Chapter 18

SUPPRESSION AND MANAGEMENT OF COTTON INSECT POPULATIONS ON AN AREAWIDE BASIS

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INTRODUCTION

COTTON INSECT PESTS AND COTTON PRODUCTION

Cotton, *Gossypium* spp, in the United States is grown annually in 15 to 17 southern states from the Atlantic to the Pacific Ocean under a variety of arid, tropical and subtropical habitats. The annual value of the crop over the five-year period 1987-91 averaged 5.2 billion dollars (USDA, 1992).

Insect and mite pests in most of the growing areas generally are accepted as factors that contribute to high costs of production and reduced quality and yields (Newsom and Brazzel, 1968; Schwartz, 1983). Major insect pests that occur in one or more production areas are the: boll weevil, *Anthonomus grandis grandis* Boheman; pink bollworm, *Pectinophora gossypiella* (Saunders); cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter); tobacco budworm, *Heliothis virescens* (Fabricius); bollworm, *Helicoverpa zea* (Boddie); *Lygus* spp.; and sweetpotato whitefly, *Bemisia tabaci* (Gennadius). Several other insect species and spider mites, *Tetranychus* spp., may also attack the crop in restricted and/or more localized areas.

Chemical control has been and continues to be of vital importance in the protection of the cotton crop and the production of profitable yields (Cooke *et al.*, 1983). Chemicals are fast-acting, often control a complex of pests, may be used at the individual grower's discretion, and in most cases, are cost effective in relation to alternative control methods. In spite of these advantages, the peripheral problems (resistance, adverse effects on non-target organisms, secondary pests, etc.) associated with excessive use of chemicals has been of increasing concern to the scientific and public communities. These considerations, as well as our realization that a single factor unilateral insecticide-based focus on insect control will not provide long-term solutions to our key cotton insect pests have caused reassessments of approaches to insect control methodology. However, even though substantial progress has been made in developing autocidal approaches, resistant varieties, behavioral chemicals, methods of utilizing beneficial insects and pathogens, as well as cultural methods, none of these techniques are used on the same scale as chemical control. The need to facilitate implementation of these methods into integrated, multifaceted pest population suppression systems is urgent.

AREAWIDE INSECT SUPPRESSION OR MANAGEMENT

The concept of areawide suppression and management of target insect pest species has evolved with our increasing awareness of the limitations of attacking local infestations that represent only a small part of the total pest population. Moderate and consistent pressure applied each generation to the total population results in more effective pest population suppression than intensive pressure applied against small segments of the total population (Knipling, 1979).

Some of the tools that provide a strong base for the development of effective areawide cotton pest management systems are: (a) development of new cotton varieties with more manageable growth, fruiting characteristics and insect resistance; (b) increasing knowledge of insect population dynamics and the natural factors regulating insect populations; (c) identification and synthesis of insect pheromones and behavioral chemicals for detection, monitoring and control; (d) development of genetic methods of control, new and more effective chemicals, improved cultural technology; and (e) establishment of economic thresholds, improved sampling and more accurate descriptive and predictive modeling technology.

Areawide insect population suppression involves the coordinated efforts of many facets of an agricultural community cooperating to employ pest management strategies to reduce target species to levels that are below economic thresholds and/or to prevent target species from achieving economic levels. There are differences of opinion regarding the ultimate goals of such efforts, i.e., eradication or pest population management ("living with"). However, the fundamental ecological approach with regard to pest population regulation by natural factors and, if necessary, supplementary management practices (environmentally acceptable) remain the same. Ridgway and Lloyd (1983) suggested that the areawide insect management concept integrate eradication and pest management concepts with the view that areawide management could be a step in the direction of eradication of certain target species from defined areas.

GOALS AND OBJECTIVES OF AREAWIDE SUPPRESSION OR MANAGEMENT

The goals and objectives of pest management systems are not new. Briefly stated, they are to reduce losses in crop quality and yield caused by pests and to increase net profits to the grower. Methods are selected that cause minimal environmental damage and pose little or no risk to human health. During the late 18th and early 19th centuries, scientists stressed habitat modification and ecological approaches to insect control;

this formed the basis for modern integrated pest management approaches (Bottrell, 1979). Integrated pest management has been defined by a number of authors. Bottrell (1979) traced the origin of the terminology from integrated control (Bartlett, 1956; Stern *et al.*, 1959) as broadened to become synonymous with integrated pest management (Smith and Reynolds, 1965; Smith and van den Bosch, 1967; Anonymous, 1975; Smith, 1978) and pest management (Geier and Clark, 1961). A widely accepted definition suggested by Rabb (1972) is as follows: "pest management is the selection, integration, and implementation of pest control actions on the basis of predicted economic, ecological, and sociological consequences". Lincoln and Parencia (1977) observed that these approaches have formed the basis of applied entomology since the beginning of the 20th century. Rabb (1972) described the evolvement of four principle types of control programs (strategies) after recognition and preliminary assessment of a pest situation: (a) emergency control methods; (b) management of local populations; (c) eradication; and (d) population management. Preventing the introduction and establishment of exotic pests through inspection, quarantine and regulatory action should be considered as a primary, preventative control strategy.

Almost none of our major complex and persistent insect problems have been satisfactorily managed on a local basis, and relatively few have been managed on an areawide basis. Current information indicates that the highest probability of success can be achieved when the focus is on a large area basis to affect a high percentage of the target pest population.

These programs can, but not necessarily, have the goals of eradication or total population management. Glass *et al.* (1975) suggested it to be unwise to argue that there are no circumstances in which eradication is desirable but proposed programs should be carefully evaluated as to cost benefits and probability of success. Rabb (1972) considered eradication (although incompatible with pest management) an appropriate strategy but he stressed that the decision to consider that option should be approached with considerable caution. It is not within the scope of this chapter to discuss the relative advantages and disadvantages of each of these two goals but the readers are referred to a series of papers from the symposium "Eradication of Plant Pests—Pros and Cons" for details (Eden, 1978; Knipling, 1978; Newsom, 1978; Rabb, 1978). Eradication and total population management approaches share in common the focus of their efforts on the total target insect population or at least a large proportion of it as opposed to treating local infestations, i.e., field by field. The most successful demonstration in recent years of the validity of this approach was the eradication of the screwworm, *Cochliomyia hominivorax* (Coquerel) from the southeastern United States (Baumhover, 1966) using the sterile insect release system (Knipling, 1955). This success was followed by a more extensive suppression program in the southwestern United States. While the program proved highly successful, the area under suppression was not large enough to prevent infiltration of screwworm flies each year from Mexico. Not until the program was expanded, through joint efforts with the Government of Mexico, to permit sterile fly releases in areas larger than the normal dispersal range of the flies, was progress made to achieve eradication. The pest has now been eliminated from all of the United States and Mexico as far south as the Isthmus of Tehuantepec. The history of the program was recently reviewed (Graham, 1985).

In this chapter we discuss areawide suppression of target pest species using the principles and concepts of pest management that prescribe the utilization of all suitable control methods in a compatible manner to reduce and maintain a target pest population below economic damage levels.

