trifluralin arrests cell division by preventing prophase chromosomes from properly aligning at the metaphase stage of mitosis (Hess, 1987). These effects are usually very pronounced with herbicide applications in the 1 μM range. Chromosomes are aligned during metaphase by the spindle apparatus which is composed of microtubules which, in turn, are composed of the protein tubulin.

At the ultrastructural level, a reduced number or an absence of microtubules is observed in dinitroaniline-treated cells (Jackson and Stetler, 1973; Bartels and Hilton, 1973; Hess and Bayer, 1974). Hess and Bayer (1977) later reported that trifluralin binds to tubulin protein isolated from the green alga *Chlamydomonas*. Oryzalin was found to have a binding ratio or nearly one molecule of herbicide per molecule of tubulin in *in vitro* studies (Strachan and Hess, 1983). It had insignificant binding to denatured tubulin, intact microtubules (polymerized tubulin)

and non-tubulin proteins. These data strongly suggest that dinitroaniline herbicides inhibit growth and cell development by binding to tubulin monomers and preventing their polymerization into the microtubules required for mitotic spindle formation and cell wall deposition.

This conclusion is further supported by the finding by Morejohn *et al.* (1983) that oryzalin prevents taxol-induced polymerization of rose tubulin. Similarly, Vaughn and Vaughan (1990) found that tubulin of dinitroaniline-sensitive goosegrass does not polymerize in the presence of dinitroaniline herbicides. They also found that the polymerization of tubulin from dinitroaniline-resistant goosegrass was unaffected by dinitroaniline herbicides. One of the subunits of tubulin from the resistant goosegrass biotype was found to be somewhat smaller than in the sensitive biotype. Considerable cross resistance with the phosphoric amides (such as amiprophos-methyl), another herbicide group that disrupts cell division, was found by Vaughn *et al.* (1987), supporting the view that the resistance is due to a structural alteration in tubulin, rather than changes in absorption, translocation or metabolism.

The mechanisms of resistance of other species to dinitroaniline herbicides may also be related to tubulin differences. Vaughan and Vaughn (1988) found that carrots are resistant to this class of herbicides and that their tubulin is different from that of sensitive plant species.

Hilton and Christiansen (1972) found an excellent correlation between seed lipid content and the sensitivity of eleven crop and weed species to trifluralin. Apparently, this highly lipophilic herbicide is readily sequestered into lipid bodies, away from its site of action. This may well explain the tolerance of cotton to this herbicide class because its tolerance to pyridazinones, another group of lipophilic herbicides, has been demonstrated to have a similar basis (Strang and Rogers, 1974).

GLYPHOSATE

Glyphosate (Roundup®) is a non-selective herbicide that exerts most, if not all, of its effects by inhibiting the synthesis of aromatic amino acids (phenylalanine, tyrosine and tryptophan). Aromatic amino acids are required for protein synthesis. Thus, blockage of synthesis of these essential amino acids slows and then stops protein synthesis, resulting in arrest of growth processes, cellular disorganization, followed by cellular death. Jaworski (1972) first proposed this as the mode of action, based on the finding that supplying certain organisms with exogenous aromatic amino acids would prevent reduction of growth by glyphosate.

Aromatic amino acids are synthesized by the shikimic acid pathway, a biosynthetic pathway peculiar to microorganisms and plants (Figure 4). Amrhein's laboratory found that glyphosate causes massive accumulation of shikimic acid in treated plants (Amrhein *et al.*, 1980). This led him to examine the effects of glyphosate on 5-enolpyruvyl shikimic acid-3-phosphate [EPSP] synthase, the enzyme that coverts shikimate-3-phosphate to 5-enolpyruvyl shikimic acid

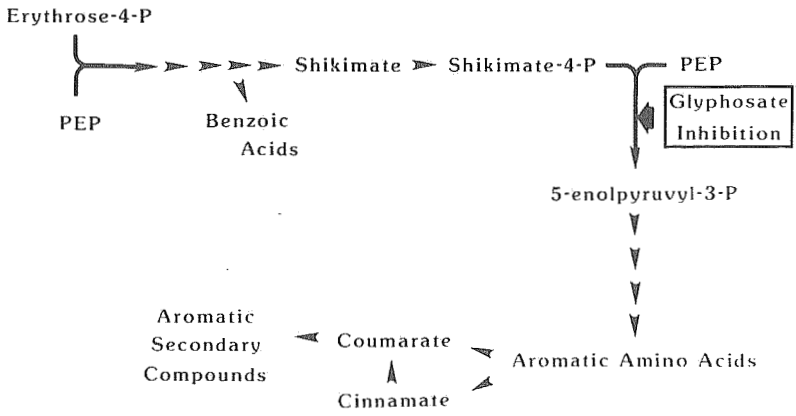


Figure 4. The shikimate pathway with the site of inhibition of glyphosate indicated. PEP = phosphoenolpyruvate.

3-phosphate (Steinrücken and Amrhein, 1980). They found glyphosate to be a potent inhibitor of the enzyme. It since has been found to inhibit this enzyme in a wide variety of plants and microorganisms (Duke, 1988).

Normally, products of the shikimate pathway regulate flow of carbon into this pathway. Inhibition of the pathway causes deregulation of the pathway and more carbon than usual flows into the pathway, removing building blocks from other essential pathways (Kilmer *et al.*, 1981; Jenson, 1986). This eventually disrupts every aspect of plant metabolism. The massive levels of shikimate that accumulate are primarily localized in the plant cell vacuole (Höllander-Czytko and Amrhein, 1983); however, some of this shikimate is used by the plant for synthesis of hydroxybenzoic acids such as protocatechuic, gallic and gentisic acids (Lydon and Duke, 1988a; Cañal *et al.*, 1987).

Glyphosate is used only as a postemergence herbicide because it is inactivated by soil due to its ionic nature. It is an ideal herbicide for foliar application because it is readily absorbed and is efficiently translocated to actively growing tissues of the plant where it accumulates (Duke, 1987; Caseley and Coupland, 1985). Thus, it will kill growing roots, rhizomes, bulbs, tubers and stolons, as well as aerial portions of plants, preventing regrowth, a major problem in controlling perennial weeds.

Glyphosate is a highly water soluble compound. Therefore, it probably moves across the leaf cuticle in hydrated pores. Indeed, absorption of glyphosate is greater in plants with more hydrated cuticles (*e.g.*, in plants under higher relative

humidity or under no water stress). Once the herbicide has crossed the cuticle to move into the solution of the intercellular spaces of the leaf, it moves slowly across the outer plant cell membranes (plasmalemmas) of the photosynthesizing cells (mesophyll) of the leaf and of the phloem cells. Gougler and Geiger (1981) postulated that the low permeability of the plasmalemma for glyphosate allows for efficient long range transport in the plant. The compound enters the phloem in the sprayed leaf, a site of high external glyphosate concentration. More of the compound moves into the phloem than into mesophyll cells because the diffusion gradient is higher across their plasmalemma due the continual movement of the compound to other parts of the plant. Because of the low permeability of the phloem plasmalemma, it does not readily leak back out into the xylem after leaving this site. Thus, its concentration becomes high at terminal sites of phloem transport such as apical meristems and fruits. Because glyphosate is not significantly, if at all, metabolized by higher plants, slow buildup of the herbicide can occur over very long periods of time, eventually resulting in cellular and tissue death.

Because glyphosate is a relatively slow-acting herbicide, the sites of absorption remain metabolically active long enough for considerable phloem transport to occur. There is generally a very high correlation between transport of photosynthate and glyphosate from leaves sprayed with glyphosate (Figure 5).

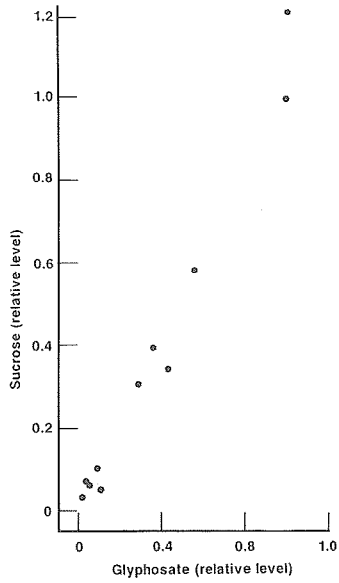


Figure 5. Correlation between sucrose and glyphosate translocation in sugarbeet. (Adapted from Gougler and Geiger, 1981.)

ISOXAZOLIDINONES

The isoxazolidinones are represented by only one commercialized herbicide, clomazone (Command®). This is a relatively new preemergence herbicide that is being tested for use in cotton (York, 1987).

Susceptible species display a loss of chloroplast pigments after treatment, resulting in light green, yellow or entirely white leaves (Duke and Paul, 1986). Unlike other herbicides that inhibit carotenoid synthesis (*e.g.* pyridazinones—see below), this herbicide blocks the synthesis of both carotenoids and chlorophyll by inhibiting the terpenoid pathway at a step early enough to prevent synthesis of geranylgeranyl pyrophosphate (Duke *et al.*, 1985; Duke and Kenyon, 1986b; Sandmann and Böger, 1986). Geranylgeranyl pyrophosphate is required for the synthesis of carotenoids, phytol (an integral part of chlorophyll), and gibberellic acid. Evidence of the loss of all three of these constituents in clomazone-treated plants has been produced. In very sensitive higher plants, there is no synthesis of carotenoids, even in darkness where photobleaching cannot account for the carotenoid loss (Duke *et al.*, 1985). The Shibata shift, a spectral shift caused by attachment of phytol to the chlorophyll chromophore, is prevented by the herbicide (Duke *et al.*, 1985; Duke and Kenyon, 1986b). Furthermore, phytol levels are lowered in algae grown in the presence of clomazone (Sandman and Böger, 1986). Etiolated growth is greatly stunted in treated seedlings (Duke and Paul, 1986; Duke *et al.*, 1985), an indicator of blockage of gibberellic acid synthesis. Sandman and Böger (1986) reversed the growth-inhibiting effect of clomazone on pea seedlings with gibberellic acid. These data all support the hypothesis of Duke *et al.* (1985) that the herbicide blocks the synthesis of geranylgeranyl pyrophosphate (Figure 6).

Sandman and Böger (1987) later demonstrated that clomazone (Command®) does strongly inhibit synthesis of geranylgeranyl pyrophosphate in a cell-free spinach preparation. In this system, they found that there was actually an increase in isopentenyl pyrophosphate, the first product in the terpenoid pathway. With each succeeding step of the terpenoid pathway, they found stronger inhibition. This led them to hypothesize that isopentenyl pyrophosphate isomerase or prenyl transferase is the inhibited enzyme. These enzymes are required for each successive addition of five carbon subunits to simpler terpenoids. They speculate that later steps are more susceptible to the herbicide because of their chloroplast location. Results of Duke *et al.* (1991) show accumulation of sesquiterpenoids in clomazone-treated tissues, indicating that only the conversion of farnesyl pyrophosphate to geranylgeranyl pyrophosphate is inhibited (Figure 6).

Susceptibility differences between soybean (tolerant) and cotton (more susceptible) are not due to uptake or translocation differences (Norman *et al.*, 1990). Similarly, Vencill *et al.* (1990) found no differences in clomazone translocation between soybean, and both susceptible and tolerant pigweed species. They did find higher levels of uptake in susceptible species of pigweed than in a tolerant species. No differences in metabolic products or rates of metabolism were ob-

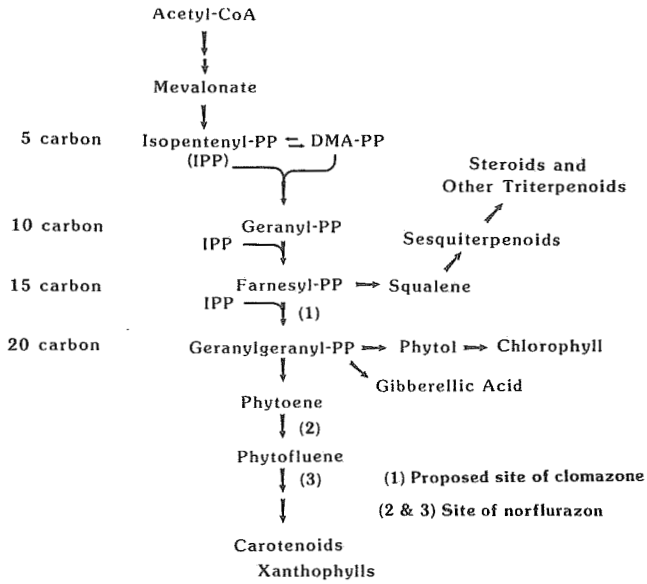


Figure 6. Isoprenoid pathway of terpenoid synthesis in higher plants with the site of carotenoid synthesis inhibition by pyridazinones (norflurazon) and the proposed site of inhibition of the isoxazolidinones (clomazone). PP = pyrophosphate; IPP = isopentenyl pyrophosphate.

served in this study. However, Norman *et al.* (1990) found that susceptible cotton may metabolize clomazone to a herbicidal metabolite (bioactivation). Both studies hypothesized that differences at the molecular site of action may play an important role in explaining tolerance and susceptibility to clomazone.

p-NITROSUBSTITUTED DIPHENYL ETHERS

The *p*-nitrosubstituted diphenyl ethers (NDPE) are foliar-applied contact herbicides that cause rapid chlorosis in light (bleaching) and/or necrosis. Representatives of this herbicide class are acifluorfen (Blazer® or Tackle®), fluorodifen (Preforan®), fomesafen (Reflex® or Frigate®), lactofen (Cobra®) and nitrofen (Tok®).

In general, the NDPE herbicides are poorly absorbed and very poorly translocated. For instance, Ritter and Coble (1981) found only about 4 percent of applied acifluorfen to be absorbed by soybean leaves 48 hours after treatment. Less than one percent of applied acifluorfen was translocated from the treated leaf. In other species, absorption after 48 hours can range from 10 to almost 20 percent, depending on the NDPE (Hawton and Stobbe, 1971a; Ritter and Coble, 1981). However, less than two percent of applied NDPE was reported to be translocated from treated leaves in plants for up to 16 days after treatment (Hawton

and Stobbe, 1971b). Even movement of acifluorfen into cells through the cut edge of a leaf disc is extremely slow (Duke and Kenyon, 1986a).

The NDPEs are readily metabolized by leguminous species. Eastin (1971) found peanuts metabolized 88 percent of absorbed fluorodifen within 72 hours after treatment. Fluorodifen (Rogers, 1971) and acifluorfen (Frear *et al.*, 1983) are rapidly metabolized by soybeans. Detoxification of NDPE herbicides can occur through reduction of the *p*-nitro group to an amide or by cleavage of the ether linkage and subsequent conjugation of the two metabolites with glutathione and sugars (Shimabukuro, 1985).

Much physiological and biochemical information on how these herbicides act is available. Light is an absolute requirement for rapid cellular collapse and/or photobleaching, the herbicidal symptoms seen in target plants in the field (Matsunaka, 1969; Orr and Hess, 1982a). Furthermore, oxygen appears to be necessary for full activity (Orr and Hess, 1982b). Cells without the capacity for photosynthesis, but with green or yellow plastids, are generally more sensitive to these herbicides than photosynthetically active cells (Duke *et al.*, 1984; Duke and Kenyon, 1986; Kenyon and Duke, 1988). This is probably because they cannot regenerate protective reductants (Kenyon and Duke, 1985).

One of the first symptoms of damage by this herbicide group is breakage of the plasmalemma (Orr and Hess, 1982a; Kenyon *et al.*, 1985; Duke and Kenyon, 1987). Visualization of this at the ultrastructural level coincides with detection of electrolyte leakage from affected cells. These symptoms are followed by loss of photosynthetic capacity, loss of chloroplast pigments, and evidence of lipid peroxidation such as ethane evolution and malondialdehyde formation (Kenyon *et al.*, 1985).

The activity of acifluorfen (Blazer®, Tackle®) is virtually temperature independent, after a period of incubation with the herbicide in darkness (Kenyon and Duke, 1988). Thus, the herbicide acts much like a photodynamic dye that produces cellular damage by absorbing light and transferring the absorbed energy to molecular oxygen to form reactive singlet oxygen. Singlet oxygen can initiate lipid peroxidation, resulting in membrane damage and cellular leakage (Halliwell, 1985).

Apparently, the photodynamic dye that causes all of the above effects is protoporphyrin IX, a metabolic precursor of both chrorophyll and heme. Recently, several laboratories have found that NDPE herbicides cause the accumulation of this reddish-brown pigment (Becerril and Duke, 1989; Lydon and Duke, 1988b; Matringe and Scalla, 1988; Witkowski and Halling, 1988). These laboratories showed that inhibitors of synthesis of protoporphyrin IX inhibit the activity of NDPE herbicides almost completely. Protoporphyrinogen oxidase, a pivotal enzyme of the porphyrin synthesis pathway, is strongly inhibited by these herbicides (Matringe *et al.*, 1989a, b; Witkowski and Halling, 1989; Jacobs *et al.*, 1990) and it is now accepted that this enzyme is their molecular site of action in causing protoporphyrin IX to accumulate (Figure 7). Thus, NDPE herbicides

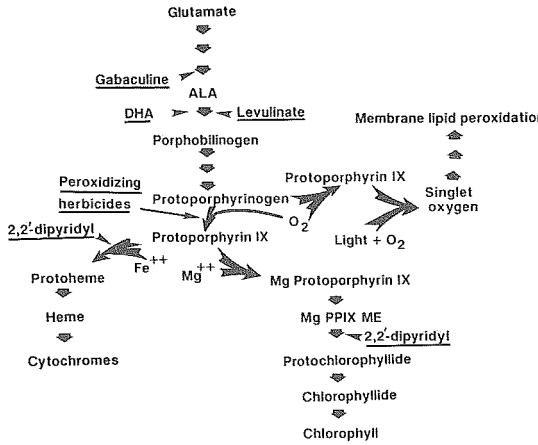


Figure 7. Mechanism of action of NDPE herbicides. NDPE herbicides inhibit the porphyrin synthesis pathway at the point of conversion of protoporphyrinogen to protoporhyrin IX, a photodynamic pigment. Protoporphyrin IX accumulates due to unregulated, non-enzymatic autooxidation of protoporphyrinogen. Gabaculine, dioxoheptanoic acid (DHA) and levulinate inhibit the porphyrin synthesis pathway and also inhibit the activity of NDPE herbicides.

appear to act in much the same way that δ-aminolevulinic acid (ALA) acts—by causing the accumulation of photodynamic tetrapyrole pigments (Rebeiz *et al.*, 1984). In the presence of light and molecular oxygen, these pigments generate highly destructive singlet oxygen which causes all of the subsequently observed effects.

The mechanisms of tolerance to NDPE herbicides are complex. There is no evidence that differences at a primary site of action can account for differences in sensitivity. As mentioned above, leguminous plants rapidly metabolize the NDPE herbicides and are generally tolerant to these herbicides. Less tolerant species such as rape, redroot pigweed, and green foxtail (Hawton and Stobbe, 1971b), cucumber (Eastin, 1972), and common ragweed and common cocklebur (Ritter and Coble, 1981) metabolize these herbicides more slowly than leguminous species. However, absorption of acifluorfen (Blazer®, Tackle®) by ragweed and cocklebur was less than by soybeans (Ritter and Coble, 1981). In studies with rape, redroot pigweed and green foxtail, Hawton and Stobbe (1971a) found that there was no correlation between absorption of and sensitivity to nitrofen (Tok®). The capacity of a species to detoxify toxic oxygen species or free radicals

also may be important in explaining differential sensitivity to NDPE herbicides. Species with ratios of ascorbic acid (vitamin C) to α-tocopherol (vitamin E) in the range of 10 to 15 are considerably more tolerant to oxyfluorfen (Goal®) than species with lower or higher ratios (Finckh and Kunert, 1985). Both ascorbate and α-tocopherol are involved in protection of the plant from toxic radicals and oxygen species (Halliwell, 1985).

PYRIDAZINONES

The only pyridazinone herbicide used in cotton is norflurazon (Zorial®). It is used extensively as a preemergence herbicide. Cotton is tolerant, but not resistant to this herbicide. Cotton is apparently less sensitive to this herbicide than other plant species because it sequesters this lipophilic herbicide into lysigenous glands that are filled with lipophilic terpenoids (Strang and Rogers, 1974). Cotton varieties without these glands are more sensitive to norflurazon than those with glands (Stegink and Vaughn, 1988). Cotton absorbs and translocates norflurazon equally well as sicklepod and corn, both of which are much more sensitive to the herbicide than cotton (Mersie and Singh, 1987). Also, cotton does not metabolize norflurazon at a greater rate than either of these two more sensitive species.

The mechanism of action of norflurazon (Zorial®) is well understood. It inhibits two enzymatic steps in carotenoid synthesis, the desaturation of phytoene and phytofluene, resulting in the accumulation of both of these precursors (summarized by Duke, 1985b and Ridley, 1982) (Figure 6). The symptoms are similar to those caused by clomazone (Command®) (see isoxazolidinones section above) since both herbicides cause total loss of chlorophyll pigments, resulting in a white plant. However, loss of chlorophyll in norflurazon-treated plants is due to the indirect effect of chlorophyll pigments not being protected from photooxidation by carotenoids. Loss of carotenoids also causes photooxidative destruction of other plastid (chloroplasts are green plastids) components. Thus, the seedling is killed by both photooxidative damage and lack of production of photosynthate.

This herbicide is not very effective on green tissue and is thus not used as a postemergence herbicide. The physiological basis for this may be related to the fact that the target enzymes are nuclear-coded and must move from the cytoplasm into the plastid before becoming active in carotenoid synthesis. Findings by Ridley and Ridley (1979) indicate that norflurazon does not enter the plastid of treated tissues and the target enzyme is protected after becoming a functional plastid enzyme. This agrees with the finding that nuclear-coded protein synthesis is required for pyridazinone inhibition of carotenoid synthesis (Grumbach and Drollinger, 1980).

SULFONYLUREAS

The commercialized sulfonylurea herbicides include chlorsulfuron (Glean®), metsulfuron methyl (Ally®), chlorimuron ethyl (Classic®) and sulfometuron methyl (Oust®). None of these are used in cotton because cotton is sensitive to

them. However, an experimental sulfonylurea herbicide, DPX-T9595 has recently been developed for use in cotton (Strachan *et al.*, 1988). Cotton rapidly metabolizes this sulfonylurea herbicide to nonphytotoxic residues, whereas most of the broadleaf weeds in cotton do not metabolize it (Wittenbach *et al.*, 1988). It promises to fill the niche of a foliar-applied, broadleaf herbicide for use in cotton.

The mechanism of action of the sulfonylurea herbicides has recently been reviewed (Beyer *et al.*, 1988; Blair and Martin, 1988). This group of herbicides initially stops the growth of target plants. Cessation of growth is followed by other symptoms such as chlorosis and reddening (anthocyanin synthesis). After several days, or even weeks, the plant dies. In some plant species, growth is stunted and the leaves turn darker green than normal. Like glyphosate (Roundup®), this group of herbicides is phloem mobile and is readily translocated to metabolic sinks (*i.e.*, growing tissues). Sulfonylurea herbicides apparently have only one important molecular site of action, the enzyme acetolactate synthase (ALS). ALS is necessary in the synthesis of the branched chain amino acids valine, leucine and isoleucine. Thus, as with glyphosate, the growth of the plant stops because proteins cannot be synthesized and metabolic processes are disrupted. Plant cells that cannot produce proteins, die prematurely because cellular maintenance is stopped.

Unlike glyphosate, the sulfonylureas are readily metabolized by many plant species. Differential metabolism has been found to be the basis of selectivity of sulfonylureas in most cases. However, it is possible to produce plants resistant at the site of action (ALS) by selection at the whole plant level (Haughn and Somerville, 1986). Thus, it is reasonable to expect sulfonylurea-resistant weeds to occur in areas in which only sulfonylureas or other ALS-inhibiting herbicides (*e.g.*, imidazolinones) are used to control particular weed species over a period of years.

S-TRIAZINES

Numerous *S*-triazines such as cyanazine (Bladex®), ametryn (Evik®), prometryn (Caparol®) and dipropetryn (Sancap®) are used primarily for preemergence control of weeds in cotton. More is known of the mechanism of action of this class of herbicides than any other.

These relatively lipophilic compounds are readily absorbed by roots and translocated to shoots of all species via the transpirational stream (apoplastic movement) (Ashton and Crafts, 1981). However, foliar absorption is much more limited and translocation from treated leaves is very limited because it is almost exclusively apoplastic (Ashton and Crafts, 1981).

Cotton roots readily absorb simazine (Princep®) and translocate it to leaves (Davis *et al.*, 1959). However, unlike in other species, it accumulates in the terpenoid-filled lysigenous glands of cotton (Davis *et al.*, 1959; Foy, 1964; Sikka and Davis, 1968) (Figure 8) as do other lipophilic herbicides such as pyridazinones

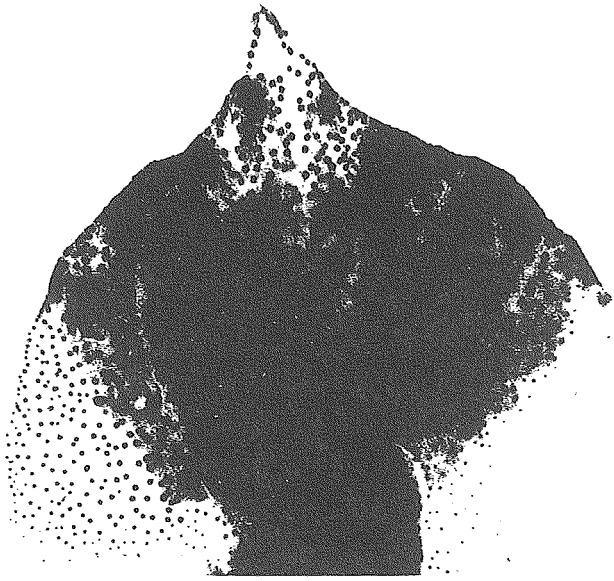


Figure 8. Autoradiogram of a cotton leaf 72 hours after treatment with ^{14}C-ipazine showing accumulation in lysigenous glands. (Foy, 1964.)

and dinitroanilines, as discussed above. In most tolerant species, tolerance to *S*-triazines is due almost entirely to metabolism (Shimabukuro, 1985). However, in cotton tolerance is due to poor translocation, metabolism by *N*-dealkylation and sequestering of the herbicide in the lysigenous glands and seed coat (Sikka and Davis, 1968; Shimabukuro and Swanson, 1970; Rubin and Eshel, 1978).

Although the *S*-triazines can have many and diverse metabolic effects on plants (Ashton and Crafts, 1981), there is no doubt that their primary effect is inhibition of photosynthesis by blocking photosynthetic electron transport (Figure 9). Good evidence of this is provided by the increase in variable fluorescence of chlorophyll in leaves treated with this herbicide class (Figure 10). Light energy absorbed by chlorophyll that cannot be dissipated by photosynthesis, chemical transfer or thermal loss is given off as variable fluorescence in the red part of the spectrum. The more inefficient that chloroplast electron transport is, the higher the level of variable fluorescence. The I_{50}'s for triazine herbicides on certain fluorescence parameters of isolated chloroplasts is as low as 0.1 μM (Brewer *et al.*, 1979).

Photosystem II inhibitors such as the *S*-triazines cause numerous secondary effects by blocking electron flow. The light energy absorbed by chlorophyll is dissipated as fluorescence and as heat; however, a particular form of light-energized chlorophyll (triplet chlorophyll) can transfer energy to molecular oxygen to form singlet oxygen, the same destructive form of oxygen thought to be the cause of *p*-nitrosubstituted diphenyl ether (NDPE) herbicide activity (see above

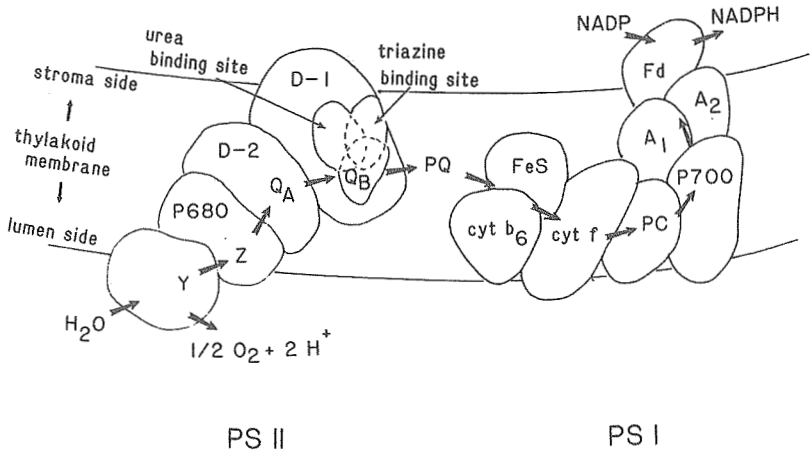


Figure 9. Schematic of components of photosynthetic electron flow (bold arrows) in thylakoid membranes of higher plants and point of inhibition of S-triazine and urea herbicides. P680 = reaction center for PS II, Z = PS II donor that is oxidized by light absorption of chlorophyll and in turn causes oxidation of water by magnesium-containing proteins (Y), D-2 = Quinone A(Q_A)-binding protein, D-1 = Quinone B(Q_B)-binding protein, PQ = plastoquinone, cyt b_6 = cytochrome b_6, FeS = non-heme iron sulfur center, cyt f = f type cytochrome, P700 = PS I reaction center, Fd = ferredoxin.

and Figure 7). The injury is not as rapid as with the NDPEs because the chloroplast is well protected from singlet oxygen by carotenoids and high levels of α-tocopherol (vitamin E). Thus, with *S*-triazines there is usually time for the cessation of carbon fixation and accompanying metabolic disruption to play a role in the deterioration of the plant. Separating singlet oxygen effects from metabolic disruption effects is difficult; however, damage caused by singlet oxygen will be relatively greater as light intensity increases.

The exact location of the blockage is the D-1 quinone-binding protein that is located between the primary quinone electron acceptor of PS II, located on the D-2 protein, and plastoquinone (Renger, 1986) (Figure 9). This location of the blockage in the electron transport chain of the chloroplast by triazines was indicated by use of artificial electron donor and acceptor couples for different components of the electron transport chain (Pfister and Urbach, 1983). With these techniques, most segments of the electron transport system can be studied separately. These results and fluorescence data led to the hypothesis that triazine

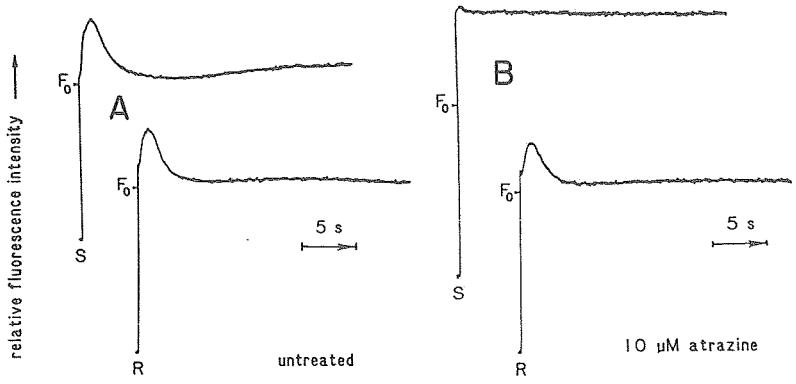


Figure 10. Variable fluorescence of untreated (A) and 10 μM-atrazine-treated (B) triazine-sensitive (S) and resistant (R) biotypes of pigweed (*Amaranthus hybridus*). (Adapted from Vaughn and Duke, 1984.)

herbicides compete for the binding site of the B quinone involved in electron transport between the PSII electron acceptor quinone Q and the plastoquinone pool (Figure 9) (Velthuys, 1981).

This hypothesis was strengthened by discovery of the identity of the quinone B binding protein (now called D-1). Its identity was obtained through the use of a form of radiolabeled atrazine (^{14}C-azido-atrazine) that irreversibly binds to the molecule closest to it when irradiated with ultraviolet light. Using this technique, Pfister *et al.* (1982) found a chloroplast thylakoid membrane protein with a molecular mass of 32 kD strongly labeled with radioactivity (Figure 11). No labeling was found in the thylakoid membranes of triazine-resistant biotypes (Figure 11). This protein is maternally inherited through transmission on the chloroplast genetic code (the plastome), as is resistance to triazine herbicides (Gressel, 1985). Furthermore, there is only a one amino acid difference (serine 264 to glycine) that eliminates triazine binding and confers triazine resistance (Hirschberg *et al.*, 1984). Biotypes with this genetic alteration are generally more than 100-fold less sensitive to triazine herbicides than sensitive biotypes of the same species.

Extensive studies of the molecular biology of D-1 and its role in photosynthesis and plant responses to light have resulted from this work on the mode of action of triazine herbicides. This work also has resulted in a much clearer understanding of other herbicide classes such as the ureas that act at the same site.



Figure 11. Thylakoid proteins of triazine-susceptible and triazine-resistant biotypes of pigweed (*Amaranthus hybridus*) separated by polyacrylamide gel electrophoresis. The lane on the left (labeled A) for each biotype has been stained for protein, and the lane on the right (labeled B) is a autoradiograph of proteins labeled with ^{14}C-azido-atrazine. (Courtesy of K. Pfister, CIBA-GEIGY.)

UREAS

The substituted ureas are among the oldest herbicide classes, introduced in the 1950s. Today, linuron (Lorox®), diuron (Karmex®) and fluometuron (Cotoran®) are used in cotton in the United States. Although structurally different from the *S*-triazines, the substituted ureas share many similarities in their mode of action and modes of tolerance.

Like the triazines, they are used in cotton as preemergence herbicides. In general, the substituted ureas are rapidly absorbed by roots and translocated through the xylem to the leaves (Ashton and Crafts, 1981). Like the triazines, the substituted ureas preferentially accumulate in the lysigenous glands and trichomes of cotton (Strang and Rogers, 1971). Cotton also metabolizes substituted ureas to nonphytotoxic metabolites (Rogers and Funderburk, 1968; Rubin and Eschel, 1971). Nevertheless, cotton is only tolerant, but not resistant, to this herbicide class.

Their mechanism of action is virtually identical to that of the *S*-triazines (see above). The substituted urea herbicides block photosynthetic electron transport at precisely the same point in the system as the *S*-triazines; however, their binding site is not identical to that of the triazines (Pfister, 1983) (Figure 9). Diuron

displaces radiolabeled atrazine on the thylakoid membrane; however, triazine-resistant biotypes of weeds are not resistant to substituted ureas (Fuerst *et al.*, 1986). Thus, the one amino acid alteration in D-1 (Figure 9) that greatly affects triazine binding has virtually no effect on the binding of substituted ureas. No instances of substituted urea herbicide resistance have been reported in higher plants. Alternating substituted urea and *S*-triazines in cotton should retard the occurence of triazine-resistance in this crop.

Although methazole (Probe®) is not a urea, once inside the plant, it is metabolized to the substituted urea DCPMU [1-(3,4-dichlorophenyl)-3-methylurea] (Jones and Foy, 1972). DCPMU is a potent inhibitor of PS II electron transport (Good, 1961). Cotton is tolerant to methazole because, after metabolizing it to DCPMU, DCPMU is further metabolized to the relatively nonphytotoxic DCPU [1-(3,4-dichlorophenyl)urea] (Jones and Foy, 1972).

BIOTECHNOLOGY AND FUTURE DIRECTIONS

HERBICIDE DESIGN

As mentioned in the introduction, understanding mode of action can be useful in the biorational design of herbicides. There is no obvious biochemical characteristic of cotton that points toward herbicide design around a particular biochemical site other than those characteristics that distinguish it from monocots. No strong degradative pathway in cotton has been found that might rapidly degrade a particular class of chemical compounds. The only feature of cotton that appears to lend tolerance to a large number of herbicides is the presence of lysigenous glands filled with lipophilic terpenoids. Sequestration of lipophilic herbicides into these glands has been implicated in the tolerance of cotton to dinitroanilines, *S*-triazines and substituted ureas. Therefore, lipophilic compounds may have a natural advantage over other herbicides for use in cotton. A potential ploy in developing new herbicides for cotton would be to increase the lipophilicity, while retaining activity, of herbicides that cannot currently be used in cotton.

Another ploy with potential for development of new cotton herbicides would be to test the phytotoxins produced by pathogens of weeds in cotton. Often, phytotoxins produced by pathogens are highly active with excellent selectivity (Duke, 1986a,b). Naturally-occuring phytotoxins are being actively screened for herbicidal activity by industry and are being patented as herbicides. These compounds often attack previously unexploited sites of action (Duke, 1986a). To date, however, none of these new chemistries have been reported to have potential as cotton herbicides.

ENGINEERING HERBICIDE RESISTANCE INTO COTTON

Cotton is an ideal prospect for genetically engineering herbicide resistance into a crop. It is third, behind corn and soybean, in herbicide usage in the United States (McWhorter *et al.*, 1985). However, unlike soybean, there are no broad-

leaf herbicides to which it is resistant or highly tolerant when used postemergence. Thus, engineering resistance in cotton to a herbicide to which a company has sole proprietary rights would fill a much-needed gap in weed control in cotton and, accordingly, should be highly profitable. However, if there is significant cross-resistance of the genetically engineered cotton to other herbicides produced by other companies, such a venture might not be profitable. This aspect of engineering herbicide resistance into cotton may limit interest by industry. Therefore, some of this type of research might best be conducted by public laboratories in which the profit motive is not a concern.

From an industry standpoint, genetically engineering resistance to a herbicide like glyphosate (Roundup®) into cotton could be a high return venture. No other herbicides are known to attack the site of action of this herbicide and no cases of resistance in higher plants have arisen. Thus, one over-the-top application of glyphosate to a field of resistant cotton should eliminate all weeds—broadleaves and grasses; annuals and perennials. Bioengineering has already produced glyphosate-resistant higher plants by several methods (Duke, 1988). One method involves transfer of a glyphosate-insensitive form of EPSP synthase (see glyphosate section above) from a bacterium to higher plants (Figure 12); the other entails increasing the number of copies of the EPSP synthase gene (gene amplification) in the plant so that significantly more herbicide is required to completely block the shikimic acid pathway. Another approach that theoretically should work would be to transfer the genes for metabolism of glyphosate from microorganisms to higher plants.

The latter approach does not require a knowledge of the mode of action of the herbicide. The other approaches require that the molecular site of action of the herbicide be understood. If the herbicide acts at more than one molecular site, genetically engineering a resistant plant by manipulation of the sites of action becomes enormously complicated. Thus, a thorough physiological and biochemical determination of the complete mode of action of a herbicide, beginning from the molecular site, should be completed before vast resources are committed to genetically engineering resistance.

A potential problem in genetically engineering resistance of crops to highly translocatable herbicides like glyphosate is that high levels of the herbicide can accumulate in terminal metabolic sinks such as fruits. High herbicide levels in these plant tissues may overcome resistance to the herbicide, causing the plant to abort its fruit or to produce abnormal fruit. If the degree of resistance is high enough to prevent aborted or abnormal fruit, unacceptable herbicide residues in the fruit may pose a problem. These problems should be most severe with herbicides that are not readily metabolized (*e.g.* glyphosate). Accumulation of glyphosate in the fruit may not be important with cotton because of the nature of the principal harvestable products—lint and oil. Because glyphosate is highly water soluble, it may not coextract with cottonseed oil. However, it could reach undesirable levels in cottonseed meal.

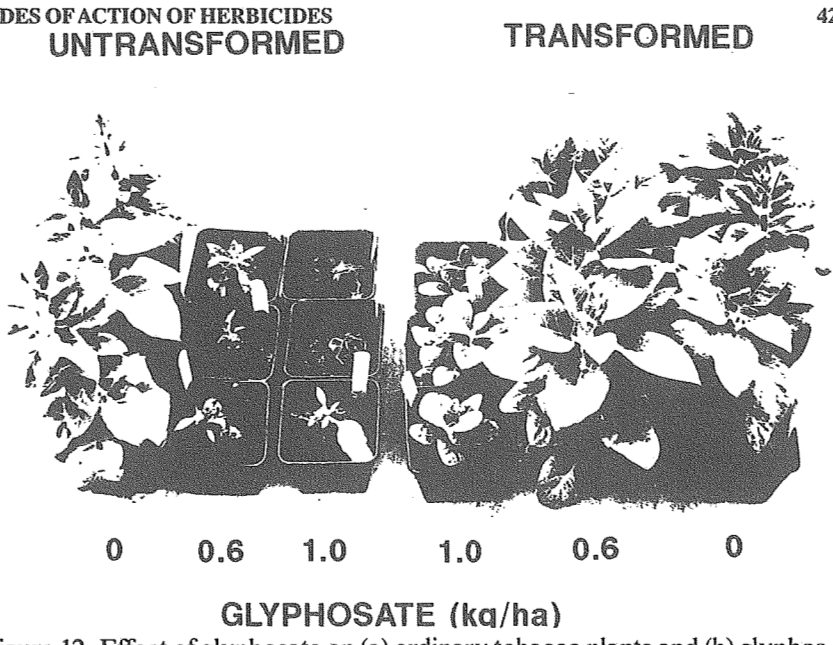


Figure 12. Effect of glyphosate on (a) ordinary tobacco plants and (b) glyphosate-tolerant tobacco plants transformed with the EPSP synthase from glyphosate-resistant *Salmonella typhimurium*. (Courtesy of Luca Comai of Calgene.)

Bromoxynil (Buctril®, Brominal®)-resistant cotton has been produced by transferring the gene from the soil bacterium *Klebsiella ozaenae* that codes for a nitrilase which detoxifies the herbicide (Stalker *et al.*, 1988). This genetically engineered cotton has been field tested by Calgene, Inc. and has potential for adding bromoxynil to the arsenal of herbicides available to cotton farmers.

SUMMARY

There is no general mode of action of cotton herbicides. The herbicides used in cotton attack a large number of biochemical and physiological sites that are summarized in Table 1. Since there is no suitable broadleaf herbicide for over-the-top application in cotton, this problem is a logical focus for future herbicide discovery efforts. The new tools of molecular biology and genetic engineering should be crucial in solving this problem. However, without a thorough knowledge of the mode of action of the herbicide being researched, significant progress with either biorational or genetic engineering approaches is not likely to improve weed control in cotton with herbicides.

Table 1. Summary of the modes of action of cotton herbicides.

Herbicide class	Mode of action
Arsenicals	Inhibition of carbon fixation by covalent bonding of arsenomethane to SH-containing enzymes
Aryloxyphenoxy alkanoic acids	Inhibition of lipid synthesis
Chlorinated aliphatic acids	Unknown, perhaps pantothenic acid synthesis
Chloroacetamides	Unknown, perhaps alkylation of proteins or lipid synthesis
Cineoles	Unknown
Cyclohexanediones	Inhibition of lipid synthesis
DCPA	Unknown, perhaps interference with tubulin function
Dinitroanilines	Interference with tubulin function
Glyphosate	Blockage of the shikimic acid pathway
Isoxazolidinones	Inhibition of the diterpenoid synthesis
p-nitrosubstituted diphenyl ethers	Inhibition of the porphyrin synthesis pathway, resulting in buildup of photodynamic pigments
Pyridazinones	Inhibition of carotenoid synthesis
Sulfonylureas	Inhibition of branched chain amino acid synthesis
S-triazines	Inhibition of photosynthetic electron transport at the Q_B site on D-1.
Ureas	Inhibition of photosynthetic electron transport at the Q_B site on D-1.