SOME BASIC CONSIDERATIONS FOR INSECT POPULATION SUPPRESSION IN AREAWIDE SYSTEMS

BASIC REQUIREMENTS

Essential in the development of an areawide cotton pest suppression program is a thorough understanding of: (a) crop production methodology; (b) the biology and ecology of the insect pest; (c) basic knowledge of its genetics, behavior and physiology; (d) relationships and interactions of the target pest with other organisms and other biological and physical components of the ecosystem; and (e) economic injury or treatment levels. This information is necessary to identify strategies, establish priorities and integrate control technologies as components of an effective suppression system that is compatible with crop production methodology as well as other segments of the ecosystem.

Knowledge of the farmland production potential, agronomic inputs, cotton plant growth, development and fruiting is essential in the development of insect management systems. Cultivar selection and planting date, as well as cultural practices (irrigation, fertilization and tillage) have a major influence on cotton phenology[1] as related to insect attack. Decisions on the need for control action must consider not only the pest insect population but also the stage of plant development and the number of susceptible cotton fruiting forms that could be damaged. There may be no justification for control action during low points in the cotton fruiting cycle because the potential loss does not exceed or equal the cost of the treatment in terms of projected boll set and maturity.

Bottrell (1979), in a review, presented the following important entomological considerations that should be addressed in formulating integrated pest management systems: (a) low levels of the target species may be desirable and do not necessarily indicate the need for control action; (b) manipulation of one component of the ecosystem may be useful in managing the target pest but may induce other pest problems or other undesirable effects; (c) natural control factors (weather, food, competition, etc.) and natural enemies must be considered and taken maximum advantage of; and (d) multi-disciplinary input is essential to consider all aspects of the ecosystem. Pest population levels that can be tolerated within a crop system can vary depending on a number of factors including crop management, harvesting schedules and inherent plant-insect tolerances. Also, reassessment of economic threshold levels may be nec-

[1]Phenology is a branch of science that is concerned with the relationship of climate and biological phenomena.

essary at periodic intervals in consideration of new cottons that fruit earlier and are more determinant.

ECONOMIC THRESHOLDS

The general principle of areawide management of a target species to maintain population levels below economic thresholds is in marked contrast to that of control based on prophylactic treatments applied to small segments of the population on a scheduled basis. The economic threshold is the population level below which the cost of taking control action exceeds the losses caused by the pest (Stern, 1973). Economic thresholds may vary from area to area, between different cultivars, between farms within the same area but under different management systems and under other circumstances. Even though economic thresholds must be flexible and are dynamic, their use and development in pest management systems is essential.

Pest and natural enemy population sampling is a vital component of pest suppression systems. Knowledge regarding the qualitative and quantitative distribution of pest and beneficial species is required to predict damage potential and the need for control action. Much progress has been made in establishing economic thresholds for cotton insects, in detection and survey methodology, and in systems management (Demichele and Bottrell, 1976; Hartstack *et al.*, 1976; Sterling, 1979; Brown *et al.*, 1979; Gutierrez *et al.*, 1980). These techniques play a vital role in cotton pest management systems. Decisions regarding the need for control action must be made on the basis of the pest population, presence of natural enemies and their potential for regulating the pest population, and the developmental stage of the cotton plant. Knipling and Stadelbacher (1983) suggest that, although the economic threshold concept is an integral part of current integrated pest management systems in cotton, it is a defensive strategy. Application of the economic threshold as a basis for the need for control action has, in most documented cases, reduced the number of insecticide applications and increased net profits to the individual grower. However, acceptance of the economic threshold strategy may result in some level of crop loss that, accumulatively, may amount to millions of dollars annually in the grower community.

The advantage of coordinated areawide pest management systems combined with the sound principles of integrated pest management is the potential for managing key pest insect populations over large areas at levels that do not approach "acceptable loss" as defined for economic thresholds. This avoids money expenditure for control action by individual growers on small local area basis.

SAMPLING

Direct sampling methods involve inspection of plants and recording of the presence or absence of pests and beneficials or damage to plant parts. These observations (measurements) are then expressed per unit of the crop measured. Indirect methods such as the use of various trapping techniques also are effective when relationships to crop infestations and damage thresholds can be established. Sampling methods vary greatly depending on the target species, but in most cases they are least efficient at low population densities. Sex pheromones (very sensitive at low population densities) of a number of species of cotton insect pests have been incorporated into trapping systems to provide improved sampling information for use in determining the need for control action (Beasley *et al.*, 1985; Rummel *et al.*, 1980; Benedict *et al.*, 1985). Additional research is needed to relate these trap indices to quantitative population levels.

MODELING

Models are being developed and/or are operational at various levels in developing pest management systems that interface with crop management and insect population management strategies (Gutierrez *et al.*, 1977; Baker *et al.*, 1983; Hartstack and Witz, 1983; Stone and Gutierrez, 1986a, 1986b; Stone *et al.*, 1986). These models can be useful particularly in describing crop and insect development and distribution. With refinement, they can be useful in predicting events that influence decision-making in crop-insect management systems that result in more effective, efficient production.

The integration of models into pest management programs can provide prediction capabilities that increase the probability of successful decision-making and provide explanations for fluctuating insect populations and cotton plant changes, as well as providing information that may make it possible to avoid adverse impacts that are identified by the model. Gutierrez *et al.* (1980) suggest that a most important use of a model in pest management systems is to define the validity and usefulness of available knowledge regarding the problem and identify information needed to explain differences that occur between the model simulation and field observations.

NATURAL MORTALITY AND NATURAL ENEMIES

The basic framework of an areawide pest suppression system that embodies the principles of integrated pest management must be constructed around natural mortality factors in the system that contribute to regulation of the pest population and development. These include, but are not restricted to weather, climate, food resources and natural enemies. Natural enemy complexes are of particular importance in most cotton ecosystems (Gaines, 1942; Ewing and Ivy, 1943; Newsom and Smith, 1949; Wille, 1951; van den Bosch *et al.*, 1956). Every effort must be made in cotton pest management systems to conserve (and possibly augment) the natural enemy complex with selective insecticides, modified application technology and/or substitution of alternative methods incorporated with sound cultural control systems.

The role of individual or groups of natural enemies in regulating cotton insect populations has been difficult to quantify because of the many species involved and their interactions, between the target species and their host plants. Their importance, however, has been universally accepted. Increased incidence of primary or secondary pests after mismanagement of insecticides that decimate natural enemy populations has been abundantly documented. The biological component of current cotton integrated pest management is focused on conservation of natural enemies that play a significant role in suppressing some pests, particularly bollworm/tobacco budworm, where entomophagous (insect feeding) arthropods are particularly effective (Ables *et al.*, 1983).

Although past efforts at developing biological control approaches for boll weevil, *Lygus* spp. and pink bollworm have been disappointing, recent studies indicate that potentially useful exotic and/or indigenous biotic agents may exist (Phillips *et al.*, 1980; Jackson, 1980). The potential impact of natural enemies on population regulation of these important cotton pests, as well as the opportunity to manipulate natural enemy populations for maximum benefit or introduce new exotic forms, will be improved with further refinement and implementation of emerging areawide pest management systems that minimize insecticide use or improve insecticide application methodology and selectivity.

ECOSYSTEM AND PEST COMPLEX

The ecosystem is extremely complex and it is unlikely that we will ever know and/or understand every absolute and biotic facet and its role in an ever-changing environment; in fact, it may be unnecessary to do so. Understanding and manipulating the interactions of the target species, their natural mortality factors, natural enemies, competitors, hosts, alternate hosts, farm management systems and the physical environment present a formidable challenge to the scientific community. Much progress has been made but much remains to be understood. Thus, the components of an areawide pest suppression system must be carefully considered and researched to assure their compatibility in the system.