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Chapter 12

HERBICIDE APPLICATION TECHNOLOGY

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INTRODUCTION

Newly introduced herbicides that will be used at less than an ounce per acre increases the importance of the uniform and precise delivery to the target. Even with well calibrated equipment and ideal working conditions, there are wide variations in the amounts of spray particles reaching the soil or plant (Wauchoupe *et al.*, 1977). The hand-pumped knapsack sprayers and spray carts with bicycle wheels have been replaced with tractor-mounted and self-propelled sprayers, and these are evolving to spray systems controlled electronically to include radar and other technologies for ground speed measurement and digital readout of speed, pressure and spray volume. Whatever the degree of sophistication in equipment, the goal is precise and uniform placement of the herbicide on the target at the correct dose and at the proper time. Successful weed control often hinges on the degree to which that is accomplished. Today we may have a better appreciation for the following words than when they were written (Ennis *et al.*, 1963):

> "The rapid advance of weed control technology and the acceptance of chemical weed control practices by farmers will have profound effects on crop production and soil and water management practices."

This chapter briefly traces the evolution of application technology in cotton weed control, describes application methodology, summarizes Cotton Belt application techniques and discusses future needs in cotton weed control application technologies. Because of the extensive use of herbicide sprays, this method of application is emphasized to include hydraulic pressure sprayer components and calibration.

TERMS AND DEFINITIONS

Herbicide applications are usually made in a time frame related to crop development (Chandler, 1984; Holstun and Wooten, 1968). The following six types of herbicide application cover most situations encountered in the production of a cotton crop. The terminology used here will generally follow that established by the Weed Science Society of America (Harger *et al.*, 1985; Beste, 1983).

Preplant Foliage (PPF)— Applied before planting cotton as a foliar application to control existing vegetation.

Preplant Incorporated (PPI)—Applied and blended into the soil before planting.

Preemergence (PRE)—Applied to the soil after planting but before emergence of the cotton to control weeds before or soon after they emerge.

Directed Postemergence (PDS)—Precise application to control existing weeds in a stand of cotton. Usually directed on a band centered over the drill with a minimum of spray contact on the cotton. Cultivation is normally used to control weeds left untreated in the row middles.

Postemergence Over-the-top (POT)—Applied over the top of growing cotton to control weeds in the crop. A broadcast or banded application above the plant canopy requires a herbicide with adequate cotton tolerance.

Late Postemergence (Layby)—Usually a directed spray applied up to the time of last cultivation for the control of existing weeds, and also for preemergence control of late-season weeds depending upon herbicide selection and rate.

Additives are frequently mixed with the herbicide spray solution to obtain more desirable results. That is especially true for postemergence applications. Terms most frequently encountered are: adjuvants, surfactants and crop oil concentrates.

Adjuvants—Any substance in herbicide formulation or added to the spray to modify herbicidal activity or application characteristics. Adjuvant is the most general term and might be used to reduce foam, improve compatibility of an herbicide mixture, or reduce drift as well as increasing herbicide uptake by the weeds for better control.

Surfactant—An adjuvant that improves the emulsifying, dispersing, spreading, wetting or other properties of a liquid by modifying its surface characteristics.

Crop Oil Concentrate (COC)—An adjuvant that contains 80 to 85 percent nonphytotoxic petroleum or vegetable oil plus 15 to 20 percent surfactant and emulsifiers.

APPLICATION TECHNOLOGY EVOLUTION

EARLY DEVELOPMENTS

With the introduction of the liquified petroleum gases in 1945 came "flame cultivation". The burners were frequently attached directly to the cultivator or used in conjunction with conventional sweeps. Two categories of burners were designed for flaming cotton: (a) those for flaming the drill-rows, and (b) those for flaming the row-middles. These flame-cultivators were effective in controlling the vine-complex after cotton stems were at least 3/16 of an inch in diameter at the ground level (Baker, 1966). A water-shielded flame cultivator was subsequently developed which provided lower temperatures on the exposed cotton stem, thus permitting flaming of younger cotton (Matthews and Smith, 1969).

Herbicidal naphtha was applied postemergence as a lateral directed spray (Talley, 1950). Excellent control of small annual weeds was obtained plus good suppression of some perennials such as nutsedges and vines. Precision application was necessary to get good coverage on the weeds without spraying too high on the young cotton seedlings and causing injury. Equipment (oiling shoes or slides) was designed with parallel action mounting so that nozzles were positioned at a constant height and angle (Holstun and Wooten, 1968). These oiling shoes typically had two opposing nozzles mounted to spray into and across the cotton drill, and two nozzles mounted to spray a 4- to 5-inch band on either side of the drill.

Herbicides appeared on the farm scene following World War II, which increased research and development efforts on hydraulic pressure nozzle sprayers. The phenoxy herbicides were a breakthrough in technology, but they lacked selectivity for use in cotton. By the early 1950s, herbicides were being used to control weeds in cotton and reduce the strong dependence on hand labor (Porter *et al.*, 1957; Denver, 1984). Chlorpropham (Chloro-IPC®), dinoseb (Premerge®), and diuron (Karmex®) were applied preemergence in treated bands centered over the drill. Planter-mounted hydraulic drop nozzles with even spray-pattern tips evolved with the use of these herbicides.

Lever-operated knapsack and compression hand sprayers were used to treat small areas (spot-spray) in cotton fields in the early 1950s with herbicidal oil. This application method is still used, but the herbicides have evolved from non-selective herbicidal oil to the selective grass herbicides sethoxydim (Poast®) and fluazifop-P (Fusilade-2000®) (See Chapter 7). The compression and, to a lesser extent, the knapsack sprayers are still in use, but it is now common to see all-terrain vehicles (ATV) equipped with hydraulic pressure sprayer systems, and hand-operated spring-loaded plunger spray guns in use for spot spraying.

As herbicide treatments such as diuron plus surfactant applied as a PDS (directed postemergence) (McWhorter and Sheets, 1961) were introduced, a flurry of activity in PDS applicators followed. Front and rear mounted slide units equipped with two to four nozzles per row became available, and the parallel-

action oiling shoes were modified for this purpose. Cultivators were modified that included two to four nozzles per row for PDS application in conjunction with cultivation. Half-wing sweeps were used to leave a 10- to 20-inch band centered on the drill-row undisturbed to which the PDS were applied. Cultivators were later equipped with nozzles for PDS mounted on the rear of fender shields. Directed sprays increased the demand for tapered flat-fan nozzle tips, and helped spur development of off-center tips.

Layby application of cotton herbicides paralleled the PDS concept. With the practice came the use of flooding or deflector spray nozzles which permitted broadcast directed layby spray application using one nozzle per row. Williford (1981) described the array of postemergence equipment available to growers.

SOIL INCORPORATION

Research during the early 1960s with trifluralin (Treflan®) led to a new approach for herbicide application in cotton. Because trifluralin was volatile and photodegraded, significant loss occurred with surface preemergence sprays; thus, it was applied preplant and incorporated into the soil. The new application method resulted in consistently higher weed control levels with less dependence upon rainfall as compared to the conventional preemergence treatments. A burst of activity followed with the development of all kinds of equipment for soil incorporation. The conventional disk harrow was readily available but new equipment ranged from many types of ground-driven incorporators to power tillers. Tapered flat-fan, flooding or deflector, raindrop and wide angle cone nozzles became common components of broadcast soil incorporation devices as they became available.

AERIAL APPLICATION

The first widespread use of aerial application for herbicides in cotton came about with the broadcast preplant use of dinitroanilines (Figure 1). Wide tandem-disk harrows or field cultivators followed closely behind the herbicide application, and large acreages were treated quickly. Aerial application using spray volumes of 3 to 5 gallons per acre are now usual, but ultra-low volumes (ULV) of 1 quart per acre or less are possible (Shankland and Tucker, 1980).



Figure 1. A Cessna Ag-Wagon equipped with disc-core combination nozzles spaced 10 inches apart applying a dinitroanaline herbicide in water at 5 gallons per acre for subsequent soil incorporation.

HERBICIDE FORMULATIONS AND ADDITIVES

Application techniques may vary somewhat according to how the herbicide is formulated. Historically, herbicides were formulated primarily as a wettable powder (WP) or emulsifiable concentrate (EC) for mixing with water and applying as a spray. The wettable powders require agitation in the spray tank to prevent the insoluble powder from settling to the bottom of the tank. Resuspending the settled-out powder and active ingredient is often difficult following an overnight work stoppage or for a breakdown or rain shower during the day.

Granular herbicide formulations have been available with the active ingredient attached to clay particles for distribution as a solid such as many fertilizers are applied. Granules have not been used extensively in cotton because of the difficulties in handling the considerable weight and bulk of solid material and lack of precision placement equipment. Sprays have been more readily accepted because several thousand gallons of a sprayable formulation can be premixed and transported to the field in trailer- or truck-mounted nurse tanks. A hydraulic pump mounted on the nurse tanks is used to refill the sprayer tank. Also, the use of nozzles for precision placement of the spray has advantages for efficacy and selectivity.

More recently, water dispersible granular formulations have become available. These are free flowing particles which avoid dust and container rinsing problems, yet readily mix in water for easy spraying. Another approach to using water

dispersible granules may be the ultimate low volume application—no water at all. A metering system using pneumatic applicators can distribute these granules fairly uniformly at the rate of one pound per acre (Gandrud and Skoglund, 1986).

Other formulations such as encapsulation and controlled-release of soil applied herbicides such as trifluralin and cyanazine (Bladex®) offer longer residual weed control.

Adjuvants added to the spray solution are often helpful in one way or another (McWhorter, 1982). Specific materials can be chosen to decrease foaming action while spraying, to improve compatibility of herbicides in a mixture, or to reduce drift. Diuron (Karmex®) was considered effective only as a soil applied herbicide until McWhorter (1963) showed that the addition of surfactant made it active as a foliar spray.

SPECIALIZED APPLICATION TECHNIQUES

Wiese (1986) has described the vast array of herbicide application equipment available, particularly for research purposes. Further discussion here will introduce special techniques which have been used in the field with a more detailed discussion later.

Recirculating Sprayer—This sprayer was first developed in 1964 for spraying in row crops where weeds are taller than the crop (Wills and McWhorter, 1981). The sprayer is mounted on a tractor and the height adjusted hydraulically so that the nozzles are positioned above the crop. The spray solution is directed horizontally across the crop row. Any spray not intercepted by the weeds is trapped in a catch basin and returned to the tank for reuse. The spray volume used depends upon the degree of weed infestation, but recovery of 70 to 90 percent of the solution passing through the nozzles is common. The recirculating sprayer has been used to spray glyphosate (Roundup®) for johnsongrass control in cotton. Some crop injury can occur from the splatter of spray particles on cotton or inadvertent dripping caused by uneven terrain. The practice is nearly abandoned now that more selective herbicides like sethoxydim (Poast®) and fluazifop-P (Fusilade-2000®) are available.

Shielded Sprayer—The herbicide glyphosate stimulated a lot of research effort in designing application equipment to utilize its great herbicidal activity despite its lack of selectivity. The shielded sprayer was developed as one method of using glyphosate (Roundup®) to control weeds in cotton without crop injury. The shields were designed to prevent spray contact on the crop stems or foliage (Jordan, 1978). Some commercial units are available and many have been built in farm shops that are useful for controlling weeds such as perennial vines, bermudagrass and nutsedge in cotton.

Wiper Applicators—Several types of wiper applicators have been used commercially. Some use a spray system and some do not, but the common objective

is to get the herbicide on the weeds without hurting the crop. The designs vary from rope-wicks to carpets and rollers.

The one used most widely was the rope-wick applicator (RWA) because of its simplicity and no need for a spray system. J. E. Dale invented the RWA and did the initial research in 1976 and 1977 (Dale, 1978). Most RWAs were made of polyvinyl chloride pipe which served as a reservoir for the herbicide solution. Braided nylon rope served as a wick to carry the herbicide solution by capillary action. As the applicator traveled over the field, the herbicide solution was wiped from the rope onto the weeds. Crop injury was avoided by adjusting the height of the applicator above a crop canopy. Only those weeds sufficiently taller than the crop were treated. Later models were designed to operate between the rows and thus treat smaller weeds.

Many of the applicators were built by farmers in their own shops. The demand was so great that the proper nylon ropes, grommets and sealing compounds were sometimes difficult to obtain. The wicking action of the rope varied considerably with the nature of the materials and physical construction of the nylon rope. This led to some standardization and measurement of rope-wicking properties (Derting, 1981b).

Chemigation—Irrigation has not been widely used for herbicide application. However, with more cotton acreage being irrigated in recent years, there is considerable interest especially in utilizing the sprinkler and drip systems to apply herbicides. In general, weed control using chemigation has been successful although uniform distribution of water and herbicide has been difficult to obtain (King *et al.*, 1980; Banks and Dowler, 1984). Satisfactory weed control has been obtained using as little water as 0.25 inch per acre for preemergence and 0.1 inch per acre for postemergence applications (Dowler, 1987).

Controlled Droplet Applications—Controlled spray droplet size is usually obtained with a spinning disc or rotary atomizer. Interest in this technique surged during the 1970s with the introduction of the Span Sprayer and the desire to reduce spray volumes (Patrick, 1970). Conventional hydraulic nozzles can be used to reduce spray volumes to about five gallons by using smaller orifices, lower pressures or faster ground speeds. However, such practices may increase the percentage of small droplets in the spray pattern and increase problems associated with drift (Taylor, 1981). The alternative method of using a spinning disk to deliver low spray volumes (LV) produces fewer small droplets of a size subject to drifting. The design and speed of the spinning disk can be changed to get the desired droplet size. Most herbicide application has been done at spray volumes around four gallons per acre with low velocity droplets of about 250 microns in diameter.

Air-assist Nozzles—The introduction of low pressure air into a hydraulic nozzle was done to permit application of low spray volumes. Research has shown

the air-assist nozzles compare favorably with controlled droplet applicators and flat-fan nozzles at four gallons per acre (McKinnon *et al.*, 1985).

Electrically Charged Spray Particles—Creating an electric field in a spray pattern to propel charged spray particles onto target weeds has shown excellent uniformity of distribution on both upper and lower surfaces of leaves (Law, 1977). The atomization of the spray solution can be accomplished with a spinning disk or by electrostatic principles. Much of this research has been done in England by ICI Plant Protection Division and has resulted in the Electrodyn Sprayer (Coffee, 1981). These sprayer units may be hand carried or mounted on tractors. The hand-held units offer a great advantage to farmers in third world countries because of their efficiency and uniform application of ultra-low volumes (0.4 to 4 pints per acre). However, charged-particle sprayers are highly technical, and except for hand-held units are not yet commercially available.

Sensing Devices—Various sensing devices have been used to activate a spray system to spray weeds extending above the crop or outside the crop row. Such an automated system mounted on a tractor allows fast and economical spot treatment. The herbicide is conserved and applied only where needed.

Although demand was not great enough for commercial production, researchers built directed spray equipment to apply herbicides in a continuous band or only on the hills of cross-plowed cotton. A plant sensor and solenoid valve powered from the tractor battery was used to automate the spot spraying. Spraying only the cotton hills reduced herbicide rates 60 percent (Fulgham and Wooten, 1972).

Electronic Control Systems—Sprayer monitors have evolved along with the development of better herbicides. The need for precise chemical application has been recognized even more with rising herbicide and application costs along with environmental concerns. Over 30,000 spraying monitoring systems are now sold annually (Mueller, 1985). At the heart of some systems is a radar device which measures true ground speed. With electronic controls and a constant measure of true ground speed, the sprayer can be programmed to deliver a given herbicide rate and spray volume. Delivery is automatically adjusted to compensate for changes in ground speed (Weaver, 1984). Tractor manufacturers are now offering performance monitoring packages that will monitor spray applications.

APPLICATION METHODOLOGY

Herbicides are applied by four basic methods: sprays, granules, direct contact and irrigation (Matthews, 1982). The technology associated with these methods and time of application; preplanting, preemergence and postemergence include ground and aerial equipment designed to deliver the herbicide to the target. This section will describe the basic components of some of the equipment used in the four methods of application.

SPRAYS

By far the most common method of herbicide application in cotton management systems is liquid sprays. Most herbicides are applied with low-pressure sprayers. Sprayers range in size from small engine-driven pump units to large self-propelled sprayers. Spray pressures can range up to 145 pounds per square inch (Bode, 1987). Regardless, all low-pressure sprayers have several basic components; a pump, a tank, an agitation system, a flow-control assembly and a distribution system (Bode and Butler, 1981).

Pumps—The heart of the low-pressure sprayer is the pump which may be positive or non-positive types. Positive types (the roller pump, Figure 2A) displace a specific volume of liquid with each stroke or revolution of the pump. Some form of pressure relief or pressure control device must be used so that the spray solution not used in the application is bypassed back to the source tank. Unlike non-positive types (the centrifugal pump, Figure 2B) which are not self-priming, the positive displacement pumps do not require mounting below the tank level. However, non-positive pumps do not require bypass relief (Figure 2B), and they generally last longer (Bode, 1987).

Pumps used for applying herbicides include piston, diaphragm, centrifugal, roller, flex impeller, gear and vane. The most commonly used are the roller, centrifugal and diaphragm. Regardless, the pump should provide enough spray solution to supply the flow required by the nozzles and the tank agitator, and have a reserve capacity of 10 to 20 percent (Bode, 1987).

Centrifugal pumps are the most popular type used because of their durability, simple construction, and ability to handle wettable powder herbicide formulations. Their high output (40 to 130 gallons per minute at pressures up to 75 pounds per square inch) provides sufficient agitation for high-volume spray solution tanks. Though somewhat more expensive than a roller pump, its long life and low maintenance make it an economical choice.

Because of the need to operate at high impeller speeds (3,000 to 4,500 rpm), some type of step-up mechanism is required when operating from power-take-off (PTO) shafts. The simplest and least expensive is a belt-and-sheave assembly. Other step-up mechanisms include planetary gears completely enclosed and mounted directly to the PTO shaft, and a close-coupled, high-speed hydraulic motor. Use of a hydraulic motor to drive the pump keeps the PTO shaft free for other uses. To eliminate the need for a step-up mechanism, turbine pumps are available that operate similar to centrifugal pumps except they can provide the normal flow rate at pressures up to 75 pounds per square inch when mounted directly to the PTO shaft.

Roller pumps are also popular for low-pressure sprayers because of low initial cost, compact size, ease of repair and efficient operation from PTO shafts. A wide assortment of roller pumps are available with outputs ranging from 5 to 40

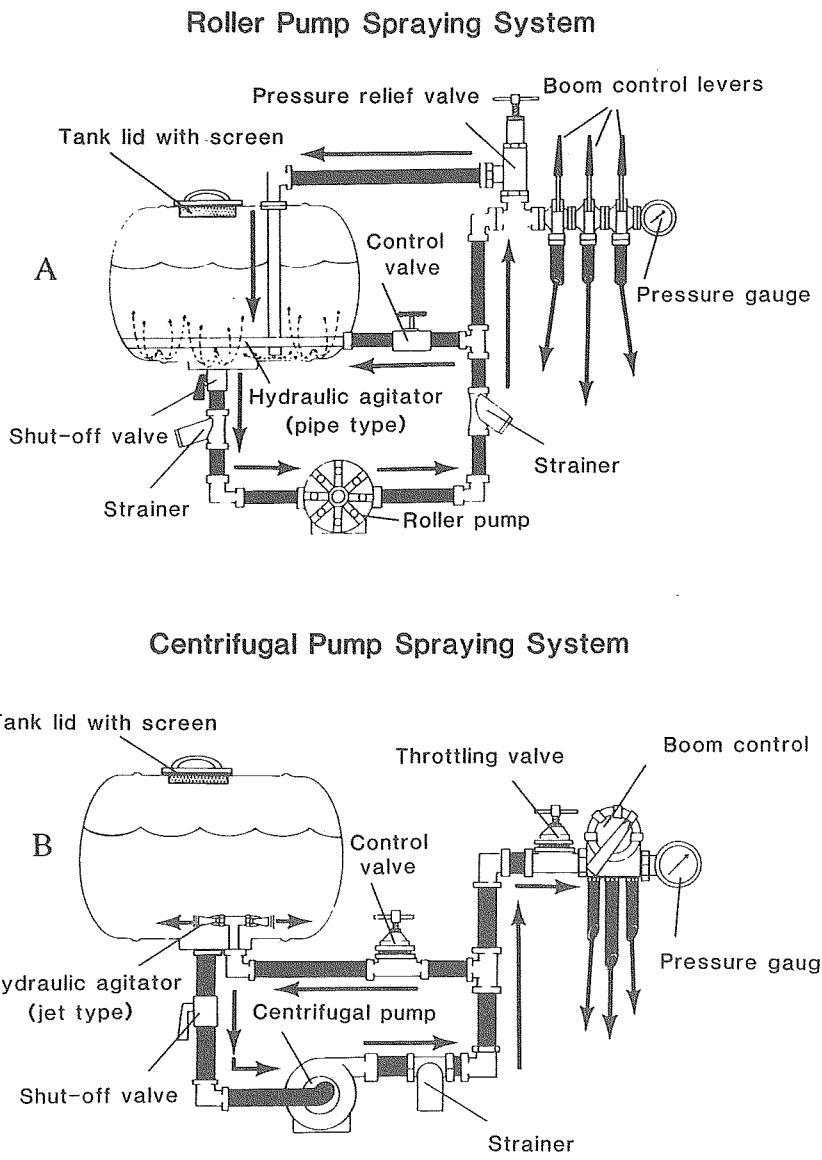


Figure 2. Components of low-pressure sprayers. Positive-displacement roller pump (A), and non-positive centrifugal pump (B).

gallons per minute and maximum pressures ranging from 145 to 290 pounds per square inch (Bode, 1987).

Nylon or polypropylene rollers have proven to be the most resistant to herbi-

cides and are recommended for multipurpose sprayers (Bode, 1987). When the pump is used only for water solutions and wettable powder suspensions at pressures under 100 pounds per square inch, rubber rollers are preferred.

Diaphragm pumps are available in medium to high pressure (145 to 725 pounds per square inch) models with flow rates ranging from 15 to 50 gallons per minute. Diaphragm pumps are self-priming, positive displacement pumps, and require less horsepower than other pump types with similar flow and pressure ratings.

Tanks—Spray tanks should be selected that are large enough not to require frequent refilling. They should also be resistant to corrosion, easy to fill and clean, shaped suitable for mounting and effective agitation, have adequate openings for pump and hydraulic or mechanical agitation connections, and should have a clearly marked sight gauge or other external means of determining spray solution level (Bode, 1987). Tank openings should be large enough for unrestricted tank filling and cleaning, and be equipped with a cover to avoid spillage. A drain that opens through the bottom should be provided so that the tank can be completely drained of its contents. Tanks are constructed of several materials, and their features are listed in Table 1.

Table 1. Features of low-pressure sprayer tank construction materials. (Adapted from Bode, 1987.)

Material	Advantages	Disadvantages
Fiberglass	Strong, durable Repair kits available Equal to aluminum in cost Safe for most herbicides	Break or crack on impact Affected by some solvents Extra mounting support required
Aluminum	Strong, durable Equal to fiberglass cost Repairable	Subject to corrosion from some herbicides Tank volume not visible Cannot use liquid nitrogen solutions with phosphoric base
Galvanized steel	Strong Inexpensive	Easily corroded Corrosion results in strainer, screen, and nozzle tip clogging Tank volume not visible
Polyethylene	Tough, durable Relatively inexpensive Several sizes and shapes Safe for herbicides	Break or crack on impact Cannot be repaired Subject to ultraviolet light—inhibitors reduce damage Extra mounting support required
Stainless steel	Strong, durable Resistant to corrosion from any crop chemical	Expensive compared to other materials Tank volume not visible

Agitation—Agitation requirements depend largely upon the formulation of the herbicide being applied. Soluble liquids and powders do not require special agitation once they are in solution, but emulsions, wettable powders, and liquid and dry flowables will usually separate if they are not agitated by some means. Separation causes the concentration of the herbicide spray to vary greatly as the tank empties. Thus, thorough agitation is essential. Either mechanical paddles or hydraulic jets can be used to agitate the spray solution (Bode, 1987).

Hydraulic agitation is most commonly used on low-pressure sprayers (Bode, 1987). The fluid is circulated by returning a portion of the pump output to the tank and discharging it under pressure through holes drilled in a pipe running the entire length of the tank (Figure 2A) or through special (jet) agitator nozzles

(Figure 2B). Agitator orifices should receive fluid from a separate line on the discharge side of the pump and not just from the bypass line, although the bypass line does provide some agitation.

Flow Control—A roller or other positive-displacement pump usually has a flow-control assembly consisting of a bypass-type pressure regulator or relief valve, a control valve, a pressure gauge and a boom shut-off valve (Figure 2A). The bypass pressure relief valve is needed to prevent damage to the pump and other components when the boom is shut off (Bode, 1987).

To properly adjust the roller pump or other positive-displacement pump system: (a) close the control valve in the agitation line and open the boom shut-off valve; (b) start the sprayer and run the pump at operating speed, and adjust the pressure relief valve until the pressure gauge reads about 10 pounds per square inch above the desired spraying pressure; and (c) slowly open the agitation line control valve until the spraying pressure is at the desired level.

A pressure relief valve and bypass line are not needed with a flow-control assembly for a centrifugal pump, but throttling valves to accurately control the spraying pressure are preferred (Figure 2B). Two control valves (one in the agitation line and one in the spray boom line) are used to control the spray pressure. This permits independent flow control of the agitation line and nozzle output. Especially useful for enclosed cabs of tractor-mounted sprayers are electric-controlled throttling valves (Bode, 1987).

To adjust the centrifugal pump system: (a) prime the pump with all valves open; (b) close both valves and, with the pump running, open the boom control valve until the pressure gauge indicates the desired spraying pressure; and (c) open the agitation line control valve for sufficient agitation. Restore the boom pressure if opening the agitation line control valve caused a pressure change.

As a group, sprayers use one of four types of atomizing nozzles: hydraulic pressure, pneumatic, rotary and electrostatic. Atomizing nozzles regulate the flow rate of the spray solution, form individual droplets, and disperse the droplets into an acceptable distribution pattern (Bode, 1987).

Hydraulic pressure nozzle is the most common atomizing nozzle. These are available as fan-spray, flooding or deflector spray, cone spray and straight stream nozzles. As a group, these hydraulic pressure nozzles produce a wide range of droplet sizes.

Flat-fan spray nozzles are designed to produce a thin sheet of spray with a spray angle ranging from 15 to 110 degrees when pressure forces the liquid solution through the nozzle orifice. Tapered flat-fan nozzles are usually mounted on 20-inch centers and operated at pressures of 25 to 40 pounds per square inch to provide 25 to 30 percent pattern overlap for optimum distribution (Figure 3). Nozzle distance to target (spray height) is 10 to 24 inches depending upon nozzle spray angle and pressure (Table 2). As spray angle increases (while holding pressure constant), the spray height required to maintain 25 to 30 percent spray pat-

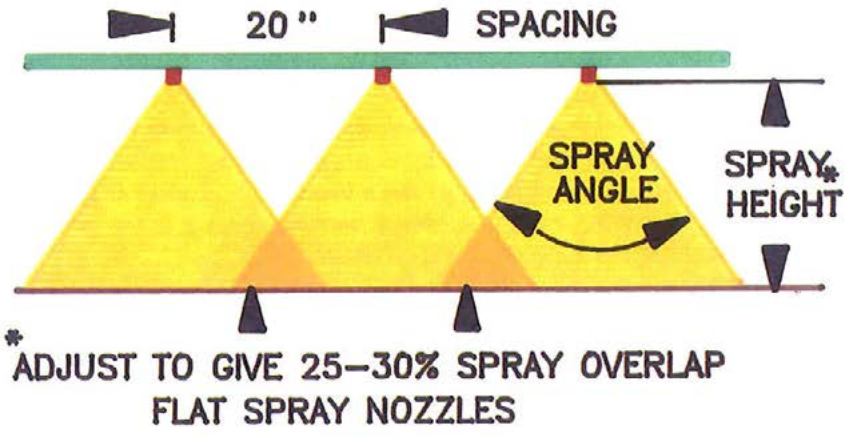


Figure 3. The relationship of nozzle spray angle, spacing, and tip height for tapered flat-fan spray nozzles to result in proper spray pattern overlap.

Table 2. Nozzle height in inches above target surface needed to provide 25 to 30 percent spray pattern overlap. (Adapted from Bode, 1985.)

Tip spray angle	Nozzle spacing	
	20 inches	30 inches
	—Nozzle height—	
(degrees)	(inches)	
65	21 to 23	32 to 34
73	20 to 22	27 to 29
80	17 to 19	24 to 26
110	10 to 12	14 to 18

tern overlap is decreased. Thus, the 95 to 110 degree nozzles can be operated close to the spray target which is often needed when wind speeds increase. Flat-fan nozzles that will produce a normal fan angle and distribution pattern at low pressures (15 pounds per square inch) are also available. These low pressure fan nozzles produce larger drops at lower pressures than regular fan nozzles, but also produce smaller droplet sprays at higher pressures (30 to 60 pounds per square inch) (Spraying Systems Co., 1985).

For band preemergence application of herbicides, the even flat-fan nozzle is available. Unlike the tapered flat-fan nozzles, these nozzles provide uniform cov-

erage across the spray pattern width. Band width is determined by adjusting spray height (Figure 4, Table 3). Again, as spray angle increases, the nozzle can be mounted nearer to the target for a given band width. Band width for preemergence applications is usually two inches greater than the planned width of the first cultivation.

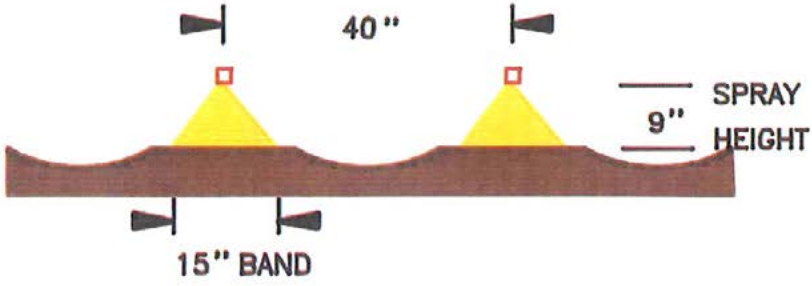


Figure 4. Eighty degree even flat-fan nozzles positioned 9 inches above target to result in a band width of 15 inches.

Table 3. Nozzle height in inches above target surface needed to provide a given band width using even flat-fan spray nozzle tips. (Adapted from Spraying Systems Co., 1985.)

	Nozzle tip spray angle (degrees)		
Band width	40	80	95
		—Nozzle height—	
(inches)		(inches)	
8	11	5	4
10	14	6	5
12	17	7	6
14	19	8	7
16	22	10	8

Tapered flat-fan nozzles also can be used effectively on directed postemergence spray rigs. Each nozzle may be set down and back (in relation to travel direction) to overlap 25 to 30 percent across the drill while maintaining the desired band width (Figure 5A). Nozzle height adjustment needs to provide spray coverage of weeds, but with minimum contact of the cotton foliage. The off-center tapered flat spray nozzle (Figure 5B) also is an alternative in constructing a down-and-back direct spray system. Where spray overlap on successive passes is not desired, an off-center nozzle can be used on the boom as the outside nozzles. Applying herbicides to the skip of a skip-row cotton planting pattern is one example where such an arrangement could be utilized.

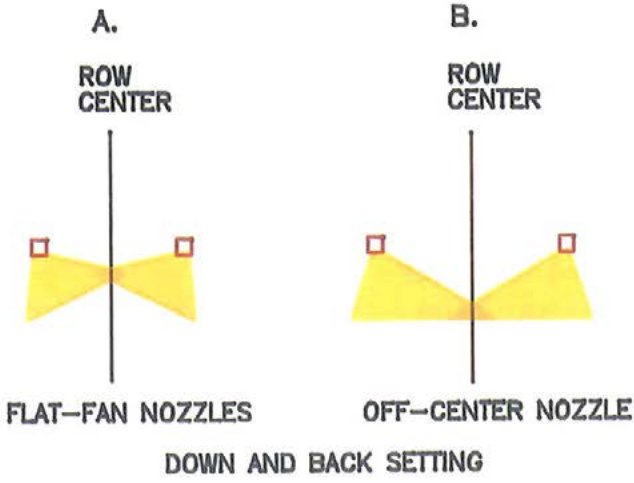


Figure 5. Overhead view of tapered flat-fan nozzles (A) and tapered off-center flat-fan nozzles (B) set to apply a directed spray in a down and back (in relation to direction of travel) pattern.

Flat-fan nozzles are sometimes used in fixed-wing aerial ULV application of certain cotton insecticides. Similar applications of the selective grass herbicides could be made where small but concentrated spray droplets are desired (Barrentine and McWhorter, 1988).

Twin orifice flat-fan nozzles have been developed to provide greater flexibility in boom sprayer use. One nozzle has two orifices side-by-side to produce a wide spray angle pattern. They can be mounted on a drop-pipe from the boom in the row middle to provide directed spray coverage. A nozzle with two orifices front and back is also available that produces two flat-fan spray patterns 60 degrees apart.

Flooding or deflector spray nozzles produce a wide-angle flat spray pattern of 70 to 145 degrees (width depending upon design and pressure) with operating pressures ranging from 10 to 40 pounds per square inch. These nozzles are usually mounted on 40-inch centers, and can be mounted so that the spray pattern is straight down or at any angle as long as 100 percent spray overlap is achieved. To provide 100 percent overlap with flooding nozzles mounted on a disk harrow (Figure 6A), a spray height of about 18 inches with the nozzles tilted up 45 degrees (0 = straight down) is required. For any incorporation device, pattern overlap should be adjusted with the device set at the depth of operation. Flooding nozzles are used in the application of preplant herbicide and liquid fertilizer mixtures. The spray boom can be raised or lowered and the nozzles (or boom and nozzles) rotated to provide 100 percent spray pattern overlap forming an umbrella like spray pattern as illustrated in Figure 7.

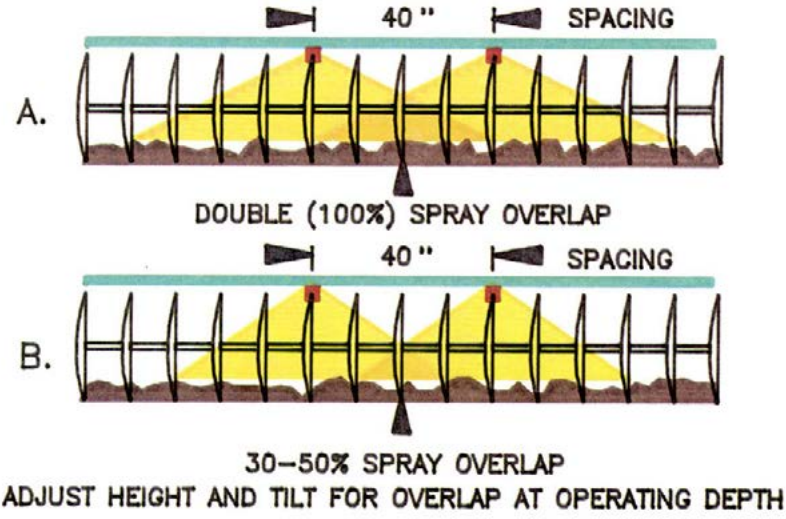


Figure 6. Flooding or deflector nozzles (A) and full-cone wide-angle nozzles (B) mounted on a disk harrow illustrating proper spray pattern overlap.

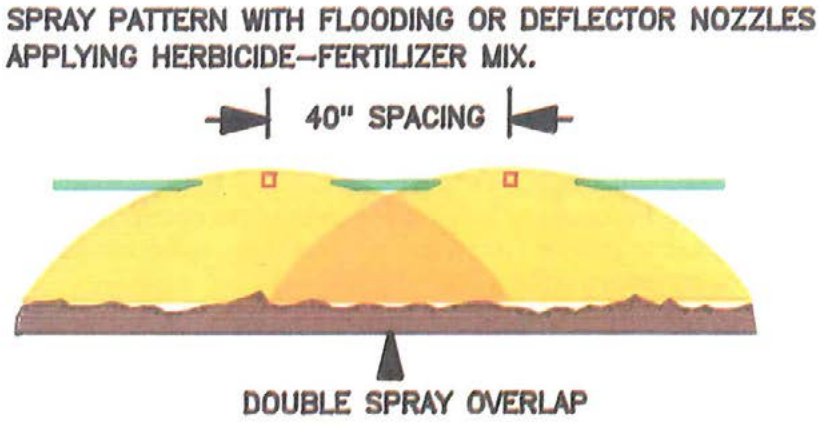


Figure 7. Illustration of a boom equipped with flooding or deflector nozzles tilted up to form an umbrella like spray pattern with double (100 percent) overlap.

Cone spray nozzles are designed to produce a full or hollow cone spray pattern of various angles. Bode (1987) describes the production of a cone spray pattern in detail. The wide-angle (up to 120 degrees) cone nozzle is the most commonly used full cone nozzle in cotton production. These are often mounted to a soil incorporator on 40-inch centers to provide 30 to 50 percent spray pattern overlap at 15 to 30 pounds per square inch (Figure 6B). To improve spray distribution and compensate for restricted height adjustment, nozzles may be tilted 30 to 45 degrees. Hollow cone nozzles have limited use in cotton weed control, but the selective grass herbicides could be band-applied using the two nozzle per row arrangement shown in Figure 8. When cotton exceeds the 8-inch stage, the two-nozzle spacing may be increased from 22 inches to 24 inches and their height from 11 inches to 15 inches, and a third nozzle centered 23 to 24 inches above the cotton drill may be added (Baldwin *et al.*, 1988). The three-nozzle arrangement would be suitable for application of foliar applied selective herbicide and fertilizer mixtures as it is for defoliants.

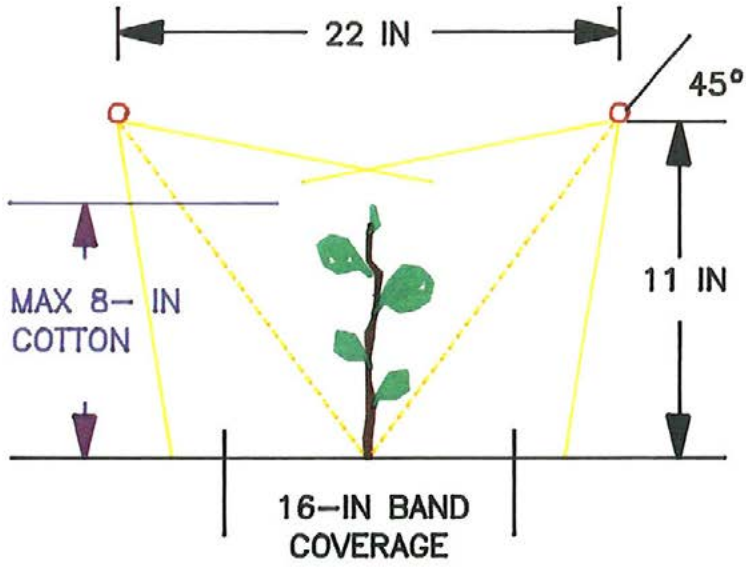


Figure 8. Positioning hollow-cone nozzles when applying over-the-top sprays to a band from two nozzles per row. (Adapted from Baldwin *et al.*, 1988.)

The straight-stream cone nozzle produces a straight but somewhat unstable spray pattern. This nozzle has limited use except for recirculating sprayers (Wills and McWhorter, 1981) and spray guns used for spot-spraying. Straight-stream disc-core nozzles are more often used to meter herbicide solutions that are injected into the soil. This nozzle consists of the usual nozzle body, cap and filter (screen) but the orifice is a flat disc to provide varying flow rates at various pressures.

Spot-spraying equipment used in cotton weed control varies from the traditional hand-operated (compressed air, knapsack, etc.) sprayers (Figure 9) to those which are tractor-mounted with the spray nozzles turned on-off via a solenoid valve activated when weeds taller than the cotton plants interrupt an infrared light beam.[1] A tractor-mounted unit which utilizes a moisture sensing system and solenoid valve for spray on-off is under evaluation[2] (Figure 10A). As the weeds which are taller than the cotton contact the moisture laden sponge, the three-nozzles-per-row arrangement (Figure 10B) delivers a momentary spray. It is not uncommon to see all-terrain vehicles (ATV) equipped with hand operated sprayers (Figure 11) applying spot sprays early in the growing season.[3] Spot gun applicators (Figure 12A,B) which apply known volumes of known concentrations of glyphosate (Roundup®), sethoxydim (Poast®), or fluazifop-P (Fusilade-

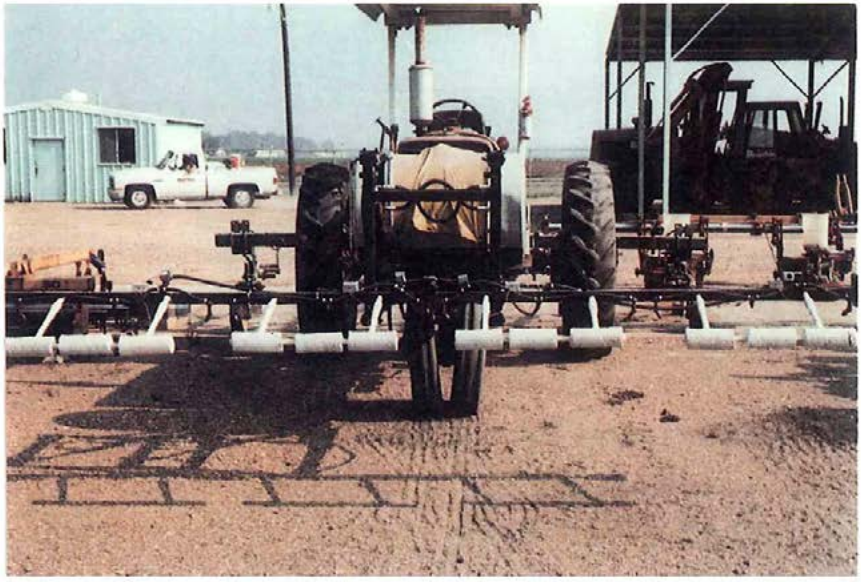
[1]HEC Sprayer. Town Country Airpark, Lubbock, TX 79404.
[2]Private communication. J. R. Williford, USDA, ARS, Stoneville, MS.
[3]Spraymate 26, Ag Enterprises, Route 1, Box 69, Grainfield, KS 67737.

2000®) to spots of rhizome johnsongrass in cotton are also in use. Figure 12C illustrates a 0.67 ounce (20 milliliters) "shot" which was applied mid-way up the culms of a "spot" of rhizome johnsongrass.



Figure 9. Spot-spraying rhizome johnsongrass with a hand-held compressed air sprayer.

A



B



Figure 10. A front-mounted boom (A) with 3 nozzles per row which applies a momentary spray to weeds growing taller than the crop plants when the moisture sensitive pad (B) interrupts the weeds and activates on on-off solenoid valve.



Figure 11. One of several types of all terrain vehicles equipped with a sprayer which can be used for spot-spraying.

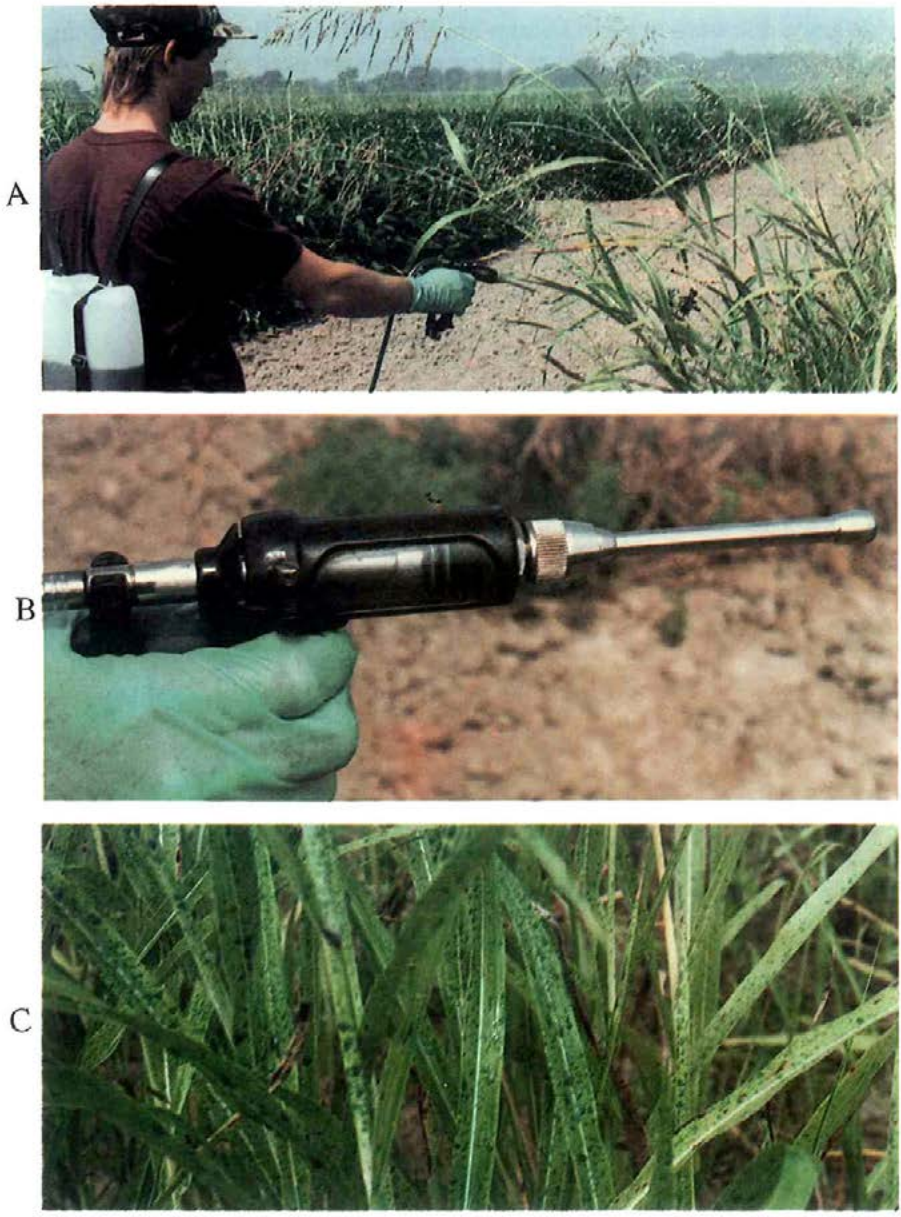


Figure 12. A back-pack (A), spot-gun (B) applicator applying a 2/3 oz "shot" to a spot of rhizome johnsongrass. The blue dye (C) illustrates coverage.

Disc-core-hollow-cone and whirl nozzles are also used on aerial spray booms. They are mounted to the rear and down no more than 45 degrees. Selection of

wide angle disc-core or whirl nozzles are to be avoided (Bouse, 1987). Multiple jet or combination nozzles (Figure 13) are common on fixed wing aircraft.

The raindrop cone nozzle, as the name implies, produces larger droplets than other cone types, and is often used in the aerial application of preplant herbicides where drift may be a problem. Its use for contact herbicides may result in unsatisfactory weed control (Bouse, 1987). Spinning atomizers as depicted in Figure 14A, B also are used for LV application. Figures 15 to 23 provide examples of aircraft and nozzle arrangements that may be used to apply herbicides.

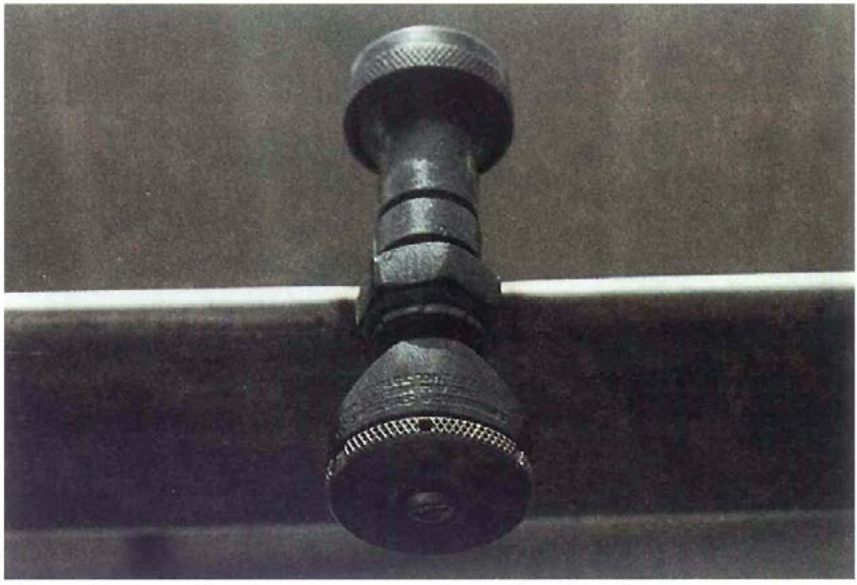
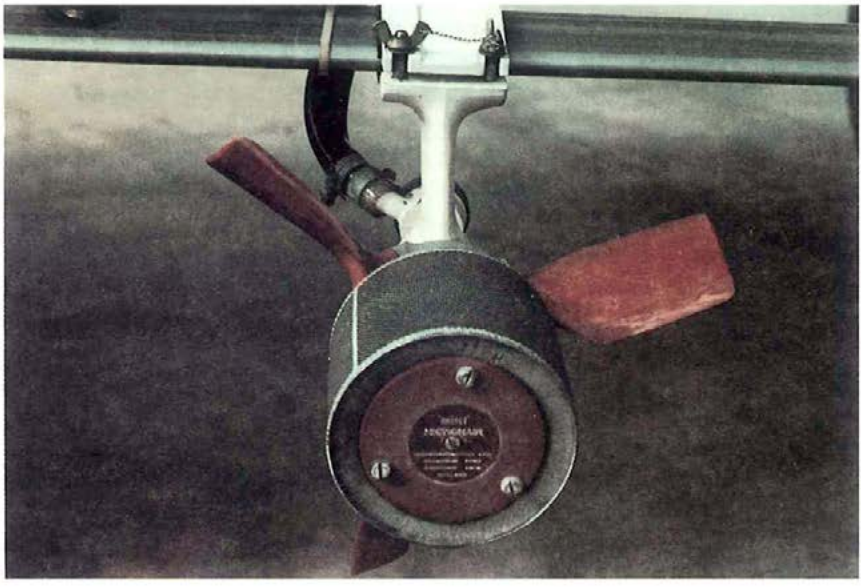


Figure 13. A combination pressure nozzle used on aircraft.

A



B



Figure 14. Spinning atomizer nozzles used on aircraft: Micronair (A) and Unimizer (B).

Liquid sprays are the primary methods of applying herbicides in cotton weed management systems, and pressure or hydraulic nozzles the primary means of metering and dispersing the spray. Yet, no single aspect of applying herbicides in

cotton weed management is as important, and more often given improper attention to, as sprayer calibration and determining the herbicide-water spray mix. Methods of calibrating low-pressure hydraulic nozzle sprayers are described and accompanied with examples in the Appendix at the end of this chapter.

Pneumatic nozzles atomize the liquid solution by impacting the metered solution with air. Air impaction of the liquid may be outside (external), as in the common paint spray nozzle, or inside (internal) the nozzle. The internal-mixing nozzle is actually a combination pressure-pneumatic nozzle. The metered liquid under pressure is impacted against a pin protruding from the base of the internal mixing chamber which partially atomizes the liquid. Atomization is completed by low volume air introduced into the mixing chamber under low pressures—hence, the name air-assist nozzle. A modified flooding or deflector nozzle tip is used to regulate the air flow into and out of the liquid-air mixing chamber and to produce the spray distribution pattern. The nozzle is designed to apply liquid solutions at 2 to 10 gallons per acre using liquid pressures from 30 to 60 pounds per square inch, and air pressure ranging from 4 to 12 pounds per square inch (Reed, 1985). These nozzles could be used to apply the selective grass herbicides in cotton.

Rotary nozzles were produced as an alternative to the pressure or pneumatic atomization nozzles to provide a spray pattern with a narrow range of droplet sizes. Droplets are formed by introducing the liquid onto a rotating cup, disk or cone. Centrifugal force moves the metered liquid to the outer periphery. Droplet formation and final size is a function of flow-rate, disk diameter and design and rotational speed (Gebhart and Kapusta, 1987).

Several designs of rotary atomizers are available, but most commonly seen is the spinning cone or control droplet applicator (CDA) which utilizes a cone-shaped cup with grooves on the inside and serrations (teeth) on the periphery of the cup lip. These are available with either a direct current electrical motor or a hydraulic motor.[4] A second unit uses an electrically driven horizontally spinning disc with grooves on the inside surface.[5] A third unit utilizes a shielded, smooth-surface disc with outer edge serrations mounted vertically.[6] One other unit uses an inverted cup as a rotary atomizing device.[7] These rotary atomizers could be used for LV or ULV selective herbicide application, but weed control has generally been inconsistent because of inadequate spray coverage (Gebhart and Kapusta, 1987).

Electrostatic nozzles are not used in cotton weed control; however, three different types of electrostatic sprayers have received considerable research effort (Gebhart and Kapusta, 1987). The basic principle is to create a charged spray

[4]Micron Corporation, P. O. Box 19698, Houston, TX 77024 and Sprayright Manufacturing Company, P. O. Box K, West Helena, AR 72390.

[5]Spraying Systems Co., North Avenue, Wheaton, IL 60188.

[6]Techoma S.A., Epernay, France.

[7]J & J Guy Systems, Inc., P. O. Box 241, San Born, MN 56083.

droplet that will adhere to the target (plant part and/or soil). The droplet must be of appropriate mass and charged so that the electric field created between the spray droplets and target surface is sufficient to overcome wind, gravitational and inertial forces that will otherwise cause the droplets to miss the target.

Law (1978) developed an internal-atomizing pneumatic spray nozzle to produce droplets. The charging electrode imbedded in dielectric material for protection, is located within the atomizing chamber and the upper operating voltage was about 2,000 volts. His unit successfully applied water sprays at LV and ULV.

Coffee (1981) designed the only known commercially available electrostatic sprayer for ULV applications. Electrostatic principles not only charge but generate the droplets. Degree of atomization can be varied by changing the charging voltage. This allows for some control over droplet size and charge. Voltage requirements were so low that standard 1.5 volt flashlight batteries would power the commercialized hand-held units.

Others have utilized the rotary atomizer principles in the design of spinning disk electrostatic atomizers for ground (Arnold and Pye, 1980; Marchant, 1986) and aerial (Carlton and Bouse, 1980) equipment. Coffee's design remains the sole commercial unit. The principles are very sound, but the major problem is getting the droplets to the desired target (Gebhart and Kapusta, 1987).



Figure 15. Cessna A188B Ag-Wagon equipped with combination nozzles.



Figure 16. Cessna A188B Ag-Husky-Turbo equipped with combination nozzles.



Figure 17. Cessna A188B Ag-Truck equipped with combination nozzles.



Figure 18. Rockwell Thrush Commander 600 equipped with combination nozzles.



Figure 19. Gruman G-164A Ag-Cat equipped with combination nozzles.



Figure 20. Gruman G-164B Ag-Cat equipped with combination nozzles.



Figure 21. Air Tractor AT-301, 600, equipped with Model 10 Unimizer spinning atomizers.



Figure 22. Air Tractor AT-301, Turbo 680, equipped with Micronair spinning atomizers.



Figure 23. Continental Copter, Mark 5 Tom Cat, equipped with Warner spray system nozzles.

GRANULES

Granular formulated cotton herbicides are not used to any great extent in the Cotton Belt. The preplant incorporated herbicides could be easily applied in granular form, but the continuing need for weed control with postemergence sprays probably accounts for the lack of any trend toward granular application.

Early problems with calibration and granular distribution were encountered. This was due to the adoption and modification of granular fertilizer and seeding equipment for use in applying granular herbicides. Because of the poor distribution obtained with this equipment, weed control was often less than satisfactory.

Herbicides with a relatively high water solubility such as cyanazine (Bladex®) can provide better weed control when applied preemergence in granular form than in a liquid spray (Feeny and Coble, 1964). Those which volatilize and/or photodegrade after application were also more effective in granular form than in liquid sprays. Thus, the weed control from trifluralin (Treflan®) and pendimethalin (Prowl®) applications could be more effective when applied in granular form as compared to liquid sprays.

The concept of controlled release herbicides (Schreiber *et al.*, 1987) may also spur an increase in applying herbicides in granular form. The object of controlled release is to deliver the herbicide to the target site at a constant but effective concentration over a specified period of time (Lewis and Cowsar, 1977). The herbicide is chemically attached or physically entrapped (encapsulated) within another substance.

Because of its volatility and photodegradation properties, trifluralin should be immediately incorporated. Encapsulated trifluralin granules permitted incorporation to be delayed for up to 8 days after application while maintaining weed control (Foley and Wax, 1980). Fall, winter or early spring applications of encapsulated trifluralin gave season-long control without incorporation at planting time and opens the possibility for its use in minimum-till systems (White and Schreiber, 1984).

Other herbicides used in cotton which have been encapsulated are linuron (Lorox®), cyanazine (Bladex®) and metolachlor (Dual®). Most of the herbicides used in preemergence and/or layby applications in cotton could be encapsulated and applied with granular applicators.

The state-of-the-art ground granular applicator uses a pneumatic system. This development permits the use of one application system for ground application of granular fertilizers and/or herbicides. The Gandy Company's[8] pneumatic granule delivery system is capable of applying granules from 1.0 to 270 pounds per acre. The application equipment may be mounted on a combination tool to apply herbicides broadcast preplanting (Figure 24A) or in conjunction with a planter for band preemergence application (Figure 24B) of herbicides. The minimum dry fertilizer-herbicide granular rate suggested to ensure uniform application is

[8]The Gandy Company, Owatonna, MN 55060.

200 pounds per acre (Lowery, 1987); thus, this unit could be used for their application.

A



B

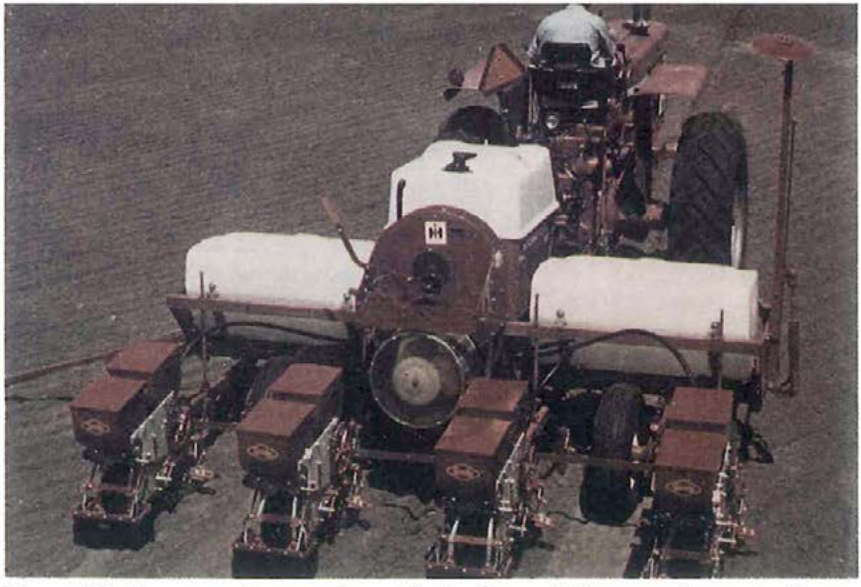


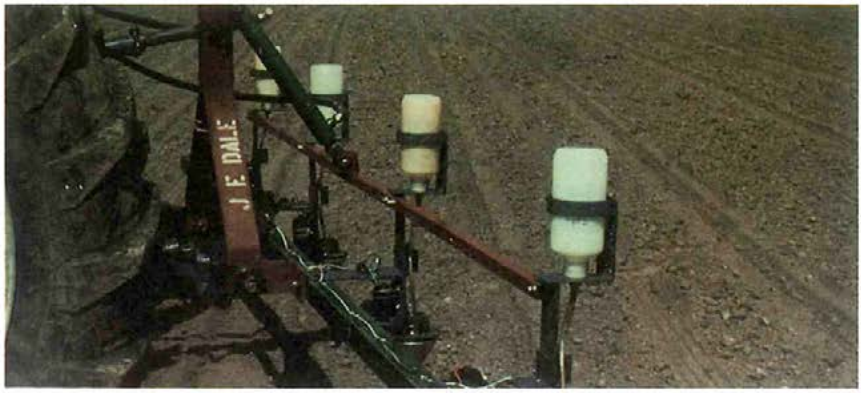
Figure 24. A pneumatic granule applicator for applying granular or dry flowable formulations mounted on a combination tool for secondary tillage and herbicide incorporation (A) or planter attached for band preemergence applications (B). (Courtesy The Gandy Co., Owatonna, MN 55060.)

Dry flowable herbicide formulations have also been applied and evaluated with this device (Haugen and Ganrud, 1983a). Weed control compared favorably with the granular and liquid formulations (Haugen and Ganrud, 1983b).

Many aircraft are equipped with the venturi type spreader for dry herbicide applications. The same hopper used for liquid sprays is used for the granular herbicide. The materials are metered from the hopper into an opening in the top of the venturi-shaped throat of the spreader. Vanes or fins within the spreader deflect the dry particles laterally to increase swath width. Helicopters use on-board spreaders or a self-contained bucket spreader. On-board hoppers are mounted on each side, and the dry granules flow from the hoppers to either centrifugal or pneumatic distributors. The self-contained (including power unit) spreader is suspended on cables beneath the helicopter, and is operated electronically from the cockpit (Bouse, 1987).

A novel, but highly promising, ground granular spreader for the application of dry-herbicide formulations utilizing the rotary principle has been reported by Dale (1987). The device consists of a detachable hopper (Figure 25A) of containerized granules with a preselected circular orifice (Figure 25B) to regulate the flow of granules, and a revolving hollow-cone spreader (Figure 25C) turned by an electric motor. Based on patterns of distribution achieved with commercial trifluralin granules, parallel and perpendicular to a linear path, the device could be used to apply herbicide granules in row crops. When trifluralin granules were applied preplant incorporated, seedling johnsongrass control was 80 to 95 percent.

A



B



C

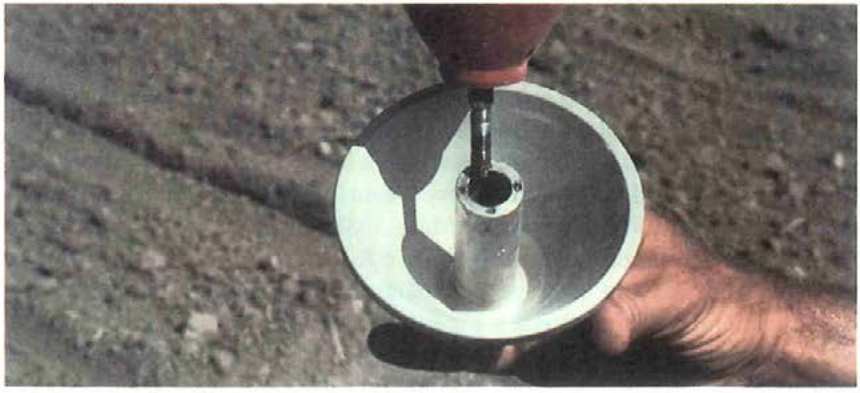


Figure 25. An experimental ground granule spreader for application of dry-herbicide formulations; consisting of containerized granules in a detachable hopper (A) with a preselected circular orifice (B) to regulate flow and a revolving hollow-cone spreader (C). (Courtesy J. E. Dale, USDA, ARS, Stoneville, MS 38776.)

CONTACT

This mode of herbicide application includes equipment-herbicide technologies that were more rapidly evaluated and adopted by growers than any other single advance in herbicide application. This mode of contact application is wiper technology or better known in general as rope-wick application.

Wiping a herbicide onto weeds was not a new concept as producers for a number of years used a boom wrapped with burlap or other material and saturated it with 2,4-D to selectively control hemp sesbania in soybeans. This was followed by the initial research (McWhorter, 1966) and commercialization of the 2,4-D wax bar. The discovery and development of glyphosate (Roundup®) is credited with renewing the interest in wiper application of herbicides and in advancing wiper technology (McWhorter and Derting, 1985).

The rope-wick applicator (RWA), invented by Dale (1978), is credited with initiating research and development in both public and private sectors that led to sale of selected herbicide wiper applicators. The use of RWAs for johnsongrass treatment growing above cotton plants in the early 1980s was common across the Cotton Belt and at least 50 percent of the acreage in the Mid-South region was treated.

Detailed descriptions of the various types of wiper applicators are given by Derting (1987). The basic essentials of a RWA include: (a) a reservoir for the herbicide solution, (b) a suitable wicking material mounted to draw the herbicide solutions from the reservoir, and (c) a method of transporting through the field. The most widely used RWAs were passive; the herbicide solution was fed to the wick by gravity and capillary action. The reservoir pipe of the RWA developed by Dale (1978) also served as the structure for mounting the wick in place.

Active wicking systems use similar reservoir-wick mounting, but they use a closed-system with pressure on the reservoir. This is accomplished either by air in the head above the reservoir or an in-line pump between the reservoir and wick. These systems allow better movement of solution through the ropes, particularly in arid and semi-arid climates typical of the western United States.

The fiber and braid characteristics were found to significantly affect johnsongrass control with RWAs (Wu and Derting, 1981; Derting, 1981A). This facet of RWAs was of such importance in obtaining effective weed control and increasing the wear time that one cordage manufacturer developed the polyester over acrylic diamond braid to provide a superior wick (Revelle, 1982). This cordage is produced on a diamond braider with polyester cords on all ribbons which is braided over a core of acrylic yarn. It has a tough wearing exterior and a high wicking capacity interior.

The passive Stoneville RWA usually required two passes over the johnsongrass for effective (≥85 percent) control using a 1:3 parts solution of glyphosate to water and, because of dripping, caused cotton injury. A newer RWA design that provided excellent johnsongrass control in a single pass with only slight visible cotton injury was the recirculating double pipe wick (McWhorter and

Derting, 1985). This unit consists of two parallel pipes, one mounted above and forward of the other, connected by the rope-wicks. This RWA not only increased the wiping surface area, but the herbicide solution is continuously aspirated from the bottom pipe to the top to maintain fully saturated ropes without drip loss. Once the solution flow through the wicks is adjusted, no other field adjustment is needed regardless of weed infestation level. Solution not wiped onto johnsongrass is recovered for continuous use. In comparative studies, its performance was superior to that from all other active and passive wiper designs evaluated on sloping terrains. The double pipe wick was also the most efficient as measured by the maximum number of acres treated per unit of glyphosate (Roundup®) (McWhorter and Derting, 1985).

Rowcrop carpet wiper applicators of several design modifications have been constructed and evaluated, but commercial sales were limited compared to the RWAs. The first carpet roller applicator was a tractor-mounted aluminum cylinder covered with nylon carpet (Wyse and Habstritt, 1977). A hydraulic motor rotated the cylinder counter clockwise to the direction of travel. A PVC pipe with one-inch holes drilled two inches apart was mounted directly above the carpet roller sumps. Herbicide solution was pumped from a reservoir through tubing to the PVC pipe from which the solution dribbled onto the carpet roller sumps. Optimum cylinder rotation was 20 rpm to prevent dripping. Solution saturation of the carpet was maintained with an electrical sensing device.

A recirculating carpet applicator was designed possessing the elements of a passive wiper, recirculating sprayer and hydraulic sprayer (Chandler, 1981). Called the "Ultimate Stoneville Applicator," carpet was mounted to expanded metal and fit into an opening cut in front of an eight-inch diameter by 80-inch long aluminum pipe which was closed off at each end. Herbicide solution was sprayed onto the back of the carpet through cone nozzles spaced 10 inches apart. Excess spray solution drained from the pipe to a sump and was filtered and recirculated. The commercial unit with some improvements was called the "Carpetbagger" (Roach and Chandler, 1982).

The recirculating sprayer (McWhorter, 1970) was superseded by the rope-wick applicator (RWA) and the RWA is being replaced by over-the-top sprays of the selective grass herbicides. Sethoxydim (Poast®) and fluazifop-P (Fusilade-2000®) are very effective when applied as sprays postemergence to cotton and seedling and/or rhizome johnsongrass and bermudagrass. Regardless, wiper application will continue to be a weapon in the cotton producers arsenal for johnsongrass and other tall weed escapes, because of its simplicity of design and operation, and because numerous units are currently owned by cotton producers.

CHEMIGATION

Herbicide application in irrigation water to selectively control weeds is a recent development in weed technology which can increase crop production effi-

ciency by reducing cost for equipment, labor and fuel (Threadgill, 1981). Nitrogen fertilizers have been applied for several years in irrigation systems, particularly sprinkler systems (Bryan and Thomas, 1958). Advances in irrigation systems and associated injection equipment design have stimulated research which resulted in expansion of this technology to include herbicides (Threadgill, 1985a). Herbicide application in irrigation water is known as Herbigation,® a trademark of ICI Americas, but the application of pesticides and/or fertilizers in general fall under the collective term, chemigation.

Several advantages in applying herbicides through a properly designed irrigation system have been reported (Threadgill, 1985abc). These include: (a) excellent uniformity of herbicide application is possible with sprinkler irrigation systems to include center-pivot and linear-move units when compared to aircraft or ground sprayer applications, (b) application of herbicides can be applied on a timely basis even when fields are too wet for tractors or when weather conditions preclude aircraft application, (c) chemigation precludes the requirement for moisture for precise depth of incorporation because the appropriate amount of water can be applied through irrigation which will incorporate the herbicide to the depth desired and be in place to control the germinating and emerging weeds, (d) in soils where soil compaction is a problem, chemigation can reduce compaction caused by tractors and other tillage implements, (e) mechanical damage to the crop caused by tractors or other spray application equipment which can increase disease problems is avoided, (f) exposure to operators of herbicide application equipment is reduced, and (g) with an adequate irrigation system already in place, economic data has shown chemigation to be cost effective.

Conversely, several disadvantages should be considered in chemigation systems. The most obvious is the additional capital outlay required, particularly where no irrigation system is in place. Safety factors to prevent water supply contamination is of utmost importance. This problem is well recognized by the industry and regulatory agencies and practical safety components are commercially available (Ogg and Dowler, 1987). Chemigation requires very good management and a well designed system that applies water uniformly and permits accurate calibration. A thorough knowledge and understanding of the concept is a necessity. Application of herbicides to control weeds via sprinkler irrigation postemergence has produced inconsistent results because the herbicide is lost from the plant surface by runoff due to the high volume of water usually applied ($\geq$2700 gallons per acre). Another possible disadvantage is that chemigation requires considerably more time to apply the herbicide to a large field as compared to aircraft or ground equipment.

The components of a basic system for delivering the herbicide into an irrigation system (Figure 26A) includes a chemical supply tank, an injection pump, and the appropriate safety and anti-siphon devices that prevent potential contamination of the water source (Figure 26B) (Ogg *et al.*, 1983). Some essentials for a chemigation system, including design and safety features, equipment construc-

tion materials, supply tanks, injection pumps and equipment calibration, are discussed by Ogg and Dowler (1987). An injection system used on a sprinkler center-pivot research system is shown in Figure 26B.

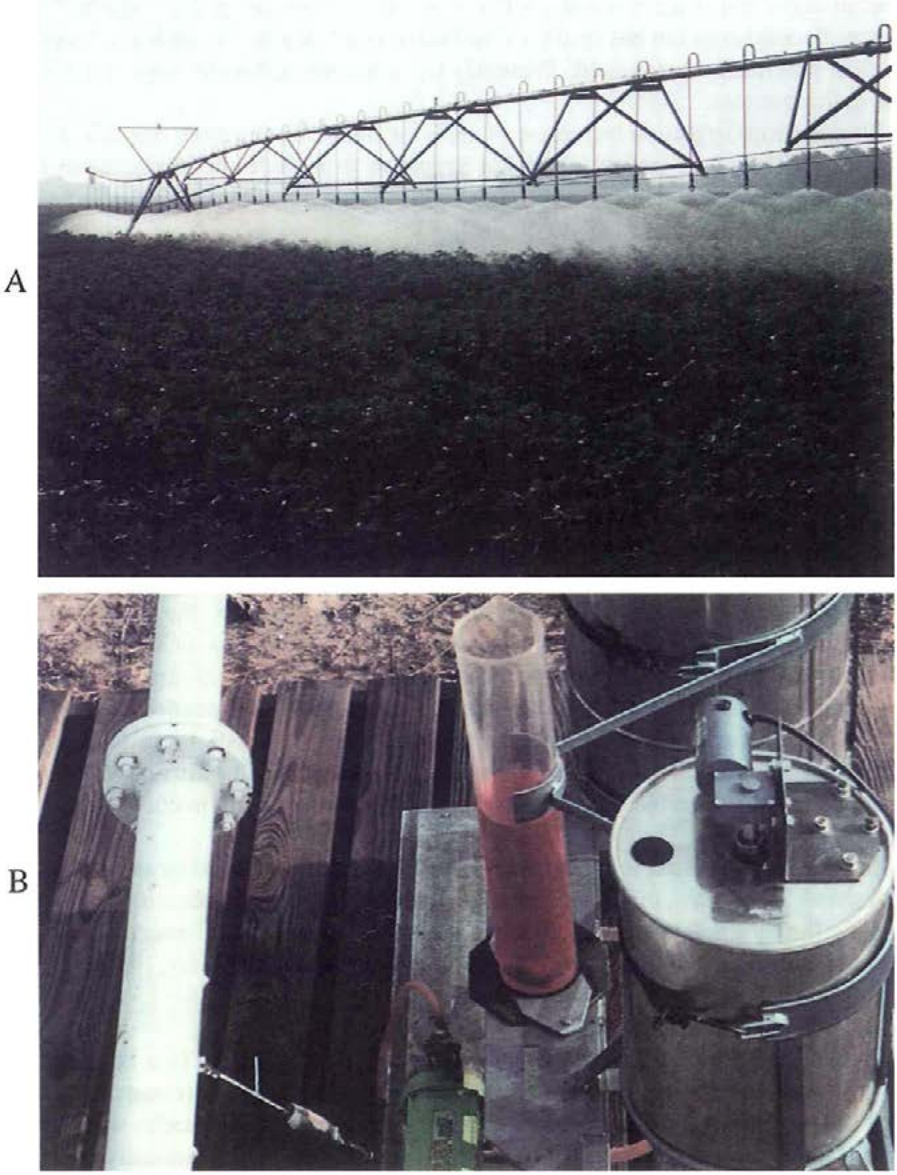


Figure 26. A center-pivot irrigation system (A) equipped for experimental (B) use in applying herbicides and/or liquid fertilizers using irrigation water as the diluent.

In nonpressurized or gravity flow systems (flood or furrow irrigation), a constant head siphon can be used instead of an injection pump to meter the herbicide into the irrigation water. Herbicides can be applied immediately after planting or later at layby but irrigation water will control weeds usually in the irrigated furrow or flooded area but not on top of the bed or ridge; therefore, additional weed control practices are required. Presently there are no herbicides registered for use in this manner.

Trickle (drip) irrigation technique of applying herbicide has been described by Ogg *et al.* (1983). A review of trickle irrigation to include the applications of herbicides is presented in a two volume series published by the American Society of Agricultural Engineers (Anonymous, 1985). The application of herbicides through trickle irrigation systems is not widely used because of problems associated with uneven herbicide application, rapid degradation of the herbicide near the emitters and potential health hazards to workers who might drink treated water from delivery lines. Currently there are no herbicides specifically labeled for application through trickle irrigation systems.

Research in Arizona (Anonymous, 1985) has indicated that weed control in cotton has been inconsistent where trickle irrigation is the exclusive method of applying herbicides. A preplant soil incorporated treatment for grass control followed by effective post-directed foliar and/or preemergence herbicide treatments are essential. A particular problem in cotton fields was the nutsedge species that thrive under the wet conditions provided by trickle irrigation.

In stationery, center-pivot or lateral move sprinkler systems, the grass herbicides fluazifop-P (Fusilade-2000®) and sethoxydim (Poast®) plus a COC (crop oil concentrate) have been applied postemergence with excellent control of annual grasses. Acceptable control of the annual grasses and small-seeded broadleaf weeds have also been reported from preemergence applications of trifluralin (Treflan®), pendimethalin (Prowl®) and metolachlor (Dual®). Currently, metolachlor is the only herbicide registered for sprinkler application in cotton (Anonymous, 1985).

Co-chemigation, that is the application of liquid fertilizers and/or other pesticides with herbicides, offers a distinct advantage in reduced application costs as well as timely application of fertilizers and other agricultural chemicals. However, co-chemigation at the present is in its infancy (Ogg and Dowler, 1987).

SOIL INCORPORATION

Delivering herbicide to the soil does not insure performance. This is particularly true of herbicides which require soil incorporation. Initial research found that the performance of the equipment used to incorporate herbicides was variable. Considerable research, utilizing both qualitative and quantitative techniques, has been conducted to determine the soil incorporation characteristics, including depth and uniformity, of numerous devices. A detailed discussion of this subject is reported elsewhere (Barrentine, 1987).

A soil incorporator is defined as any device used to mix or blend a herbicide into the soil (Harger *et al.*, 1985). When the dinitroanaline herbicides were introduced in the early 1960s, soil incorporation was accomplished with various tillage tools already in use; namely, the four-gang tandem disk harrow, rotary hoes, spike-tooth harrows and, to a less extent, power tillers. A description of these devices and others follow.

Four-gang tandem disk harrows may be in-line, front gang off-set or double-gang off-set (Figure 27A, B and C). The disk blades may be spherical or conical in shape with or without notches (Figures 27 D, E, F, and G). Spacings between disk blades may vary from 6.5 to 12 inches and blade diameters from 18 to 30 inches. The finishing disk, combination disk and cutting disk are classified based on their use for primary or secondary tillage and blade spacing, diameter, shape and weight (Table 4). Because it can be used for primary and secondary tillage, the combination disk harrow is the most prevalent.

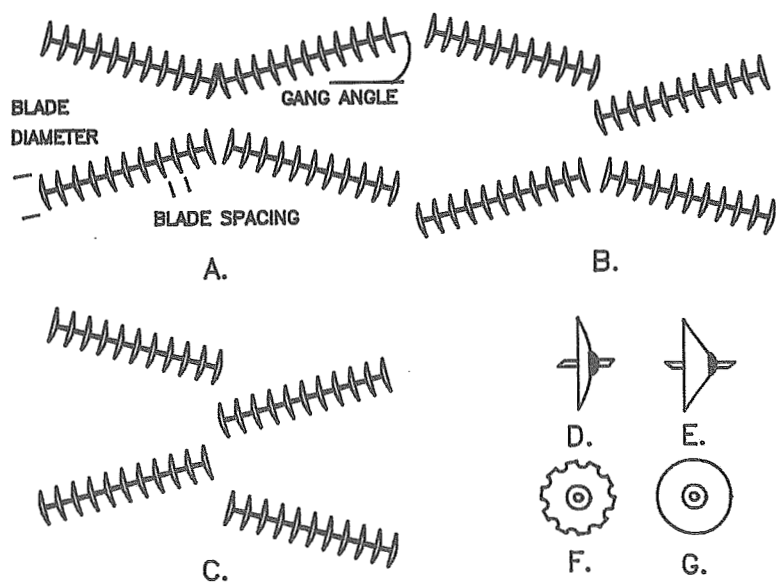


Figure 27. Four-gang tandem disk harrows may be in-line (A), one-gang offset (B), or two-gangs offset (C). Disk blades may be spherical (D) or conical (E) with notches (F) or without notches (G).

Drag harrows are secondary tillage tools used for seedbed preparation and herbicide soil incorporation. Drag harrows are of two basic types, the spike-tooth and the coil-tine harrow. The coil-tine harrow is often referred to as a spring-tooth, coil-tooth, tine-tooth, flex-tine, flexible spring harrow or a flexible tine drag. These harrows have two to five bars with the spikes or tines staggered to have a working spike every 1.5 to 2 inches or a working tine every 4 inches.

Table 4. Descriptive features of four-gang tandem disk harrows.

Disk descriptive name	Tillage use	Disk blade		
		Shape	Spacing	Diameter
			(inches)	
Finishing	Secondary	Spherical	⩽ 8	⩽ 20
Combination	Primary and secondary	Spherical or conical	8 to 9	20 to 24
Cutting	Primary	Spherical or conical	⩾ 9	⩾ 24

Field cultivators are equipped with two or more rows of spring steel shanks spaced 6 to 9 inches apart in a staggered pattern. The shanks may have a forged point or mounting holes for replaceable chisel or shovel sweeps. The shanks referred to as "C" shanks are rigid or spring mounted. Sweeps are usually 110 percent as wide as the shank spacings.

The flexible shank cultivator, often called the Danish or S-tine harrow or Danish or S-tine cultivator, is similar in basic construction to the field cultivator. The coiled-S or S-tine shanks normally are placed in two to four rows with an effective spacing of 6 inches. The tines may be equipped with small 0.75 inch chisel point or 2.5-inch 'goose-foot' (or duck-foot) sweeps.

Power-driven (PTO) tillers may be primary or secondary tillage implements equipped with blades or tines of various types which are forced into and through the soil by transfer of tractor engine power via the PTO. Three basic types of power tillers are available: (a) vertical-action tiller, often called rotary tillers or power-driven rotary hoes, in which the L-, C-, or straight-knife type blades of various lengths rotate about a transverse axis to the direction of tractor travel; (b) horizontal-action tillers are equipped with tapered spikes which rotate and stir the soil in complete circles or oscillate; and (c) combination tillers are equipped with straight tapered spikes and engage the soil with both vertical and horizontal motion.

Ground-driven tillers are of several types, but three major devices are available. The rolling cultivator consists of gangs of ground-driven tine wheels with curved, twisted, partially flat tines which radiate from the center as spokes on a wheel. This unit may be used for broadcast or band incorporation on flat or bedded seedbeds. The rotary hoe consists of one or more gangs of ground-driven tine wheels with round, tapered, curved tines radiating from the center. This device has long been used to uproot seedling weeds pre- or postemergence to various crops, but is used for shallow herbicide incorporation. The open-steel mesh wheel is primarily used for shallow incorporation of a herbicide in a band over the row drill. Often, the mesh wheel replaces the planter press wheel.

Combination tools (seedbed conditioners) are basically two or more tillage

tools mounted in series. For example, a ground-driven rotary spiral-cutter reel followed by a spike-tooth harrow and a drag board or plank. Others are constructed using various combinations of secondary tillage tools. Examples of combination tools available include: (a) disk harrow gangs plus two rows of spring mounted C-shanks with chisel points; (b) disk harrow gangs plus four rows of flexible shanks with shovel sweeps plus spike-tooth harrow or spiral-cutter reel; (c) disk harrow gangs plus three rows of spring-mounted C-shanks with shovel sweeps plus five rows of coil-tine harrow; (d) two rows of spring-mounted C-shanks with shovel sweeps plus spiral-cutter reel plus three bars of spike-tooth drag harrow plus drag board or rolling basket; (e) four rows of spring-mounted C-shanks or coiled-S-tine shanks with chisel point or shovel sweeps plus a three-bar coil-tine drag harrow; and (f) disk gangs plus spring-mounted C-shanks with shovel or chisel sweeps plus a spiral-cutter reel plus three rows of S-tined flexible shanks with chisel or goosefoot sweeps plus two rolling baskets.

Attachments to secondary tillage tools used for herbicide soil incorporation are commonly used. These include the coil-tine harrows, spike-tooth harrow and rolling baskets. The rolling baskets are often called reels, rolling harrows, rolling reels, packer reels and rotary basket crumplers. These are particularly popular on combination tools. L-shaped tines are also vertically stagger-mounted on two or more bars as a drag attachment. These are commonly used in conjunction with the flexible shank (Danish) cultivator.

Table 5 lists what is considered to be the optimum operating parameters for equipment used to soil incorporate herbicides. These parameters were based partially on qualitative and quantitative evaluation studies, herbicide labels and equipment manufacturer instructions. However, the specific manufacturer's operating procedures and labels for the specific herbicide should be consulted.

Table 5. Operating parameters for equipment used to incorporate herbicides into the soil. (Adapted from Barrentine, 1987.)

Equipment	Description of operating parameters
Disk harrow, finishing	Set angle to move soil a distance equal to blade diam., operate 6 to 7 mph to cut 3 to 5 inches; 2 passes perpendicular. Higher ground speeds require less gang angle, lower speeds and a single pass usually results in streaking. Mixing can be improved by attaching a spike-tooth or coil-tine drag harrow.
Disk harrow, combination	Same as finishing disk. Use spherical rather than conical blades.
Field cultivator	Shank spacing with shovel sweeps should leave no soil unturned; set tilt angle so cultivator shanks are all operating at the same soil depth, 3 to 4 inches; operate at 5 to 7 mph 2 passes, preferably perpendicular. Drag harrows attached improves horizontal distribution.
Flexible-shank cultivator (Danish or S-tine)	Same as field cultivator; ground-driven reel attachments slightly improve horizontal distribution and reduce ridging. 'Goosefoot' sweeps are usually used.
Combination tool-Field cultivator shanks + spiral-cutter reel + spike tooth drag harrow	Set all components level with soil. Operate shanks 3 to 5 inches deep at least 5 mph. Shank spacing with shovel sweeps should leave no soil unturned. One pass is usually adequate on coarse or medium textured soils.
Combination tool-spiral—cutter reel + spike-tooth harrow + drag board or ground-driven reel attached	Set all components level with soil. Operate 2 to 4 inches deep at 4 to 6 mph. Work best on coarse and medium textured soils. Under bedded culture strike-off beds to planting height and incorporate with a single pass. Two passes are needed for flat-planting culture.

Table 5. Continued.

Rolling cultivator	Under bedded culture on coarse and medium textured soil. Strike-off beds to planting height. 4-gangs/bed usually suggested. Two, three-tined gangs on the bed top trailed by a four- or five-tine gang on each side of the bed. Set front gangs flat, slightly angled toward the center, and trailing gangs at a 15-20 degree angle to the direction of travel and tilted to match bed slope. On flat-planted land, set all gangs level with soil surface. Space gangs in tandem to work entire soil surface. Operate 2 to 4 inches deep at 5 to 7 mph.
Power-driven (PTO) tiller Horizontal-action Roterra	Operate 3 to 6 inches deep at 4 mph. Set tine rpm at 200 to 400. (See operators manual for specifics.) Direct spray pattern into the rear of the spinning tines. Single pass, but use some primary tillage first. Check for uniform working depth prior to incorporation.
Power-driven (PTO) tiller Vertical-action L-shaped blades	Operate to depth of desired incorporation at 6 mph. Set rotor blade rpm at ca 300 (See operators manual for specifics.) Operate so blade bites overlap but not excessively (blade rpm too fast in relation to forward ground speed). No overlap results in poor incorporation and tillage.

COTTON BELT APPLICATION TECHNIQUES

To provide a valid opinion of application techniques, a state-by-state survey was conducted. Survey forms were sent to state weed scientists, county extension personnel and cotton producers in 13 of the cotton producing states: (a) Alabama, Georgia, South Carolina and North Carolina in the Southeast region; (b) Missouri, Louisiana, Arkansas, Mississippi and Tennessee in the Mid-South region; (c) California and Arizona in the West region; and (d) Texas and Oklahoma in the Southwest region. Texas was divided into four areas: Coastal Bend, South, Plains and Blackland (Figure 28).

One hundred and nine surveys were returned. Although the results varied from state to state and within states, they were of such consistency that producer use of herbicide application types and devices could be determined. Results of the survey are presented on a regional and Cotton Belt basis.