In most cotton growing areas we are confronted with a pest complex not a single species. Experience has taught us that adoption of a single control measure for the target pest or the complex is predestined to fail at least occasionally. Joint use of multiple pest suppression techniques has the highest probability of success over the long-term in pest management programs. Areawide pest suppression systems involve many aspects of the agricultural community and require interdisciplinary cooperation in research and development and on the implementation of pest management programs (Bottrell, 1979).

MANAGEMENT AREAS

GEOGRAPHIC AREA

Areawide management systems that target the total pest insect population, in most cases, will involve large geographic areas that may extend across county and state, and, in some cases, national boundaries. Thus, in addition to the technical complexities of target pest suppression, a high degree of local, state, national and sometimes international cooperation will be essential to assure a high probability of success. The cohabitation of the target species and other species within the influence of the biological and physical environment in an area form the ecosystem management unit (Bottrell, 1979). The interaction of biotic (living) and abiotic (non-living) factors influencing the target insect and other components of the ecosystem become more complex as the boundaries of the management unit become larger and involve more diverse biological and environmental components.

IMPACT OF INSECT MIGRATION

Many insects, both beneficial and pest species, move short distances in expanding their distribution and/or travel long distances during their lifetime to new or similar habitats (Williams, 1957; Schneider, 1962; Johnson, 1966, 1969). Movement of insect pests and beneficial species is of particular importance in the areawide management system. Each species appears to exhibit unique and characteristic movement and migration behavior that is influenced by a broad spectrum of ecological, biological and physical stimuli. The boundaries of an areawide management unit may be delineated by natural factors such as climate or geographical barriers such as large bodies of water, mountain ranges, and/or by host distribution. In many cases, artificial barriers such as the release of sterile screwworms to isolate the native population in Florida during the Southeastern eradication programs (Knipling, 1955) or the buffer zone method used in the boll weevil eradication effort (Lloyd, 1972; Boyd, 1976; Ganyard *et al.*, 1981) may be required to effectively prevent movement of target insects into the management area. Other artificial systems such as the use of insect pheromones and/or other biological systems also may have potential as barriers to prevent insect movement into management areas (Lingren *et al.*, 1977).

Long distance movement of key cotton insect pests (pink bollworm, bollworm/tobacco budworm, boll weevil) is well documented (Davich *et al.*, 1970; Sparks, 1972; Stern and Sevacherian, 1978; Raulston, 1979). However, the relationship of the migrating insects to establishment, population development and dynamics is not well understood. Until this information is available, key issues in long-term areawide management programs include: (a) the potential for migrant populations to initiate new infestations where management programs have reduced populations to low or nondetectable levels, and (b) the potential for establishment of high-level infestations in excess of the capabilities of suppressive action used in the management system.

LONG TERM MAINTENANCE OF AREAWIDE SUPPRESSION OR MANAGEMENT AREAS

The principle of continual maintenance of barriers or buffer zones is highly controversial on the basis of the cost involved and the perception that when it is required it indicates that the suppression technology used in the management area was inadequate initially or has become less effective in some way during use in the program. The cost of maintaining an effective barrier is not likely to exceed a small percent of the losses the pest would cause if not eradicated. Also, if a maintenance program alleviates the need for intensive and extensive use of ecologically disruptive insecticides there would be added benefits (Personal communication, E. F. Knipling, USDA, ARS, Expert-Pest Management, Beltsville, MD). The matter is controversial but, when related to economic losses of a major pest species, the objections may be unjustified if areawide suppression or eradication is technically and operationally feasible and advantageous from economic and environmental standpoints. The need for technology to isolate or delineate a pest management area may not always exist. Phillips and Nicholson (1979) and Phillips *et al.* (1981) reported that bollworm migration was not a major factor contributing to outbreaks of the insect in a highly successful community areawide pest management program in Arkansas. In contrast, Knipling (1979) suggested that the effects of insect dispersal have been confounded in the results of several areawide insect population suppression experimental programs and prevented clear-cut analysis of the results of the studies.

These differences will be explained only with a more complete understanding of the factors affecting insect dispersal. It appears that major research efforts on key cotton insect pests are needed to identify and define migrating insect behavior; factors influencing migration; and the role of migrating populations in initiating new infestations and their contribution to the population development of established infestations.

POPULATION SUPPRESSION METHODOLOGY

TECHNOLOGY

Methods of insect control such as autocidal techniques, sex pheromones, attractants, exotic and indigenous biological agents, cultural controls, resistant varieties and improved, selective chemicals are being developed and continually improved. Combinations of these and other methods are being selected and integrated into compatible systems to develop efficient, effective population management of cotton pest complexes with full consideration for social, economic and environmental values. Knipling (1979) discussed the value and importance of combining two or more control methods for management of insect populations and stressed the need for compatibility of the methods used. He proposed that when two or more methods of control are applied concurrently or sequentially to an insect population, three types of suppressive action may occur: (a) the total level of suppression is less than the effect of each method alone, i.e., one method negates or partially negates effects of the other method; (b) the total level of suppression effect is the sum of two methods individually since they act independently; or (c) the total level of suppression is greater than the sum of the two methods alone since one of the methods potentiates the action of the other method. It is important to know and understand how the various control methods work alone and when integrated into a system to suppress an insect population.

The complexities of the biological and environmental factors and their interactions that determine the quantitative population development and distribution of target species in the ecosystem demand multi-disciplinary input to provide information and solutions essential in the formulation of an effective management system. The potential social, economic and environmental benefits accruing from implementation of systems to manage major key insect pests justify a high level of research, extension and technology transfer activities.

TARGET PESTS OF MAJOR CONCERN

Research to obtain essential information for developing management systems for the boll weevil, bollworm/tobacco budworm, *Lygus* spp. and the pink bollworm, as well as other insect and mite pests, is being conducted at a number of locations across the Cotton Belt by state, federal and industry scientists. Much progress has been made, but continuing research, extension activities and other educational efforts as well as support by administrators must be realized to accomplish extensive acceptance and implementation of areawide integrated pest management programs to suppress major cotton insect and mite pests.

SELECTED EXAMPLES OF PROGRESS IN DEVELOPING AREAWIDE COTTON INSECT SUPPRESSION PROGRAMS

BOLL WEEVIL

The boll weevil has caused serious damage to cotton in the United States since 1892 (Townsend, 1895). Although synthetic organic insecticides were initially highly effective for control, the peripheral problems of resistance, secondary pests and environmental concerns stimulated an emphasis on alternate control methods (Ridgway and Lloyd, 1983). Also, a renaissance of ecological approaches using cultural control methods occurred (Frisbie and Walker, 1981). The results of over ninety years of research and practical experience have led to the development of several effective areawide boll weevil management programs based on the biology, behavior and ecology of the insect. Cross (1983) summarized some of the fundamental biological and ecological boll weevil characteristics and how that knowledge may be used in management strategies. The limited boll weevil host range (surviving principally on cotton), low overwintering survival, knowledge of overwintering habitat, spring emergence patterns, reproductive biology and role of the aggregating pheromone have been important considerations. Studies of the overwintering stage of boll weevils have revealed that this time in its life cycle is a particularly vulnerable period. Diapause is associated with boll feeding, cool temperature and short days. In general, diapause weevils begin to occur in late August, or earlier, depending on host conditions, but some adults remain reproductive until frost. Reduction of late-season, reproductive-diapause boll weevil populations has been an important component in the development of boll weevil management systems (Brazzel *et al.*, 1961). Equally important was the pheromone trap index system for predicting the need for overwintered boll weevil control (Rummel *et al.*, 1980), and the adoption of early stalk destruction (Hunter and Hinds, 1905).