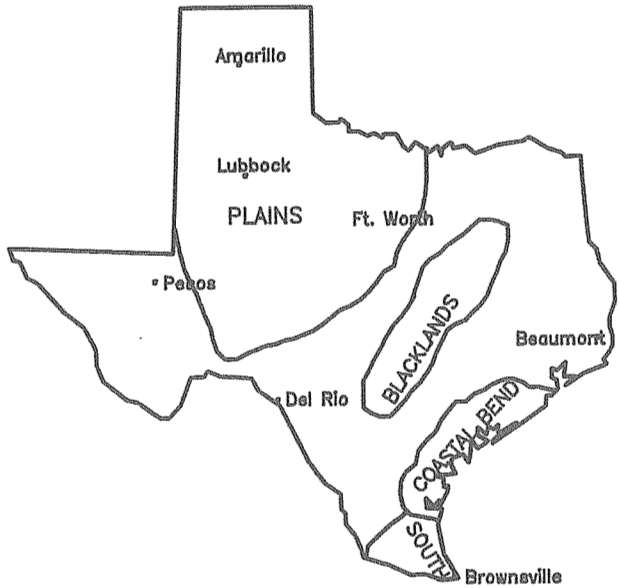


Figure 28. Four major cotton growing areas of Texas (Plains, Blackland, Coastal Bend, and South) used in the opinion poll of application techniques.

SOUTHEAST

Only 2 percent of the acreage in the Southeast receives a preplant foliar (PPF) application, while 97 percent receives some type of preplant incorporated (PPI) material (Table 6). Of the 97 percent that receives PPI applications, only 2 percent is to a band and the remaining 98 percent is broadcast. Approximately 80 percent of these PPI applications are applied with tractor-mounted spray equipment (Table 7). Producers in Alabama apply 30 percent of their PPI herbicides in liquid fertilizer. The remaining portion of PPI applications is applied by air or with high-clearance ground rigs. Incorporation devices vary, but within the region, 71 percent of the incorporation is conducted with four-gang tandem-disk harrows (Table 8) and 14 percent with combination devices. The remaining portion is done with some type of field cultivator or power-driven tiller. Except for minor use in Georgia, Alabama accounts for all the incorporation with combination devices. Power driven tillers are not used often with a 10 percent use-rate being the highest indicated in Georgia and North Carolina.

Preemergence (PRE) treatments are applied to 94 percent of the acreage in the Southeast. Eighty-three percent is to a band and 17 percent is broadcast (Table 6). Producers in Georgia and North Carolina apply a larger portion of their materials broadcast as compared to other states in the region. Nearly the entire acreage (97 percent) is treated with ground equipment (Table 7). A large portion of this (68 percent) is applied with a planter attachment which accounts for band application as the preferred choice.

Table 6. Percentage of cotton acreage treated by various types of herbicide application.

	Southeast					Mid-South						West			Southwest							Cotton Belt
	AL	GA	SC	NC		MO	LA	AR	MS	TN		AZ	CA		TX					OK		
Type of Application					Mean						Mean			Mean	Coastal Bend	South	Blackland	Plains	Mean		Mean	Mean
											(Percent)											
PPF	2	1	2	0	2	1	1	1	3	2	2	2	28	15	1	0	0	15	4	1	3	6
PPI	92	99	100	98	97	95	95	79	98	95	92	89	95	92	94	96	92	81	91	94	93	93
Band	4	1	3	0	2	79	3	12	33	1	26	28	18	23	2	20	0	10	8	5	7	16
Broadcast	94	99	97	100	98	21	97	88	67	99	74	72	82	77	98	80	100	90	92	95	93	84
PRE	98	86	97	95	94	94	98	99	100	99	98	21	0	10	78	22	50	64	54	12	33	47
Band	94	80	93	65	83	94	99	98	99	89	96	100	—[1]	50	82	33	100	80	74	86	80	88
Broadcast	6	20	7	35	17	6	1	2	1	11	4	0	—	0	18	67	0	20	26	14	20	12
POT	46	66	47	20	45	10	26	39	31	75	36	6	30	18	6	10	25	20	15	7	11	23
Band	50	59	78	50	59	39	28	42	18	18	29	42	65	53	30	24	100	31	46	30	38	45
Broadcast	28	34	22	50	34	20	15	20	18	66	28	5	7	6	60	17	0	11	22	32	27	21
Spot	20	7	0	0	7	41	57	38	64	16	43	52	28	40	10	59	0	58	32	38	35	35
PDS	83	58	55	50	62	96	98	95	81	11	76	16	12	14	5	22	10	9	12	3	7	31
Band	90	91	96	100	94	99	100	98	99	91	97	75	90	82	—	67	100	25	64	67	66	82
Broadcast	5	9	4	0	5	1	0	2	1	8	2	25	10	17	—	33	0	75	36	33	34	18
LAYBY	57	35	32	2	32	47	48	52	79	8	47	69	10	39	0	38	5	16	15	3	9	30
Band	9	42	6	0	14	97	20	24	20	0	41	20	58	39	—	100	100	33	78	100	89	51
Broadcast	88	58	93	100	85	3	80	76	80	100	68	80	42	61	—	0	0	67	22	0	11	49

[1]Not indicated.

Table 7. Percentage of specific methods for making preplant incorporated (PPI), preplant foliar (PPF), preemergence (PRE) or postemergence over-the-top (POT) herbicide applications.

	Southeast					Mid-South						West			Southwest							Cotton Belt
	AL	GA	SC	NC		MO	LA	AR	MS	TN		AZ	CA		TX					OK		
Type of Application					Mean						Mean			Mean	Coastal Bend	South	Blackland	Plains	Mean		Mean	Mean
												(Percent)										
PPF + PPI																						
Ground	95	98	100	100	98	99	98	93	97	99	97	91	60	75	94	99	90	95	94	96	95	89
Tractor-mt	63	72	97	85	79	69	98	75	89	92	85	85	95	90	51	59	88	98	74	99	86	85
Hi-clearance	5	13	0	10	7	3	2	21	2	6	7	13	5	9	2	41	12	2	14	1	7	8
Planter	1	12	0	5	5	0	0	4	5	0	2	2	0	1	18	0	0	0	4	1	3	2
Air	5	1	0	0	2	1	2	4	2	1	2	9	40	25	5	1	10	5	5	4	5	10
Other[1]	30	0	3	0	8	29	0	3	5	2	8	0	0	0	26	0	0	0	6	0	3	5
PRE																						
Ground	98	96	93	100	97	99	99	99	99	100	99	85	—[2]	—	96	100	—	97	98	78	88	91
Tractor-mt	18	26	23	20	22	1	54	7	39	6	21	78	—	—	28	56	—	40	41	51	46	43
Hi-clearance	2	16	3	20	10	1	0	13	1	5	4	15	—	—	19	38	—	12	23	12	18	13
Planter	79	58	73	60	68	98	48	80	60	90	75	8	—	—	53	6	—	48	36	36	36	45
Air	2	3	3	0	2	1	1	1	1	0	1	15	—	—	4	0	—	3	2	22	11	8
POT																						
Ground	92	95	96	100	96	91	94	95	90	99	94	99	95	97	73	92	—	94	86	74	80	90
Tractor-mt	40	56	48	55	50	61	38	62	57	53	54	64	62	64	34	70	—	67	57	30	44	53
Hi-clearance	45	40	48	40	43	35	28	28	4	46	28	2	12	7	42	26	—	19	29	10	20	20
Spot	18	3	2	0	6	3	32	4	35	4	16	33	25	28	6	1	—	5	4	42	23	21
RWA	1	1	2	5	2	1	1	6	4	0	2	0	0	0	12	3	—	8	8	15	12	5
Air (Fixed-wing)	8	5	4	0	4	9	6	5	10	1	6	0	5	3	22	8	—	6	14	26	20	9
Other[3]	0	1	0	0	1	0	0	1	0	0	<1	0	0	0	5	0	—	0	2	0	1	1

[1]Flotation applicators along with liquid or dry fertilizer, treatments along with custom application of fertilizer, Hi flotation N-Sol spreaders.

[2]Not indicated.

[3]Rotary wing aircraft.

Table 8. Producer preference for general types of soil incorporation devices when applying preplant incorporated PPI herbicides.

	Southeast					Mid-South						West			Southwest							Cotton Belt
	AL	GA	SC	NC		MO	LA	AR	MS	TN		AZ	CA		TX					OK		
Type of Application					Mean						Mean			Mean	Coastal Bend	South	Blackland	Plains	Mean		Mean	Mean
												(Percent)										
Tandem-disk harrow	33	83	75	93	71	26	38	10	20	20	23	57	46	46	46	49	54	52	55	62	58	51
Field cultivator	6	3	10	3	6	41	54	3	28	13	28	23	10	22	31	22	18	20	5	0	3	14
Flexible shank cultivator	4	4	0	0	2	7	4	3	6	0	4	>1	1	12	0	3	2	2	3	2	3	3
Power driven tiller	2	10	10	3	6	1	0	0	1	0	<1	>1	8	0	0	2	2	2	7	26	16	7
Spike/spring tooth harrow	0	>1	0	0	<1	2	2	16	13	0	7	>1	0	8	0	2	>1	2	3	1	2	3
Ground-driven devices	2	>1	5	0	2	17	0	3	18	>1	8	19	27	2	6	13	25	19	8	5	6	10
Combination devices	53	>1	0	0	14	6	2	63	16	67	31	0	8	11	17	9	0	4	20	5	12	13

Postemergence over-the-top (POT) applications are applied to 45 percent of the acreage in the Southeast (Table 6). Georgia producers reported 66 percent of their acreage receives some type of POT treatment while North Carolina producers reported 20 percent. For the region, 59 percent is applied to a band, 34 percent is applied broadcast and 7 percent as a spot treatment. Of the POT applications applied in the Southeast, 94 percent are applied with ground rigs with less than 5 percent going out by air (Table 7). Fifty percent of the ground applications are applied with tractor-mounted sprayers and 43 percent with high-clearance spray applicators. Only 2 percent of the POT treatments in the Southeast are with rope-wick applicators.

In the Southeast, 62 percent of the acreage is treated with a postemergence-directed spray (PDS) with 94 percent of these applications on a band. North Carolina producers use these treatments the least while Alabama producers use them the most (Table 6).

Layby treatments are applied to 32 percent of the acreage with 85 percent applied broadcast. North Carolina producers utilize layby treatments on less than 5 percent of their acreage while Alabama producers treat nearly 60 percent of their acreage with some type of layby treatment (Table 6).

MID-SOUTH

Very little (<2 percent) of the cotton acreage in the Mid-South region receives a preplant foliar (PPF) application. But, 92 percent of the acreage is treated with a preplant incorporated (PPI) treatment, with 26 percent of these applications applied to a band. Missouri reported that nearly 80 percent of its PPI applications are to a band which accounts for most of the high regional response (Table 6).

Nearly all soil incorporated materials are applied by ground equipment with 85 percent applied with tractor-mounted sprayers (Table 7). Missouri reported that 'Do-Alls' with boom attachments were used nearly 30 percent of the time. The Mid-South region reported a wider variation in general methods of incorporating than did the Southeast (Table 8). The four-gang tandem disk harrow is used 23 percent of the time, while combination devices and field cultivators are used 31 and 28 percent of the time, respectively. Louisiana producers use field cultivators over half the time while Missouri and Tennessee producers prefer combination devices two-thirds of the time. Arkansas and Mississippi producers use ground driven devices (mostly rolling cultivators) nearly 20 percent of the time.

Acreage treated preemergence in the Mid-South and Southeast regions was about equal, but 96 percent of the acreage in the Mid-South was to a band as compared to 83 percent for the Southeast (Table 6). Nearly all the acreage treated PRE was applied with a ground rig, and 75 percent was applied with a planter attachment (Table 7).

Thirty-six percent of the acreage in the Mid-South region receives a POT treatment with producers in Tennessee utilizing this type of application most often (Table 6). More than 40 percent of the acreage treated postemergence over-the-

top (POT) is applied as spot treatments. Ninety-four percent is applied by ground application with tractor-mounted sprayers accounting for over 50 percent of this (Table 7). Sixteen percent use certain types of spot sprayers designed specifically for spot treatment with Louisiana and Mississippi producers the most frequent users.

Post-directed sprays were utilized on 76 percent of the acreage in the Mid-South. Nearly all of this applied to a band with cultivator attachments (Table 6).

Slightly less than 50 percent of the acreage in the Mid-South region received some type of layby application. Nearly 70 percent of the acreage was treated broadcast using slide units or modified cultivators (Table 6).

SOUTHWEST

Due to the diversity of cotton culture, Texas was divided into four areas in order to highlight any contrast of interest within the state. Fifteen percent of the acreage in the Plains area of Texas is treated PPF (Table 6). This rather high percentage is a result of one respondent that produced no-till cotton and required this treatment for seedbed preparation on his entire acreage. This may also account for the somewhat low percentage (81) treated PPI in the Plains. However, more than 90 percent of the cotton acreage in Texas is treated with a PPI material of which 92 percent is broadcast, and, with the exception mentioned above, is quite consistent from area to area. Five percent is applied aerially with the remaining portion applied by ground rig, mainly tractor-mounted sprayers (Table 7). Nearly half of these applications are incorporated with the four-gang tandem disc harrow and slightly more than 20 percent use the field cultivator (Table 8).

In contrast to the Southeast and Delta regions, producers in Texas treat only 54 percent of their acreage with a PRE treatment (Table 6). South Texas producers use this type of application less than 25 percent of the time, while those in the Coastal Bend area utilize it 78 percent of the time. Nearly 75 percent is applied to a band statewide; however, this type of application varies widely within Texas. South Texas producers apply two-thirds of their PRE treatments broadcast and are the only Texas producers to apply a majority of their PRE applications as broadcast treatments. Producers in all other areas of Texas utilize band treatments at least 80 percent of the time.

Nearly all of the preemergence treatments are applied with ground equipment (Table 7). Methods of these applications are fairly evenly distributed between tractor-mounted sprayers, high-clearance ground rigs and planter attachments. However, due to the rather large acreage treated broadcast, very few planter attachments are used in South Texas. The Coastal Bend and Plains producers use this method approximately one-half of the time, while South Texas producers use tractor-mounted sprayers a majority of the time.

Postemergence over-the-top applications are used on only 15 percent of the acreage in Texas with a range of 6 percent in the Coastal Bend area to 25 percent in the Blackland area (Table 6). Eighty-six percent of these applications are ap-

plied with ground rigs, and the remaining portion is applied with fixed- or rotary-wing aircraft (Table 7). About one-third of this acreage receives spot sprays. Nearly 50 percent of the over-the-top applications are to a band.The Coastal Bend area accounts for a large portion of the aerial applications in Texas.

Only 12 percent of the acreage in Texas is treated with a PDS application (Table 6). South Texas producers treat 22 percent of their acreage in this manner—the largest of all areas in Texas. Statewide, the majority of these applications are to a band but this varies for each specific area in Texas. Very little of the acreage in South Texas or the Plains is treated with post-directed sprays.

Fifteen percent of the acreage in Texas receives a layby treatment with a majority of this acreage in South Texas (Table 6). The Coastal Bend area reported no acreage treated with a layby application. The South Texas and Blackland areas reported that 100 percent of these applications are to a band which is in sharp contrast to treatments in the Delta and Southeast.

Farmers in Oklahoma use PPI treatments on 94 percent of their acreage with 95 percent of this applied broadcast (Table 6). Of these PPI applications, 96 percent is by ground rig, with tractor-mounted sprayers used 99 percent of the time (Table 7). Four-gang tandem disk harrows are used to incorporate PPI applications over 50 percent of the time in Oklahoma (Table 8). Field cultivators are used 18 percent of the time, and ground-driven devices 25 percent of the time.

Only 12 percent of the acreage receives a PRE treatment which is mostly (86%) to a band (Table 6). The remaining 14 percent are applied broadcast and 22 percent of these treatments are applied aerially. POT, PDS and layby treatments are used on a very limited amount of acreage in Oklahoma, with less than 8 percent of the acreage treated by any of these methods.

WEST

Of those producers responding from California, 28 percent of their acreage is treated with a PPF treatment, usually to fallow beds during the winter (Table 6). Except for minimum-tillage operations, this was the highest percentage beltwide. Producers in Arizona and California treat more than 90 percent of their acreage with a PPI treatment with less than 25 percent of this to a band.

More than 90 percent of the PPI applications are applied with ground rigs in Arizona, while California producers use aircraft 40 percent of the time (Table 7). Tractor-mounted sprayers are the preference for ground applications in both states.

Four-gang tandem disk harrows are used 55 percent and 62 percent of the time for incorporation in California and Arizona, respectively (Table 7). Arizona producers reported that power-driven tillers were used 26 percent of the time and this was the highest percentage for any of the 13 states. Combination devices are used 20 percent of the time in California.

In Arizona, only 21 percent of the acreage is treated PRE but all applications were to a band. California producers reported no acreage treated in this manner

(Table 6). Ground rigs were utilized 85 percent of the time and aircraft 15 percent of the time to apply PRE treatments in Arizona.

Arizona producers treat only 6 percent of their cotton acreage with a POT treatment (Table 6). California producers use this same type of treatment on 30 percent of their acreage. Sixty-five percent of the acreage treated POT in California is on a band with 28 percent spot-treated. Over 50 percent of the acreage treated POT in Arizona is with spot-treatments. Nearly all of the POT applications in both states are applied with ground rigs with two-thirds of these applied with tractor-mounted sprayers (Table 7).

Sixteen percent of the acreage in Arizona is treated PDS while 12 percent is treated PDS in California (Table 6). The majority of this acreage is treated to a band.

Arizona producers tend to rely on layby applications more than on PDS sprays. Sixty-nine percent of the acreage in Arizona is treated with a layby application while only 10 percent is treated layby in California. Eighty and 42 percent of the acreage treated layby is broadcast applied in Arizona and California, respectively.

COTTON BELT

Procedures and methods of applying herbicides are fairly consistent across the Cotton Belt except for preplant foliar (PPF) treatments. California producers treat 28 percent of their acreage, while the remaining areas treat from 2 to 15 percent. Because of higher than average rainfall and price reductions on the herbicides, paraquat (Gramoxone Extra®) and glyphosate (Roundup®, D-Pak®), the authors estimate that 45 percent of the Mid-South acreage received a PPF treatment in 1990.

On the average, 93 percent of the acreage receives some sort of preplant incorporated (PPI) treatment with 84 percent applied broadcast (Table 5). An average of 89 percent of these applications are applied with ground applicators, primarily tractor-mounted sprayers (Table 7). These Cotton Belt averages are fairly representative of each individual region for PPI applications with only a few exceptions.

Cotton producers use four-gang tandem disk harrows 51 percent of the time (Table 7). Field cultivators, combination devices and ground-driven devices are used in some fashion 10 to 15 percent of the time.

Combination devices are used extensively in certain regions and represent about 13 percent of the total (Table 8). There are numerous types and combinations of these implements. However, the ones mentioned most frequently involve the use of a rotary spiral cutter-reel followed with a spike-tooth harrow. A dragboard or plank was the most common third component of these implements. A fourth component commonly referred to was a field cultivator or flexible-shank cultivator mounted just behind the cutter reel and in front of a spike-tooth harrow.

Power-driven tillers are used in small areas of the Cotton Belt. Producers in Georgia, North Carolina and Arizona were the most frequent users of these implements.

An average of 47 percent of the cotton acreage is treated preemergence (PRE) and nearly 90 percent is to a band (Table 6). Acreage treated PRE varies from 98 percent in the Mid-South to 10 percent in the West. Forty-five percent of the ground PRE applications are with planter attachments (Table 7). This is because most of the acreage is treated on a band basis in a once-over planting-spraying operation.

About one-fourth of the acreage in the Cotton Belt is treated postemergence over-the-top (POT) (Table 5). This low acreage figure is due, in large part, to the lack of selective herbicides. Thus, most of these POT applications are with the selective grass herbicides. Nearly 50 percent of these applications are to a band and 35 percent of the acreage is spot-treated.

Another type of POT treatment for cotton is rope-wick aplicators (RWAs), although only 5 percent of the POT applications are applied with RWAs (Table 7). About 21 percent of all acreage receive spot sprays. The Coastal Bend area in Texas and Oklahoma account for the major portion of the RWA use.

To increase the selectivity of currently available cotton herbicides, producers have turned to post-directed sprays. These applications are mostly to a band on the 31 percent of the acreage treated in this manner (Table 6). The majority of these applications are made in conjunction with mechanical cultivation using shielded cultivators with specialized sprayer attachments designed to treat a 12- to 18-inch band and cultivate the untreated portion of each row. Over half of the acreage treated in this manner is treated two or more times.

Typically, the last herbicide application in cotton is a layby treatment which usually occurs just prior to bloom. Thirty percent of the Cotton Belt acreage is treated with some type of layby treatment with about half of this on a band and half applied broadcast (Table 6). Layby applications are commonly applied with slide units or oiling shoes designed to position one flooding or deflector nozzle or 2 flat-fan nozzles under the crop to control late emerging weeds. These layby herbicides also provide residual control from time of application until harvest. The Mid-South and Southeast producers are the predominant users of layby applications in the Cotton Belt.

FUTURE NEEDS

Weed scientists as a group have long recognized the need for improved application methodology. There are problems with sprayer calibration and with obtaining optimum equipment operation parameters that result in distributing and getting the herbicide to the target at the proper dose and time. In a recent survey of research needs, the WSSA (Weed Science Society of America) membership gave the broadly defined research need; "develop new methods for controlling

the movement of herbicides and their metabolites into ground water, surface water, and air", its highest priority ranking. The membership agreed that this need would most likely be satisfied by expanding research in the area of development of new application techniques (McWhorter and Barrentine, 1988).

The industry in general also recognizes the need for such research. At a 1984 Agricultural Research Institute Conference, the need for a conference on pesticide application technology emerged as a predominant conclusion (Hall, 1985). Such a conference followed in 1985 and the specific needs identified were: (a) new and improved agricultural chemical application technology with an emphasis on basic concepts and (b) movement of chemicals from target sites in drift through aerial transport, water transport and other mechanisms. The major conclusions of the attendees at this conference were: (a) critical lack of interdisciplinary research in agrochemical application technology; (b) application technology research has a low priority for funding in spite of public concern of environmental contamination and the need for precision application; (c) application technology is not keeping pace with chemical technological advancements; and (d) innovative technology and engineering concepts from other sciences and industries are not being adapted.

Cotton producers' needs are obviously the ultimate objective of research. Thus, their opinions are sought by most all weed scientists involved in application technology. The most often voiced need in cotton weed control is a selective over-the-top herbicide for broadleaf weeds, particularly the morningglory complex. Without such a herbicide at present, application technology looms as the greatest need. At a recent meeting of Mid-South cotton producers with federal, state, and private research representatives, panel Chairman, Robroy Fisher of Glen Allan, Mississippi, said "We're using the same chemical application technology used 30 years ago". He further commented that "we need technology that's sensitive to the interaction of the chemical and the way its applied—something that will help us cut down on chemical use, but give us more effective control" (Gordon, 1987). It is still not uncommon to use hand-hoeing to rid cotton fields of weeds for which there are no selective herbicides or other effective means of control (Figure 29).

Reduced spray volume and diluents other than water need to be evaluated in cotton weed management systems. In soybeans, application of the selective grass herbicides in paraffinic oil or once-refined soybean oil at one gallon per acre effectively controlled seedling johnsongrass at reduced rates (Barrentine and McWhorter, 1988). Would oil-soluble or miscible formulations of currently available herbicides applied as directed postemergence (PDS) for broadleaf weed control respond similarly? Would such herbicide treatments applied at ULVs in oil increase control of the morningglory complex without significantly increasing cotton injury? If so, research to develop a practical and economical ground applicator for such treatments would be invaluable.

Rotary atomizers have provided a means of producing droplets of a more uni-



Figure 29. Hand-hoeing weeds in cotton for which there are no selective herbicides or other effective control techniques. (Marks, Mississippi, July 1987.)

form size, but the major deficiency resulting in inconsistent weed control has been coverage (Gebhart and Kapusta, 1987). Models have been developed to supplement droplet distribution with an air source, but their performance evaluation is limited. Such evaluations require large plots which few researchers have, but they are needed.

Based on the research of Haugen and Ganrud (1983b) and Dale (1987), efforts on evaluation of concentrated dry formulations of herbicides should be expanded. Performance has been equivalent to liquid sprays, and the concept offers a means of avoiding spray drift and possibly reducing surface and groundwater contamination.

Until such time that more effective and selective herbicides are developed, extension educational efforts should be increased to more effectively utilize current practices. Calibration clinics are needed to stress the need for accurate calibration and proper equipment operating parameters under field conditions. A survey testing of over 100 farm sprayers in North Dakota found that 60 percent were operated with a calibration error greater than 10 percent (Hoffman *et al.*, 1986). Forty-three percent of the sprayers were equipped with nozzle tips which varied more than 10 percent from the proper discharge volume. Travel speeds were inaccurate in 32 percent of the sprayers and 27 percent were operated at an improper boom height for the nozzle spacing and recommended spray height to

provide optimum spray pattern overlap. Pressure gauge reading indicated that most application pressures were too low, and 13 percent were inaccurate.

Finally, research efforts should be expanded to include the direct-injection-closed system sprayers now coming on the market. Spray equipment distributors indicate that there is little or no demand for these sprayers at present.[9] What effect the emerging good laboratory practices, endangered species and ground water regulations will have on this demand is yet to come.

SUMMARY

Liquid sprays are the major method of applying herbicides in cotton weed management systems, with the hydraulic pressure atomizing nozzles the primary means of metering and dispersing the spray. Rotary atomizers are not used to any extent in cotton primarily because of a lack of selective herbicides to control broadleaf weeds and inadequate coverage which results in poor control of target weeds (Gebhart and Kapusta, 1987). A selective herbicide to control broadleaf weeds is required before use of air-assist nozzles and chemigation methods for delivering herbicides to the target can be expanded. The effects of chemigation on potential groundwater contamination must also be accessed. Only metolachlor (Dual®) is currently registered in cotton for use with sprinkler irrigation. Expansion in use of granular cotton herbicides will require efficacy and economic evaluations. Recent research in this area indicates there may be a place for the application of concentrated dry formulations. Such formulations will reduce the need for large hoppers and/or frequent refilling. The greatest need is increased research with adequate funding to develop new application techniques.

Procedures and time of applying herbicides–preplanting, preemergence and postemergence–are fairly consistent across the Cotton Belt. Ninety-three percent of the acreage is treated preplant incorporated and 47 percent is treated preemergence. The most frequently used implement for soil incorporation is the four-gang tandem-disk harrow. In certain regions, combination incorporation devices are popular and are used 13 percent of the time. Ninety percent of the acreage treated preemergence is on a band. The acreage treated preemergence varied from 95 percent in the Mid-South to 10 percent in the West. Lack of selective herbicides accounts for the low (<25 percent) percentage of the acreage treated postemergence over-the-top. Contact application (rope wick) is used on only 5 percent of the acreage with the Southwest Plains area accounting for most usage. However, 21 percent of the cotton acreage receive spot sprays. Layby applications are more commonly used in the Mid-South and Southeast regions.

[9]Private communication. R. A. Norris, Vice-President, S & N Sprayer Co., Inc., Greenwood, MS.

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Chapter 12

APPENDIX

CALIBRATION OF LOW-PRESSURE HYDRAULIC SPRAYERS

Low-pressure sprayers equipped with hydraulic pressure nozzles are the primary means of metering and dispersing herbicide spray solutions to the target in cotton weed management programs. Proper sprayer calibration and calculation of the herbicide-water spray mix are the two most important aspects of delivering the herbicide spray solution to the target at the correct dose. Presented below are calibration methods, with examples, that will insure accurate sprayer calibration and herbicide-water spray mix determination. The first method is a commonly used, easy and practical method of calibrating low-pressure sprayers, and this is followed by methods utilizing mathmatical formulas which can be used in widely varying situations.

128th METHOD

There are several methods of calibration, but one commonly used calibration procedure is the 128th method. This procedure is based on the fact that there are 128 ounces in one gallon and the number of ounces applied to 1/128 acre equals gallons per acre. The steps in using this method, adapted from Anonymous (1988) and Baldwin *et al.* (1988), with examples, are presented below. Spray volumes determined with this method are always gallons per land acre, regardless of whether the application is broadcast over the field or to a specified band width on rows of a specified spacing.

Step 1. From Table 1, determine the calibration distance in relation to the row or nozzle spacing for the sprayer and application situation. For broadcast applications such as preplant soil incorporation with a pulverizing disk or field cultivator, use nozzle spacing. If application is to a band surface preemergence behind the planter press wheel or a directed postemergence spray application, use row spacing. Mark off this distance in the actual field to be sprayed.

Step 2. With the application tool attached (field cultivator, directed spray rig, etc.), select the desired operating gear and throttle setting, and perform the operation down and back over the marked out calibration distance and note the time in seconds required for each pass. Two or more runs are suggested from which the average time in seconds is calculated.

Table 1. Travel distance in feet required to spray 1/128 acre at a given row or nozzle spacing in inches.

Row or nozzle spacing	Calibration distance
(inches)	(feet)
40	102
38	107
36	113
34	120
32	127
30	136
28	146
26	157
24	170
22	185
20	204
18	227
16	255
14	292
12	340
10	408

Step 3. Using the same throttle setting of Step 2, turn on the sprayer and adjust and note spray pressure. If using a broadcast boom with nozzles evenly spaced, catch the spray output from one nozzle for the time measured in Step 2 in a container graduated in ounces. Ounces caught from one nozzle is equal to gallons per acre. When row spacing was used in Step 1 and more than one nozzle per row is used, such as a directed spray application, catch the output from each nozzle for the time noted in Step 2, and combine the spray output of all nozzles spraying on a single row. Combined output in ounces from all nozzles per row equals gallons per acre.

Step 4. Check the output from each nozzle across the broadcast boom or the combined output from all nozzles spraying on each single row to assure equal spray output across the width of the spray boom or for each row of the sprayer, by repeating Step 3. Change-out and recheck any nozzle tip which varies more than 10 percent from the desired output. More than 10 percent variation indicates excessive nozzle wear which affects output and(or) spray pattern distribution. Adjust boom or nozzle height, position, etc. according to the type of application, and check the quantity remaining in the spray tank after spraying 1 to 3 acres to verify that the intended spray application rate (gallons per acre) is being applied.

Example 1—Apply a 4-pound-per-gallon emulsified concentrate of Treflan® at 0.75 pound active ingredient per acre (1.5 pints per acre) using a broadcast boom,

with tapered flat-fan nozzles spaced 20 inches apart, mounted underneath the front tractor frame (belly-mounted). A four-gang pulverizing tandem disk harrow set to cut 4-inches deep will be used for incorporation. The tractor-sprayer is equipped with two, 200-gallon saddle tanks.

A. Calibration:

Step 1. From Table 1, the distance to travel for 20-inch nozzle spacing is 204 feet. Measure off this distance in the field to be sprayed.

Step 2. Select the desired operating gear, throttle setting and cutting depth of the disk harrow and operate the disk down and back over the 204-foot course, recording the time in seconds for each pass. Assume it required an average of 25 seconds.

Step 3. Set the throttle at the setting used in Step 2 and adjust and note spray pressure. Catch the output from one nozzle for 25 seconds. Output in ounces equals gallons per acre. Assume 15 ounces were caught in 25 seconds, then the sprayer is applying 15 gallons per acre.

Step 4. Repeat for each nozzle and check for uniformity between nozzles, replacing tips varying more than 10 percent. Adjust boom height for proper spray overlap, and verify application rate is 15 gallons per acre.

B. Tank mix calculation:

Acres per 200-gallon tank.

$$\frac{\text{200 gallons per tank}}{\text{15 gallons per acre}} = \text{13.3 acres per tank or 26.6 acres per 400 gallons}$$

The desired rate of Treflan® per acre was 1.5 pints, thus 13.3 acres x 1.5 pints per acre = 20 pints per 200-gallon tank or 40 pints per 400 gallons.

NOTE: When refilling, mix only the amount of solution required to refill the tanks, not for the total tank capacities. If, for example, there were 50 gallons of solution remaining in each tank, mix 300 gallons refill per 15 gallons per acre = 20 acres per refill = 30 pints Treflan® or 15 pints per tank.

Example 2—Apply a tank mix of Bladex® 90 DF plus Zorial® 80 DF at 0.9 + 1.0 pound active ingredient per acre (1.0 + 1.25 pounds product per acre) to a 16-inch band on 40-inch rows surface preemergence behind the planter. A single flat-fan even spray drop-nozzle is planter-mounted behind each press wheel. The tractor-sprayer is equipped with two, 200-gallon saddle tanks.

A. Calibration:

Step 1. From Table 1 the distance to travel for 40-inch row spacing is 102 feet. Measure off this distance in the field to be sprayed.

Step 2. Select the desired operating gear, throttle setting and, with the planter mounted and set to proper planting depth, operate the tractor-planter down and back over the 102-foot course, recording the time in seconds for each pass. Assume it required an average of 15 seconds.

Step 3. Set the throttle at the setting used in Step 2 and adjust and note spray pressure. Catch the output from the nozzle of one row for 15 seconds. Output in ounces equals gallons per acre. Assume 8 ounces were caught in 15 seconds, then the sprayer is applying 8 gallons per acre.

Step 4. Repeat for each nozzle and check for uniformity between nozzles for each row, replacing tips varying more than 10 percent. Adjust nozzle height to spray a 16-inch band. Verify application rate is 8 gallons per acre.

B. Tank mix calculation:

Reduce the broadcast rates to a 16-inch band:

16-inch band ÷ 40-inch row = 0.4 x 1.0 pound Bladex® 90DF = 0.4 pound; and 0.4 x 1.25 pound Zorial® 80DF = 0.5 pound per acre on a 16-inch band.

$$\frac{\text{200 gallons per tank}}{\text{8 gallons per acre}} = \text{25 acres per tank or 50 acres per 400 gallons}$$

25 acres x 0.4 pound Bladex® 90DF = 10 pounds per 200-gallon tank, and 25 acres x 0.5 pound Zorial® 80DF = 12.5 pounds per 200-gallon tank or 20 pounds Bladex® 90DF and 25 pounds Zorial® 80DF per 400 gallons. See **NOTE** for **Example 1** on refills.

Example 3—Apply a 4-pound-per-gallon flowable formulation of fluometuron (Cotoran® 4L) plus nonionic surfactant at 0.4 pound active ingredient per acre (0.8 pint product per acre) plus 0.25 percent volume per volume to a 14-inch band on 38-inch rows as a postemergence directed spray using two tapered flat-fan nozzles per row. Nozzles are mounted on the rear of a shielded cultivator to spray a down-and-back pattern to each row. Tractor-sprayer is equipped with two, 200-gallon saddle tanks.

A. Calibration:

Step 1. From Table 1 the distance to travel for 38-inch row spacing is 107 feet. Measure off this distance in the field to be sprayed.

Step 2. Select the desired operating gear, throttle setting, and operate the directed spray-equipped cultivator down and back over the 107-foot course, recording the time in seconds for each pass. Assume it required an average of 18 seconds.

Step 3. Set the throttle at the setting used in Step 2 and adjust and note spray pressure. Catch the output from both nozzles of one row for 18 seconds. The

output from both nozzles in ounces equals gallons per acre. Assume a total of 10 ounces were caught in 18 seconds, then the sprayer is applying 10 gallons per acre.

Step 4. Repeat for each nozzle of each row and check for uniformity between nozzles for each row, replacing tips varying more than 10 percent. Adjust both nozzles for each row to spray a 14-inch band with 25 to 30 percent spray pattern overlap between the two nozzles centered over the drill. Verify application rate is 10 gallons per acre.

B. Tank mix calculation:

Reduce the broadcast rate to a 14-inch band:

14-inch band ÷ 38-inch row = 0.368 x 0.8 pint Cotoran® 4L = 0.3 pint per acre for a 14-inch band.

$$\frac{\text{200 gallons per tank}}{\text{10 gallons per acre}} = \text{20 acres per tank or 40 acres per 400 gallons}$$

20 acres x 0.3 pint Cotoran® 4L = 6 pints per 200-gallon tank. Total per 400 gallons mix = 12 pints. Add 0.25 percent nonionic surfactant per 200-gallon tank = 0.0025 x 200 = 0.5 gallon (4 pints). Total per 400 gallon mix = 1 gallon (8 pints). See **NOTE** for **Example 1** on refills, which would also apply to the surfactant.

Often times in calibration, the first selected nozzle tip size may not provide the desired output. Assume that in **Example 1**, the sprayer was equipped with 80015 flat-fan tips, the pressure was 32 pounds per square inch and 7 ounces per nozzle were collected in 25 seconds, or about half that desired. Doubling the spray pressure will not double the flow rate. To double the flow through the nozzle, the pressure must be increased four fold, or in this case to 128 pounds per square inch. Such a high pressure would be unacceptable as would doubling the ground speed; so, the obvious solution is to double the nozzle tip size (rated flow). The desired 15 ounces in 25 seconds should result from 8003 tips with a slight pressure adjustment. Changing spray pressure should only be used to make minor adjustments in flow rate.

Tip size is stamped on the nozzle tip, and has been made easy to understand. Spraying Systems Company utilizes a four to six digit number stamped on the tip. Reading from left to right, the first two or three numbers are the tip spray pattern angle: 60, 73, 80, 95, 110. The remaining numbers are the flow rate in gallons per minute. For example, a nozzle tip marked 8002 indicates that the tip is a tapered flat-fan rated to deliver 0.2 (02) gallons per minute at a spray angle of 80 degrees (80). For tips designed to produce an even spray distribution pattern (such as used in **Example 2**), the four to six digits are followed by the letter E. An alpha numeric code is used by Delavan Corporation. A tip marked LF2-80 indicates a tapered flat-fan tip (LF) rated to deliver 0.2 gallons per minute (2) at a

spray angle of 80 degrees (80). Even spray flat-fan tips are marked with the alpha code E in lieu of the F. The number sequence and meaning remain the same. Refer to the manufacturer's catalogs for codes of other types of nozzle tips.

The gallons per minute ratings for flat-fan tips are usually based on a standard pressure of 40 pounds per square inch. Exceptions are the low pressure tips which are rated at 15 pounds per square inch. Spray pattern angle, thus effective sprayed swath width, will decrease as pressure is reduced below the standard rated pressure.

In situations where the solution is not as obvious as doubling the nozzle size (as stamped on the tip in gallons per minute), the following procedure will permit calculation of the nozzle tip size needed when using the 128th method:

$$\text{Nozzle size in gallons per minute desired} = \frac{0.46875 \text{ (a constant)}}{\text{travel time in seconds}} \text{ x gallons per acre}$$

Therefore, in **Example 2**:

$$\frac{0.46875}{15 \text{ seconds}} \text{ x 8 gallons per acre} = 0.25 \text{ gallons per minute}$$

This is nearest to 0.3 gallons per minute. Thus, 8003E or LE3-80 even spray nozzle tips are needed. In situations where there is more than one nozzle per row as in **Example 3**, divide the result by the number of nozzles per row. From **Example 3:**

$$\frac{0.46875}{18 \text{ seconds}} \text{ x 10 gallons per acre} = 0.26 \text{ gallons per minute from two nozzles}$$

0.26 gallons per minute from two nozzles per row = 0.13 gallons per minute per nozzle which is nearest to 0.15 gallons per minute. Thus, two 80015 or LF1.5-80 tips per row are needed.

FORMULA METHODS

No single method of calibration is best for everyone, and the methods described below use mathematical equations or formulas. A knowledge of nozzle types and sizes and the recommended operating pressure ranges for each type of nozzle and desired spray volume per treated acre is required. The first method described calculates nozzle flow rate (nozzle tip size) in gallons per minute which is then converted to ounces per minute for calibration. The second calibration method results in the number of seconds required to catch a quart of spray solution, which is then used to calculate nozzle tip size (gallons per minute). Except for rounding errors, these two methods result in the same answers.

The formula methods are suitable for calibrating broadcast boom, band, direct spray rigs or row crop spray applications. Application rate (spray volume) is

always gallons per treated acre, and there is no need to know what the application rate is to a band. Tank mix calculation also does not require reducing herbicide rates to a band basis. However, calculations are needed to determine land acres covered per tank mix capacity if desired.

Rate of application in gallons per treated acre is affected by the sprayer ground speed (miles per hour), nozzle output or flow rate (nozzle tip size, gallons per minute) and effective spray width of the nozzle (nozzle spacing or band width in inches).

Equations Needed:

Ground speed is a common variable in the equations needed to calculate nozzle tip flow rate and gallons per acre spray volume. Speedometers or tachometers are usually not an accurate measure of speed. Errors of 20 to 30 percent in speedometer reading can result from wheel slippage. However, there are kits available that do not use drive wheels for speed measurements.

Ground speed can be calculated from **Equation [1]:**

$$\text{miles per hour} = \frac{\text{course distance in feet x 3600 seconds per hour}}{\text{course time in seconds x 5280 feet per mile}} \qquad [1]$$

In laying out a field course to determine travel time, suggested distances are 100 feet for speeds up to 5 miles per hour, 200 feet for speeds from 5 to 8 miles per hour, and 300 feet for speeds greater than 8 miles per hour. Table 2 lists the travel time in seconds required to traverse courses of 100, 200 and 300 feet at speeds from 3 to 9 miles per hour.

Ground speed may also be calculated based on the fact that 1 mile per hour = 88 feet per minute. Time the sprayer over the field course for one minute and measure the distance traveled in feet and divide by 88 to give miles per hour:

$$\text{miles per hour} = \frac{\text{travel distance in feet per minute}}{\text{88 feet per minute}}$$

Another variable affecting the rate of spray applied per acre is nozzle tip flow rate or output (gallons per minute) and is used to indicate nozzle tip size. As discussed above, flow rate varies with the size of the tip and pressure. To minimize drift hazard, keep the operating pressure within the recommended range for each nozzle tip type.

Nozzle output or flow rate is calculated from **Equation [2]:**

$$\text{gallons per minute} = \frac{\text{gallons per acre x miles per hour x W*}}{\text{5940 (a constant)}} \qquad [2]$$

*For broadcast spraying W = nozzle spacing in inches

*For band spraying W = band width in inches

*For directed sprays or row crop applications

$$W = \frac{\text{row spacing or band width}}{\text{number of nozzles per row or band}}$$

Table 2. Ground speed determination. (Adapted from Spraying Systems Company, 1988.)

	Time in seconds required to travel a distance of:		
Ground speed	100 feet	200 feet	300 feet
(miles per hour)		(seconds)	
3.0	23	45	68
3.5	20	39	58
4.0	17	34	51
4.5	15	30	45
5.0	14	27	41
5.5	—	25	38
6.0	—	23	34
6.5	—	21	31
7.0	—	19	29
7.5	—	18	27
8.0	—	17	26
9.0	—	15	23

Equation [3] is to convert gallons per minute to ounces per minute:

$$\text{gallons per minute} \times 128 \text{ ounces per gallon} = \text{ounces per minute.} \quad [3]$$

The seconds per quart method utilizes **Equation [4]** to calculate the number of seconds required to catch a quart (32 ounces) of spray solution from one nozzle.

$$\text{seconds per quart} = \frac{89{,}100 \text{ (a constant)}}{W^* \times \text{miles per hour} \times \text{gallons per acre}} \quad [4]$$

This method, however does require the use of **Equation [5]** to calculate nozzle tip size (gallons per minute) unless the nozzle tip size is already known.

$$\text{gallons per minute} = \frac{15 \text{ (a constant)}}{\text{seconds per quart}} \quad [5]$$

Manufacturer's catalogs often list ounces per minute along with gallons per minute, and they can be used once the flow rate in gallons per minute is calculated.

Gallons per treated acre when using the gallons per minute method is calculated from **Equation [6]**:

$$\text{gallons per acre} = \frac{\text{gallons per minute} \times 5940 \text{ (a constant)}}{W^* \times \text{miles per hour}} \quad [6]$$

To calculate spray volume per treated acre (gallons per acre) with the seconds per quart method use **Equation [7]**:

$$\text{gallons per acre} = \frac{89{,}100 \text{ (a constant)}}{\text{W* x miles per hour x seconds per quart}} \quad [7]$$

Spray volume (gallons per acre) from **Equations [6]** and **[7]** is always gallons per treated acre when spraying broadcast or to a band. If the spray volume in gallons per land acre applied to a band of known width on rows of known spacing is desired, use **Equation [8]**:

$$\text{gallons per land acre} = \frac{\text{band width (inches)}}{\text{row spacing (inches)}} \text{ x gallons per treated acre} \quad [8]$$

To calculate spray volume per treated acre when the spray volume on a band is known, use **Equation [9]**:

$$\text{gallons per treated acre} = \frac{\text{gallons per acre on band}}{\text{band width} \div \text{row spacing}} \quad [9]$$

Equation [10] is needed to calculate the land acres covered by the spray operation when applications are to a band.

$$\text{acres covered} = \frac{\text{row spacing}}{\text{band width}} \text{ x } \frac{\text{tank(s) capacity (gallons)}}{\text{gallons per treated acre}} \quad [10]$$

The three examples in the 128th method above are used to demonstrate calibration using the formula methods.

GALLONS PER MINUTE METHOD.

Example 1.

A. Calibration

Step 1. Calculation of ground speed. It was assumed that it required an average of 25 seconds to traverse the 204-foot course with the disk-harrow. From **Equation [1]** the speed is calculated to be 5.6 miles per hour:

$$\frac{204 \text{ feet x } 3600 \text{ seconds per hour}}{25 \text{ seconds x } 5280 \text{ feet per mile}} = 734{,}400 \div 132{,}000 = 5.6$$

Step 2. The spray application rate per treated acre was 15 gallons per acre, and nozzle spacing was 20 inches; thus, the nozzle flow rate is calculated to be about 0.3 gallons per minute from **Equation [2]:**

$$\frac{15 \text{ gallons per acre x } 5.6 \text{ miles per hour x } 20 \text{ inches}}{5940} = 1680 \div 5940 = 0.283$$

As a check, calculate application rate (gallons per acre) using **Equation [6].**

$$\frac{0.283 \text{ gallons per minute x } 5940}{20 \text{ inches x } 5.6 \text{ miles per hour}} = 1681 \div 112 = 15$$

Step 3. Convert gallons per minute to ounces per minute using **Equation [3]** to give: 0.283 gallons per minute x 128 ounces per gallon = 36 ounces per minute.

Step 4. Install 8003 or LF3-80 tapered flat-fan tips in the boom, set throttle to that used in determining travel speed, and adjust pressure to 40 pounds per square inch. Catch the output from one nozzle for one minute. Adjust pressure to result in a flow rate of 36 ounces per minute. Check remaining nozzles for consistency in output.

B. Tank mix calculation. Same as **Example 1** of the 128th method.

Example 2.

A. Calibration

Step 1. Calculation of ground speed. It was assumed that it required an average of 15 seconds to traverse the 102-foot-course with the planter attached. From **Equation [1]** the speed is calculated to be 4.6 miles per hour:

$$\frac{102 \text{ feet x } 3600 \text{ seconds per hour}}{15 \text{ seconds x } 5280 \text{ feet per mile}} = 367{,}200 \div 79{,}200 = 4.6$$

Step 2. The desired spray application rate was 8 gallons on a 16-inch band (W) or, from **Equation [9]**, $8 \div (16 \div 40) = 20$ gallons per treated acre using one nozzle per row; thus, flow rate in gallons per minute is calculated to be 0.248 gallons per minute (**Equation [2]**) which is nearest to 0.3 gallons per minute.

$$\frac{20 \text{ gallons per acre x } 4.6 \text{ miles per hour x } 16\text{-inch band}}{5940} = 1472 \div 5940 = 0.248$$

As a check, calculate application rate (gallons per acre) using **Equation [6]**.

$$\frac{0.248 \text{ gallons per minute x } 5940}{16\text{-inch band x } 4.6 \text{ miles per hour}} = 1473 \div 74 = 20$$

Step 3. Convert gallons per minute to ounces per minute using **Equation [3]** to give: 0.248 gallons per minute x 128 ounces per gallon = 32 ounces per minute.

Step 4. Install 8003E or LE3-80 even spray flat-fan tips in each nozzle, set throttle to that used in determining travel speed, and adjust pressure to 40 pounds per square inch. Catch the output from one nozzle for one minute. Adjust pressure to result in a flow rate of 32 ounces per minute. Adjust nozzle height for an effective sprayed swath of 16 inches. Repeat for each nozzle checking for consistency in output.

B. Tank mix calculation.

$$\frac{\text{200 gallons per tank}}{\text{20 gallons per acre}} = \text{10 acres per tank or 20 acres per 400 gallons}$$

10 x 1.0 pounds Bladex® 90DF = 10 pounds per 200-gallon tank and 10 x 1.25 pounds Zorial® 80DF = 12.5 pounds per 200-gallon tank. Total per 400 gallons mix = 20 pounds Bladex® 90DF and 25 pounds Zorial® 80DF. See **NOTE** on refills.

Land acres covered per 400 gallons of mix is 50, as calculated from **Equation [10]**:

$$\text{acres covered} = \frac{\text{40-inch rows}}{\text{16-inch band}} \times \frac{\text{400 gallons}}{\text{20 gallons per acre}} = 50$$

Example 3.

A. Calibration

Step 1. Calculation of ground speed. It was assumed that it required an average of 18 seconds to traverse the 107-foot course with the cultivator attached. From **Equation [1]** the speed is calculated to be 4.1 miles per hour:

$$\frac{\text{107 feet x 3600 seconds per hour}}{\text{18 seconds x 5280 feet per mile}} = 385{,}200 \div 95{,}040 = 4.1$$

Step 2. The desired spray application rate was 10 gallons on a 14-inch band or, from **Equation [9]**, 10 ÷ (14 ÷ 38) = 27 gallons per treated acre using two nozzles per row; thus, flow rate in gallons per minute per nozzle is calculated to be 0.13 gallons per minute per nozzle (**Equation [2]** where W = band width number of nozzles per row) which is nearest to 0.15 gallons per minute per nozzle.

$$\frac{\text{27 gallons per acre x 4.1 miles per hour x (14-inch band} \div \text{2 nozzles)}}{5940} = 775 \div 5940 = 0.13$$

As a check, calculate application rate (gallons per acre) using **Equation [6]**.

$$\frac{\text{0.13 gallons per minute x 5940 gallons per acre}}{\text{(14-inch band} \div \text{2 nozzles) x 4.1 miles per hour}} = 772 \div 28.7 = 27$$

Step 3. Convert gallons per minute to ounces per minute with **Equation [3]** to give: 0.13 gallons per minute x 128 ounces per gallon = 17 ounces per minute per nozzle.

Step 4. Install 80015 or LF1.5-80 tapered flat-fan tips in each nozzle, set throttle to that used in determining travel speed, and adjust pressure to 40 pounds per

square inch. Catch the output from one nozzle for one minute. Adjust pressure to result in a flow rate of 17 ounces per nozzle. Adjust both nozzles of each row for an effective sprayed swath of 14 inches with 25 to 30 percent overlap centered over the drill. Repeat for each row checking for consistency in nozzle output.

B. Tank mix calculation

$$\frac{\text{200 gallons per tank}}{\text{27 gallons per acre}} = \text{7.4 acres per tank or 14.8 acres per 400 gallons}$$

7.4 acres x 0.8 pint Cotoran® 4L = 6 pints per 200-gallon tank. Total per 400 gallons mix = 12 pints. Add 0.25 percent = 0.0025 x 200 gallons = 0.5 gallon (4 pints) nonionic surfactant per 200-gallon tank. Total per 400 gallons = 1 gallon. See **NOTE** on refills.

Land acres covered per 400 gallons of mix is 40, as calculated from **Equation [10]**:

$$\text{acres covered} = \frac{\text{38-inch rows}}{\text{14-inch band}} \times \frac{\text{400 gallons}}{\text{27 gal per acre}} = 40$$

SECONDS PER QUART METHOD.

This method is often preferred because seconds to catch a quart of spray solution precludes the need to convert gallons per minute to ounces per minute before catching the nozzle output. **Equation [4]** is used to calculate the number of seconds to catch a quart.

Example 1.

A. Calibration

Step 1. Same as **Example 1** for the gallon per minute method.

Step 2. The spray application rate per treated acre was 15 gallons, and nozzle spacing (W) was 20-inches; thus, the seconds to catch a quart equals 53 from **Equation [4]**.

$$\text{Seconds per quart} = \frac{89{,}100}{\text{20 inches x 5.6 miles per hour x 15 gallons per acre}} = 53$$

Step 3. Calculate nozzle tip size (gallons per minute) from **Equation [5]**

$$\frac{15}{\text{53 seconds per quart}} = 0.283 \text{ (nearest to 0.3 gallons per minute per tip)}$$

Step 4. Install 8003 or LF3-80 tapered flat-fan tips in the boom, set throttle to that used in determining travel speed, and adjust pressure to 40 pound per square inch. Catch the output from one nozzle for 53 seconds. If not 1 quart, adjust

pressure to result in a flow rate of 1 quart (32 ounces) per 53 seconds. Check remaining nozzles for consistency in output.

B. Tank mix calculation. Same as for **Example 1** for the gallon per minute method.

Example 2.

A. Calibration

Step 1. Same as **Example 2** for the gallon per minute method.

Step 2. The desired spray application rate was 8 gallons on a 16-inch band (W) or, from **Equation [9]**, 8 ÷ (16 ÷ 40) = 20 gallons per treated acre using one nozzle per row; thus, the seconds to catch a quart equals 61 from **Equation [4]**.

$$\frac{89{,}100}{16 \text{ inches} \times 4.6 \text{ miles per hour} \times 20 \text{ gallons per acre}} = 61$$

Step 3. Calculate nozzle tip size (gallons per minute) from **Equation [5]**

$$\frac{15}{61 \text{ seconds per quart}} = 0.246 \text{ (nearest 0.3 gallons per minute per tip)}$$

Step 4. Install 8003E or LE3-80 even spray flat-fan tips in each nozzle, set throttle to that used in determining travel speed, and adjust pressure to 40 pounds per square inch. Catch the output from one nozzle for 61 seconds. If not 1 quart, adjust pressure to result in a flow rate of 1 quart (32 ounces) per second. Adjust nozzle height for an effective sprayed swath of 16 inches. Repeat for each nozzle checking for consistency in output.

B. Tank mix calculation. Same as **Example 2** for the gallons per minute method.

Example 3.

A. Calibration

Step 1. Same as **Example 3** for the gallon per minute method.

Step 2. The desired spray application rate was 10 gallons on a 14-inch band or, from **Equation [9]**, 10 ÷ (14 ÷ 38) = 27 gallons per treated acre using two nozzles per row; thus, the seconds to catch a quart equals 115 from **Equation [4]** where W = band width ÷ number of nozzles per row.

$$\frac{89{,}100}{(14 \text{ inches} \div 2 \text{ nozzles}) \times 4.1 \text{ miles per hour} \times 27 \text{ gallons per acre}} = 115$$

Step 3. Calculate nozzle tip size (gallons per minute) from **Equation [5]**

$$\frac{15}{115 \text{ seconds per quart}} = 0.13 \text{ (nearest to 0.15 gallons per minute per tip)}$$

Step 4. Install 80015 or LF1.5-80 tapered flat-fan tips in each nozzle, set throttle to that used in determining travel speed, and adjust pressure to 40 pounds per square inch. Catch the output from one nozzle for 115 seconds. If not 1 quart, adjust pressure to result in a flow rate of 1 quart (32 ounces) per 115 seconds. Adjust both nozzles of each row for an effective sprayed swath of 14 inches with 25 to 30 percent overlap centered on the drill. Repeat for each row checking for consistency in nozzle output.

B. Tank mix calculation. Same as **Example 3** for the gallons per minute method.

Chapter 13

EFFECT OF HERBICIDES ON GROWTH OF COTTON AND ASSOCIATED CROPS

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INTRODUCTION

Herbicides are an essential part of cotton culture in the United States where labor is relatively expensive. This may not be the case in parts of the world where labor is abundant and relatively inexpensive. For the most part, herbicides used in accordance with state recommendations and labeling do not adversely affect cotton growth or production. However, with improper use such as overdose or uneven application or adverse weather which slows crop growth, herbicides may cause crop injury. A combination of the above circumstances can destroy a crop. Herbicide residues in soil from previous crops, and drift of non-target herbicides also can seriously injure cotton. In most cases, adverse effects from herbicide use are compensated for by reduced competition from weeds.

Surveys were conducted in 1962, 1965 and 1968 to determine how much herbicide persistence created a problem for various crops (Danielson *et al.*, 1965; Danielson *et al.*, 1968; Jansen *et al.*, 1972). In 1962, nine states indicated herbicide residues were a problem for cotton producers and five states were not affected by herbicide residues. All three western states—Arizona, California and New Mexico—indicated a problem. In 1965, eight states had troublesome herbicide residues in cotton and nine states were not troubled with herbicide residues. In 1968, the survey was more comprehensive and five percent, or 500,000 acres,

of the 10 million acres of cotton were affected by herbicide residues. However, this was a decrease from 1965 because seven states had a problem and 11 did not.

This chapter will provide information about potential herbicide injury: (a) from herbicides used in cotton on growth and yield of the crop, (b) when cotton is exposed to residues of persistent herbicides used in prior crops, and (c) from drift of nontarget herbicides to cotton. In addition, the effect of cotton herbicides on subsequent crops, and response of cotton cultivars to herbicides will be discussed. Finally, the roll of genetic engineering and biotechnology on production of cotton and other crops will be presented.

EFFECT OF COTTON HERBICIDES ON COTTON GROWTH AND YIELD

There are four major visual herbicide injury symptoms in cotton: stunting, chlorosis, necrosis and malformation (Cudney, 1986). Stunting or lack of growth can be caused by trifluralin (Treflan®) or pendimethalin (Prowl®) residues in soil that restrict root growth and development; top growth can be reduced by drift from some postemergence herbicides. Chlorosis (yellowing or whitening of foliage) results from herbicides such as diuron (Karmex®, others) and prometryn (Caparol®) that restrict photosynthesis. Residues of atrazine (AAtrex®, others) or propazine (Propazine, Milogard®) in soil can cause this type of injury. Necrosis or death of plant tissue is usually preceded by severe chlorosis, and occurs only from severe overdose or herbicide carry-over in soil. An exception to this generality would be drift of a non-target contact herbicide such as paraquat (Gramoxone®).

Non-lethal doses of contact herbicides may cause dead spots or flecking on leaves. Malformations of top growth of cotton are usually caused by drift of hormone type herbicides. Malformation can be twisting or bending of stems as well as unusual or abnormal growth of leaves. Dicamba (Banvel®), 2,4-D and MCPA have caused the most damage, but chlorsulfuron (Glean®), metsulfuron (Ally®) or glyphosate (Roundup®) which are not considered hormone herbicides can cause malformations to cotton plants. Common herbicide injury symptoms to cotton are summarized in Table 1.

Although not discussed here, injury symptoms caused by herbicides can be confused easily with problems caused by diseases, poor plant nutrition and toxic gasses in the air.

In 1984, there were 21 herbicides registered for weed control in cotton (Chandler, 1984). Of this group the following were marketed in 1988:

alachlor (Lasso®)
bensulide (Prefar®)
cyanazine (Bladex®)
dalapon (Dowpon®)
DCPA (Dacthal®)
diuron (Karmex®)
EPTC (Eptam,® Eradicane,® Short Stop,® Genep®)
fluometuron (Cotoran®)
glyphosate (Roundup®)
linuron (Lorox,® Lunuron)
methazole (Probe®)
MSMA
norflurazon (Zorial®)
oryzalin (Surflan®)
paraquat (Gramoxone®)
pendimethalin (Prowl®)
prometryn (Caparol®)
trifluralin (Treflan®)

Since 1988, the following have been added to this list:

metolachlor (Dual®)
fluazifop-P (Fusilade 2000®)
oxyfluorfen (Goal®)
sethoxydim (Poast®)

Injury symptoms caused by herbicides most commonly used in cotton are discussed below.

DINITROANILINES (TRIFLURALIN, PENDIMETHALIN AND ORYZALIN)

Trifluralin (Treflan®) and pendimethalin (Prowl®) can severely stunt cotton when incorporated too deeply into the soil. Oryzalin (Surflan®) must be sprayed preemergence to avoid injury. The effect is especially pronounced if cold wet weather follows planting. Growth of roots may be slowed; roots become stunted and swollen; and development of root hairs and secondary roots can be inhibited or prevented (Hicks and Fletchal, 1964; Holstun, 1957; Miller *et al.*, 1964; Mitchell and Bourland, 1986; Oliver and Frans, 1965). These symptoms were more pronounced when a fungicide and systemic insecticide were added to the soil with trifluralin (Schweizer and Ranney, 1965; Skroach *et al.*, 1986) (Figure 1).[1] Hardpans in the soil can cause injury symptoms to cotton roots very similar to those from dinitroaniline herbicides. Hardpans are most likely to occur in sandy soils that are wet and compacted by tractor traffic before and during planting. The worse injury develops if sandy soil is dry for several weeks immediately after planting.

S-TRIAZINES (PROMETRYN AND CYANAZINE)

Prometryn and cyanazine interfere with photosynthesis by inhibiting electron transport in the Hill reaction. This in turn reduces normal chlorophyll production and usually results in a yellow interveinal chlorosis. However, under some conditions, veinal chlorosis occurs. Severe injury results in stunting and death. This injury is most likely to occur on sandy soils with low organic matter and high pH

[1]All of the figures in this chapter are placed as a group toward the end of the chapter between the text and Literature Cited section.

Table 1. Herbicide injury symptoms on cotton (Monaco *et al.*, 1986).

Herbicides	Injury symptom[1] category	Injury symptoms
Trifluralin (Treflan®) Pendimethalin (Prowl®) Oryzalin (Surflan®)	3	Thickened hypocotyls and tap roots having reduced lateral roots and root hairs resulting in stunted plants.
Diuron (Karmex®) Linuron (Lorox®)	1a	Veinal chlorosis (yellow) and stunting. Occasionally interveinal chlorosis.
MSMA (Many) DSMA (Many)	4	Red stems and leaf petioles, abnormal bolls and stunting.
Norflurazon (Zorial®)	1b	Veinal chlorosis (white) and stunting.
Alachlor (Lasso®) Metolachlor (Dual®)	3	Stunted with rolled leaves that do not open normally.
Paraquat (Gramoxone®)	4	Drift can cause leaf flecking to complete destruction of leaves.
Chlorsulfuron (Glean®) Chlorimuron (Classic®) Metsulfuron (Ally®) Imazaquin (Scepter®)	3	Stunting, mild chlorosis of leaves, and reddish purple stems.
Atrazine (AAtrex®) Simazine (Princep®) Propazine (Milogard®) Fluometuron (Cotoran®) Prometryn (Caparol®)	1a	Interveinal chlorosis (yellow) and stunting. Occasionally veinal chlorosis.
Fomesafen (Relfex®)	4	Stunted seedlings with yellow leaves. Dead leaves turn brown or black as if burned.
2,4-D and other phenoxy herbicides Dicamba (Banvel®) Picloram (Tordon®)	2	Stunted with crinkled, strapped, elongated and malformed leaves.

[1]Injury symptom category: 1a = Photosystem II (photosynthetic) inhibitors; 1b = carotenoid (pigment) inhibitors; 2 = growth regulator herbicide; 3 = cell division inhibitors; 4 = contact (membrane destruction) herbicides.

(Black, 1985; Brian, 1964). Interveinal chlorosis can be caused by iron deficiency and is impossible to distinguish from herbicide injury (Figure 2).

It may be possible to distinguish injury by the weeds or volunteer crops that are controlled. For example, prometryn (Caparol®) would severely injure corn but cyanazine (Bladex®) would not.

UREAS (DIURON, FLUOMETURON AND LINURON)

These herbicides also inhibit the Hill reaction in photosynthesis. However, the symptoms on cotton plants vary. With diuron (Karmex®) and linuron (Lorox®), leaf veins become yellow and tissue between veins stays green. Fluometuron (Cotoran®), on the other hand, causes yellow interveinal chlorosis similar to the s-triazines, prometryn and cyanazine. This symptom can occur following an overdose in the soil or following postemergence directed sprays. However, on occasions, intervenial chlorosis has been observed (Figure 3).

ARSENICALS (MSMA AND DSMA)

MSMA and DSMA are used widely for controlling johnsongrass, annual grasses, cocklebur and nutsedge in cotton. Sprays should be directed at the base of cotton plants but frequently are applied over-the-top to the crop. Typical injury symptoms from MSMA and DSMA are stunting and red discoloration of cotton stems and petioles. In most cases, both stunting and discoloration disappear as the season progresses. With severe injury from overdose, bolls can be abnormally shaped reducing both turnout and yield. Injury symptoms are most likely to develop from topical sprays at early square (Lucas, 1964; Guthrie, 1986; Wiese and Hudspeth, 1968).

PYRIDAZINONES (NORFLURAZON)

Norflurazon (Zorial®) is a carotenoid or pigment inhibitor. These pigments are associated with protection of chlorophyll. Injured cotton has whitish to pale yellow leaf veins and green interveinal tissue. Chlorotic areas may have pink or red coloration around the edges (Figure 4) (Monaco *et al.*, 1986). In corn and sorghum, leaves become white, and if severe enough, leaf tissue dies along the edges. Under low rainfall and high pH soils common in semi-arid areas, norflurazon persists a long time and white leaves may show up on sensitive crops for several years after the herbicide is used. Severely affected seedlings may be devoid of chlorophyll and severely stunted.

CHLOROACETAMIDES (ALACHLOR AND METOLACHLOR)

These herbicides, Lasso® and Dual,® interfere with cell division, cell elongation and protein synthesis. Under cool wet conditions and when rain or irrigation comes shortly after planting, cotton plants may be severely stunted and have rolled or poorly shaped leaves. Also, root growth may be inhibited, leaving plants

subject to diseases. With severe injury, germination can be inhibited or stopped (Monaco *et al.*, 1986).

GLYPHOSATE

Although cotton is moderately tolerant, glyphosate cannot be sprayed safely on top of the crop. The herbicide is registered for use on weeds before the crop is planted, or applied with ropewick or roller applicators for weeds that extend above the crop (Keeley *et al.*, 1984a; Keeley *et al.*, 1984b). Also, glyphosate has been used extensively for spot-treating perennial weeds in cotton. Severe stunting may result if the herbicide contacts cotton plants. Most serious injury will occur when glyphosate is sprayed over-the-top of cotton at 1.5 to 3 pounds per acre. These rates delay maturity and decrease boll size enough to reduce yield (Banks and Santelmann, 1977). In another study, glyphosate sprayed over-the-top of cotton reduced blooming, fruit set and yield (Frans *et al.*, 1982). Repeated treatments at 0.5 pound per acre almost eliminated growth and yield of cotton. At normal use rates, once glyphosate contacts soil it is no longer toxic to cotton.

PARAQUAT

Paraquat (Gramoxone®, others) is used to control weeds prior to planting and for desiccating cotton to speed harvest. The herbicide is absorbed by green plant tissue; it is nonselective and fast acting–produces wilting, tissue darkening and necrosis within a few hours after treatment depending on environmental conditions. Symptoms from spray drift are necrotic spots often referred to as leaf flecking. Paraquat is a divalent cation that is reduced to an unstable form in the plant's photosynthetic system. The unstable products interact with plant parts triggering a series of events leading to rapid breakdown of cell membranes. Young actively growing plants are extremely sensitive to injury. Paraquat is adsorbed by clay and organic matter in soil; consequently, soil residues are not a problem except in very sandy soils with low organic matter (Monaco *et al.*, 1986).

CYCLOHEXENONES (PHENOXAPROP AND SETHOXYDIM) AND ARYLOXYPHENOXY ALKANOIC ACIDS (FLUAZIFOP-P)

These herbicides (Poast® and Fusilade 2000®) are postemergence growth regulators that are sprayed on plant foliage. Injury to cotton has not been observed at rates of application up to 10 pounds per acre. These herbicides are very toxic at 0.5 pounds per acre or less to both annual and perennial grass weeds that infest cotton or other broadleaved crops. Injury symptoms on treated grasses include reddening of stems and leaves. This is followed by necrosis and gradual death of the plant (Figure 5). In large plants that have a well defined stem, the top internode is the first part of the plant to die. Leaves or heads of affected plants can be pulled out easily because of the dead node.

EFFECT ON COTTON OF HERBICIDE CARRYOVER FROM OTHER CROPS

When cotton is grown in rotation with other crops, persistent herbicides used in previous crops may cause serious injury to cotton. In general, herbicide persistence varies with location in the Cotton Belt, and consequently recropping intervals vary accordingly (Table 2). Herbicides persist longest under dry conditions, cool temperatures and in soils with high pH. Herbicide persistence is the longest in the Southwest and West, intermediate in the Mid-South, and least in the southeastern part of the Cotton Belt. The most common offenders are chlorsulfuron (Glean®) and metsulfuron (Ally®) used in wheat; atrazine (AAtrex®, others) and propazine (Milogard® and others) used in sorghum or corn; and metribuzin (Sencor®, Lexone®), chlorimuron (Classic®), imazaquin (Scepter®) and fomesafen (Reflex®) used in soybeans. The more herbicide applied, the longer period of persistence in soil.

Table 2. Recropping intervals for cotton after using herbicides in crops rotated with cotton.

			Recropping interval		
Crop	Herbicide	Rate	Southwest	Mid-South	Southwest/West
		(LB/A)		(Months)	
Corn	Atrazine	3	12	12	12
Sorghum	Propazine	3	12	12	12-18
Soybeans	Metribuzin	0.75	8	8	12
	Chlorimuron	0.016	9	9	NR[2]
	Imazaquin	0.125	18	18	NR
	Fomesafen	0.19	10	10	NR
Wheat	Chlorsulfuron[1]	0.024	NR	14	14-26
	Metsulfuron	0.004	NR	NR	34

[1]On soils with pH less than 7.9.
[2]NR = Not registered in that area.

A bioassay is the safest and cheapest way to determine if residue in soil will injure a crop. The easiest and quickest bioassay can be done in a greenhouse or a south window. About twenty samples of soil should be taken to a 6-inch depth over the field in question and carefully mixed. Soil from another field known to be free of herbicide residues should be taken to the same depth, mixed and used for a check or untreated control. At least three pots of soil from each of the two fields should be planted to the crop in question. Crop injury will be observable in three to six weeks.

With sulfonylurea herbicides, planting the crop in the field is the only effective bioassay because greenhouse bioassays are not as sensitive as field bioassays.

The amount of herbicide that will injure a susceptible crop varies with soil type

as well as crop. It takes less herbicide to injure a crop in a coarse textured soil than in a fine textured soil.

Soil can be sent to a laboratory for a chemical analysis. However, the amount of herbicide, usually given in parts per million (ppm), does not indicate if a crop can be grown safely. The ppm reading from the analyses can be related to pounds per acre by assuming the top three inches of soil weights one million pounds and all of the herbicide is in that soil layer. Then a ppm reading is equal to pounds per acre. If six inches of soil is sampled, dividing the ppm reading by two will give pounds per acre because two million pounds of soil were sampled. Very little research has been done to relate herbicide concentration (ppm) in soils and injury to various crops.

SULFONYLUREAS (CHLORIMURON, CHLORSULFURON AND METSULFURON)

Sulfonylurea herbicides produce toxic effects by inhibiting cell division and growth (Anonymous, 1983). The primary mode of action is through inhibition of valine and isolucine biosynthesis (Ray, 1984) (Figure 6). This leads to stunting, mild chlorosis, purpling or anthrocyanin expression and eventually death.

Chlorimuron (Classic®) is used postemergence in soybeans at 0.008 to 0.012 pounds per acre for control of common cocklebur, pigweed, yellow nutsedge, smartweed and annual morninglories. It can be applied anytime from soybean emergence to sixty days before harvest. A second application may be made two to three weeks after the first, but total amount applied may not exceed 0.016 pounds per acre. Recropping intervals vary with soil pH and area of the country. Cotton can be planted nine months after application of chlorimuron anywhere if soil pH is 6.8 or less. In the Southeast and Mid- South, cotton can be planted nine months after application if soil pH ranges from 6.9 to 7.5. The interval is eighteen months in Tennessee and southern Missouri.[2]

Chlorsulfuron (Glean®) is registered in many states–including the cotton producing states of Arkansas, California, Louisiana, New Mexico, Oklahoma and Texas–for use in small grains and fallow land. In these states, the maximum use rate is 0.024 pounds per acre on soils having a pH of 7.9 or less.[3] No more than one application of this amount can be made to a crop or fallow period.

In Arkansas, Louisiana, eastern Oklahoma and eastern Texas, the rotation interval is fourteen months regardless of rate of application, but can be extended longer until there is at least 25 inches of precipitation. In western Oklahoma and central Texas, maximum rate of application is only 0.016 pounds per acre in order to have a 14-month rotational interval before planting cotton. In western Texas, a field bioassay must be used prior to planting cotton.

Metsulfuron (Ally®) is used in small grains and may persist in soil for more than one year at high enough concentrations to injure cotton. Metsulfuron is regis-

[2]Classic® label, E. I. duPont De Nemours & Co., Willmington, DE 19898.
[3]Glean® label, E. I. duPont De Nemours & Co., Willmington, DE 19898.

tered at 0.004 pounds per acre in several states, but the list includes only New Mexico and Texas that produce cotton. No specific crop rotation guidelines are established for cotton, but a minimum crop rotation interval of thirty-four months is suggested on the label.[4] A field bioassay should be used the year before planting cotton to determine if residues are no longer injurious to cotton. A field bioassay can be conducted by planting strips of cotton across the field perpendicular to the way it was sprayed.

IMIDAZOLINONE (IMAZAQUIN)

Imazaquin (Scepter®) is a broad spectrum herbicide for soybeans that can be applied preplant incorporated, preemergence or postemergence for control of most common broadleaf and grass weeds. It is registered for eastern, central and southern United States, and is used in a variety of rotations with soybeans and cotton. Imazaquin kills plants by inhibiting production of the amino acids valine, leucine and isoleucine. Consequently, symptoms of injury are very similar to those caused by sulfonylurea herbicides. Maximum application rate is 0.125 pounds of active ingredient per acre for all times of treatment. Small grains and rice may be planted four months after application, but cotton planting must be delayed for eighteen months.[5]

S-TRIAZINES (ATRAZINE, SIMAZINE AND PROPAZINE)

Atrazine (AAtrex®, others), simazine (Princep®, others), and propazine (Milogard®, others) are marketed under many trade names, and have been used for over twenty-five years. Residues of these herbicides can be a problem when cotton is grown in rotation with corn or sorghum. Injury from *s*-triazine herbicides is typified by chlorosis (yellowing) along the edge of leaves followed by necrosis. With more serious injury, yellowing occurs between leaf veins (Figure 7). This is in contrast to veinal chlorosis caused by the urea herbicide, diuron (Monaco *et al.*, 1986).

Rotational crop restrictions vary for the three herbicides. Atrazine treated fields can be rotated only to corn or sorghum the year following application. Corn is the only crop that can be planted the year following use of simazine. With propazine, recropping restrictions vary with location. In Arkansas, Louisiana, Texas Gulf Coast, Texas Blacklands and the Southeast, fields treated with propazine can be planted to cotton, soybeans or corn twelve months after treatment. In Oklahoma, New Mexico and West Texas, treated fields can be planted to cotton if no more than 1.0 pound per acre was used the previous year.[6]

BENZOIC AND PHENOXYACETIC ACID (DICAMBA, 2,4-D)

Safe use of dicamba (Banvel®) or 2,4-D for controlling weeds just before plant-

[4]Ally® label, E. I. duPont De Nemours & Co., Willmington, DE 19898.
[5]Scepter® label, American Cyanamid Company, Wayne, NJ 07470.
[6]Milogard®, Princep®, and AAtrex® labels, CIBA-GEIGY Corporation, Greensboro, NC 27419.

ing cotton in no-tillage cropping systems varies with location. In the dry parts of the West and Southwest, dicamba should not be used in the spring prior to planting cotton otherwise seedlings may be killed. Applications of 2,4-D may be made until six weeks before planting; however, if it does not rain during this time, serious injury may result. In the more humid areas of the Cotton Belt, such as the Mississippi Delta, dicamba at 0.25 or 2,4-D at 2.0 pounds per acre could be sprayed on stale seedbeds sixteen days prior to seeding cotton without reducing yields. Cotton planted three or nine days after spraying was seriously injured by the herbicides (Baker, 1988).

FOMESAFEN

Fomesafen (Reflex®) is a postemergence herbicide for soybeans that controls most broadleaf weeds at 0.19 pounds per acre or less. Some perennial grass weeds are suppressed at this rate of application. The product is registered for the cotton producing states along the Atlantic seaboard west to Missouri, Arkansas, Louisiana and southeastern Texas.[7] When fomesafen residues in soil cause injury to susceptible plants, seedlings are stunted, leaves turn yellow, and plants eventually may die. Dead leaves turn dark brown or black and appear burned. Small grains are very tolerant of fomesafen and may be replanted on treated fields four months after application. Cotton, corn, peanuts and rice may be replanted after ten months.

EFFECT OF SPRAY DRIFT ON COTTON

PHENOXYS AND OTHER HORMONE-LIKE HERBICIDES

The phenoxy and other hormone-like herbicides such as picloram (Tordon®), dicamba (Banvel®), triclopyr (Garlon®) and clopyralid (Lontrel®) are extremely important for control of weeds and brush on grazing lands. However, these herbicides will cause injury if allowed to drift from sprayed areas to cotton fields.

2,4-D—Ergle and Dunlap (1949) showed that greenhouse-grown cotton (Stoneville 2B) was sensitive to low rates of the sodium salt of 2,4-D. Plant height and the number of main-stalk nodes decreased in proportion to the amount of 2,4-D applied. The 2,4-D inhibited development of fruiting branches and reduced leaf weight. The two highest concentrations suppressed flower production, boll set and seed yield. Fiber weight, maturity and tensile strength also were reduced by low rates of 2,4-D. The authors concluded that, if evenly dispersed, 0.06 pounds of 2,4-D could cause serious damage to every cotton plant in 35 acres.

It was recognized early that drift from 2,4-D could cause serious injury to cotton (Brown *et al.*, 1948; Dunlap, 1948; Ergle and Dunlap, 1949) (Figure 8). Arle (1954) reported injury to cotton also could occur from volatilization of 2,4-D ester, use of 2,4-D contaminated sprayers, 2,4-D carried in irrigation water,

[7]Reflex® 2LC label, ICI Americas Inc., Willmington, DE 19897.

smoke from burning weeds and brush treated with 2,4-D and reuse of 2,4-D containers.

In Mississippi, Carns and Goodman (1956) indicated that applications of 0.001 pounds per acre of 2,4-D at the seedling stage delayed cotton maturity, but had little effect on seed yield. Application of 0.01 pounds per acre delayed maturity and reduced yield. At the squaring stage, 0.001 pounds per acre had no clear-cut effect on yield or earliness, but 0.01 pounds per acre reduced yield. At flowering, applications of 0.001 and 0.01 pounds per acre had little effect, but 0.1 pounds per acre reduced both yield and earliness. The boll stage was most resistant to 2,4-D.

In Arizona, Arle (1954) found that seed yields from 'Acala 44' cotton were reduced when spray applications of the amine salt of 2,4-D were made at low rates on June 7 (a few squares on each plant) and picked on September 30. However, at later harvests the trend was reversed and yield from treated areas was consistently higher than from untreated areas. Application made on July 7 (numerous squares and blooms) caused greater yield reduction at the first and second picking than June treatments, but late-season recovery on December 28 yielded about 350 percent over the control. The August 7 treatment had little or no adverse effect on quantity of cotton picked. Arle's experiments also indicated that cotton could tolerate quantities of up to 1.0 pound per acre of 2,4-D in irrigation water without adversely affecting yields.

2,4-D Versus Other Phenoxys—Most research indicates that 2,4-D is more phytotoxic to cotton than other phenoxys (Behrens *et al.*, 1955; Goodman, 1953; Miller *et al.*, 1963; Porter *et al.*, 1959; Watson, 1955). Goodman (1953) indicated that 2,4-D reduced yield of 'Coker 100W' cotton more than 2,4,5-T. Goodman *et al.* (1955) found that, at equal rates, 2,4-D reduced yield of cotton ten times more than 2,4,5-T. MCPA caused more leaf modification in cotton than 2,4,5-T, but yield response was similar. Cotton exposed to 2,4-D generally was most sensitive at the seedling and square stages than at flowering or boll stages. Cotton response to MCPA and 2,4,5-T was similar to 2,4-D except magnitude of injury was less. The butyl ester of silvex was more injurious than the butyl ester of 2,4,5-T. Dichlorprop had little or no effect on cotton yield. Watson (1955), using 'Coker 100W' cotton, generally agreed with Goodman (1953) and Goodman *et al.* (1955) except that 2,4-D and MCPA were about equal in reducing yields of cotton. Watson (1955) indicated the amine salt of silvex was more injurious than the amine salt of 2,4,5-T, and that the sodium salt and ester of silvex were more injurious than the amine salt.

At four locations in Texas, Behrens *et al.* (1955) found that 2,4-D caused more leaf malformation in cotton than 2,4,5-T and MCPA. Silvex resulted in no appreciable leaf malformations. Similarly, 2,4-D caused greatest reduction in cotton yield followed by 2,4,5-T and MCPA with silvex causing the least reduction in yield.

Porter *et al.* (1959) evaluated low rates of several herbicides at four stages of cotton growth. The 8- to 10-leaf stage was most sensitive to 2,4- D when measured by yield reduction. Silvex and 2,4,5-T were nonspecific in yield reduction relative to stage of cotton growth. Rates of 2,4-D as low as 0.0001 pound per acre did not stimulate yield of cotton as reported by other investigators. Miller *et al.* (1963) reported cotton seed yields were most drastically reduced by 0.01 and 0.1 pound per acre of 2,4-D applied during the flowering and fruit-setting stages. Seed quality was reduced by 2,4-D treatment and fiber quality was reduced by foliar application of 2,4- D at 0.1 pound per acre.

Other Hormone Herbicides—Recently Smith and Wiese (1972) compared 2,4-D to dicamba (Banvel®), picloram (Tordon®), bromoxynil (Buctril®) and 2,3,6-TBA. Order of damage to cotton was 2,4-D ester > 2,4-D amine >> dicamba > MCPA > picloram >> bromoxynil >> 2,3,6-TBA. Sprays of 2,4-D, dicamba or MCPA at 0.1 pound per acre reduced lint yields from 20 to 97 percent. Yield losses were most severe when cotton was sprayed before blooming. However, lint quality (micronaire and length) was not affected by these herbicides.

Patterson and Buchanan (1981) found that commercial formulations of 2,4,5-T might contain trace quantities of 2,4-D. Experiments were conducted to determine if the 2,4-D contaminant was sufficient to cause greater injury to cotton then purified 2,4,5-T applied alone. Commercial formulations of 2,4,5-T with small quantities of added 2,4-D caused slightly more visual injury to cotton than purified 2,4,5-T. However, there were no differences in cotton seed yield among materials. The only treatment that decreased cotton yield was 0.1 pound per acre of 2,4-D ester.

Bovey *et al.* (1968) found that 'Blightmaster' cotton could be planted in a tropical soil two months after applications of the potassium salt of picloram at 6.0 pounds per acre, the butyl ester of 2,4-D + 2,4,5-T at 12 pounds per acre each, or a 2:2:1 mixture of the isooctyl esters of 2,4-D + 2,4,5-T + picloram at a total of 15 pounds per acre. 'Tamcot' cotton seedlings were injured by foliar sprays of 2,4,5-T, triclopyr (Garlon®) and clopyralid (Lontrel®) at 0.03 pound per acre in the greenhouse (Bovey and Meyer, 1981). No new growth occurred when cotton was treated with 0.125 or 0.5 pound per acre of 2,4,5-T or triclopyr. Clopyralid was less injurious to cotton than triclopyr and 2,4,5-T and only slight leaf malformations occurred at 0.03 pound per acre or less. Since clopyralid has shown excellent control of honey mesquite in Texas, damage from spray drift of this herbicide should be minimal.

PHYSIOLOGICAL EFFECTS OF 2,4-D AND PICLORAM

2,4-D—All seed from bolls (one to 15 days old) set prior to treatment with 0.0000036 or 0.000036 ounce (0.1 or 1.0 mg) of 2,4-D per plant produced seedlings which exhibited symptoms of 2,4-D injury in 60-day old 'Stoneville 2B' cotton (McIlrath *et al.*, 1951). Some seedlings from seed produced in bolls initi-

ated eight weeks after application of 0.0000035 to 0.00035 ounce (0.1 to 10 mg) 2,4-D per plant exhibited 2,4-D injury, but seed formed fourteen weeks after application did not produce malformed seedlings. Plants treated with 0.00000035 or 0.0000012 ounce (0.01 or 0.04 mg) of 2,4-D at seedling or floral primordia stages showed no transmission of the stimulus into seed embryos, but seed embryos formed in bolls initiated five weeks after anthesis showed significant 2,4-D injury. McIlrath and Ergle (1953) showed that 2,4-D symptoms persisted in 'Stoneville 2B' and 'Marie Galante' cottons up to six months. The 2,4-D was extracted eighty days after application from plants showing leaf malformation characteristic of 2,4-D. However, Morgan and Hall (1963) indicated that cotton decarboxylated the side chain of 2,4-D several times faster than sorghum and in young leaves and bolls slowly converted 2,4-D to a chromatographically different material. After cotton recovered from 2,4-D treatment, it could not be detected in subsequent vegetative or reproductive growth.

Picloram—Picloram increased the soluble protein concentration of cotton when applied at 1 ppb into the roots of seedlings (Baur *et al.*, 1970). At 100 ppb picloram, soluble protein tended to be reduced but was not different than for untreated plants.

RICE HERBICIDES

In certain areas, cotton is grown adjacent to rice. The potential for drift or accidental overspray of rice herbicides on cotton can be significant.

The most widely used rice herbicide is propanil (Stam®, Stampede®). Smith *et al.* (1977) demonstrated that low rates of propanil were most injurious to small cotton. Propanil at 0.5 pound per acre or above resulted in significant yield reductions when applied to 2- to 4-inch tall or 10- to 22-inch tall cotton. Generally, those plants not killed produced new leaves and near-normal yields, but often maturity was delayed.

Eastin (1975)[8] concluded that propanil was the most injurious of several rice herbicides evaluated on 3- to 5-leaf cotton. In addition, molinate (Ordram®) at 3.0 pounds per acre and oxadiazon (Ronstar®) at 0.8 pound per acre reduced cotton yield. Combinations of molinate, thiobencarb (Bolero®), and oxadiazon with Stam® also resulted in yield reductions comparable to using Stam® alone. However, propanil was the chemical causing the majority of injury.

Hurst (1982, 1984) and Smith *et al.* (1977) concluded that leaf injury did not always result in reduced yield because plants recovered from initial injury. Hurst (1982) also concluded that injury was greater during years of cold or wet conditions which reduced seedling vigor, and made the plants more sensitive to herbicides. The order of phytotoxicity to cotton was propanil (Stam®, Stampede®) > bifenox (Modown®) > oxadiazon (Ronstar®) > acifluorfen (Tackle®, Blazer®) > butachlor (Machete®) = thiobencarb (Bolero®, Saturn®) (Hurst, 1982). When ap-

[8]Eastin, E. F. 1975. Unpublished data.

plied to 5- to 8-node cotton, propanil was the only herbicide that caused significant injury at lower than recommended rates for rice.

In response to problems of cotton adjacent to rice fields, Helms *et al.* (1987) determined the effect of propanil and thiobencarb when applied preemergence to the cotton. Although propanil is a contact herbicide with little preemergence activity, cotton grown in contaminated soil was injured and yield reduced. Addition of aldicarb (Temik®) or disulfoton (Di-syston®), in-furrow cotton insecticides, increased herbicide injury. When applied preemergence, addition of thiobencarb to propanil resulted in more cotton injury than from propanil alone. Simulated drift of 0.1 and 0.01 times the normal rate of application to rice resulted in significant yield reductions when applied to cotton in the cotylenden or 4-leaf stages of growth. The available information indicates that extreme care should be taken when applying rice herbicides, particularly those containing propanil, near cotton fields.