Mississippi Areawide Management Experiment — The first attempt to integrate several boll weevil control methods into a large areawide suppression program involved an area in Mississippi of more than 20,000 square miles and about 24,000 acres of cotton (Davich, 1976). The goal of the study was to demonstrate elimination of the insect from an area where it was well established with relatively high populations (Lloyd, 1972). This was not accomplished throughout the experimental area. However, the combination of suppression methods in the Mississippi program applied over a 3-year period to a high percentage of the population drastically reduced the numbers of boll weevils; demonstrating the effectiveness of an areawide multifaceted approach to boll weevil population suppression. The center of the 3-year experimental area was Columbia, Mississippi, and included all cotton (1,817 to 3,222 acres) grown within a 38-mile radius of that city. An additional contiguous area extended about 50 miles (3 concentric zones of 5, 15, and 30 miles) from the perimeter of the management area. The contiguous area served as a buffer zone to prevent or reduce boll weevil migration into the target management area since boll weevils have been known to move 45 miles to infest cotton (Davich *et al.*, 1970). The buffer or barrier zone technique was a critical factor in delineating the targeted eradication zone within the management area.

The suppression methods were: (a) trap crops; (b) pinhead square insecticide treatment; (c) pheromone traps; (d) in-season chemical control; (e) reproduction-diapause control; and (f) release of sexually sterile boll weevils. Cotton within the targeted eradication zone and first buffer area was defoliated when 60 percent of the mature bolls were open. Stalk destruction was accomplished as soon as possible after harvest to further enhance the effectiveness of the program.

Poor participation during the in-season chemical/control phase in the first year of the program (1971) and lack of early stalk destruction after harvest resulted in boll weevil populations so high that the reproduction-diapause insecticide applications were relatively ineffective. Thus, in 1972, 74 percent of the cotton fields had 8 percent oviposition (egg laying) square damage by the last week in June.

In-season insecticide efforts were much improved in 1972, and treatments were applied to all cotton in the eradication zone and first buffer zone. Also, trap crop and pheromone trapping components were included in the program to reduce overwintering populations. Oviposition damaged squares were 90 percent less than in 1971 and adults per acre were reduced 99.6 percent, indicating the dramatic effect of applying insecticide control, trap cropping and pheromone trapping pressure to a high percentage of the total population. Ground trash samples collected in the fall of 1972 and spring of 1973 revealed no boll weevils in the eradication or first buffer zone, and 380 and 143 per acre in the second and third buffer zones, respectively.

In 1973, populations were extremely low in the eradication zone, and from May 7 through August 10, only nine adult weevils (7 in June) were found in nine trap crops. Only nineteen native boll weevils were found in 15 cotton grower fields, and only 2,279 oviposition damaged squares were found in 183 collections from 77 fields. Of 236 fields (1,817 acres), boll weevil infestations were found in 34 fields (167 acres). Over two-thirds of the infested fields were in areas adjacent to a heavily infested area outside the eradication zone.

It was not possible to accurately and precisely determine the relative contributions to the boll weevil population suppression of each of the three major suppression components—insecticides and cultural measures on in-season and overwintering populations; use of grandlure pheromone traps to reduce weevil populations emerging in the spring; and sterile boll weevil releases.

The insecticide management component involved in-season applications to reduce the developing population coupled with late-season applications to reduce reproductive weevils that continued to produce diapause progeny as well as weevils already in diapause.

Grandlure® (boll weevil sex pheromone) was used to trap overwintering weevils before they entered the cotton fields and also to attract weevils to early-season systemic insecticide-treated cotton. The insecticide component was estimated to reduce the boll weevil population to about two per acre and the pheromone component was estimated to reduce the overwintering population an additional 80 percent (i.e., 80-90 percent of two per acre) (Knipling, 1979; Hardee and Boyd, 1976).

Sterile boll weevils were released at the rate of about 50 per acre per week. Taking into consideration the non-competitive nature of the released insects, Knipling (1979) estimated the effective ratio was 250 sterile to one native, and no reproduction of native weevils occurred. He also suggested that, since no evidence was found for reproduction in 170 fields that were more than 25 miles from infested cotton, some partially sterile-released females may have produced all the weevils found.

The results of the study clearly demonstrated the technical feasibility of reducing boll weevil populations to extremely low levels through a coordinated effort employing several management strategies that adversely impacted a high percentage of the boll weevil population over a large geographical area.

The effect on nontarget organisms in the eradication area was as expected (Harris *et al.*, 1976). Predator populations were reduced because of the heavy insecticide use (in-season and reproduction-diapause control), but increased dramatically when boll weevil populations were low as a result of population suppression measures that resulted in the need for little or no insecticide application. In contrast, bollworm/tobacco budworm populations were highest under extreme insecticide pressure for the boll weevil and the related low predator populations, but were low when predator populations increased and insecticide use decreased.

Mississippi Optimum Pest Management Study — A subsequent study was conducted during 1978 to 1980 in Panola County, Mississippi. It incorporated several additional boll weevil and other cotton insect management tactics into an areawide cotton insect management program (Andrews, 1981; Hamer *et al.*, 1983). The results were compared with cotton grown under standard boll weevil management practices in Pontotoc County, about five miles distant, and comparable in cotton production, boll weevil populations and crop management. The components of the pest management system were: (a) pheromone (boll weevil and bollworm/tobacco budworm) and black-light traps (bollworm/tobacco budworm); (b) uniform planting dates; (c) pinhead square insecticide applications; (d) scouting; (e) in-season control of boll weevils, bollworms, plant bugs, spider mites and other pest species; (f) boll weevil reproduction-diapause control; and (g) early stalk destruction.

Grandlure®-baited traps were distributed at the rate of one trap per 20 acres of cotton in Panola County and in representative fields in Pontotoc County. The detection of five weevils per week in May alerted consultants and producers to the need for field surveys to determine the need for pinhead square treatment. Uniform planting dates were encouraged and all participating growers planted cotton as soon as soil temperatures were acceptable.

The first application of insecticide for reproduction-diapause boll weevil control was scheduled 10 days after the producers ended in-season control followed by the second, 10 days later. The third and fourth applications were at 15-day intervals. The initial applications were applied on September 10, September 20 and September 10 in 1978, 1979 and 1980, respectively. The number of per acre in-season insecticide applications in 1978, 1979 and 1980 was 3.3, 3.41 and 3.01, respectively. Up to 4 reproduction-diapause insecticide treatments were applied to most of the cotton acreages in the management area in the fall of 1978, 1979 and 1980. In the spring of 1979 and 1980, boll weevil captures were 78 and 94 percent less than occurred in Pontotoc County where standard in-season insect control practices were followed. Further, the need for pinhead square treatments was reduced because of the reproduction-diapause control program, and only 57 acres (105,000 total acres planted during a 3-year test) received insecticide applications in 1980. The effectiveness of the reproduction-diapause control program resulted in reduced insecticide use because boll weevil and bollworm populations rarely reached economic threshold levels. Yields were higher in Panola County than in the six surrounding counties where the number of in-season insecticide applications averaged 3 to 8 per acre.