SOYBEAN HERBICIDES

Careless use of mixtures of bentazon (Basagran®) or acifluorfen (Blazer®, Tackle®) can result in drift damage to cotton. Injury is characterized by blotchy yellow areas on leaves that were hit by the spray (Figure 9). Fortunately, this injury does not cause serious reduction in yield of cotton.

EFFECT OF COTTON HERBICIDES ON OTHER CROPS

Herbicides used in cotton can injure other crops by spray drift from adjacent areas or by persisting in the soil. Of herbicides used in cotton production, glyphosate (Roundup®) and paraquat (Gramoxone®, others) are most likely to drift to adjoining crops such as winter small grains. Drift of either herbicide must be prevented or serious damage may result. Yates *et al.* (1978) observed drift of glyphosate over 300 feet downwind from a ground rig using conventional nozzles. Drift from sethoxydim (Poast®) or fluazifop-P (Fusilade 2000®) may injure grass crops. These herbicides are toxic to susceptible plants immediately after spraying, but do not persist and affect subsequent crops (Buhler and Burnside, 1984; Chernicky and Slife, 1986).

TRIFLURALIN AND PENDIMETHALIN

Trifluralin (Treflan®) and pendimethalin (Prowl®) applied either at layby or preplant incorporated can injure sorghum planted before May 15 of the following year in West Texas (Abernathy and Keeling, 1979; Wiese *et al.*, 1969). If more than recommended rates were applied at layby, sorghum planted after the middle of May was injured. There is not a carryover problem with these herbicides in areas with more precipitation than West Texas. Layby applications of these herbicides may seriously reduce stand of sugarbeets (Warner *et al.*, 1987).

FLUOMETURON

Fluometuron (Cotoran®) persists in the soil longer than either trifluralin (Treflan®) or pendimethalin (Prowl®), and can injure soybeans at very low rates (Bode and McWhorter, 1977). Postemergence sprays also can reduce yield of soybeans when sprayed during the mid-bloom stage. The effect of three cotton herbicide programs on yield of subsequent crops of wheat, hairy vetch, corn, sorghum, rice, soybeans and cucumber was determined on three soil types (Rogers *et al.*, 1986). Herbicide systems were either: (a) none, (b) fluometuron (Cotoran®) applied preemergence followed by a mixture of MSMA and fluometuron applied twice postemergence, and (c) trifluralin (Treflan®) preplant incorporated, fluometuron preemergence, two sprays of fluometuron plus MSMA postemergence, followed by a directed spray of linuron (Lorox®). Herbicide injury to wheat and hairy vetch planted immediately after cotton harvest was most pronounced on Sharkey silty clay but was less on Dundee silt loam and Loring silt loam soils. The intensive herbicide program (c) was most injurious. The following year, corn and grain sorghum suffered the least damage while rice, soybeans and cucumbers were injured most. Fluometuron residues in the soil was the chief cause of injury.

In most areas, crops other than cotton cannot be planted until six months after the last application of fluometuron. No more that three applications of fluometuron should be made per season. In Arizona, California and New Mexico, cotton, corn and grain sorghum can be planted the next crop season but other crops should not be planted for one year after the last application.[9]

NORFLURAZON

Norflurazon (Zorial®) persists in soil for more than one year in dry areas and is not registered for the entire Cotton Belt. There are rotational crop restrictions in certain states. Holt (1986) indicates norflurazon has an initial half-life of thirty to sixty days, but a second half-life is usually six to twelve months. Speed of breakdown is affected by soil type, incorporation method, moisture and temperature. These results were from fields that had been treated for three years at recommended rates and incorporated prior to planting. Norflurazon persisted longest in soil with high silt content. The year following the third annual application of norflurazon at 1.25 pound per acre, there was less than 0.62 pound per acre in the soil. Seedlings of corn and sorghum planted the year following the last application were bleached after eight weeks but by twelve weeks were normal (Figure 10).

In a similar study, norflurazon at 1.5 and 3 pounds per acre was sprayed annually for three years and incorporated with tandem disking on a Bosket silt loam soil in Mississippi (Hurst and Tupper, 1981). A greenhouse bioassay indicated enough norflurazon present in the soil two months after cotton harvest to injure wheat and soybeans.

[9]Cotoran® label, CIBA-GEIGY Corporation, Greensboro, NC 27419.

PROMETRYN AND METOLACHLOR

Prometryn (Caparol®) and metolachlor (Dual®) do not persist in the soil for more than a few weeks and are registered on many crops.[10] If these herbicides are used on cotton and the crop fails, other labeled crops can be replanted. Cabbage, okra, onions, peas, red beets and sweet corn may be double-cropped immediately after cotton harvest following prometryn applied preplant or preemergence. In California and Arizona, spring-seeded crops and vegetables may be planted after April 1. Barley, oats, rye or wheat may be planted 4.5 months after treatment with metolachlor. Most other crops can be planted the next spring.

TOLERANCE OF COTTON CULTIVARS TO HERBICIDES

GLYPHOSATE

During the late 1970s, researchers tried glyphosate (Roundup®) as a postemergence topical herbicide in cotton and soybeans (Banks and Santelmann, 1977; Wills, 1978). In order to increase cotton tolerance to glyphosate, Jordan and Bridge (1979) evaluated resistance of 405 genotypes to sprays of 0.75, 1.5 and 3.0 pounds per acre during early bloom. There was considerable difference in tolerance, and six of the most resistant lines were sprayed the next year at 0.5 and 0.75 pound per acre. None of the treated lines yielded as much as untreated comparisons; however, genotypes 'DES 04-11' and 'DES 04-606' yielded more than untreated controls when glyphosate at 0.5 pound per acre was directed at the base of the cotton plants. Although there was considerable tolerance of some cotton lines to glyphosate, it was not safe to spray the many varieties that are planted. Because the crop is quite tolerant, glyphosate can be used in ropewick applicators, recirculating sprayers or for spot treatments to control perennial weeds in cotton (Keeley *et al.*, 1984a, 1984b). Using a ropewick applicator to control johnsongrass markedly increased yield of cotton compared to cultivating and hoeing (Keeley *et al.*, 1984b). When mixed with the defoliant DEF®, glyphosate has been used to control regrowth prior to harvest (Cathy and Barry, 1977).

2,4-D

Differential tolerance of cotton cultivars to 2,4-D was noted when drift from neighboring fields caused injury in a yield trial (Regier *et al.*, 1986). Under these conditions, 'Paymaster 145' cotton did not show injury symptoms and outyielded eleven other cultivars. Yield of the twelve cultivars was negatively correlated with an injury rating where 1 was no leaf injury, and 5 was when all leaves had 2,4-D injury symptoms. 'McNair 307' and 'G&P 3774' cotton were injured most by the 2,4-D drift. In an effort to explain the tolerance of 'Paymaster 145', two studies were conducted to determine if leaf hairiness affected resistance to 2,4-D

[10]Caparol® and Dual® labels, CIBA-GEIGY Corporation, Greensboro, NC 27419.

(Dilbeck *et al.*, 1987). In the first study, lines used were 'Paymaster 145' along with 'Texas marker- 1' isolines 'pilose' and 'smooth leaf'. A single spray of 2,4-D at 0.5 pound per acre was allowed to drift across the three lines. In a second study, five lines were sprayed with 2,4-D at 0.001, 0.01, and 0.05 pound per acre. Visual ratings and lint yield indicated an advantage to leaf hairiness, but 'Paymaster 145' yielded most, showing presence of an additional genetic mechanism for tolerance to 2,4-D.

PROPAZINE AND ATRAZINE

Atrazine (AAtrex®, others) and propazine (Milogard®, others) were sprayed preemergence at 0.5 pound per acre on forty-eight cotton cultivars in a sandy clay loam soil (Abernathy *et al.*, 1979). Injury over two years averaged from 8 to 80 percent for atrazine and 3 to 53 percent for propazine. 'Paymaster 303', 'Stripper 31 A', 'Auburn M', 'Acala B-3030' and 'Acala 1517-70' were most tolerant to atrazine, and 'Stripper N' was most susceptible. The most tolerant cultivars to propazine were 'Auburn M', 'Acala 3080', 'Paymaster 303', 'Coker 5110' and 'Coker 312'. The most sensitive were 'Paymaster 110', 'Deltapine SR-2' and 'Blightmaster A-5'. In another trial, lint yield of 'Paymaster 303' was not reduced by preemergence sprays of propazine at 1.0 pound per acre while lint yield of 'Paymaster 101A' was reduced from 371 pounds per acre on untreated areas to 112 pounds per acre where the herbicide was applied.

TRIFLURALIN

Twenty cotton cultivars were evaluated for tolerance to trifluralin (Treflan®) (Mesri, 1980; Bourland *et al.*, 1981). Laboratory evaluation with germination paper or cups of sand treated with trifluralin indicated 'McNair 235' and 'DES 24' had some tolerance. Later field evaluations at one, two and three times labeled rates of trifluralin showed that 'Tamcot CAMD-E', 'Stoneville 603', 'Stoneville 825' and 'McNair 235' cottons had the highest tolerance.

BIOTECHNOLOGY AND GENETIC ENGINEERING

Biotechnology and genetic engineering are two areas of research that have emerged and grown rapidly during the last fifteen years. Biotechnology is a general term that deals with application of biological and engineering techniques to microorganisms, plants and animals. Genetic engineering relates to the part of biotechnology where genetic components of organisms are altered by human intervention. Traditional plant breeding by crossing lines among species that hybridize, as well as more modern techniques where genes or chromosomes are moved from one organism to another are part of genetic engineering. Genetic engineering has been used for over one hundred years to select and create plants and animals with desired characteristics.

The laws of inheritance were discovered by Mendel (1866) when he made crosses, observed and interpreted the definite pattern of flower color in the offspring of peas. About three years after Mendel's work on the laws of inheritance, Miescher (1869) discovered nucleic acids, which later were proved to be the building blocks of heredity. These two discoveries remained unused for decades.

Mendel's principles of inheritance were not rediscovered until the early part of the 20th century when Bateson *et al.* (1905) again reported additional cases of the interaction of factors or genes. Shortly thereafter a number of individuals contributed to the theory that genes were located on chromosomes. The scattered bits of information were summarized and interpreted by Morgan *et al.* (1915) in "The Mechanism of Mendelian Heredity". Other developments that led to modern hybrid plants were published by Shull (1908, 1909). He demonstrated that a genetically heterogeneous crop like corn could be selfed and resolved into a large number of genetically uniform and stable inbred lines. Jones (1918) took this information a step farther and proposed a system of double-crossing the selfed lines of corn. He demonstrated hybrid vigor and thereby laid the foundation for practical production of high yielding hybrids of corn and other crops.

The key to genetic engineering in the modern sense was discovered by Watson and Crick (1953) who described the double helix structure of desoxyribonucleic acid (DNA). DNA in cells acts like a magnetic tape and directs each phase of development, be it a single cell or a highly specialized plant or animal. The long double strands of spiraling thread-like molecules of DNA are located in chromosomes in the cell nuclei of all plants and animals. The term "gene" is given to the region of the DNA molecule that gives rise to a particular genetic characteristic. Genes control synthesis of specific protein molecules within the DNA which are comprised of different combinations of the four amino acids: adenine, thiamine, cytosine and guanine. Combinations of the four amino acids hooked together in long sequences constitute the almost unlimited number of genetic codes that control development of organisms.

PLANT CELL AND TISSUE CULTURE

Regeneration of plant cells or tissue cultures is a part of biotechnology. Using many different techniques, a variety of plants can be grown from single cells or tissues (Legates, 1986). This technique has the potential of producing a large number of genetically identical plants from another plant having rare or desirable characters such as superior growth or disease resistance. The best method currently developed involves placing tissue into a container of culture medium made up of plant hormones, auxin and cytokinin along with organic and inorganic nutrients necessary for growth. The cells divide and form a mass of cells called callus. When callus cells are transferred to a special regeneration medium, they differentiate into roots and shoots and, in some instances, develop into whole plants. Detailed methods of doing this are provided by Camper (1986).

RECOMBINANT DNA TECHNOLOGY

The technique called recombinant DNA technology is relatively new. It involves removing or adding genes in an individual species. The purpose of this technique is to transfer a desirable characteristic from one organism to another that cannot be crossed by conventional plant breeding methods. This sounds simple, but is very complicated. First, it is difficult to identify a specific gene in a chromosome that controls a particular characteristic. Once this is done, however, it is even more complicated to transfer a gene to another plant or animal.

Incorporating genes from one species to another has been accomplished by using restrictive enzymes that cut DNA strands at a specific sequence of amino acids. This technique makes it possible to isolate specific genes. Restrictive enzymes also are used to incorporate the isolated gene into the receptor organism. Scores of restriction enzymes have been isolated that are capable of cutting DNA at specific points.

PRACTICAL APPLICATIONS OF BIOTECHNOLOGY

Several applications of biotechnology and genetic engineering have been used to modify plants. The ability to make a toxin has been transferred from a bacterium that does not normally occur in the root zone to a bacterium that grows on or near plant roots. This new modified bacterium produced the toxin which inhibited cutworms feeding on roots of young plants.

Resistance to the herbicide imazapyr (Arsenal®) has been transferred into lines of corn. Similarly, resistance to bromoxynil (Buctril®), a postemergence herbicide used in small grains and corn, has been transferred into tomatoes and tobacco (Arthur, 1987). A gene that is tolerant to glyphosate (Roundup®) was isolated from a soil bacterium and transferred into *Agrobacterium tumefaciens* that causes crown-gall disease in certain plants. The leaves of poplar trees were infected with the new bacterium containing the gene for glyphosate tolerance. This moved the desirable gene into cells of the poplar leaves. Then the bacterium was killed, and poplar shoots were regenerated by tissue culture from these leaves. This resulted in poplar trees that could be sprayed with glyphosate giving foresters a new herbicide for poplar nurseries. Similar resistance to glyphosate has been genetically engineered into petunia and tobacco plants (Camper, 1986). Tissue and cell culture techniques also have been used to study herbicide resistance and metabolism.

Prospects for future improvement in plants have scientists in industry and academic institutions excited (Fraley, *et al.*, 1984; Sundquist *et al.*, 1982; Widholm, 1984; Wild, 1984). Transferring a single gene between varieties or lines of plants that normally cross could be more rapid by molecular techniques than by conventional plant breeding. A trait could be transferred into a new variety without six to eight backcrosses normally used to transfer desirable characteristics from one variety to another.

The ability to produce multicellular plants from a single cell or protoplast of-

fers many possibilities for plant improvement. The most exciting possibility is using recombinant DNA to improve economically important plant species by transferring genes from one species to another that do not normally hybridize. For example, corn and sorghum will not cross, but transferring certain traits such as disease resistance or drought tolerance would be highly desirable. Wild or exotic species could be more readily utilized in breeding programs by introducing whole sets of new genes or genomes. Also, with new molecular techniques, it may be possible to modify a gene from one species before inserting it into another. Resistance to pests or pesticides, for the most part, is controlled by single genes that may not be found in crop plants. Creating cultivars of cotton and other crops that are resistant to certain pests or pesticides should be relatively easy because of the simple inheritance.

Another exciting possibility that will be more complicated is transferring genes for nitrogen fixation from microorganisms into non-leguminous plants such as cotton. The increased supply of nitrogen for crop growth would be especially beneficial in Third World countries where nitrogen fertilizer is not readily available or is too expensive. Transferring characteristics such as stress tolerance, quality and yield which are controlled by numerous genes or groups of genes will be difficult to accomplish.

Biotechnology and genetic engineering combined with conventional plant breeding will hasten production of new and improved varieties of cotton and other crop plants. It is most likely that in the next ten to twenty years, cotton seed will be available that is resistant to many common diseases and insects. In addition, cultivars will have tolerance to specific herbicides. Weed problems in cotton may be eliminated by over-the-top sprays of such herbicides as glyphosate, paraquat or imazapyr. Farther in the future, cotton cultivars may release toxins into the soil that eliminate weeds.

SUMMARY

Herbicides are an essential part of cotton culture and, if used according to label instructions, neither cotton or crops grown in rotation will be injured. When cotton is injured by misuse or poor application of herbicides, yields may be maintained or increased because of decreased competition from weeds. However, a combination of adverse circumstances can result in serious injury to cotton and other crops grown in rotation.

Stunting, necrosis, chlorosis and malformation are the four major herbicide injury symptoms in cotton. Overdose or misuse of trifluralin (Treflan®) or pendimethalin (Prowl®) can cause stunting because root growth is restricted. This injury occurs when the herbicides are incorporated into beds several inches below where cotton seed are planted. This problem is most pronounced when dry weather follows planting. Compacted soils, as well as herbicides, may restrict

root development. In many instances, damage to roots caused by soil compaction has been blamed on trifluralin or pendimethalin.

Stunting or malformed growth can be caused by drift of 2,4-D or similar compounds. Injury to cotton from drift of 2,4-D and similar herbicides will be a problem as long as cotton is grown near wheat and sorghum crops where 2,4-D is the most economical herbicide available. Also, in areas where cotton is grown near brush-infested rangeland, some damage from drift will continue to be a problem. However, since 2,4,5-T was banned, drift damage decreased because new herbicides for brush are less toxic to cotton. Chlorosis or yellowing of leaves is caused by herbicides that inhibit photosynthesis. This includes diuron (Karmex®), prometryn (Caparol®), fluometuron (Cotoran®), linuron (Lorox®), atrazine (AAtrex®, others) and propazine (Milogard®, others). Norflurazon (Zorial®) inhibits pigment formation and causes cotton and other plants to turn white.

Atrazine, propazine, chlorsulfuron (Glean®) and metsulfuron (Ally®) are persistent herbicides used in other crops that can injure subsequent crops of cotton. Herbicide persistence in soil has been a problem to cotton producers on five percent or about 500,000 acres. This problem is most severe in the driest part of the country, including the states of Texas, New Mexico, Arizona and California. Herbicide persistence in soil is increased when dry weather occurs the year before cotton is planted. Herbicides used in cotton that may affect subsequent crops are trifluralin, pendimethalin, fluometuron and norflurazon. Sorghum is most frequently injured by trifluralin and pendimethalin. This injury can be prevented by planting after May 15. Fluometuron and norflurazon are not registered in parts of the West and Southwest because of potential for injuring crops following cotton.

Certain cotton cultivars and lines have tolerance to glyphosate, 2,4-D, propazine, atrazine and trifluralin. Biotechnology including genetic engineering offers the promise of greatly increasing production of cotton and other crops. Present advances in biotechnology include development of corn and tobacco that can tolerate specific herbicides. Using a combination of conventional crop breeding and biotechnology, cotton cultivars will be developed that are resistant to many diseases and insects as well as specific herbicides such as glyphosate.

A



B



Figure 1. Injury to cotton (upper) and sorghum (lower) roots caused by trifluralin (Treflan®). In the cotton deformed roots on outside and normal on inside. (Courtesy of J. R. Abernathy, Texas Agricultural Experiment Station and L. R. Oliver, University of Arkansas.)

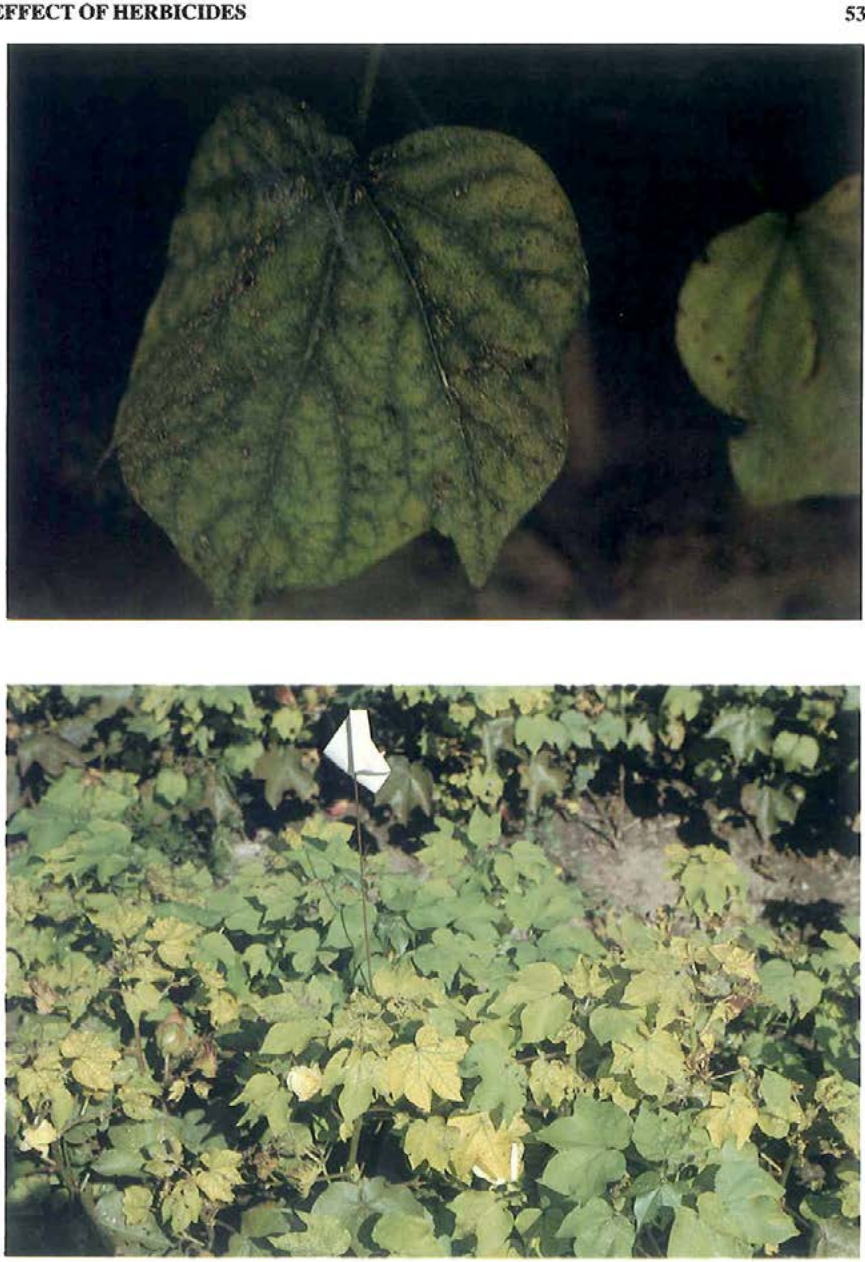


Figure 2. Interveinal chlorosis: (upper) caused by a poorly directed application of cyanazine (Bladex®) mixed with DSMA, and (lower) iron deficiency in cotton. (Courtesy of C. T. Bryson, USDA, ARS and J. R. Abernathy, Texas Agricultural Experiment Station.)



Figure 3. Veinal chlorosis can be caused by overdose of diuron (Karmex®) and under some circumstances by prometryn (Caparol®) which normally causes interveinal chlorosis. (Courtesy J. R. Abernathy, Texas Agricultural Experiment Station.)



Figure 5. Red johnsongrass leaves caused by a spray of fluazifop (Fusilade®).

A



B

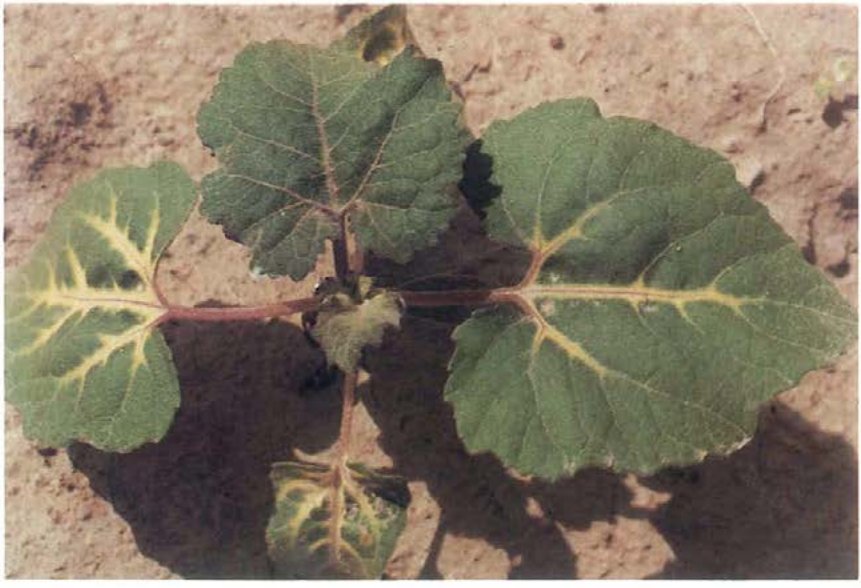


Figure 4. Veinal chlorosis (white) caused by norflurazon (Zorial®) on cotton (upper) and common cocklebur (lower). (Courtesy of C. T. Bryson, USDA, ARS and L. R. Oliver, University of Arkansas.)

A



B



Figure 6. Sulfonylurea injury to cotton: (upper) metsulfuron (Ally®) 0.005 pounds per acre preplant incorporated and (lower) chlorsulfuron (Glean®) 0.001 pound per acre postemergence.



Figure 7. Interveinal chlorosis on cotton caused by preplant incorporated application of atrazine (AAtrex®, others) at 1 pound per acre.



Figure 8. Effect of 2,4-D drift on cotton leaves. Upper, middle and lower: light, moderate and severe damage, respectively.

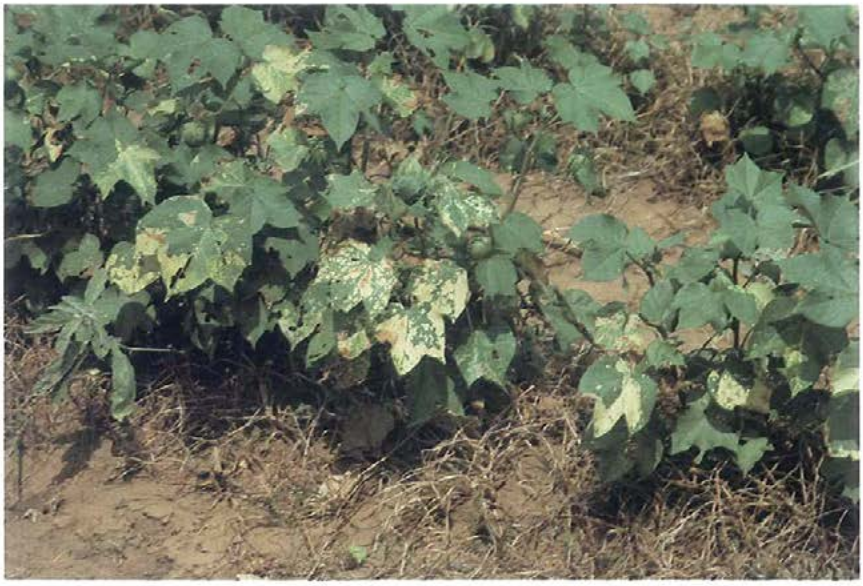


Figure 9. Leaf chlorosis in cotton caused by drift from bentazon (Basagran®). (Courtesy of J. R. Abernathy, Texas Agricultural Experiment Station.)



Figure 10. Norflurazon (Zorial®) injury to corn. (Courtesy of L. R. Oliver, University of Arkansas.)

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Chapter 14

TEAMWORK IN THE DEVELOPMENT OF WEED MANAGEMENT PROGRAMS FOR COTTON FARMERS

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INTRODUCTION

HISTORICAL ASPECTS

Controlling weeds has been a part of "farming" since before historic recording. In America farmers rarely used chemical techniques prior to World War II. Non-chemical techniques used included the continuing present standards of cultivation, hand-weeding, crop rotation and perhaps use of weed-free seed. Most farmers learned these techniques from their parents or neighbors, but the national network (now global) of experts who share ideas was unheard of then. Successful farmers were often "artists" at farming, rather than users of scientific principles.

RECENT COOPERATIVE EFFORTS

Because weed science has been one of the most recent components of crop protection to widely utilize chemistry in integrated weed management systems (Street, 1957; Miller, *et al.*, 1961; Miller *et al.*, 1962; Arle and Hamilton, 1963), the analysis of roles played by various collaborators is most revealing. The major emphasis with herbicide development has been pragmatic; that is, to control weeds more economically. As the recent regulatory focus has shifted from permitting development of efficient weed control systems to health risk assessment of pesticides, a reduction in candidate herbicides for registration by the United States Environmental Protection Agency (USEPA) has occurred. More aca-

demic weed scientists have shifted toward the elucidation of scientific principles that make up weed science, rather than just to develop weed management techniques.

During the past three decades—beginning with the introduction of the highly successful substituted-urea herbicides, such as diuron (Karmex®, etc.) and fluometuron (Cotoran®, etc.), and the triazines such as prometryn (Caparol®, etc.), simazine (Princep®, etc.), and atrazine (AAtrex®, etc.) to the present time when sethoxydim (Poast®) and fluazifop-P (Fusilade 2000®) have entered the marketplace—considerable cooperative effort has been a characteristic of these successes. Yet, considerable evolution of who is doing what has occurred. This is due largely to the widening circle of technology used in protecting crops from weeds.

One can easily identify the various cooperators who team up to make weed management programs work. The manufacturers (Figure 1) are primary, but the land-grant university staffs, the U.S. Department of Agriculture's Agricultural Research Service (ARS) and the State Extension Services all play key roles in researching and finding the best fit for a given candidate herbicide (Turner, 1981). Their work is greatly facilitated by cooperating dealers and distributors, consultants and the farmers who integrate new lower-cost technology into their operations. All of their effort, over several years, must be within the framework of regulatory laws and rules promulgated by federal, state and county agencies.

Early efforts might now be called "shot-gun" approaches to control. But with



Figure 1. Industry representatives such as Elanco have held annual diagnostic field days for consultants (1979).

the passage of a couple of decades, "weed management" is now regularly practiced. It utilizes an array of weed science principles and in-field experience. Much more research on weed science principles is needed along with systems to utilize these research findings. But much has been written on weed science and weed management, a percentage privately published. (See "Useful publications for weed management in cotton" in the Appendix at the end of this chapter.)

Since weeds—like other components of nature—are always dynamic, continued updating and "resetting of sails" is needed as we move toward our not totally known destination. Resistance to herbicides, as to insecticides and pathogens, is present in populations of weeds. Continued use of a given herbicide for a decade or more can shift the numbers in that population where many are resistant rather than one in a million or a billion (Day *et al.*, 1983). Therefore, continued effort is needed to stay ahead of Mother Nature's natural phenomenon of resistance.

As with other crop protection disciplines, the weed scientist's goal must not be to kill weeds, but to protect our crops efficiently so we can compete internationally. Thus the benefits from optimum quantities of quality food and fiber may be secured, with minimal downside effects.

Recently, it seems that the urban and political perspectives on the seriousness of trace findings of pesticides, using increasingly precise analytical technology, has resulted in new legislation with potential for great impact on what we have strived for the past three decades to accomplish. These laws may dismantle a large portion of our arduously obtained production systems (Ames *et al.*, 1983). Without major educational effort of the urban sector of our team, we will permit an undoing of most that we have accomplished in this young science. That effort may be coming into place in the 1990s (Archibald and Winter, 1989; Whelan, 1990).

WHO DOES WEED RESEARCH

Since about 1.5 billion pounds of crop protection chemicals are sold annually in the United States, and about half are used on our cropland, a considerable staff of professionally trained personnel must be employed. About 65 percent of all pesticides are herbicides (Anonymous, 1987).

Access to Weed Science Society of America (WSSA) membership lists provides insight into the number who work on field crop weeds in cotton-growing states (Table 1). These data are not exact because not all weed science researchers are members.

The compilation shows that the manufacturing companies far out-number USDA, university department and extension personnel inputs. Of course, not all field crop researchers are doing research on cotton but the numbers give some insight into how many are doing research in the regions of cotton production. It provides little indication of how many extension personnel such as county agents, or distributors, dealers, independent consultants or applicators, are involved since these are not normally members of WSSA.

Table 1. Weed Science Society of America members in cotton-growing regions of the United States who are involved in field crops. (From Directory of North American Weed Scientists and WSSA Members World-Wide. Weed Science Society of America. July 1986. 173 pp.)

State	Manufacturers		USDA & Universities		Extension services	
	Number	Time	Number	Time	Number	Time
		(percent)		(percent)		(percent)
AZ	5	57.4	0	—	2	100.0
CA	106	70.9	9	64.4	23	46.3
FL	18	66.7	9	86.7	0	—
GA	14	55.5	4	78.7	5	68.0
KY	4	93.8	2	100.0	0	—
LA	8	85.0	13	65.0	0	—
MS	27	66.9	20	72.3	3	80.0
MO	44	86.9	12	60.0	0	—
NC	36	70.3	9	71.1	0	—
NV	0	—	4	13.8	0	—
OK	2	62.5	10	57.0	1	40.0
TN	12	73.8	4	86.3	1	30.0
TX	24	57.5	25	72.8	4	48.8
Totals	300	71.3	121	68.7	39	54.1

Manufacturing personnel are mostly involved (300) in cotton-growing states: USDA/university department scientists are second (121); and, extension personnel are third (39). Data on pest control advisors and consultants were evaluated but not included; most apparently do not belong to WSSA.

Other sources of numbers of weed scientists involved were found. Parochetti (1982) reported that there were 281 people (121 Full-Time Equivalent [FTE] assignments) as extension weed specialists at land-grant universities in the United States. That compared to 145 plant pathologist and nematologist FTE's, and 258 entomologist FTE's. County agents and regulatory professions were not included. It would be interesting to know how many regulatory people are involved in pesticide regulation. The authors tried but were unsuccessful in determining those numbers.

Dunster (1982) reported that in the Western Society of Weed Science, 45 percent were public agency personnel and 55 percent were industry personnel. His survey of 26 industry colleagues, with 20 responses, showed the trends on who was doing what (Table 2).

Dunster's evaluation of his colleagues' perspectives on university involvement in field research suggested that industry was carrying an increasing percentage of the research load. Since 1982 most would agree, I believe, that industry is now

Table 2. Evaluation of public sector involvement in field research. (Evaluations by industry researchers. From Dunster 1982. Proc. West. Soc. Weed Sci. 35:109-112.)

1. The primary need or justification for public sector involvement is impartial evaluation of:	
a. Field Performance	80%
b. Environmental factors	40%
c. Other aspects	20%
2. The interest and ability of university programs to respond to pesticide registration needs has:	
a. Increased	15%
b. Stabilized	30%
c. Decreased	55%
3. Relative involvement of public sector personnel in field R & D activities has:	
a. Increased	5%
b. Stabilized	20%
c. Decreased	75%
4. Financial support of university programs by industry has:	
a. Increased	70%
b. Stabilized	20%
c. Decreased	10%

doing a much higher percentage of the many studies additionally required since then. Studies on residue testing, metabolism, persistence and groundwater must now be done in accordance with EPA's "Good Laboratory Practices" (GLP) manual. The GLP manual must be followed exactly or the results will not be accepted by EPA evaluators. Only researchers trained in the practices manual can do such research, precluding university involvement in many cases.

THE EXPERIMENT STATION TEAM

America's agricultural experiment stations, both USDA and state, provide an environment for weed scientists to cooperate with other scientists on localized weed control problems in various farm commodities. In most states, new weed management practices are developed by university researchers. The principles of weed management can be researched by using well-controlled experiments—researched with or without the latest technical advances in cultivars, other pesticides, cultural practices, fertilizers, etc., to determine the contribution of each input.

Weeds always have been best managed by a variety of practices. For thou-

sands of years mankind has used combinations of timely planting, tillage, mowing, rotation and environmental management in his struggle against weeds. "Integrated Weed Management" is a term used by weed scientists to emphasize that herbicides are only one component of a total system for managing weeds in crops. An integrated weed management program combines all forms of weed science technology into a coordinated strategy to obtain maximum benefits, including minimal costs and risks. In an integrated weed management program, managers recognize the problem, determine what kind of control is needed, and organize and employ the most cost-efficient strategy to minimize the effects of the weeds. Herbicides are considered a component used in conjunction with other methodologies, but they are essential for profitable cotton production (Dowler and Hauser, 1974, 1975). Herbicides are used on almost all cotton acreage in the United States (Whitwell *et al.*, 1985). (Also, see Chapter 3).

In the research and development of new weed management programs, experiment station scientists must understand why weed problems develop. Why do we continue to have such a problem with weeds when we have highly effective herbicides to supplement all the traditional methods?

Weed problems develop year after year because of our inability to cope with their great reproductive capacity, massive recycling potential, and sporadic germination and establishment patterns. Another factor is the ecological or botanical shift toward more tolerant and aggressive species due to reduced tillage and/or repeated use of the same herbicide program. For example, continuous use of trifluralin (Treflan®, etc.) in cotton has decreased the population of annual grasses, but allowed increases in the population of nutsedges (*Cyperus* spp.) and annual broadleaf weeds. Continuous use of fluometuron (Cotoran®) has decreased the population of annual broadleafs, but has led to increases in annual grasses and nutsedges (Coble and Schrader, 1974; Dowler and Hauser, 1974, 1975). Therefore, growers use herbicide programs that are designed for broad-spectrum weed control. This helps to delay and reduce population shifts in continuously planted cotton (Dowler and Hauser, 1974).

In the early days of increasing herbicide usage, the dramatic results of many new herbicides shifted emphasis away from study of these ecological trends. But the current herbicide era has not cancelled the ecological principle concerning the spread of species to their limits of adaptation. The pernicious character of weeds is further enhanced by the development of resistance in specific weeds to herbicides (Bandeen *et al.*, 1982; Gressel *et al.*, 1982). Development of resistance has been documented in North and South Carolina cotton fields with a population of goosegrass (*Eleusine indica* L.) that is highly resistant to trifluralin (Treflan®, etc.) and other dinitroaniline herbicides (Mudge *et al.*, 1984; Slater, 1984). Common cocklebur (*Xanthium strumarium* L.) populations in South Carolina cotton fields show some plants highly resistant to DSMA and MSMA, the organic arsenical herbicides (Haigler *et al.*, 1986). These resistant populations must be managed as new and exotic pests in cotton. Past resistance problems have

been managed by the use of herbicide mixtures, sequential treatments and the rotation of herbicides and crops. However, this has led to increases in production costs.

Effective weed management is only one of the many production practices required for a successful and profitable crop production system. It has been documented (Gaylor *et al.,* 1983) that various production practices, including those used to control pests, are not independent of each other . Therefore, many local variations have to be considered in fitting a new herbicide or a new farm tool into a specific cropping system. Scientists cannot go their separate ways; they must keep abreast of recent developments in other disciplines because progress in one area only can go forward along with progress in other areas. Past examples are mechanical harvesting, plant breeding and cultural practices. State and federal researchers have constantly looked for innovative ways to use herbicides in basic agricultural practices. For example, the concept of conservation tillage originated before 1970, but expanded research and more effective herbicide programs have led more and more farmers to adopt some form of reduced tillage in most crops. Higher energy costs and the need to reduce soil erosion also contributed to the acceptance of this practice.

Since the introduction of diuron (Karmex®, etc.) in the 1950s, refinements have permitted increasing sophistication in spray equipment. The importance of precise placement of herbicides (Figures 2 and 3) to obtain maximum efficiency on soils, in soils and on plants and the variables that affect placement has long been recognized (Dawson, 1963; Holstun, 1966; Klingman, 1964). Putting herbicides on target weeds or sites by application systems have been vastly improved. Post-directed sprays using selective oils permitted application to cotyledon-stage cotton in the 1950-1960 era. Later, with the introduction of diuron (Karmex®, etc.), fluometuron (Cotoran®, etc.) and other herbicides, "oiling shoes" permitted growers to be as precise as possible with post directed sprays (PDS). More recently, specialized application equipment such as the recirculating sprayer and various types of wiper applicators for glyphosate (Roundup®) application has enabled farmers to control tall growing weeds in crops that have escaped other control measures (Dale, 1978; McWhorter, 1970). In addition to being a new application technique, this equipment reduces drift, reduces the amount of herbicides used and the volume of water required. Chemigation, a technique for applying herbicides through center pivot or solid-set irrigation systems, is being adopted by farmers (Dowler *et al.,* 1982). Each method reduces application costs, improves the consistency of performance for some herbicides and is suited for the application of many soil-applied and foliar-applied herbicides in volumes of water as low as one gallon per acre (gpa) or as high as 27,000 gpa (one acre-inch).

Experiment station researchers also have contributed to the development of new uses for old products and procedures for proper use. In the early 1960s, soil-applied diuron was found effective as a post directed spray application for cotton

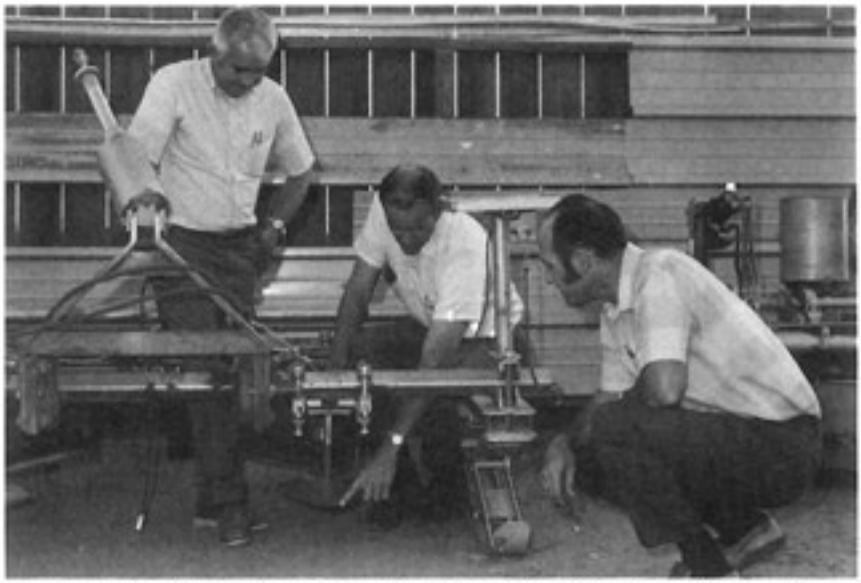


Figure 2. The Stoneville spray-blade was modified and tested at the USDA Cotton Research Station, Shafter, CA, in 1959 with Dr. Paul Keeley (left), Lyle Carter, Engineer (right), and Harold Kempen (center). Subsequent extension field testing with trifluralin was promising and growers used it for several seasons. But, if rainfall occurred immediately after planting, retardation was moderate. Currently, metham (Vapam®) is successfully bladed preplant on several California crops (1964).

when used with adjuvants (McWhorter, 1964). This discovery led to greater flexibility and efficiency with herbicide applications in other crops. Occasional delayed applications of the organic arsenical herbicides DSMA and MSMA by growers suggested yield reductions. Beltwide research showed that topical applications at advanced growth stages reduced cotton bloom, delayed maturity and increased the arsenic content in cottonseed (Baker *et al.*, 1969). These findings alerted farmers to the multiple dangers of late applications.

Experiment station researchers developed principles based on the effects of weeds on crops and the variables that influence weed competition (Figure 4). Many studies have shown the need for early-season weed control in cotton (Buchanan and Burns, 1970; Buchanan and McLaughlin, 1975; Higgins *et al.*, 1983; Patterson *et al.*, 1980; Rogers and Buchanan, 1976). While control for six to eight weeks after planting usually is adequate, factors such as soil type, soil fertility, geographical location, weather conditions, weed species and their population levels, crop varieties and row spacing can modify that period (Buchanan and Burns, 1971a, 1971b; Chandler and Meredith, 1983; Oliver *et al.*, 1981; Robinson, 1976; Rogers and Buchanan, 1976; Snipes *et al.*, 1983). Some early-

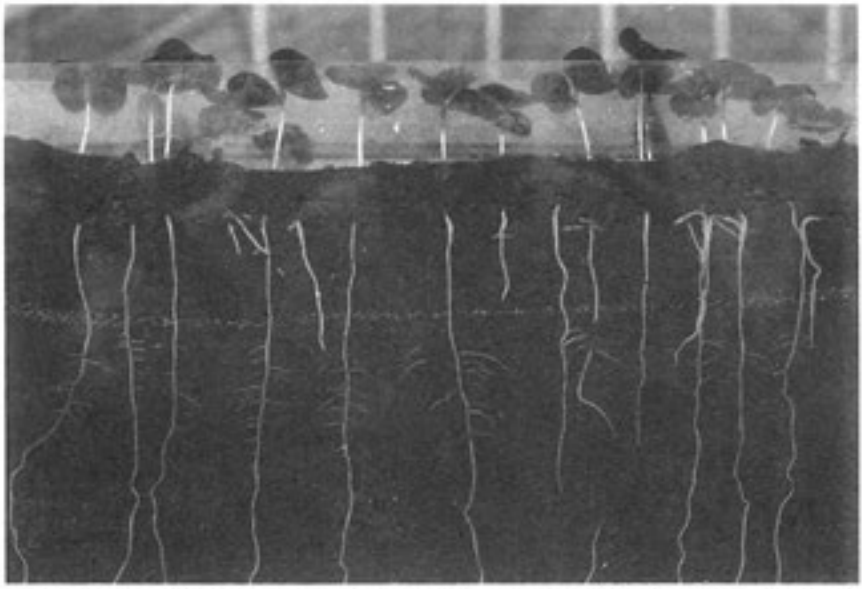


Figure 3. The classic glass box studies with dinitroanilines dramatized "root pruning" differences.

season weed interference will not significantly reduce yields if weeds are removed and the cotton is maintained weed-free for the remainder of the growing season (Buchanan and McGlaughlin, 1975); Higgins *et al.*, 1983; Keeley and Thullen, 1975; Patterson *et al.* 1980; Rogers and Buchanan, 1976). Results from these studies have helped in developing efficient weed management programs and is being incorporated into computer models which should help future growers.

Weed scientists continually work with geneticists and plant breeders in developing and releasing new cultivars to determine how they will respond to the herbicides generally used on the crop. Other cooperative research efforts continually are emerging to improve the efficiency of weed management.



Figure 4. A 1961 observation on irrigated cotton planted into moist soil showed that with no rainfall after planting, barnyardgrass survived on the primary root until post-plant irrigation. Adventitious roots then developed rapidly one, two and seven days later.

EXTENSION'S ROLE IN WEED MANAGEMENT PROGRAMS

Extension was institutionalized by the Smith-Lever Act in 1914, which obligated cooperation between the USDA and land-grant colleges whose state legislatures accepted the provisions of the federal Act (Evans, 1938). It appropriated the money to set up county-based agents who would work with local farmers in setting up local demonstration programs. The Morrill Act in 1862 provided the "Land-grant" concept for state university experiment stations. In 1887 the Hatch Act provided cooperative federal grant-in-aid funding for agricultural research that each state land-grant university justified and undertook. The extension service mission was to "extend" that information to growers.

In the early years, extension was accomplished by schooled professionals who would then stay on the front end of the learning curve by working with innovative colleagues, farmers and others. Since then extension personnel continue to do that but often supplement the latest innovative practices with in-field adaptive research. Especially in weed control, extension weed specialists and county-based personnel usually have well-established programs aimed at developing weed science and weed management data which establishes new practices and

verifies existing practices. This in-field research is widely sought after by innovative farmers so that they might profit from the latest technology.

Typically, extension personnel work with the most innovative growers who then introduce new, more economical farming practices into the community. After most growers utilize such practices, the savings from efficiencies are passed on to the consumers in the form of lower prices. For example, the price of cotton during the Civil War in 1864 was 95 cents per pound of lint. Other conditions, however, have greatly altered prices. After Eli Whitney invented the cotton gin in 1792, the price in 1802 was 14.7 cents a pound. In 1898 it dropped to six cents; in 1931 during the depression, it dropped to 6.3 cents; in 1945, the maximum price during World War II was 27 cents (Brown and Ware, 1958). Prices in 1986-87 ranged from 70-80 cents per pound. Efficiencies have not prevented price variations but certainly increases in prices are much less than increases for manufactured goods. More detail on prices appears in Chapter 2.

With the introduction of radio—and more recently other communication mediums such as television, video cassettes, fascimile machines and desk-top publishing—the information flow has markedly accelerated (Kempen, 1989). Concomitantly, new ideas from anywhere in the world can find an end-user in a given region. Regular conferences, brochures and books, computerized databases along with an increasingly mobile population of farmers result in extension employees being deluged with information. For this reason, more emphasis must be given to quality and less on quantity. That does not mean color or shiny paper, but well-composed grower manuals that are easily used or "user-friendly" computer databases.

Extension's capability at "keeping up" is increasingly at risk due to these new changes. Industry has massive databases which are not publicly accessible, but which enable them to research, develop and market their products. While extension can utilize public databases, it has greater difficulty focusing on getting all components together. Yet, its collective contribution, despite downside problems, is enormously important to our increasingly urbanized society.

In many other nations, extension has been non-existent, or linked to national research and regulatory agencies rather than to the land-grant research and teaching universities that we have in the United States. Some of them are attempting to charge for services rendered, but indications are that these systems will not be successful.[1]

In the United States, most universities now charge for extension publications and weed recommendation guides. Some are attempting to recover operational costs by additional means. Some are trying to have a greater urban focus (to accommodate urban voters). In California, extension specialists and farm advisors are doing most of the field research. Few experiment station researchers are available to do problem-solving field research. Those present must also teach

[1]Personal communication with Don Luvisi, Extension Advisor, while on sabbatical in Australia, 1988.

and do basic research for publication, their key to promotion. All these personnel management aspects impact on inputs into grower weed management programs. But because weed science is the latest of the crop protection sciences to gain recognition among university agricultural disciplines, it has been affected more than most other disciplines by these pressures. Grants-in-aid from crop commodity groups and from the chemical industry have helped in production-oriented weed management studies, but not significantly in basic weed science. Where extension specialists do considerable field research, they have often generated enough grants from industry and commodity groups to hire extra help (Figure 5). In California, the California Planting Cottonseed Distributors, a non-profit group, has funded weed and other research by cooperative extension farm advisors and department researchers for several decades.

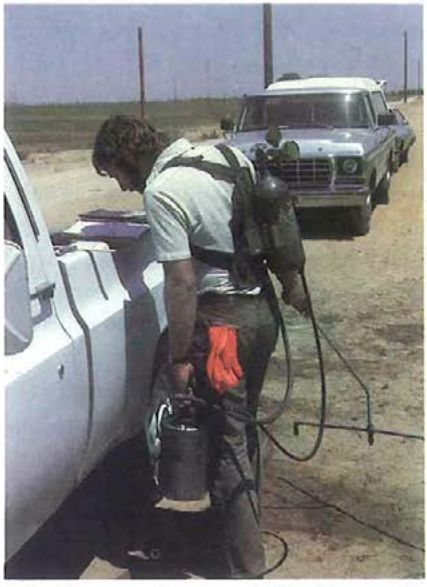


Figure 5. Grant funds from cotton marketing/research groups and manufacturers have enabled extra research assistants for conducting field experiments.

HOW INDUSTRY WORKS WITH PUBLIC AGENCIES

Without a viable agricultural chemical industry, weed management as we know it today would not exist. Industry employees are the ones who invent the chemistry, evaluate it, develop it, sell it and then continuously monitor the results of their efforts. Without the successful sale of herbicides, they would not exist and the marvels of new herbicides such as glyphosate (Roundup®), fluazifop-P (Fusilade 2000®) and sethoxydim (Poast®) would not be commonplace in agricul-

ture today. Millions of dollars would be spent on the arduous task of hand-weeding in the hot sun instead of such labors going into more useful exploits. Only those who grew up doing such tasks, know the dullness and drudgery of such work.

Weed scientists know the cost-effectiveness of products such as atrazine (AAtrex®, etc.), diuron (Karmex®, etc.) and trifluralin (Treflan®, etc.). Prices have not changed appreciably over decades despite continuing inflation of most industrial products. The value to mankind of the newer discoveries such as glyphosate (Roundup®), fluazifop-P (Fusilade 2000®) and nicosulfuron (Accent®), when they have no patent protection and generic introductions appear on the market, will be in the billions of dollars! (Figure 6) And the introduction of biotechnology products will permit development of herbicide-resistant crops which will permit use of low rates of some of these very low animal toxicity, environmentally suitable products on a wide array of crops. The value to mankind will be tremendous, not to mention the reduction in acreage needs devoted to food and fiber production for man's benefit. But, as with the pharmaceutical industry, advances in protecting crops with "farmaceuticals" will not come without profit to the innovators.

Nature's dynamic changes in the genetics of weeds, as with insects, has resulted in the selection of species now resistant to herbicides. A viable industry will stay ahead of this normally occurring reality-of-life on this planet. Otherwise, we will not be able to develop and produce the crop protection chemicals necessary to sustain agriculture in an efficient manner, one that will provide the increasing population of man with ample quantities of quality food and fiber.

Industry's role in the cooperative development of reliable weed management practices is obvious. Regulatory requirements before registration on about five crops cost as much as $25 million. But costs continue after registration due to continuing and new requirements. The successful manufacturer must be uniquely qualified in many areas to be able to cope with it all. And increasingly the manufacturer does it himself, providing partial or total renumeration to those who work with them on these lengthy projects. Whereas industry could fairly well judge where, when and how big their market was, in recent times environmental regulations may eliminate a market or a product. New laws may incur clean-up costs or litigation costs over alleged as well as real hazards. Industry employees must nurture a product from the cradle to the grave, monitoring its development and profitability all along the way.

Industry solicits inputs from academic researchers fairly early in the game, but they must obtain legal control of their products prior to release to the academics. Often larger companies will have done adequate field efficacy studies to obtain EPA and state registrations. But they highly value the inputs of experiment station and extension researchers, in part because of their independent status and their capability to compare with existing products in existing field practice. Also, university department and extension personnel must know the product prior to

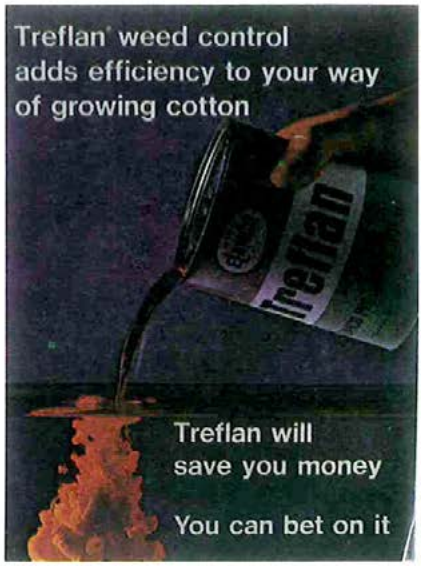


Figure 6. Trifluralin (Treflan®), one of our miracle cotton herbicides, now is sold under generic names at no greater cost per gallon than when registered in 1963.

its introduction so that they can assist growers in its integration with existing practices. Often, the public agency people aid considerably in grower acceptance if a herbicide indeed does work and is cost-effective. In generic markets, new product mixes called "pre-mixes" are introduced to "cannibalize" the market (in business jargon) to gain market share.

When a new proprietary product is introduced, a heavy burden falls on the manufacturer representatives. They have researched the product and know its advantages and disadvantages as well as anyone. They must educate the consultants, applicators and end-users as to how they might best utilize it. Litigation risk is greatest when products are introduced, so they must monitor it well in its early years to see that it is properly used, where further research is needed and where further education is needed. Product awareness is most important. Growers do not use new cost-effective technology without being aware of its existence. So sales efforts are needed, with incentives to distributors and dealers, so that all possible users are advised and aided. Actually, it is a massive effort, and many techniques are used to accomplish the job. Aiming at innovative growers, well-respected specialists and consultants, both directly and through media and promotional programs, they are able to ensure "saturation" of the area needing the effort. Marketing involves complex techniques these days and is a science in itself, which, with the aid of computers, permits reasonably exact analysis of the results from efforts made.

As with the consultants, time is usually the limiting factor in getting the job done well. The circle of technology in agriculture, as in other sciences, is enlarging. New products compete with older (and usually cheaper) ones but, because herbicides can be risky if not used correctly, servicing of older, less profitable products is necessary. Such reduced profit margins put more burden on the sales staff, their technical support team and the researchers themselves. Again, the race is to do research well, sell efficiently, keep up with competitor activity, assist and encourage academics and regulatory personnel so that they are not countering industry efforts and keep the image of the product healthy.

So, increasingly within industry, as with other groups, specialization is necessary. But to manage it all is also necessary. Largeness seemingly is becoming a necessity for all to "stay in the game," be they industry, government, consultants, sales organizations, the popular publications or farmers. Advocacy groups may not like it but they are probably most instrumental in causing this trend. Products registered on minor specialty crops or minor uses in major crops are lost because of lack of profitability. Fortunately, cotton is one of the major crops and efforts to develop new products for it are still major, but not for one weed such as "minor" nutsedge which only infests 10-20 percent of the cotton acreage. With 10 million acres of cotton, 10 percent is only one million. If growers chose to treat 50 percent of the acreage, only 500,000 acres would be treated. To get return on a $25 million development investment in four years after registration, that would need a return of $12.50 in profit per acre treated after all investment and marketing costs. With a 100 percent markup, that means growers would need to be convinced that $25 per acre was a good investment on their part.

Perhaps the biggest lack of cooperation in the entire "working together" concept is from the regulatory and urban sector. Since the regulatory sector operates at the will of politicians who tend to be responsive to the urban sector, it behooves the industry and its cooperators to maintain ties with that sector. We also must help the urban public to understand the upside as well as the downside of crop protection chemicals, and why herbicides have made our American agricultural system so efficient. Without that effort, they who eat will be impacted with greater food and fiber costs. That may not affect the middle classes but it may affect the poor, if we return to paying 23 percent of our disposable income for food as in 1951 as the National Agricultural Chemical Association (NACA) suggests, rather than the 16 percent we spend now (Anonymous, 1987).

THE CONSULTANTS ENTER THE SCENE

Consultants are relatively new to weed management aspects of agriculture. Few independent consultants work on weeds alone. Most advice to growers from consultants come from those who also sell the product.

Nationwide, independent consultants have organized into a group called the

"National Alliance of Independent Crop Consultants (NAICC).[2] There are about 200 members in this organization. Members provide general and specific advice to farmers. While crop protection advice generally is the major service provided, services also include agronomic, horticultural, economic, legal (litigation) and other advice. Some of the consultants also do independent research on agricultural chemicals. The organization's objectives are to share the latest technology and, through monitoring of member performance, meetings, etc., improve the professional standards.

In the area of the Cotton Belt from the Carolinas to the Rio Grande Valley in Texas, there are state and regional organizations of independent consultants. There are some 320-350 independent consultants who work with farmers. In this area, growers appear to use independent crop consultants more widely than in the West. Many focus on entomological and weed management services to growers. Some focus on scouting insects and making recommendations. They usually hire temporary help to do the scouting. If they "do weeds", they must monitor and advise growers themselves since it is too complicated for novices. Many also serve as production consultants, being opportunistic in providing whatever service they can for whatever fee they can get. Relationships are all-important. They source information from university academic and extension staff and regularly attend industry programs on their products. They key in on competent specialists wherever they can find them and thereby try to provide the best information to their grower clients.

In the West, most consultants sell agricultural chemicals to growers as well as provide recommendations (usually written) on the use of all crop protection chemicals including herbicides. In California they are called "Pest Control Advisors" (PCA's). They have organized into an advocacy and upgrading group called the California Agricultural Production Consultants Association (CAPCA). Of the 3,921 registered with the California Department of Food and Agriculture, about 10 percent work with cotton.[3] They must meet educational standards set by a group that is advisory to the Director of the Department. To become a PCA, minimum college requirements must be met, such as a B.S. degree in Biological Science, Agricultural Sciences or Pest Management, or 60 semester units of such coursework, plus two years of internship to a licensed PCA. Other specific coursework such as chemistry, production and pest management and then completion of examinations in laws and regulation, plus each category of crop protection must be met. Of interest is that municipal district pest control employees in cities and irrigation districts must also meet these requirements beginning in 1992. Fees for registration are $80.00 biennially.

Since herbicides are now widely used, pest control advisors have become proficient in weed control practices as well as with insecticides and fungicides (Figure 7). Some also sell fertilizers and rarely crop seeds. They see their larger-

[2]Personal communication with Dr. Louise Henry of NAICC, May, 1988.

[3]Personal communication with Mac Takeda, CDFA, September, 1990.



Figure 7. Consultants monitor grower fields and repeatedly learn of interactions such as here between phorate and trifluralin (1965).

acreage growers weekly during the production season and monitor the progress of the crops enroute to harvest and advise the grower on needs, formulations and technique. They are "on call." Some, through their dealer or distributor franchises, provide in-field application services while others only sell the product and leave the application to commercial applicators or to the grower's staff. On the largest farms, managers have a resident agronomist or other technical employees who are college-educated and who provide recommendations to field staff who manage segments of the agricultural operation (Figure 8). Very few provide independent weed management consulting services for a fixed per-acre fee, citing liability as the chief reason. As do independent consultants in the South, these resident experts seek out the counsel of specialists who they feel are most competent. They do not stop at the local county specialist, but go anywhere in the state, nation, and sometimes internationally to get the information they need. These people need and use the best written material and computerized databases on the subjects for which they are responsible.

Because of the increasing complexity of regulations, including the requirement for written recommendations by regulatory agencies (and by some growers), private consultants are finding a larger proportion of their expertise diminished by paperwork. But the increased complexity logically mandates more written recommendations for applicators, be they commercially hired or farmer managed. Computers are being utilized by some to facilitate the transfer of accurate recommendations and environmental precautions and, no doubt, their use will

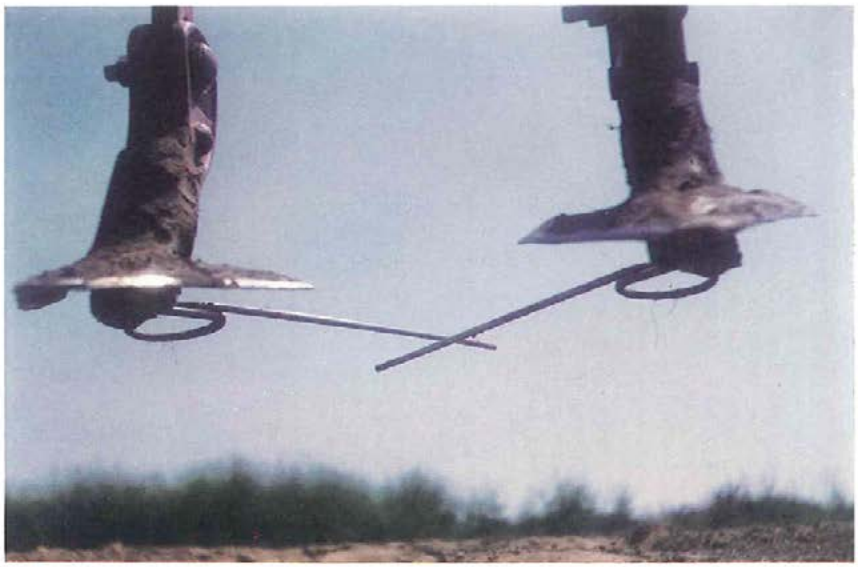


Figure 8. Farm agronomists often find very simple answers to weed problems like this tine weeder for removing seedling weeds out of 8-24" cotton (1972).

be increased in the future. They also may lead to more regulatory controls and result in more problems, such as recent California plant-back restrictions which are legal, not scientific (Kempen, 1987). Full reporting of all pesticide applications by site were required by California law beginning in 1990. The intended objective is to show that not all registered pesticides are being used.

The requirements of the laws—including groundwater contamination rules, plant-back restrictions, cancer or birth-defect considerations, endangered species, transportation, hazardous waste and storage considerations—are becoming so complex that the smaller dealers are unable to cope with the problem. Larger ones increasingly are using computers to keep track of all the detail so as to aid the consultant.

The need to be accurate on weed identification, herbicide application rates, timing, weather conditions, irrigation and regulations, along with grower capabilities and limits, makes the need for a weed consultant logical (Kempen, 1977). Public agency personnel cannot provide all the service needed to growers and growers cannot do it themselves because the circle of technology and regulations have continued to expand. Since many crops are grown with cotton in the West, consultants find themselves limited by time more than anything when getting the best information for the problem. Many become exceptionally competent, since they see many situations in many fields unlike an individual farmer who must keep his shadow in the field. If they monitor the results of their own weed recommendations, they can become very precise in future recommendations. How-

ever, often they do not have time to do this. If selling consultants were paid for monitoring crop protection needs by the acre, or salesmen had larger margins of profit, they could provide growers with the depth of service needed. But competition between dealers plus the growers' acute concern for keeping costs down prevent that. Therefore, all the consultants must rely on public and industry researchers to provide side-by-side comparisons and evaluations of products under many environmental conditions. They also must rely on public agency reseachers for identification of specific weeds new to them.

Consultants are now a most important link in the line of cooperative effort to get from original synthesis of a new herbicide to its fit in a reliable, integrated weed management program. Some also sell herbicide products, but they are reliable because growers are their source of repeated sales. Not many mistakes are allowed. Increasingly, the consultant is the grower's first reliable contact for all crop protection decisions.

THE CAPABILITY OF THE FARMER

Extension and industry managers have determined long ago that there are innovative growers, early acceptors, go-alongs and late adaptors. They tend to work with the innovative growers because other farmers recognize these as the leaders and emulate their newly developed practices.

It is the innovators who are continually involved in the development of new weed management practices. These growers are willing to risk loss from tests or demonstration plots because they get to see the results first and have an advantage over their "competitor" neighbors. Of course, it does take more management to provide this service to cooperating university and industry researchers, but they see the value and the prestige of doing so.

Often they are well-educated individuals and have a flair for doing things well. Their greatest help to researchers is that they can see the "fit" of a new practice and are quick to point out the flaws and limits of it. This is acutely valuable to researchers of new products because no one can afford to waste time on a product that won't be a "new mouse-trap." Growers usually know equipment, irrigation interactions, timely operational requirements, varietal aspects and other "little things" that can make or break a new product. Researchers often are not farmers, and in recent times, most were never reared on a farm. So, the help of various farmers is essential to successful field research. Conditions on various farms vary considerably and growing techniques also vary. Such farmers may permit a new product to become established, or after years of use, develop a new modification of practice which permits greater utility. They are also quick to find out if the product is not reliable from season to season. (Figure 9)

While the use of a new piece of equipment may permit successful usage of a given product, the market potential or penetration of the market is reduced or delayed if growers do not have the proper equipment in hand. A good example



Figure 9. Growers on sandy loams developed this 8-row incorporator-planter unit—called ROCAP (Rolling Cultivators At Planting) in California—for applying trifluralin into moist soil (1963).

of that is the use of sled-shoes (or oiling shoes) in California. They have been used successfully for 35 years in the South because of their need with products like herbicidal oil, and dinoseb (before it was banned in 1986). More recently diuron (Karmex®, etc.), prometryn (Caparol®, etc.), cyanazine (Bladex®), and methazole (Probe®) are combined with MSMA as post-directed sprays. But they have not been needed in California. Recent research has shown that they would be very useful for control of nightshade—a more recent weed problem in cotton—but grower acceptance has been slow due to lack of understanding of the concept (Figure 10). In large part this is due to the unavailability of equipment both on the farm and at the equipment dealer.

As a group, growers are lacking with respect to introduction of new herbicides in that they are too quick to jump into a new practice after one successful experience. Extension and industry advisors know from their broad base of experience that more than one trial and one year is needed before reliability is established. In recent times, the extremely long lag period between efficacy trials and registration of new herbicides makes the chance of risk with newly registered herbicides less, but nonetheless still real. While other new agricultural practices may be advantageously accepted by innovators, they are more likely to experience periodic problems with new herbicides. New, more stringent regulations on research are tending to make field research more precise but less broadly based. This probably will make for more risk with new herbicides. For the grow-

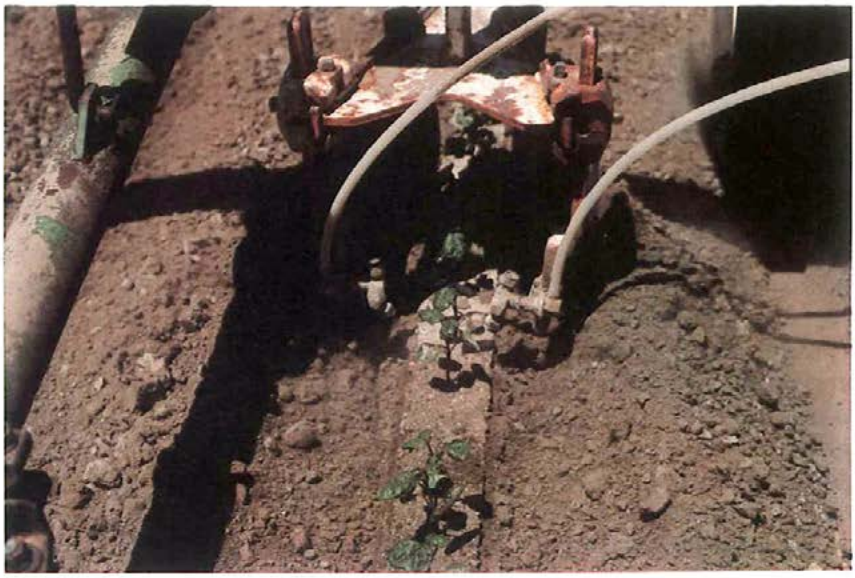


Figure 10. A post-directed spray (PDS) unit set-up by a California production consultant (PCA) for nightshade control in cotton. "Oiling shoes" have been used in the South for decades. Now, this concept is needed in the West (1988).

ers sake, extension leaders should continue to suggest limited treatment with new herbicides.

Growers generally do not know their soil types very well. Most have "light" and "heavy" soils on their farm. But these soils may all be sandy loams or all clay loams. This makes it difficult for them when herbicide recommendations based on soil type are made. They do tend to use minimum label rates when first using new herbicides. Sometimes they discard them because they failed to provide adequate weed control due to too low a rate.

The concept of depth of application was very important with the dinitroaniline herbicides. Some time elapsed before western growers finally switched from disc-harrows designed for field tillage to finishing discs for soil incorporation of herbicides. In the South, growers often disced in trifluralin and then bedded (hipped) up and planted on top of the bed. Roots didn't penetrate the treated zone until corrective practices overcame "cotton stunt" or "saw-tooth" growth in the early season. All in all, it is those growers who have learned to apply science to their farming operations that have survived the agricultural economic recession of the mid-80s.

REGULATORY CONTRIBUTIONS

Regulatory agencies are probably mentioned more frequently in unkind terms than all other cooperators to scientific utilization of weed management. They may deserve it, but often their efforts and actions are little understood by farmers and their advisors, and rarely are regulatory personnel allowed the chance to defend themselves.

Regulatory agencies have done the herbicide industry many favors. When 2,4-D was first introduced, it was seen as a valuable tool but little was known about its downside risks. It caused all sorts of damage to neighboring crops, often for many miles downwind. But the regulatory agencies, such as the California Department of Food and Agriculture through its Title 3 regulations (California Code Section 6464) were able to develop rules and guidelines which allowed end-users to take advantage of its value for the past 40 years. Today millions of acres of crops are still treated with 2,4-D although Cotton Belt users are not kindly disposed to it. One pound can destroy 1000 acres of cotton (Miller *et al.*, 1963).

The greatest regulatory impact is at the beginning of herbicide development. The rules for proving the safety of a new chemical product have expanded enormously and show little sign of abating (USEPA, 1984). Yet in France, by contrast, pesticides were not legally registered until 1990. Perhaps the name accounts for a difference in attitude. In France they call pesticides "produits phytosanitaire."

Single interest advocacy groups have been highly successful in the arena of toxicology and environmental protection, using the mass media to their advantage with a public sector who knows little of agriculture. Yet new products are necessary if we are to continue to protect our crops against a dynamic Mother Nature. Perhaps recent research reported by Ames, Magaw and Gold (1987) or Ames and Gold (1990) showing that many natural carcinogens and anticarcinogens exist in man's diet and pose a greater risk than pesticides will alleviate the major concern that the general public has for agricultural chemicals.

How the regulatory sector—which now includes many non-agricultural groups such as water quality, air quality, health, ecology, fish and wildlife and transportion—will respond to agriculture's needs will determine the future of weed management in cotton and other crops. If biotechnology is accepted by the general public, it might allow American agriculture to advance without many herbicides because several promising techniques could allow the efficiencies we need to afford our current standard of living. But the crop protection industry must remain economically viable, with enough resources to carry on the research needed to meet the broadening requirements of regulatory agencies. Otherwise the entire chemical industry will stagnate and the chances for maintaining today's standard of living in America will diminish.

SUMMARY

Putting together all the elements that make an acceptable end-product, namely a successful weed management program for cotton, involves the efforts of many people who are employed by several different organizations. It is highly systematic and is most effective when people work well together. The system has worked well resulting in excellent improvements to management of weeds in cotton, particularly due to the introduction of several unique herbicides. It has taken many man-years of in-field research, education and servicing to enable it all to happen. Refinements continually occur due, in some cases, to shifts in weed species and, in other cases, higher standards of excellence that are demanded by cotton growers. Getting the best from the herbicides without the problems that can occur requires intensive inputs from manufacturers, distributors, dealers, university and federal research staffs, extension specialists, consultants and the farmers themselves. More recently, consultants have enabled growers to best utilize weed management technologies. With increasing environmental restrictions, they will be more needed by growers in the future.

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Chapter 14

APPENDIX

USEFUL WEED MANAGEMENT PUBLICATIONS

State Extension publications on recommended chemicals (herbicides) such as:

Recommended Chemicals for Weed and Brush Control. Univ. of Arkansas Coop. Ext. Serv., Little Rock, AR 72203.

Growers Weed Management Guide, *2nd Edition.* 1989. Harold M. Kempen. Thomson Publications, P.O. Box 9335, Fresno, CA 95618 (Written for irrigated farming areas, with specific recommendations on 22 crops including cotton. Also weed susceptibility charts and seven chapters on weed management, safety, herbicide use guide and organic farming. $25. 250 pp.).

Other weed management/herbicide publications such as:

Farmers Weed Control Handbook. 1985. King, R, A. Appleby, R. Fawcett, G. Kapusta, G. Mullendore and D. Murray. Doane Publ. 11701 Borman Drive, St. Louis, MO 63146 (A national publication on wheat, corn, soybeans, cotton and milo. It provides good concepts with very good sections on calibration, weed and herbicide basics, label interpretation, safety. Written for farmers for $15-20. 240 pp.).

Delta Crop Digest or California-Arizona Crop Digest. Annually updated. Farm Press Publ. P.O. Box 1420, Clarksdale, MS 38614 (A summary of production and crop protection information from University sources, on major crops. A good source book for farmers and consultants. $7 or less. 215 pp. with advertising).

The Quick Guide. Annually revised. B. C. Page & W. T. Thomson. Thomson Publications, P.O. Box 9335, Fresno, CA 93791 (A listing of insecticides, herbicides and fungicides registered, what organisms they work on, conversions and calibrations and basic manufacturers in the world.).

Crop Protection Chemicals Reference. Updated annually. John Wiley & Sons, Inc., 605 Third Ave., New York, NY 10158. (A compilation of most national crop protection chemical [pesticide] labels in one hardcover book. About $60, but worth it to professionals. 2021 pp.).

Weed Control Manual. Updated annually. Ag Consultant and Fieldman, 37841 Euclid Ave., Willoughby, OH 44094. (A listing by crop of registrations, including weeds, herbicide combinations and rates. About $25. 386 pp.).

Principles of Weed Control in California. Revised, 1988. California Weed Conf. Thomson Publications, P.O Box 9335, Fresno, CA 95618 (Written by 70 special-

ists for California college students. Hardbound, it includes general crop-by-crop information and weed science aspects. About $29. 474 pp.).

University and regional IPM Manuals on cotton, such as:

IPM for Cotton in the Western Region of the U.S. ANR Publ. 3305. DANR, Univ. of California, 6701 San Pablo Ave., Oakland, CA 94608-1239. (Primarily weed identification and monitoring with some information on herbicidal and other techniques.) 144 pp. with color photos. $15.00.

Weed Identification Guide, Set I, II, III, IV. Elmore, C. D., W. A. Skroch, E. C. Murdock, J. F. Miller, E. J. Retzinger, Jr., D. Hall, L. R. Oliver, R. D. Williams and C. Bryson. Southern Weed Science Society. (Available from WSSA, 309 W. Clark St., Champaign, IL 61820 for a fee. Excellent colored photos of 200 weeds of the South).

Growers Weed Identification Handbook. *#4030* University of California Cooperative Extension Offices (County Farm Advisors), or directly from UC at DANR Publications, U.C., 6701 San Pablo Ave., Oakland, CA 94608-1239. (An excellent colored photo guide to crop weeds. About $60.00. 247 weeds in 1990).

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Herbicide Manual: A Water Resources Technical Publication. 1984. U.S. Department of Interior; Bureau of Reclamation. Denver. 346 pp.

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Weed Control in Limited-Tillage Systems. $22.50

Composite List of Weeds. $10.00

Films Involving Weed Science and Weed Identification Publication. Free

5th Edition Herbicide Handbook. $10.00

Germination and Establishment of Weeds for Experimental Purposes. $10.00

Crop Losses Due to Weeds in Canada and the United States. $2.00

Methods of Applying Herbicides. $35.00

Bibliography and Cross-Reference of Weed-Crop Interference and Crop Losses Due to Weeds. $12.00

WSSA Weed Management Database. © 1991. (A listing of 750 extension publications from the United States and Canada. $20.00).

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OTHER SOURCES OF INFORMATION

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University and private short courses.

Chapter 15

WHAT IS IN THE FUTURE?

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INTRODUCTION

This chapter will explore the future of the control of weeds in cotton. Agronomic changes including reduced and no-tillage planting, management practices including the use of on-farm computers, advancements in science including biotechnology and biological weed control, and regulatory, environmental and commercial issues will be discussed. It is by intent that, in most of the discussions, the subject is not reduced to quantification of numbers. If the authors can give readers an insight and an awareness that allow them to anticipate and prepare more effectively for the future, then the objective will be reached. Ideas, concepts and extrapolations are of more value than tables and charts in this particular case.

The most significant factors that will shape the future of cotton weed control and weed control practices in general in the United States are non-technical in nature. These factors—which impact all industries from automotive and steel to agriculture—are regulation, public interest and concern about pesticides, farmer attitudes and the economic status of agriculture. This impact is obvious to those involved in the above industries. More restrictive and/or demanding regulations will delay or eliminate new herbicides or herbicide practices in terms of obtaining regulatory approval. Many current products or practices will be eliminated because registrations are cancelled, label restrictions prevent effective use of the product, or the costs of maintaining registration are excessive.

As public concern about the extent of pesticide use grows, local federal and state regulations will become more restrictive. Further, as urban sprawl moves farther out into agricultural areas, pressures to restrict the use of pesticides will increase.

Finally, poor economic conditions are driving the farmers into modifying all of their practices, including those of weed control. There is far more interest in low-

cost weed control. When all of these factors plus others that are non-technical in nature are considered, the impact on weed control in cotton will be significant.

A difficulty in arranging the subject matter for this discussion is that the issues are interrelated to a significant degree. It is difficult to discuss environmental issues without discussing the parallel regulatory issues, or the impact on future farmer practices. Trends in the cotton acreage planted each year will impact weed problems. As planted acres increase, the new acres will have a different weed complex. The economic outlook for cotton also impacts the control practices used by the farmer. The acreage of cotton has varied from 14.5 million to 9.5 million during the last two decades. Barring political programs which override supply and demand forces, it will probably vary that much in the next two decades. In the early days of chemical weed control, the rate of change in practices depended primarily on how rapidly the technology could evolve. Performance in terms of weed control and crop safety were the two most important considerations as new molecular structures were developed. Methods of application received considerable attention. Those people concerned with weed control in cotton—or those who had an impact on weed control in cotton—were, for the most part, limited to farmers, researchers, extension staffs of academic institutions and USDA, and personnel from industry involved in the process. The use of herbicides in cotton was regulated by USDA and, when required, FDA. Subsequent changes in federal law during the early 1970s have positioned EPA as the lead agency in pesticide regulation. Today, effects upon man and the environment are given more consideration as selection criteria in evaluating new molecules.

The rate of change is accelerating in our society and weed control is no exception. As we consider the changes over the last three decades, the most fascinating of all are within the research process for discovering new compounds. Beginning with the synthesis of candidate molecules through the generation of data to support registration, the equipment, techniques and procedures have evolved at an astounding rate. Today, most synthesis efforts are computer assisted with literature reviews and patent searches also computer-based. Many procedures used in initial biological evaluations have changed from labor-intensive to automated. Examples are pot filling, seed counting, and even evaluation. Data are entered directly into a computer, with statistically analyzed results waiting for the scientist when he returns to his desk. Compared to the laborious and slower hand operations of 30 years ago, this is a remarkable change.

BIOTECHNOLOGY

The future of weed control in cotton will be strongly influenced by the emergence and commercialization of a new science—that of biotechnology. Biotechnology is usually defined as the science of genetic modification of organisms, primarily through recombinant DNA techniques, but is not limited to that approach.

The field of biotechnology is advancing so rapidly that scientific milestones which were expected to be reached in years are being achieved in months. It can now be stated with high probability that biotechnology will impact conventional weed control. Earlier estimates of practical applications available for field use have been advanced from the first decade of the next century to the decade of the 1990s. Perhaps a more accurate prediction of the future will be the emergence of biotechnology as a key element in the control of weeds in cotton through integration of the science of biotechnology with conventional weed science as practiced in the 1980s.

CONVENTIONAL SCREENING PROCESS

The conventional and proven method of bringing a new chemical herbicide to the marketplace usually involves a sequence of science and technology in the following order:

1. The selection of cotton as a target crop, which means that herbicide candidates will be evaluated early in the testing procedure to determine safety on cotton;
2. The identification and selection of appropriate weed species for the screening procedure;
3. The synthesis and evaluation of large numbers (several thousand) of new compounds as herbicide candidates;
4. The selection of promising candidates for more thorough examination;
5. Identification of the final candidate as a target for commercialization;
6. The initiation of a number of processes to generate the data required for regulatory approval including toxicology, detoxification, and safety to users and non-target life forms in the environment;
7. Determination of the commercial effectiveness of the compound; and,
8. Process studies to design and build facilities to produce, formulate and package the candidate. This process—from the initiation of screening to first farmer-use of a registered cotton herbicide in the United States—can take a minimum of six to eight years or as many as 15 to 20 years.

BIOTECHNOLOGY PROCESS

The procedure for a product of biotechnology research to be utilized in cotton is somewhat speculative and less precisely defined, but, nevertheless, is now underway.

The selection of cotton as a target crop and identification of weed species will parallel that of the conventional method. In both cases, key parameters must be considered. These include size of market, estimated length of time to success,

technical and commercial probability of success, resources required to sustain a research and development program and a comparison with other opportunities competing for resources.

In the new situation, instead of screening new chemical candidates, the sequence is:

1. A search for a gene or gene sequence which confers herbicide tolerance;
2. Insertion into the genetic base of an individual cell of a cotton plant;
3. The cell regenerated to a new plant; and,
4. The desired traits demonstrated in that plant and in second-generation plants.

Once it is established that the new gene(s) is being expressed in the progeny, the utility of the gene must be demonstrated in field trials analogous to that of field-testing a new herbicide. The technology is at a stage where routine regeneration of cotton from cells and the insertion, transformation and expression of new genes in cotton will not be a barrier to using this new science for improved weed control in cotton. The most likely first product of biotechnology that will impact weed control in cotton will be the insertion of a gene that will confer resistance to glyphosate, N(phosphonomethyl)glycine (Roundup®), applied at commercial use rates. Glyphosate is a broad-spectrum, non-selective, post-emergence herbicide used for the control of many annual and perennial broadleaf and grass species (Baird *et al.*, 1971). It has minimal impact on the environment—*i. e.*, no soil residual, no bio-accumulation, and minimal leaching. (Rueppel *et al.*, 1977).

The insertion of the new gene will allow glyphosate to be sprayed over the top of cotton at rates which will control a wide range of weeds including johnsongrass, cocklebur, prickly sida, and crabgrass. This new development will give the cotton farmer a high degree of flexibility in his weed control program. Cotton resistance to other herbicides through biotechnology also is likely, and by the year 2000, the farmer should have a choice of several very effective herbicides which are currently phytotoxic to common varieties of cotton.

The availability of cotton with engineered herbicide tolerance will have a number of advantages for the cotton farmer. Most important would be immediate access to current herbicides which have met the regulatory requirements, and whose performance is comparatively well understood. The impact of soil type, moisture, rate, and susceptibility of weed species will have been observed under farmer-use conditions. This also may allow planting in fields infested with weeds which could not be controlled economically with conventional herbicides. No-tillage and reduced-tillage cotton planting also could expand in areas where selective herbicides were not available.

NEW ISSUES AND CONSIDERATIONS

Every new breakthrough in science brings a new set of issues. Biotechnology

poses new issues to weed science in cotton. In addition, some current issues are involved. As herbicides are registered for new uses in crops as well as for new crops, regulatory requirements ranging from establishment of new tolerances to determination of impact on the acceptable daily intake (ADI) must be considered. For instance, an over-the-top application of a herbicide already registered for pre-plant application may change the residue levels on or in cotton seed and thus require establishment of a new regulatory tolerance.

New performance issues must be dealt with in the control of weeds in a genetically-modified, herbicide-tolerant crop. For instance, is the degree of resistance expressed as well under conditions of drought stress as under excessive moisture? What are the effects of colder than normal versus warmer than normal air and/or soil temperatures on the genetic expression of resistance? If the herbicide is postemergence active and its previous use was as a preplant treatment, as in the case with glyphosate, will the influence of the crop canopy on the control of small weeds require different nozzle arrangements? Will the spectrum of weeds and stages of weed growth present in cotton differ from those already labeled and require adjustment of the rate? Are there new problems of interaction with other pesticides that are analogous to the propanil-carbamate (*e.g.* herbicide [Stam®], insecticide [Sevin®]) interaction that causes severe injury to rice? These issues are not barriers to the genetic modification of crops to be resistant to herbicides; however, it is clear that the need for insightful, well-designed experiments in the area of applied weed science will be critical to the successful commercial introduction of this new, exciting science.

The seed industry will have a significant role to play as herbicide-resistant cotton varieties are brought to the marketplace. In the past, when a new cotton herbicide was commercialized, seed companies were involved to the extent that the herbicide had sufficient safety on the companies' varieties. Some soybean breeding programs have resulted in the selection of a variety with increased herbicide tolerance, *i. e.* 'Tracy M'. The use of a herbicide-resistant cotton variety will call for major technical input from the seed company over several years. This commitment of resources will not be made frequently. The practical implementation of biotechnology will depend upon the capability of the seed supplier to bring the engineered varieties to the cotton farmer.

Another requirement for the practical use of biotechnology in weed control in cotton is apparent and must be addressed. It is the need for collaboration and teamwork by scientists working in biotechnology with those in traditional weed control programs. The successful introduction of weed control practices and the rapid and widespread use of chemical weed control for cotton in the United States was due in no small part to the early and continuing cooperation by a wide range of scientific disciplines—the plant physiologist, taxonomist, chemist, biochemist, agricultural engineer, agronomist, horticulturist, forester and soil scientist. With few exceptions, there were no departments of weed science comparable to departments of entomology and plant pathology. The weed scientist, by

necessity, was exposed to a broader array of scientific disciplines and weed science moved forward on a faster track.