Boll Weevil Management in the Lower Rio Grande Valley, Texas — Under subtropical conditions in the Lower Rio Grande Valley of Texas, cotton regrowth (resulting from inadequate stalk destruction after harvest) and volunteer cotton are serious problems in boll weevil management systems. The benefits of an areawide approach to early-season cotton stalk destruction and early crop plowdown management components have been effectively reemphasized recently. Summy *et al.* (1985, 1986a, b) estimated that more than 190,000 adult weevils per acre could be produced during fall and winter cotton regrowth under Lower Rio Grande Valley conditions. The authors suggested alternative cultural practices that result in nearly complete stalk destruction and use of herbicides to kill volunteer cotton seedlings (Summy *et al.*, 1986b). An areawide surveillance system based on color infrared photography of more than 250,000 acres revealed large areas of cotton regrowth (Summy *et al.*, 1984). The identification of the problem areas resulted in achieving 98 percent reduction in stalk destruction through the cooperative efforts of the entire agricultural community. Adult weevil populations were reduced to nondetectable levels where early plowdown was accomplished; in areas of poor to moderate stalk destruction, weevil populations remained at economically damaging levels. This demonstrated the efficiency of areawide stalk destruction as a boll weevil management component in the Lower Rio Grande Valley of Texas.

Areawide Boll Weevil Management in Arizona — One of the most recent community-wide IPM programs in Arizona was established in the area surrounding Laveen, Arizona. During the 1985 growing season about 75 percent of 10,000 acres of cotton were infested with boll weevils and growers applied up to 22 insecticide treatments (Farr and Lame, 1987.). For 1986, cooperating cotton growers adopted the University of Arizona's Cooperative Extension Service IPM program of: (a) uniform planting, March 25 to April 15; (b) pinhead square stage insecticide applications, three treatments at 5-day intervals initiated at 850 accumulated degree day heat units (55F base); (c) in-season insecticide treatments (5-day intervals) based on economic thresholds of 5-8 percent square infestations, or treatments at 3-day intervals when over 20 percent square infestation occurred; (d) irrigation termination by September 1; (e) plant growth regulator application by mid- to late-September to remove non-harvestable fruiting forms; and (f) stalk shredding immediately after harvest but no later than December 1, 1986. In the 1986 season, over 80 percent of the growers used fewer or the same number of insecticides compared to 1985, and most boll weevil field infestations were kept below 10 percent. Plant growth regulators to accelerate mature boll opening and accomplish defoliation were applied about one week earlier than in 1985, and crop plowdown by January 1 was considerably advanced as compared to previous years.

In 1987, trap cropping strategy was integrated into the program along with the previously-described management system (Moore and Watson, 1990). Trap crops (34 fields) planted 15 days ahead of the regular crop had as many as 16,000 boll weevil damaged plants per acre before insecticide applications. Five insecticide applications at 3-day intervals destroyed the weevils in the trap crop before it was plowed down prior to squaring of the current year's commercial crop. Average percent infested squares (20 fields) were 0.6 and 2.8 on July 8 and 29, respectively, as compared to 4.9 and 15.1 on the same dates in 1986. In 1987, percentages of infested squares ranged from 0 to 9.2 during July 1 to September 6 as compared to 4 to 23.4 percent in 1986 in 19 fields during the same sampling period.

In 1985, the year before the IPM program was initiated, the host-free period was 45 days compared to 105 and 120 days in 1986 and 1987, respectively, following initiation of the program. Cotton yields in 1985 were 840 pounds of lint per acre; they were 1200 and 1344 pounds of lint per acre in 1986 and 1987, respectively, with comparable (17-18) insecticide applications (Unpublished data, Marc L. Lame, Ombudsman, Arizona, Department of Environmental Quality, Phoenix, Arizona).

The results from the Laveen IPM project and two other boll weevil community-wide IPM projects near Phoenix resulted in an estimated gain of an average of $40/acre as a result of increased yield and reduced production input; a combined increase of $1.2 million for the approximately 80 growers involved (Personal communication, Leon Moore, Department of Entomology, The University of Arizona, Tucson, Arizona).

Other Boll Weevil Management Strategies — Prior to the advent of the organic insecticide era, scientists relied on knowledge of cotton crop development and the interaction with insect population development in efforts to manage insect populations and prevent losses. This was particularly true with the boll weevil. Hunter and Hinds (1905) recognized the value of early planting of early maturing varieties and early harvest followed by thorough stalk destruction in boll weevil population suppression. Scientists have expanded these principles and developed additional tools that form the basis for boll weevil management in many cotton production areas. For example, the development of early fruiting cottons with determinant growth characteristics have had a major impact on cotton production systems in the Rio Grande Valley of Texas. Short-season varieties (130 to 140 days from planting to maturity) with two early-season insecticide treatments for boll weevil control resulted in below economic threshold populations for an average of 59 days after the last insecticide application (Heilman *et al.*, 1977). Lint yields were equal to or greater in short-season systems with four less insecticide applications than lint yields from plants grown in conventional systems. An economic evaluation of the early-maturing varieties, selective insecticide use and efficient water management systems showed that the production cost advantage of the integrated short-season system was $0.18 per pound of cotton lint as compared with conventional long-season cotton-growing systems (Heilman *et al.*, 1978).

Considerable progress is being made in developing short-season cotton production methodology. Generally, less insect control input has been required because of the reduced opportunity for insect damage per unit of growing time, and because of the longer host-free period that reduces numbers of developing overwintering insects and increases natural winter and spring mortality. Integrating short-season production systems with resistant varieties, cultural methods—methods that include manipulation of planting dates to escape early-season emergence from overwintering or to enhance early maturity before economic infestations develop—and early harvest and plow-down are insect control components that should be incorporated in areawide insect management systems.

Sources of plant resistance such as frego bract, red plant color and male sterile characters have been demonstrated to have potential in boll weevil population suppression programs. Incorporation of the characters into cotton types that are agronomically acceptable has not been accomplished, but research progress is being made and it is highly probable that such varieties will be developed which will also include resistance characters to other cotton insects such as bollworm/tobacco budworm and plant bugs.

BOLLWORM AND TOBACCO BUDWORM

The cotton bollworm and the tobacco budworm have emerged in recent years as the cotton pest complex causing the highest losses in cotton yields and costs of control (Frisbie and Walker, 1981). A number of authors have documented the evolution of the bollworm/budworm complex and the associated peripheral problems—resistance, effect on nontarget organisms, pest resurgence, secondary pests and environmental considerations—across the Cotton Belt as a result of the unilateral reliance on insecticides for pink bollworm and boll weevil control (Newsom and Smith, 1949; Wille, 1951; Gaines, 1942, 1954, 1955; Ewing and Ivy, 1943; van den Bosch *et al.*, 1956; Van Steenwyk *et al.*, 1975). Insecticides will retain a vital role in cotton production systems but must be incorporated into a sound management system that utilizes an ecological approach incorporating effective natural and cultural control practices.