Continued involvement by a wide range of disciplines will be necessary to capture the value of biotechnology for weed control in cotton. To be effective in bringing practical results to the farmer in a timely and efficient process, the cell biologist, the geneticist and the plant breeder—together with their related disciplines—must interact just as comfortably with those involved in weed science, as others did in the past.

BIOLOGICAL CONTROL

Insects, fungi, bacteria and viruses represent possible agents for weed control in cotton. Considerable attention has been given to this approach in the past. Commercialization has occurred in citrus, pasture and rangeland. The control of northern jointvetch was proven technically possible in rice, but was not commercially successful. This approach will accelerate in the future for several reasons. First, regulatory and public pressures are pushing this new approach. More resources are being invested in biological control as an alternative to chemical weed control. Government, academic and industrial scientists are proceeding in a cooperative manner to identify candidate organisms. Researchers now have the knowledge, skills and experience to obtain consistent, predictable and acceptable levels of weed control. Finally, the integration of biotechnology and biological weed control will substantially increase the number and quality of candidate organisms for this use.

As with any emerging technology, the use of biological weed control agents is confronted with several new issues, in addition to those encountered by conventional herbicides. These include: (a) new, different and increasing regulatory requirements; (b) the influence of environmental factors and climate upon effectiveness; (c) performance criteria; (d) possible escape of an introduced organism to non-target hosts; (e) market opportunity for the basic producer; (f) patent coverage considerations; (g) new delivery and application systems; and, (h) new educational and sales programs.

Regulatory history on the registration of biological weed control agents is limited. Only a few organisms have been successfully released within the last decade. Based upon events within the past two years, it appears that regulatory procedures and requirements will become more demanding, rigid and time-consuming. This will occur even where the biological agent is native to the environment. Public concern of the scientific community is high regarding the release of living life forms into a new area, particularly if they are microorganisms. The level of concern is even more acute for bioengineered organisms.

New regulatory demands will occur not only at the federal level, but also at the state and local levels as agencies respond to this new technology. While promulgated as being of assistance to the development of an emerging new technology,

the regulations enacted, in fact, will be precautionary in nature. The real effect will be longer and more costly development programs and delayed availability to the cotton grower.

Based upon knowledge and experience gained so far, considerable improvement in results will be required for consistent performance in the field. Environmental factors including temperature, relative humidity, solar radiation and soil moisture must be better understood as to their effects upon a biological agent's ability to colonize and grow in the crop environment.

Acceptance of new performance criteria by growers who successfully use biological agents will sometimes be required. Growers accustomed to observing necrosis on treated weeds within days or hours after application of a herbicide will be concerned with slower symptom development from a biological agent and the continued growth of weeds for perhaps days after treatment. Related questions are posed. If the biological agent fails, will retreatment at a later stage of weed development be effective? If the biological agent is narrowly host-specific, will control of the host weed result in death of the biological agent for lack of a food supply, thereby necessitating a second application for newly emerged weeds?

New economic thresholds for weed control may be required with some biological agents. This will be true particularly for cotton growers, who generally have exceptionally high performance standards versus those for soybeans. This is due largely to the use of mechanical harvesters and loss in grade due to grass or stain in the gin sample. A weed which has been successfully colonized by a pathogen or insect may be rendered essentially noncompetitive with the crop even though it remains alive. Cooperative studies by traditional weed scientists and biological control scientists will be necessary to determine the correct population and timing thresholds for most profitable use by growers.

Delivery or application systems must be developed for effective use of biological agents. Traditional herbicides are formulated for application by granular units or hydraulic sprayers. These have been effective with some plant pathogens, but modifications will be in order for others. For instance, a pathogen which requires abrasion of the leaf surface for successful inoculation might be significantly more virulent if minute, sharp particles were included in the formulation or added to the air or liquid carrier. This would require the use of components in the applicator which would be largely unaffected by the particles. Time of application will need to be determined. For instance, fungal organisms used for weed control generally have higher survival rates when moisture is maintained on the infection court during inoculation—in practical use, this means that success is highest when the application is made to wet foliage under humid conditions maintained for the number of hours required for infection of the weed.

Adequate market size is important to a potential producer of a new product. Just as a young man contemplating farming as a career cannot economically justify a 20-acre cotton operation, a potential producer of a new biological herbi-

cide must consider the market size. Since it can be anticipated that biological weed control agents will be weed-specific, the market potential for any given product will be comparatively small. The cost of registration is essentially the same regardless of the size of the market, so it will not be economically feasible to commercialize small market products. This specificity is well demonstrated by a product trade-named Collego® which was based upon the microorganism *Colletotrichum gloeosporiodes*. This organism is pathogenic to northern jointvetch and does not injure rice. It was developed and registered for use in rice and was successful on the target weed. It was not well accepted by rice growers, however, due to its lack of activity on Indian jointvetch, a related species which inhabits rice. Thus a scientific success following many years of research and development culminated in commercial failure due to weed specificity.

Another example of a technical success in the control of a weed with a biological agent is that of the control of stranglervine in Florida citrus with a species of *Phytophora*. A product based upon the organism was so effective on stranglervine, a major problem weed, that future sales will be limited to scattered small infestations. Such narrow specificity is desirable in that it allows use on a target weed without injury to non-target species. Yet, that very characteristic makes it financially unattractive to the product manufacturer.

The biological control of weeds in cotton is in the early stages of development, with no current farmer use. Yet progress is predicted and, in fact, is inevitable. One only has to observe insects selectively feeding on horsenettle in the field or see morningglory diseased with a naturally-occurring pathogen to be optimistic. The rate of advancement is increasing both in the public and private sectors. The most significant advancements will probably be based upon genetically altered organisms and research programs where scientists in biotechnology and traditional weed control work together.

HERBICIDE RESISTANCE AND ENHANCED DEGRADATION

Two major areas of investigation during the next two decades will be genetic resistance in weeds to herbicides and the buildup in the soil of microorganisms which detoxify the herbicide to prevent acceptable weed control.

Tolerance is perhaps a better term than resistance in that the latter implies an absolute condition. Populations of weed species in the field are heterogeneous and several generations of seed are likely present. Thus the genetic diversity which helps ensure survival of the species can result in lines or varieties of a species in which a genetic character for tolerance to a particular herbicide is repeated in succeeding generations. With repeated use or exposure to the same herbicide over a period of years, the percentage of the native population of that weed species carrying the resistant trait is increased. With sufficient repeated use and production of viable seed, the resistance-bearing strain may repopulate to

the point that it predominates. This is particularly true where control of the susceptible species is maintained at a high level over a period of years where crop rotation and herbicide rotation are not exercised.

The development of herbicide-resistant strains of weed species has been anticipated, based upon the history of insect resistance to individual insecticides and then to classes of insecticides. It was found that repeated use and dependence upon a single insecticide, such as DDT, resulted in the selection of a tolerant strain. With continued exposure, each succeeding generation contained a larger number of offspring carrying the trait for tolerance. Effective control required increasing rates of the insecticide and eventually forced growers to switch to other compounds within the same insecticide class, and then to completely different classes.

The development of herbicide resistance in weed species has been slow to actually occur. As compared to insects, most weeds which infest cultivated row crops have much longer life cycles, are generally exposed to only one or two applications of a single herbicide annually, and would thus require a longer period of time for a tolerant population to develop through random selection pressure from the herbicide.

In reviewing the results of a 14-year integrated weed management system research program conducted in Illinois, Shaw (1982) reported there was no evidence of increased resistance to any specific herbicide by any specific weed species. The results of the use of chemical weed control programs were: significantly increased yields of corn and soybeans, reduced weed seed populations in soil, reduced tillage, improved harvesting efficiency, reduced labor and increased net farm income.

Mudge *et al.* (1984) confirmed the presence of a dinitroanaline-resistant biotype of goosegrass in South Carolina. He reported that resistant goosegrass had been suspected since the early 1970s in a cotton-producing area, and that subsequent field experiments with trifluralin (Treflan®) and related dinitroaniline compounds confirmed the low level of activity reported by growers in the area. Laboratory research conducted by Vaughn and Koskinen (1987) in Mississippi traced resistance to one gene and one protein in the resistant goosegrass plants.

The most recent assessment of the development of herbicide-resistant weeds was given by LeBaron (1987) who reported that 58 species of weeds have become resistant to seven different types of herbicides in 32 states and 13 countries. He further stated that several are present and spreading in several of our southern states. However, we estimate that less than one percent of herbicide usage worldwide is impacted by resistant weeds.

From an overall economic viewpoint, herbicide resistance is unlikely to be a significant threat to the financial well-being of the United States Cotton Belt. Climate, soils, weed species and cultural practices vary widely across the Belt. Control practices therefore vary widely. The presence of several weed species,

including both annuals and perennials, precludes reliance upon single herbicides or single cultural practices for control.

While the Beltwide threat of resistant weeds is considered remote, the occurrence is more likely in localized areas where cotton is grown continuously and the same weed control programs and herbicides are used repeatedly. Shaw (1982), in his review of the 14-year study with corn and soybeans, reported that net profits were greater where both rotational cropping and rotational herbicides were used. The cotton grower is fortunate in having at his disposal an array of weed control tools, chemical and mechanical. Seldom is he dependent upon herbicides alone or upon single herbicides. Due to the variety of control methods employed in today's integrated weed management programs, genetic resistance to herbicides is unlikely to be economically important outside localized areas.

Care must be taken to ensure that one new favorable development—herbicide-resistant cotton (and other crops)—does not exacerbate the unfavorable situation of herbicide-resistant weeds. A very effective herbicide used on one crop in a rotation system could be used on other crops on the same land in a rotation system if those crops were genetically modified to be resistant to the herbicide. However, the increased use of the herbicide on the same land could expedite resistance development in the weeds.

Additional studies should provide information on the cultural practices required to give the best balance between the avoidance of weed resistance or herbicide susceptibility to microbes while maintaining an effective, low cost herbicide program. With proper effort, those two objectives should not be mutually exclusive.

Harvey and Schuman (1981) reported degradation of EPTC (Eradicane®) by naturally occurring soil organisms which feed upon the active ingredient and result in detoxification. The manufacturer added a compound to extend the herbicidal life of the active ingredient against microbial breakdown. Results of the addition of the protectant were positive, however, rapid degradation and unacceptable weed control have since been reported by growers with repeated use on the same fields.

COMPUTER TECHNOLOGY AND WEED CONTROL

COMPUTER-ASSISTED FARM MANAGEMENT

The computer age has not left the cotton producer on the outside looking in. Desktops, PCs, CRTs, RAM and disk drives are now part of the vocabulary on many cotton farms. Once primarily used to store and organize financial, production and personnel records, they are being used increasingly as an aid in both financial and production planning including weed control programs.

Several factors will accelerate the adoption of computers as a routine tool for the farmer. The costs of information systems, the computer and the software are dropping rapidly so that the cost per unit of information is dropping even faster.

Small computers are now available that can easily handle a large, complex farm operation. With the trend toward larger farms, the owner and/or manager will be capable of and more likely to utilize computers as part of a management system.

Most land-grant universities across the Cotton Belt have programs available to their growers through the county extension office. For instance, the state extension weed specialist in Mississippi[1] has a program on sprayer calibration available to county agricultural agents. He also has a spread sheet available in disk form to aid in herbicide selection. The grower can use it with the computer located in the county agent's office or with his own compatible PC. In Alabama, the state extension weed control specialist[2] has disks with sprayer calibration information and herbicide weed control ratings charts for the major crops. Computers in the county extension offices are telephone-connected to the Auburn University campus. Georgia[3] and North Carolina[4] have similar programs. The programs and equipment differ within each state but are designed to meet the specific needs of cotton and other crop producers within their respective states.

Radio Shack and IBM equipment are now common in the county agent's office. Most software programs which aid growers in selecting their weed control programs require that they manually insert the major weed species to be controlled, the herbicides available, rates per acre and purchase costs per unit. The programs then display the most cost-effective options. Once selections are made, a hard copy is printed. Most programs contain information on each product registered for the crop, a species list and control rating by product, and application technique. A few programs also contain information on weed competition and yield response by time and duration of competitiveness. The computer-assisted programs available from all states are evolving toward providing the most cost-effective control programs to growers. In cotton, competition data are available which show the influence on crop yield of these species: pigweed, sicklepod, some morninglories, prickly sida, spurred anoda, johnsongrass, bermudagrass, unicorn plant, silverleaf nightshade, yellow nutsedge, velvetleaf and cocklebur. With the large amount of data available on weed biology and crop interference, it is inevitable that better and more useful computer-assisted programs will be available to growers, consultants and others on how to obtain the most cost-effective and environmentally sound weed control programs.

Farm managers will be helped in their decision-making process by the increasing availability of computer information. Agricultural experts from universities, USDA, seed companies and chemical companies will rely upon computer software as a major means of disseminating information. Much more detailed infor-

[1]Houston, Douglas W., Mississippi State University, Mississippi State, Mississippi, 39762. Personal communition.

[2]Everest, John W., Auburn University, Auburn, Alabama 36849. Personal communication.

[3]French, Michael C., University of Georgia, Athens, Georgia 30602. Personal communication.

[4]Coble, Harold D., North Carolina State University, Raleigh, North Carolina 27695-7620. Personal communication.

mation on each herbicide will be available than now appears on the label because the information can be developed for localized soil and climatic conditions.

In weed research, with utilization of the enhanced capability of computer technology, it should be possible to predict the impact of specific production practices on the weed problems of the cotton farmer ranging from local areas to large regions. Those who interface with the cotton farmer—the suppliers, consultants, researchers and extension workers—must also become computer-literate.

COMPUTER-ASSISTED GROWTH SIMULATION MODELS

Plant growth and yield models for several major agronomic crops including cotton have been constructed. The models are based upon precise observation and measurement of crop growth and development, and the influence of soil moisture or other specific factors upon that growth and development. The growth measurements are repeated, verified and tried for predictability at additional locations. Once a growth response is repeated at a high level of probability, it is stored on software (computer disk). Plant growth and development which occurred under real conditions then serve as the data base to allow the computer to simulate crop growth under a theoretical condition—for instance, to predict the effect of 20 days of dry weather beginning at first square.

The GOSSYM computer model, which simulates the growth of the cotton plant during the entire year, is a highly advanced model with proven value to producers (Baker *et al.*, 1983). It simulates the growth and development of the cotton plant including roots, stems, leaves, blooms, squares and bolls and is updated daily with information on maximum and minimum temperature, solar radiation and rainfall.

COMAX, a computer program that performs logic or analyses of large quantities of data, was developed to work in conjunction with the GOSSYM growth model on cotton (Lemmon, 1986). By using a database (GOSSYM) and daily updated weather data, COMAX can sort information and logically calculate the correct timing for irrigation, fertilizer and defoliants. Use in large-scale grower trials in Mississippi and South Carolina verified its accuracy.

In the future, with increasing availability of computer modeling and more attention to the growth characteristics of weeds, it should be possible to anticipate and predict the impact of changes in production practices on the weed population, and therefore on the need for changes in weed control practices.

Simulation modeling of weed growth and development is in its infancy. Orwick *et al.* (1978) reported on a growth simulation model for *Setaria*. Work on a number of species toward computer modeling is underway in Florida and North Carolina. Bridges (1987) recently developed a model which predicts the date of flowering of seedling johnsongrass within 24 hours. Research on computer modeling of weed growth and development currently is underway on a large number of species in several states. Given an existing database, progress will come quickly. Where a database on an individual species is lacking, several years will

be required before information can be made useful to the grower in making weed control decisions. The availability of weed competition data will make growth models even more useful. Much more complex analyses will be required when weed/crop interference data involving several weeds simultaneously are analyzed for their combined influence on crop yield. Weed growth and development information will be needed on each species to serve as a database.

Local environmental measurements (on-farm or near-farm weather data) will be necessary to support decision-making. Without supporting weather information, knowledge of the growth and development of the crop and competing weed will be inadequate to the weed control decision. For instance, McWhorter (1987) determined that moisture stress was basic to the competitiveness of johnsongrass with soybeans. The yield response to johnsongrass population and time and duration of competition were inconsistent from year to year until correlated with soil moisture measurements.

Growth simulation models for the major weeds across the Cotton Belt would require information on germination, emergence, growth and development in response to temperature, soil moisture, solar radiation and related factors. Where these data exist, simulation modeling is underway at a number of universities. Benefits to cotton producers would be as follows: (a) knowledge of when to expect emergence of individual species; (b) understanding of when to anticipate certain species in response to certain weather conditions; (c) knowledge of rate of growth under given conditions; and (d) ability to properly time control measure, particularly of postemergence herbicides.

COMPUTER-ASSISTED WEED MAPS

The changing farm practices in the cultivation of cotton become both a cause and effect in the characterization and control of weeds. In some cases, the farmer changes his practices for purposes unrelated to weeds, or the consideration of weed control is secondary to the main purpose. As a result of the change, however, the weed population shifts and therefore the farmer's weed control practices must shift.

On-the-farm mapping of weed infestations is one of the most neglected aids to good weed control management. Like good soil and cropping maps, a weed map of each field is a useful aid to next season's planning. Crop selection and tillage can be dependent on weed control. On land newly planted to cotton or operated by a new tenant, a weed species map is valuable. This is particularly true with the residual herbicides applied preplant, incorporated and preemergence. It is not uncommon to assume that prickly sida infests an entire field when in fact it occurs only across one side. Accurate weed maps allow better decision-making at lower cost.

Herbicide use maps can be equally as useful as weed maps, particularly where crop rotation is used. A two-year history of the weed control program, including herbicides, can pay dividends. This is particularly true where land ownership or

management changes hands. Knowledge of the weed control program used the previous year, along with weed maps of individual fields, can prevent a costly herbicide carryover problem and can help match the correct control program to the weeds present. The increasing availability of personal computers and software will aid farmers in developing and storing weed and crop maps as management tools.

COTTON MONOCULTURE

Continuous planting without rotation is no stranger to the Cotton Belt (Broyles, 1987). Most communities have a story about some particular field being in cotton for as long as anyone remembers. Technical advances, particularly in insect control and disease resistance, have allowed continuous cotton production and supported the concentration of acreage on the best producing fields in high-yielding areas. Expansion of planted acreage will, in many areas of the Cotton Belt, result in even greater continuous cotton on the top yielding soils. Shifts in weed infestations, both by individual species and by population densities, can be expected. Continuous cotton eliminates rotation as a potential weed control measure. Frans (1969) attributed an increase in broadleaf weed populations in cotton to widespread and repeated use of trifluralin, reduced cultivation and reduced hand hoeing. Baker (1982) reported on specific weaknesses of individual cotton herbicides which he believed could result in changing weed problems with continued use of those herbicides. Weaknesses reported were cyanazine (Bladex®) on annual grasses, diuron (Karmex®) on prickly sida and norflurazon (Zorial®) on pitted morningglory. Baker predicted that with long-term repeated use of the individual compounds, changes in the weed infestation would require the use of supplemental practices such as directed postemergence herbicide sprays and hand weeding. Based upon later research, Baker (1984) reported on a three-year field study in which diuron and fluometuron (Cotoran®) were weak on erect spurge. With continued use of both products which are recommended and widely used in cotton, spurge infestations would be expected to increase unless supplemental control measures were employed.

An advantage to continuous cotton is that it allows the use of long residual herbicides which might otherwise pose rotational restrictions. Concentration of the cotton acreage into monoculture areas could allow the development of herbicides having long residual activity (Broyles, 1987). Annual applications routinely practiced today might not be required, particularly as new products having high unit activity (grams/acre rates) are developed. Application timing in the off season several months ahead of the planting date when schedules are less hectic could become routine.

In summary, monocropping is expected to increase in high-producing cotton areas. Shifting weed populations will require shifts in weed control practices which can be effective with today's materials. In the long-term, producers may

benefit by the development of more effective residual herbicides which are selective only in cotton.

IRRIGATION

While irrigation is necessary to cotton production in much of the western United States, the rainbelt area has largely been dependent upon natural rainfall. For several reasons, the use of irrigation in the rainbelt area has been increasing. These include drought and unstable prices during the early 1980s. Many growers are reducing their risk of crop loss by installing irrigation. Its increasing use has resulted in increasing weed infestations. As with rainfall, a new flush emerges with each irrigation. Some growers have been unprepared to handle this problem, particularly where rainfall followed the irrigation and prevented timely control measures. Greater weed infestations may be present before layby or may occur after layby, particularly where the crop canopy is not closed. Irrigated skip-row cotton can be particularly susceptible to mid- and late-season weed infestations. Unless fields are relatively weed-free, irrigation often results in increased need for postdirected, topical and layby herbicides. Perennial species including purple nutsedge and bermudagrass as well as annuals have been reported as troublesome by growers who irrigate. The products and recommendations are available to control weeds in irrigated cotton. New irrigation users, particularly on skip row plantings, will find that late postemergence and layby programs are more important.

NEW APPLICATION TECHNOLOGY

Cotton growers have used a myriad of new application techniques and tools to control weeds in the past three decades. These have ranged from subsurface injection and subsurface layering to recirculating sprayers and wiper devices for postemergence herbicide applications. Carrier volumes per acre have been reduced to save time and money while maintaining effective control. Adjuvants to reduce drift from postemergence herbicides and the use of helicopters with specially equipped booms allow more precise placement with reduced threat of off-target drift. Controlled droplet applicators (CDA) produce spray patterns in which particles can be confined to a narrower size range with fewer fines and oversize droplets. Highly accurate speedometers which are independent of engine speed or wheel revolution are in common use. Injection pumps and metering devices now available on sprayers allow delivery of undiluted liquid and flowable products to be injected in the liquid carrier line between the pump and nozzle. Advantages of this system are that unused product can be returned to the original container, incompatibility of products can be reduced, and small quantities of both herbicide and carrier can be accurately measured. A trend in herbicide application has been the use of higher travel speeds. It is common to see large

three-wheel and four-wheel field sprayers operating at 15 mph across the Cotton Belt.

More precise spray tips produced from a variety of materials, including hardened stainless steel, are available, as are those designed to reduce drift. New nozzle body and cap designs with color coding allow quick, convenient and safer maintenance and changes. Some technologies including electronic weed control with high-voltage, tractor-drawn generators have not proven practical in field use. Others, including electrostatically charged particles, appear promising for better retention and deposition of postemergence herbicides.

The advancements listed above have been useful, particularly at the practical level for grower benefit. Yet, it is widely perceived among professionals working in weed science that advances in chemical technology have outdistanced application technology.

At a conference on application technology sponsored by the Agricultural Research Institute, USDA's Agricultural Research Service, and the U. S. Environmental Protection Agency in 1985, it was concluded among other things that research in this area is inadequate in spite of public concern for potential environmental contamination and a growing need for precision application (Hall, 1985).

This view also is expressed in a report by McWhorter and Barrentine (1988) in which weed science research needs were ranked. Members of the Weed Science Society of America ranked high the research area to "develop new application techniques that minimize or eliminate herbicides and their residues in air and water." Increased focus on the mechanics of herbicide delivery and placement and upon equipment operation, in fact, can be expected to reduce herbicide residues from air and water. Major breakthroughs in the basic systems used to apply herbicides in the past three decades have been direct wipers and CDAs. Based upon these developments, it is predicted that continued progress will be on the order of steady small steps with occasional giant leaps forward. It is further predicted that progress in the giant-leap category is likely to occur from a joint effort by the product formulation chemist, engineer and weed scientist.

Previous advances have been made in the design and component perfection of either liquid, granular or air carrier systems and in products formulated for those systems. It is now appropriate that the reverse order will prevail—that new delivery systems will be developed to meet the rapidly occurring advances in formulation technology. Dry flowables, water soluble granules, water dispersable granules, microencapsulation, time-released formulations and new grams/acre activity levels of new classes of herbicides will be of most benefit to the cotton grower when application systems and components are designed specifically for this technology rather than retrofitted.

NEW CULTURAL PRACTICES

Current production trends and research investigations into new control techniques and strategies point the way toward future weed control programs in cotton. These are responsive to the trends toward reduced preplant tillage, increased mechanization, less labor availability, the need for tighter production budgeting, heightened awareness of environmental safety, more stringent registration requirements, and the cancellation of some products such as dinoseb (Premerge®). The trend toward reduced tillage, particularly preplant tillage, was accelerated by petroleum price increases and the need to reduce production costs. Growers who had traditionally used six to ten preplant tillage trips learned that yields were maintained with fewer trips. In fact, in response to reduced soil compaction, yields may be increased.

No-tillage, the ultimate in reduced tillage, appears promising in upland rainbelt cotton. Interest in no-tillage cotton is increasing in response to the soil conservation provisions of the 1985 Farm Act. Soil erosion losses which exceed the tolerances established by the Soil Conservation Service on many upland fields can be reduced to acceptable levels with no-tillage production. The elimination of preplant tillage will result in the substitution of chemical for mechanical weed control. Some growers are cultivating the row middles after no-tillage crop establishment; however, this allows increased erosion loss and may stimulate additional weed seed to germinate. Most herbicides registered for use at preplant, preemergence and postemergence timings in conventionally tilled cotton also are used in no-tillage cotton. Thus, the products and programs are available to allow effective weed control in no-tillage cotton. Refinements in rates of application and timing, particularly in the use of directed postemergence applications, will be required as adoption of no-tillage increases. Sandy soils still present a problem for effective no-till operations.

Major ecological shifts in weeds can be expected to accompany reduced and no-tillage culture. These will be manifested in changes in the complex of species which infest fields as well as in different population densities. Just as Frans (1969) reported an increase in broadleaf weed populations in cotton which he attributed to widespread and repeated use of trifluralin, reduced cultivation, and reduced hand hoeing, in no-tillage the elimination of preplant soil-incorporated dinitroanilines and of cultivation would be expected to result in increasing populations of annual grasses. Also, increasing populations of the perennial weeds, horseweed and trumpetcreeper, have been observed by the authors of this chapter in no-tillage cotton fields. Conversely, repeated flushes of annual grass and dicot weeds associated with conventional tillage and cultivation have not been observed in no-till cotton. Thus, the changes in weed infestations may tend to be offsetting, but weed-control programs will need to be responsive to changing weed ecology. It is predicted that six significant changes in control practices will occur in no-tillage cotton:

1. The use of preplant foliage-absorbed herbicides having perennial weed activity;
2. The use of preemergence annual grass products;
3. An increase in the use of topically selective grass active herbicides in-season;
4. An increase in the use of post-directed broadleaf herbicides in areas where usage is currently low;
5. Increased use of broadcast applications; and,
6. Increased use of pre- and post-harvest herbicides to reduce overwintering populations of perennial species.

Integrated weed control programs will be incorporated into integrated pest management programs. Research into new technologies such as biological weed control will be integrated with traditional methods to support the overall goal of profitable cotton production. On-farm use of computers with their large memory capacity and ability to sort information and simulate logic will greatly assist the pest-management decision process.

A trend which has moved from west to east across the Cotton Belt has been the increasing use of consultants for pest control, including weed control. Consulting pest control in cotton was once synonymous with insect control. Private consultants who provide weed control recommendations to growers have increased since petroleum price hikes. Many growers find that dealing with one consultant is better than obtaining information from many different sources. For others, the convenience of dealing with one source is secondary to the desire to obtain quality recommendations, routine inspections, and weed maps which allow weed control decisions to be updated on a more timely basis than staying with one plan put together during the winter months.

ENVIRONMENTAL AND REGULATORY ISSUES

INTRODUCTION

Environmental and regulatory issues will have an enormous impact on the practice of controlling weeds in cotton in the future. As knowledge expands about herbicides and their fate in plants, soil, water and the air, then concern for environmental impact will increase. This process will accelerate in response to improved analytical methods and greater sensitivity of detection, and increasing public concern about the environment. The farmer will be brought under direct regulatory control on environmental issues dealing with use of cotton herbicides.

GROUND AND SURFACE WATER

Herbicide usage in cotton will be impacted by the presence of herbicides and their metabolites in ground and surface water. In recent years, studies have led to a number of conclusions by legislators, public groups, farm groups, and industry that substantial attention must be devoted to the care and management of our

groundwater on a long-term basis. Non-point sources are now recognized as a factor that must be considered in any program designed to protect and improve groundwater.

The concern will probably have several consequences. Intensive studies will be required of present and new cotton herbicides as to leaching, persistence and presence in groundwater. These studies will be costly, time-consuming and necessary to maintain or obtain registration. Based on these studies and other considerations, label restrictions will be placed on the use of herbicides by soil type, rate of application, rainfall patterns, irrigation practices and state of the groundwater in the area of projected herbicide use. It is likely that some cotton herbicide usages or the products themselves will become unavailable for farmer use. These developments will have an impact on the weed problem of the farmer, and the solutions available to the farmer.

Surface water issues are not substantially different from those of groundwater. An impact of new technology is that monoclonal and/or polyclonal antibodies can be used for detection and quantitative analysis of pesticides in water. Monoclonal and polyclonal antibody kits are now commercially available that will detect several key cotton pesticides quickly and accurately down to fractions of one part per million in water. As it stands now, any person can buy a kit, dip a strip of paper in water, and determine what, if any, level of certain pesticides is present. This technology is evolving rather rapidly. The implication of the use of this technology by the farmer, the citizen, the regulator and the inevitable plaintiff are numerous. Used as an aid in judging whether a rotational crop can be planted following a particular herbicide, it has a potentially enormous benefit. As an adversarial tool, it also could prove extremely significant.

Availability of surface and groundwater for irrigation will diminish in the cotton-growing regions of the United States. Frequency and amount of irrigation will obviously impact the dynamics of weed population and therefore the herbicide programs used by the grower.

ANALYTICAL SENSITIVITY

New and more sensitive methods of analysis continue to support the pragmatic expression that zero is theoretical and does not exist in the analytical sciences. Traces of pesticides are now measurable at levels a million times more sensitive than a decade ago. This enhanced sensitivity will lead to the detection of pesticides, including cotton herbicides, both in the field and on non-target organisms. The ramifications of this are several. Appropriate studies must be designed and implemented that will provide information on the biological significance, if any, of the residues found. The protocols for such studies, indeed the need for such studies, are not subject to general agreement in the scientific community at this time.

Improved monitoring devices for measuring the non-target distribution from the application of pesticides will be required. Application equipment and tech-

niques must be modified to further reduce the non-target distribution of pesticides.

New requirements by various regulatory bodies demand that protective clothing be worn by the applicator and that reentry restrictions be placed on the use of the herbicides. These new label restrictions must be supported by thorough, costly applicator exposure studies submitted by the registrant, together with appropriate metabolism and toxicology studies that will be used to establish the limits and significance of the exposure. In the future, we can expect these requirements to be demanded for all pesticides.

The reentry label restrictions will specify when it is permissible to reenter a field treated with a pesticide. In the past, this requirement has been applicable for the most part to insecticides. Current trends in regulation indicate it will be extended to herbicides, including a number of those used in cotton. Such restrictions do not impact grower operation in corn and soybeans nearly as much as in cotton, where far more in-crop operations are carried out.

THE ENDANGERED SPECIES ACT

The concern for animal and plant species in danger of extinction led to a federal statute, the Endangered Species Act of 1973, and many similar state laws. The current impact of the Endangered Species Act on the grower has been limited largely to the use of certain insecticides in specific locations. The environmental considerations were to protect endangered species of insects, or in some cases, avian or amphibian species. The greatest impact heretofore has been on industrial operations, such as the manufacture of herbicides.

A change is taking place in the administration and scope of the regulations under the Endangered Species Act. The EPA is responsible for the administration and enforcement of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), which is the law covering the production, marketing and use of pesticides. Using both the Endangered Species Act and FIFRA as statutory authorities, the EPA will place severe restrictions on a wide range of pesticides, including cotton herbicides. These restrictions will limit or prohibit the use of products in areas ranging from a few square miles to large regions of the country. In some cases, county-by-county label uses will be spelled out. Some restrictions will be by habitat, others by soil type, and still others, by time-of-year.

The implications to the cotton farmer are significant. For many farmers, choices of effective herbicide will be limited. In some cases, less effective products requiring higher rates and/or more frequent applications will be the only ones available. This, in turn, could lead to other environmental issues such as soil carryover and surface and groundwater problems as well as the more obvious ones of crop safety and yield loss.

The issue is further clouded by the fact that far more candidates are under consideration for the endangered species list than are currently listed. The re-

strictions not only will apply to cotton acreage, but also to sources of water, streams that handle run-off from crop land and land adjacent to crop land.

Several of the environmental issues addressed would be far less significant if it were not for pesticide drift and volatility, which will receive increasing attention because the ability to measure has improved. Couple this ability with increased concern about non-target exposure, the endangered species issue, pesticide residues on non-target crops, contamination of surface water, the possible toxicity of low-level exposure to pesticides and, finally, the increasing interface of urban and farm in cotton-growing regions, and the issue could become one of major proportion to the producer and user of cotton herbicides.

REGULATORY DIRECTION

Trends in regulation can be examined from the research process through the commercialization of a cotton herbicide or genetically modified cotton variety resistant to a herbicide; to farmer use; to the fate of the herbicide in the crop, soil, water, and non-target areas and species; and disposal of the container. Extrapolation of trends to assess future implications can then be made.

First, one of the most rapidly emerging trends is the increasing regulation of the research process. FIFRA for several years has required an experimental use permit (EUP) for large-scale testing of an experimental candidate.

The applicant's submission to the EPA for an EUP must include detailed plans for locations, cooperators, rates, amount and areas to be treated. Substantial data also must be submitted. Completing the approval process could require from several months to well over a year. Detailed reporting on a quarterly basis is required. In addition, state requirements also come into play. In the past, an EUP was submitted in the third year or so of the commercialization process. Now, particularly in the biotechnology area, EUP's are being required at a much earlier stage for a candidate product. This shift means a great deal more research effort is required for more candidates, and greatly lengthens the number of years required to commercialize a new product. Since only a few candidates survive the various technical and commercial hurdles through the third to fifth year, this also means substantial research resources will be applied toward "near misses" since EUP's will be required earlier in the research process on products that will not survive to commercialization. This wastes resources, inevitably slows down the flow of new products, and increases the cost of those that make it to the marketplace.

Evolving technology in analytical sciences, toxicology, environmental sciences and other scientific disciplines will result in additional regulatory requirements. As we can detect pesticides and metabolites at lower levels, then the requirements become far more costly and expand to include new areas for study.

REGISTRATION AND REREGISTRATION COSTS

The investment required for registration of any new cotton herbicide will continue to increase. Costs will increase at an accelerated rate (increased research required x increased costs per unit of research = accelerated cost of registration).

Current products also will be affected by the above changes as regulatory requirements for reregistration force the databases for old products to be updated to the new registration standards. A few products have already been cancelled voluntarily by registrants because the additional costs cannot be justified. Currently registered old products will be lost at a faster rate in the future.

FIELD-USE RESTRICTIONS

The biggest change in the regulatory impact on the cotton farmer is the trend toward regulation of farmer use as opposed to regulation of the product. In the past, the largest regulatory burden was placed on the herbicide producer who brought the product to commercialization. As described above, this task will grow larger. However, the farmer also will have a substantial regulatory burden stemming from the use of pesticide products. Some requirements are already present. Certification of applicators at the state level, as required by FIFRA, has been in effect for several years. The requirements invoked by the Endangered Species Act will place a further burden on the grower. Drift, volatility and worker protection regulations will add to the effort required of the farmer.

Restrictions on the use of herbicides will increase, impacting on the type of application equipment used, the requirement of nontreated buffer strips, the prohibition of certain pesticides within given distances to other areas such as subdivisions, endangered species habitats, drainage areas, or other crops not cleared for the pesticide proposed for use. Restrictions impacting irrigation, chemigation and ground and surface water will limit farmer flexibility to use the weed control program of choice.

Remarkable progress has been made recently in equipment, formulation and application techniques to reduce drift and volatility. Still more will be required. A significant key to the future will be continued grower and applicator education and skill.

SOIL EROSION CONTROL

Still another looming regulatory issue which will impact the farmer and his weed control program is that of soil conservation. Soil erosion and groundwater concerns easily may be the two most important environmental/regulatory issues of the next three decades. Farmers will be required to implement certain practices (and eliminate others) to reduce soil erosion, and to protect and improve groundwater quality. Practices such as minimum tillage, no-till or conservation tillage probably will be required. Land which cannot be conserved adequately

will be taken out of row-crop production and returned to permanent vegetative cover.

IRRIGATION

Dropping water tables will trigger laws and regulation that will control, limit and even prohibit irrigation for some crops under some conditions. The impact on weed control programs will be significant. Weed spectrums can be expected to change and choices of herbicides constrained.

SUMMARY

The regulatory impact on cotton weed control practices, both current and future, will become a substantially increased burden. The regulatory process will take longer, move further back into the research process and become far more comprehensive and costly. In all probability, it will lead to loss of some current products, fewer new products brought to commercialization and increased cost to the farmer for weed control. Probably the most important trend or shift is the impact of the regulations on the farmer's operations as opposed to the producer of herbicides.

HERBICIDE INDUSTRY CHANGES

The herbicide industry that supports weed control in cotton includes the basic research organization, the herbicide producer (most of the time the same company), formulator and packager, distributor and dealer. This industry is in a stage of change as rapid and significant as that of the technical and regulatory arenas. Further, as in the case of the latter two, this change is accelerating and will have major impact on the farmer.

FEWER AND BIGGER

The basic producers who also have the technical capability to discover and commercialize new products are decreasing in number. In the past few years, several basic companies have disappeared. These include Amchem, Diamond-Shamrock, Hercules, Mobil, PPG, Shell-U.S., Stauffer, Union Carbide, U.S. Borax, and Velsicol. It is widely believed that the disappearance of the basic producers will continue. One can assume that in ten years, there will be, at most, ten to twenty companies in the world that have the capabilities of research, commercialization, manufacture and marketing. This would mean survival of three to five United States companies with the above capabilities. A larger number of companies will have one or more of the capabilities. Other companies will synthesize new candidates, but not have the capability of commercialization or sales. Some can produce and/or market products but will not have the discovery or commercialization capability.

It is reasonable to assume that with the number of companies declining from a

peak of sixty or more to a low of ten or less, fewer new products will be introduced into the marketplace. Coupled with the regulatory impact, it is virtually certain that new product introduction will decline over the next decade or two.

LICENSING AND ACQUISITIONS

The pesticide industry increasingly will follow the lead of the pharmaceutical industry in that acquisition and licensing will become a more important part of the commercialization and marketing of new products. Licensing of products and candidates is one way of reducing risk and research and development resources while allowing companies to maintain a "full pipeline" of products moving to commercialization. This trend will counteract to some degree the decrease in the number of companies with research and development and commercialization capability.

MARKETING

The distribution channels of agricultural chemicals also are in the throes of change. As with the basic producers, consolidation, mergers and acquisitions are taking place. There is a trend to "one-step and two-step distribution" as opposed to the traditional three-tiered approach of producer/distributor/dealer/farmer. This results in sales directly from the herbicide producer to large dealers or even large growers. Farmer sources of information will shift because of these trends. Farmer purchase and credit terms will change, as will warehousing and ready availability of products.

PATENT AND DATA PROTECTION

The treatment of intellectual property by various government agencies on a worldwide basis is profoundly influencing the availability of pesticides, including cotton herbicides. At present, intellectual property important to agricultural chemicals includes patents, regulatory/registration data, manufacturing-process information and sales and marketing data. Regulatory and registration data have limited protection in the United States, with unsatisfactory protection under FIFRA and the Toxic Substance Control Act (TSCA) against improper use of data obtained in the United States and utilized elsewhere. Virtually all registration data with the exception of process and formulation data are available to the public under FIFRA.

Patent protection is adequate in the United States, Western Europe and Japan, as well as certain other countries. However, in Brazil and other Latin American countries, Taiwan and the People's Republic of China, patent protection is poor to virtually nonexistent. Considerable effort is being applied to obtain patent extensions on pesticides in the United States. This would allow consideration of the time lost from utilizing a patent because of the delays caused by registration procedures. Such a modification would allow the patent holder an opportunity to have a better possibility of recovering the large investment of commercializing a

pesticide. A concerted effort by industry on a worldwide basis to balance the need for public availability of information against the need for intellectual property rights is yielding useful results. On the whole, however, one cannot be optimistic about the worldwide situation on intellectual property rights.

The cotton farmer and the herbicide industry that supports the farmer will have two tasks in face of the scenario just described. The herbicides currently registered for use in cotton must continue to be registered. New herbicides with improved attributes must be discovered, registered and commercialized. The odds are not good. With patents expiring and little or no intellectual property protection for the substantial effort required to maintain registration, there is less incentive to generate data that a competitor can have for free.

As for new products, the enormous cost of bringing one to the cotton farmer—plus a deteriorating economic situation for agricultural chemicals—will have a profound impact on those making decisions as to whether to pursue pesticide development.

FUTURE NEEDS

Hindsight is history and foresight too often is myopic, but this chapter would be diminished in value without some commentary on future needs in weed control in cotton. A statement of those needs now, based upon observation of current conditions and trends, will support better planning by decision-makers—whether grower, scientist or administrator.

At the academic level, increased research on weed ecology and computer-simulated weed growth and development are needed to enable predictions on the impact of changes in production practices and weather conditions upon weed populations, competitiveness, potential losses, and returns to the cost of control.

Increased commitment to reducing herbicide residues in crops, air and water is needed. Improved application equipment allowing more precise delivery to the target would reduce the problem.

At the manufacturer level, additional products are needed for no-tillage and reduced-tillage culture; for example, a consistent and dependable preemergence annual grass herbicide. The search for new chemistries which perform as needed and then degrade to harmless components must continue to be a goal of the synthesis chemist. Public mistrust of technology dictates that this utopian dream not be discounted.

The search for effective and safe biological agents and practical delivery systems must likewise continue.

Government needs to be more responsive to the food and fiber needs of the nation. Increased patent protection of private property, regulations which maintain a high level of safety and health consciousness while supporting advancement in chemical and biological control technology, and practical oversight of the use of weed control products are appropriate roles of government.

The grower needs better label-use directions. More precise rate and timing of applications can increase the grower's profit. Research on the response to given sets of environmental conditions and upon stages of growth and susceptibility is basic to more specific label-use statements. Current labels are broadly written to cover the entire United States and three soil textures. Use directions are written for less than optimum application conditions. More specific and useful label directions can be written by better defining the influence of temperature, relative humidity, soil moisture measurement and light intensity.

From the cotton industry–from producer to ginner and merchant–a stronger and more united voice is needed in defense of current pest control products and in the request for weed science research funds.

PREDICTIONS

Predictions concerning anticipated changes in weed control technology during the next two decades are summarized here. In view of the factors already discussed in this chapter, these predictions seem reasonable.

Herbicides and tillage will continue in use as the primary control agents, but their use will be integrated with slowly evolving new technologies into more broadly based programs. Driven by government policy and by cost factors, the trend toward reduced- and no-tillage planting will continue as grower experience and confidence increase. Infestations of perennial species will increase due to less deep-tillage, and research to determine their control will be needed. Chemical herbicides will continue as the main line of defense in most control programs. Biological agents, *i. e.*, pathogens and insects, with narrow host-specific action will be used on selected weed targets for in-season control. Weed competition research and computer modeling in conjunction with economic analysis will better define economic thresholds. This, in conjunction with available control options and computer generated costs and returns data, will allow weed control decisions based upon expected profitability with higher confidence levels than are now possible. Biotechnology-generated cotton varieties possessing tolerance to specific herbicides plus new products integrated with non-chemical control methods will allow implementation of longer-term control programs covering several years as opposed to one season programs used today.

Products including biologically engineered organisms will be increasingly scrutinized for their effects upon non-target organisms and potential to bioaccumulate. Programs will be set up to monitor suspect compounds for their presence in surface and groundwater, streams and public water supplies. Periodic monitoring will be increased in foods, forage and processed products including cotton seed and oil products, and cotton forage.

The regulatory climate, while stressing environmental and human safety, will be slowly responsive to the economic needs of the grower and new products will

be registered. These will be characterized by favorable environmental and safety characteristics, high unit activity, low use rates/acre and use on other crops, thus making commercialization on cotton more attractive.

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