Bollworm/Tobacco Budworm Management Systems in Arkansas — The validity of effective pest management with coordinated areawide insecticide applications based on economic thresholds, bollworm/tobacco budworm population dynamics and cotton plant phenology was discussed by Phillips and Nicholson (1979) and Phillips *et al.* (1981). For the three years prior to the initiation of a bollworm/tobacco budworm management program, growers in a selected area in Arkansas averaged ten insecticide applications annually for control. A carefully designed research program revealed important information leading to effective areawide management strategies. The program was designed to: (a) evaluate sampling and surveillance techniques and economic thresholds; (b) develop modified life tables; (c) examine population dynamics; and (d) develop a forecasting program.

Examination of insecticide use patterns in the area indicated that mismanagement of control methods contributed significantly to the bollworm/ tobacco budworm problem. Analysis of the biology, ecology and population dynamics of the pest complex as affected by natural enemies and mortality factors showed that the magnitude of the July population was closely related to the density of the June population. When plant development approached 50,000 squares per acre, and populations of bollworm/tobacco budworm larvae reached 1,500 per acre, then control was initiated. Further, a treatment that induced areawide reduction of 50 percent of the population in June held July population development to levels below economic thresholds.

The bollworm/tobacco budworm management program in Arkansas was initiated in 1975, and expanded in 1976 to an area of approximately 50 square miles with 12,000 acres of cotton. The key strategy involved bollworm/tobacco budworm population suppression at a time during crop development when the need for square and boll production was less than occurs in mid- to late-season. This reduced population development results in fewer insects in the area during the critical crop development period.

Cotton crop scouting and treatment thresholds were based on the areawide community population levels as opposed to farm-to-farm evaluation. In the first year of the study, action thresholds, as determined by whole plant sampling at strategic locations over the entire community, were not reached until August. All cotton in the area was treated once within three days of the action threshold determination. This was followed by a second (and final) application on August 27. Careful management practices based on insect population thresholds and crop development reduced the use of insecticides 80 percent.

In the second year of the program, pest and beneficial insect scouting in relation to crop development showed that action thresholds (1,500 larvae per acre) were not reached in June (infestations were less than 500 larvae per acre). The resulting July population, as predicted, did not justify use of a hard pesticide but a microbial insecticide was incorporated into the management system. The total impact of the microbial insecticide (Elcar®) on population suppression was difficult to assess, but larval collections indicated that 25 percent mortality was virus-induced. Data taken for three years prior to the 1975 initiation of the pest management program showed a 15-fold July to August population increase; in contrast, the July to August increase after the communitywide microbial application was only 4-fold. Considerably higher population suppression may have occurred as a result of the use of the microbial insecticide than was indicated by the sampling technique used. Action thresholds again were not reached until August 12 when a final insecticide application was applied to all but 1,500 acres of late-planted cotton that required a third treatment.

The results of the third year of the study were confounded by drought conditions, low initial natural enemy populations and a large segment of the cotton grown in the management area that reverted to conventional insecticide application schedules. However, even under these adverse conditions, the pest management approach proved superior to conventional control tactics. It was clearly demonstrated that treatment on a field-by-field basis was less effective than treatment on a total areawide treatment basis. The areawide treatment program averaged 5 insecticide treatments and cotton in control areas required 11 insecticide treatments.

As a result of these research efforts, cotton farmers in Arkansas have voluntarily organized bollworm management communities in an attempt to manage bollworm and tobacco budworm populations over large land areas rather than by the more common field-by-field approaches. The intent is to coordinate control decisions so that all cotton fields in a bollworm management community are treated within a 3-day period. In 1988, there were approximately 150,000 acres in six bollworm management communities. Assessments of the economic impacts of the community approach have clearly demonstrated the benefits of the concept (Parvin *et al.*, 1984; Cochran *et al.*, 1985; Scott *et al.*, 1983).

Parvin *et al.* (1984) compared the performance of the bollworm management communities to control areas in adjacent counties to identify farm level benefits from participation in the community action approach. Significant differences in yields, insect control costs and net returns per acre were discovered. Yields were increased by 23 pounds of lint per acre; insect control costs were lowered by $1.85 per acre; and net revenue was increased by $18.57 per acre. Further, these data were used to estimate that the community program increased overall producers' incomes in 1984 by $1.5 million and reduced insecticide use by 92,000 pounds of active ingredients (Cochran *et al.*, 1985).

As an indirect benefit, it was hypothesized that the bollworm management communities also functioned as effective mechanisms for technology transfer and information dissemination. Scott *et al.* (1983) measured the effect that participation in a community program had on the adoption by the community of other Arkansas Cooperative Extension Service recommended production practices (not just pest management). The results showed that participation in a community program increased the percentage adoption of recommended practices by about 11 percent. Thus the intangible effects of community involvement provides, in addition to direct economic benefits, a forum for much needed communication leading to technology transfer.

Other Bollworm/Tobacco Budworm Management Strategies — The economic importance of the bollworm-tobacco budworm complex in cotton production systems has stimulated research efforts to develop the necessary information to supplement and improve existing management programs and to formulate new more effective, efficient management systems to prevent excessive losses. The large number of host plants, ecosystem diversity and variability of bollworm/ tobacco budworm host plant interactions make this a challenging and difficult goal to achieve. Agronomic practices of planting date, cultivation, fertilization and irrigation are intimately related to bollworm/tobacco budworm population dynamics and must be considered in management programs (Bradley *et al.*, 1986; Luttrell *et al.*, 1986; Rummel *et al.*, 1986). Quantification of the impact of these factors on populations of these pests has been difficult because of the wide range of climatic influences and diversity of agricultural systems. Manipulation of planting date as well as cultural inputs and early-fruiting varieties can be used to avoid early-season insect infestations that are initiated by overwintering insects; this is accomplished by minimizing the amount of susceptible host material during peak occurrence of the overwintering population. The value of this approach is illustrated very well in South Texas where uniform early-planting is recommended to enhance crop maturity before insect populations reach damaging levels; and in North Texas where uniformly late planting is recommended to allow maximum overwintering and spring mortality of key insect species and suicidal boll weevil emergence (Frisbie and Walker, 1981). In West Texas, a bollworm forecasting model (Hartstack *et al.*, 1976) is used to estimate bollworm oviposition (egg laying) and to manipulate irrigation scheduling to avoid lush cotton growth during peak oviposition periods. Early maturing cottons and associated cultural practices are used in South Texas to avoid late-season damaging insect infestations (Walker and Niles, 1971; Namken and Heilman, 1973; Walker *et al.*, 1977). The potential value of modified crop production systems in bollworm/tobacco budworm management programs justifies the need for intensified research to define the interactions of these cultural practices and the potential for their manipulation as components of management systems (Ridgway, 1986).

Many sources of germplasm resistance to bollworm/tobacco budworm exist (Beck and Maxwell, 1976) and research is currently directed to incorporating these traits into acceptable, high-yielding and quality cotton backgrounds. The need for early-fruiting, high-quality cottons in cotton insect management systems was suggested by Walker and Niles (1971).

The role of indigenous natural enemies in regulating bollworm/tobacco budworm population development is well documented. Control strategies in management systems must be developed to conserve natural enemy populations and maximize their effectiveness. Long-range bollworm/tobacco budworm management plans should include: (a) manipulation of systems to maximize effectiveness of natural enemies; (b) provisions for augmentation of indigenous populations of natural enemies; and (c) importation of exotic forms of natural enemies.

PINK BOLLWORM

Pink Bollworm Management in Arizona — Integrated pest management (IPM) and communitywide participation systems have been important factors in cotton production in Arizona. The basis for IPM systems in cotton was established with the development of efficient cotton scouting programs (Unpublished report, Leon Moore *et al.*, Department of Entomology, The University of Arizona, Tucson, Arizona). The benefits of this approach were quickly realized in Graham County (Carruth and Moore, 1973). Growers in 1968 adopted scheduled insecticide applications at weekly intervals over a 6-weeks period for pink bollworm control. Treatments were made regardless of insect population density. This resulted in about 80,000 acre-treatments annually. After the initiation of a scouting program in 1969, acre-treatments were reduced 93 percent, 96 percent and 82 percent in 1969, 1970 and 1971, respectively. Costs of treatment per acre in 1968 was $15. This compares to $2.70, $2.54 and $5.00 per acre, respectively, in 1969, 1970 and 1971.

The success of the Graham County program stimulated a similar program in Pinal County where a Growers Pest Management Corporation was established. Economic evaluation of the Pinal County program for 1971 (Lawrance, 1972) and 1974 (Olmstead, 1976) showed that participants in the University of Arizona's IPM program spent $10.58 and $13.66 less per acre, respectively, on cotton insect control than did growers not participating in the program.

Areawide Management to Prevent Establishment in Uninfested Areas — An areawide pink bollworm population suppression program has been conducted since 1968 in the San Joaquin Valley of California to prevent establishment of migrating native pink bollworm populations from southern California and Arizona (USDA, 1977). The program has been improved continually and currently involves: (a) pink bollworm traps baited with the pheromone gossyplure to detect native migrant moths and to indicate areas in need of suppressive action as well as to establish ratios of released sterile to native male moths; (b) release of radiation-sterilized pink bollworm moths; (c) cotton plant destruction and plowdown to maintain a 90-day host-free period; and (d) most recently, the mating inhibition and/or male annihilation technique involving field application of gossyplure slow-release systems (Foote, 1988).

The pheromone trap system has proven to be an indispensable tool in the detection of low level migrating pink bollworm populations. Native moths have been caught each year since the initiation of the program, except for 1968. The numbers ranged from 5 in 1969 to 7,402 in 1977.

About 9 million sterile moths were released in 1968. The program has expanded each year; in 1988 over 754 million sterile pink bollworm moths were released. Releases have been made by air in areas ranging in size from 15 to 350 thousand acres of cotton where native moths were found or larvae detected in bolls. Annual ratios of steriles released to native moths as measured by captures in pheromone-baited traps have ranged from about 100:1 to 6,200:1 (USDA, 1977).

The mating inhibition technique as a supplementary suppression measure may be used when: (a) 20 or more native moths are caught in a one-mile section (prior to October); (b) there is evidence of a reproducing generation; (c) larvae are found; or (d) the native to sterile moth ratio is less than 1:50 (Foote, 1988). For example, in 1988 three areas met one or more of the criteria and were treated with gossyplure slow-release materials at 8- to 12-day intervals until defoliation. Treated areas involved: 200 acres treated four times beginning July 30; 700 acres treated three times beginning August 11; and 260 acres treated twice beginning September 1.

Native male moths have been trapped in the San Joaquin Valley each year of the program since 1969; larvae found in bolls in each of five years. Diapausing pink bollworm larvae have been observed to survive, pupate and emerge in the spring in the Bakersfield area of the San Joaquin Valley (Unpublished data, A. C. Bartlett, USDA, ARS, Western Cotton Research Laboratory, Phoenix, Arizona, and R. T. Staten, USDA, APHIS, Methods Development Laboratory, Pheonix, Arizona). It is difficult to conclude with scientific certainty that the program has been the total factor preventing the establishment of the pink bollworm in the San Joaquin Valley. However, the indirect evidence supports the premise that the pheromone-trap detection system, releases of the sterile moths, early crop destruction after harvest, and in recent years, supplementary behavioral control methodology, have successfully achieved that goal.

Other Potential Components in Pink Bollworm Areawide Management Systems — Large-scale coordinated areawide management systems using all available technology for pink bollworm population suppression of established infestations have not been implemented. However, the first steps have been taken toward managing the insect on a local basis. In all pink bollworm-infested cotton areas in Arizona and California, cotton scouting is practiced, and pheromone trapping and boll sampling are used to determine to a greater or lesser extent the need for control based on established economic thresholds. Further refinements in new technology can improve current management systems; additional management components can be incorporated; and acceptance of areawide systems for population suppression can be expanded.

Several aspects of pink bollworm biology and ecology contribute to natural population regulation. Early season pink bollworm population development is affected by a large number of natural factors such as: (a) suicidal emergence (Bariola, 1978, 1983; Fullerton *et al.*, 1975); (b) natural enemies (Noble, 1969; Orphanides *et al.*, 1971; Irwin *et al.*, 1974; Jackson, 1980; Henneberry and Clayton, 1982); and (c) soil temperature effects on larvae in early season (Fye, 1971; Butler and Henneberry, 1976; Clayton and Henneberry, 1982). The results are a low (50 to 150 percent) population increase during the first generation that infests the current year's cotton crop (Graham *et al.*, 1962; Slosser and Watson, 1972; Bariola, 1978). Consequently, supplementary early-season suppression technology such as: (a) resistant plant types (Wilson and Wilson, 1976; Wilson, 1982); (b) short-season varieties and modified cotton culture (Walhood *et al.*, 1981, 1983); (c) planting dates to increase suicidal emergence (Adkisson *et al.*, 1962; Henneberry *et al.*, 1982); and (d) behavioral control with the sex pheromone (Doane and Brooks, 1981; Butler *et al.*, 1983), have the potential to further reduce early-season population increase. These methods are effective particularly at low population densities and must be integrated with techniques to reduce overwintering populations.

Mid- to late-season control is heavily reliant on chemicals. Careful sampling with sex pheromone-baited traps (Beasley *et al.*, 1985) and examination of bolls (Watson and Fullerton, 1969; Toscano *et al.*, 1979; Toscano and Sevacherian, 1980) to determine application of insecticides on a "need" basis can reduce numbers of applications and cost of chemical control substantially. Sampling pink bollworm eggs laid on bolls is a relatively new technique that also can be used to time insecticide applications (Hutchison *et al.*, 1987). A treatment threshold of 6-8 percent egg-infested bolls resulted in a 35 percent reduction in insecticide use with no reduction in yield. The maximum number of susceptible bolls occurs about three weeks after peak flowering (Fry and Henneberry, 1983). When applying insecticides, consideration should be given to pink bollworm populations and plant development stages (Reynolds, 1980; Fry and Henneberry, 1983).

Development of insecticide resistance is one of the threatening problems to the cotton industry. Pink bollworm resistance to DDT (Lowry and Berger, 1965) and tolerances to pyrethroids (Bariola, 1985) have been documented, but not to organophosphates (Reynolds, 1980). At the moment, the only possible method to prolong the life of insecticides is to reduce selection pressure that results in the development of resistant strains. This may be accomplished by limiting the use of one class of insecticides to one generation per year. Monitoring insecticide resistance and managing insecticide use patterns should be incorporated into pink bollworm management systems to extend the longevity of existing chemicals. Haynes *et al.* (1986, 1987) have developed a reproducible and economical technique for monitoring insecticide resistance in pink bollworm field populations.

Late-season management systems to reduce development of the diapause pink bollworm generation by eliminating host material (Bariola *et al.*, 1976) and/or destroying diapaused larvae, using tillage and/or irrigation techniques (Watson, 1980), are the most powerful and economical methods of population suppression of this insect pest. They should be components of areawide pink bollworm management systems.

Stalk shredding to enhance uniform and deep burial of shredded plant debris, followed by disking and effective plowing and winter irrigation treatments, effectively induce additional mortality of overwintering pink bollworms (Watson, 1980). The most effective, practical tillage practice has been deep plowing that results in turning over the soil to a depth of 8 inches or more. The earlier that winter plowing is accomplished, the higher the larval mortality, with fewer moths emerging in the spring.

Presently, the use of early-season pheromone trap monitoring and field scouting to obtain estimates of infestation levels to determine the need for control action is standard practice in most growing areas. A careful analysis indicates that incorporating short-season methodology, resistant varieties and good cultural practices of early harvest, stalk shredding and plowdown into current management systems on an areawide basis could reduce the pink bollworm populations to noneconomic levels that would allow consideration of sterile release methodology as a low-density population management tool (Henneberry and Keaveny, 1985).

DISCUSSION

Areawide suppression or management of total cotton insect populations which have multifaceted control approaches and incorporate the principles and tactics of integrated pest management as an ecological approach to more socially, economically and environmentally acceptable methods of pest control have the highest probability of success. Research, extension and other teaching efforts dealing with most of our key cotton insect pests are making significant progress in development of the concept of coordinated large area, agricultural community involvement in pest population management. The areawide approach focuses suppressive measures on the total pest population as opposed to uncoordinated efforts focused on local or farm-by-farm or field-by-field attempts to control limited segments of the population. The farm-by-farm and field-by-field approaches have not provided effective solutions to our key insect pests. Areawide programs include producers as active participants in the program which is a facet that helps to ensure success. The producer is not a bystander nor are extension and private consultants. The entire community has an active part in the program.

The technology to manage many of our key pests on an areawide basis currently is not available; however, important progress is being made in developing methods that can be incorporated in management systems that are compatible within the ecosystem. Although considerable progress has been made, much additional research needs to be accomplished to supplement our incomplete understanding of the factors affecting population density, dynamics and behavior of the target species and the role of beneficial species and their interactions as they relate to the other biological and physical components of the ecosystem.

Areawide suppression programs for many of our key cotton insect pests are at various stages of development. Existing technology is being continually modified and improved and new technology developed. The most effective and efficient areawide insect management programs incorporate multifaceted, multidiscipline inputs to achieve the desired suppression of the target species population with little or minimal impact on other components of the management unit. The ultimate impact of suppression technology applied against one species must be weighed and measured as to potential effects on other biological and physical entities within the system. The complexities of the interaction of all components in an areawide population suppression unit make it impossible to predict long-range effects that may occur and modifications that may be required to maintain the suppression system in a viable and acceptable manner.

Chemical, biological, behavioral, genetic and cultural control methods, as well as development of resistant cotton variety technology, is advancing rapidly. All control methods must be considered in areawide management or suppression systems. No single method is totally acceptable. Combining all of the available technology offers the highest probability of success in suppression/management programs. The selection and integration of compatible control methods should be based on knowledge on how each of the methods function individually and when introduced separately or simultaneously as suppression methods to achieve population reduction. Further, suppressive action must be taken within the framework of detailed knowledge of the biology, ecology and population dynamics of the target species as well as crop development.

The implementation of areawide management systems for key cotton insect pests is a major undertaking that requires the cooperative efforts of research, extension, teaching and grower communities. The potential long-term benefits of pest population suppression on an areawide basis appear to justify the efforts in terms of reduced costs, more effective pest control, less environmental contamination, and other peripheral problems associated with local uncoordinated efforts which result in year-after-year economic pest populations.

SUMMARY

Community-involved areawide cotton pest management systems for population suppression of several major cotton insect pests have been successfully demonstrated. The systems were based firmly on technical information, theoretical analysis and demonstrated documented research achievements. The accomplishments have resulted from the coordinated efforts and input from many scientific disciplines, experiment station and extension staff, the cotton industry and the grower communities, as well as state and federal agencies. Commonality of interest to maintain and/or increase crop yield, quality and net profits within the framework of effective pest management systems that are socially and environmentally acceptable has contributed greatly to successful programs.

The scientific community has made outstanding progress leading to: (a) better understanding of the benefits of focusing control actions on total insect populations; and (b) exploiting the roles of natural mortality factors, including natural enemies, in regulating populations of many of the important insect pests. Much progress has been made in developing sampling methods, economic thresholds and insect-cotton plant models that are invaluable tools for determining the need for supplementary control actions to complement natural population regulating mechanisms. The most common current array of potential cotton pest population management methodology consists of, but is not limited to: (a) chemical insecticides; (b) host plant resistance; (c) biological agents; (d) autocidal methods; (e) behavioral chemicals (for sampling, detection and control); (f) and cultural controls. Continuing research will undoubtedly refine and improve the potential of these methods and identify additional ones that will expand our selection options. Much additional information needs to be gathered. It is doubtful that we will completely reveal every aspect of the complex biological and physical interactions of agricultural ecosystems. More importantly is the development of adequate information about a target species and the ecosystem that assures, with tools available, a reasonable chance of achieving a successful areawide integrated pest management system. The effectiveness of available control methods for achieving the desired impact on the target pest population will be greatly enhanced with increasing knowledge of the ecological relationships and interactions of the pest and beneficial species, as well as other factors regulating pest population dynamics. Most importantly, but most difficult to attain, is a reasonable estimate of the absolute numbers and distribution of the target pest within the management area. The availability of such information allows analysis of the estimated impact of each potential population suppression component alone and in combination. Such an analysis would provide major guidelines for establishing priorities and selecting pest population suppression techniques with the highest probability of success. In most cases, this information and/or the methodology and expertise to obtain it has not been developed. The importance of having the capability to obtain this vital information justifies a concerted research effort in population ecology to elucidate factors affecting changes in spatial (space related) and temporal (time related) population magnitude. All pest management methods need to be examined, but each one may not be applicable or necessary in every cotton growing area for each target species. More likely, each agricultural area will have specific needs that can be satisfied by tailoring management programs through selection and integration of methodology to meet the highest priority requirements within the area. The selection and integration of technology into a pest management system that is compatible within a specific agricultural production area should be based on knowledge of the target insects and crop production methodology; it should be designed with considerations given to the agroecosystem within which the pest management system is imposed.

Several of the listed population suppression methods, but not all of them, have been combined in the areawide boll weevil management experiments in Mississippi, Texas and Arizona, bollworm/tobacco budworm management experiments in Arkansas, and pink bollworm management experiments in Arizona. These efforts clearly demonstrated that the combinations of suppression methods selected and applied over areas that encompassed a high percentage of the total target pest population significantly reduced their pest status more efficiently than "farm-by-farm" efforts previously practiced (localized control efforts). In each case, the programs provided economic benefits to the farmer and were more environmentally acceptable. Additionally, because of the experience gained, continuing research, technology transfer and extension-education efforts, the programs are being refined and continually improved.

Increasing concern over the environment, as expressed by the public and private sectors as well as the scientific community, places the challenge of providing the world with adequate food and fiber within the constraints of ecologically-based pest protection systems during and after production. Much progress has been made in providing the technology to accomplish these objectives through areawide pest management fundamentals stressing biological and ecological orientation.