CHAPTER 13

CHEMICAL CONTROL

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INTRODUCTION

Historically, production of cotton in southern areas of the United States provided the main source of income for many farm families and was the economic impetus for entire farm communities. Insects occurred as occasional or sporadic pests; however, biological and climatic factors regulated their abundance to a large degree. When the boll weevil, *Anthonomus grandis grandis* Boheman, invaded United States cotton growing areas in 1892, spreading across the Cotton Belt in subsequent years, crop failure and economic disaster followed in its wake (Gaines, 1957).

Devastation of cotton by boll weevil populations provided the impetus for the development and widespread acceptance of chemical control of insect pests of cotton. Producers became heavily dependent on chemical means of control of insect pest outbreaks. As much as 40 percent of the insecticides produced in the United States was used on cotton (Newsom and Brazzel, 1968). Widespread use of insecticides resulted in secondary and occasional pests being elevated to primary pest status as they were released from their natural biotic control (Newsom and Smith, 1949; Reynolds, 1971;

Lincoln and Graves, 1978). In the western areas of the Cotton Belt, plant bug, *Lygus* spp., and spider mite, *Tetranychus* spp., outbreaks provided similar scenarios as did the boll weevil in the eastern areas of the Cotton Belt (Reynolds *et al.*, 1982).

Calcium arsenate was the first in a long line of chemicals that were registered, successfully used, and finally replaced because of diminishing performance. Seven different classes of synthetic insecticides have been developed for use on cotton: (a) inorganics or arsenicals; (b) organochlorines; (c) organophosphates; (d) carbamates; (e) formamidines; (f) pyrethroids; and (g) avermectins. Each class was phenomenally effective upon introduction. After several years of use, some of the products required tank-mixes with other materials to achieve control and finally, with the exception of the arsenicals (which are no longer used), formamidines and avermectins, lost effectiveness due to the build-up of resistance in one or more pest species. Fortunately, new classes of chemicals were developed and approved for use as materials in the former classes were losing effectiveness. This provided only temporary relief, however, as the cycle inevitably would repeat itself. The pyrethroids, one of the latest and most widely used classes to be developed, are now going through the initial stages of resistance development in bollworm, *Helicoverpa zea* (Boddie), and tobacco budworm, *Heliothis virescens* (F.), populations (Plapp and Campanhola, 1986; Leonard *et al.*, 1987, 1988; Luttrell *et al.*,1987). Resistance management strategies have been implemented in an attempt to delay further spread of resistance (Anonymous, 1986; Plapp *et al.*, 1987). There is, however, a desperate need for new chemistry to be developed for cotton insect control.

In addition to the seven classes of insecticides mentioned above, two novel types of insecticides, biologicals and insect growth regulators, also have been registered. The biologicals receiving registration consisted of the delta-endotoxin from the bacterium, *Bacillus thuringiensis*, sold under various trade names, and a nuclear polyhedrosis virus, Elcar®. Use of these materials met with limited success against moderate to high populations of bollworm/tobacco budworm. Commercial production of Elcar® has been discontinued because of lack of use. However, biological insecticides offer a wide area of opportunity as advances in biotechnology and genetic engineering occur.

Diflubenzuron (Dimilin®), an insect growth regulator, has been registered for control of boll weevil populations. It was proven to be effective against low levels of weevils emerging from overwintering sites when scheduled applications were made beginning when cotton initiated fruiting. Commercial success of this product for boll weevil control in cotton has been limited due to a prohibitive price structure and its incompatibility with current insect pest management systems. Most recently, it has been shown to provide good suppression of populations of beet armyworm, *Spodoptera exigua* (Hübner), in cotton (Herzog, unpublished data). Other insect growth regulator materials have been tested during the last few years. Some have shown promise, but none have been registered for use on cotton primarily because of fear of environmental effects on nontarget arthropods. Nevertheless, interest continues in this area of insect control.

Two classes of insecticides with new and unique modes of action are currently under development. They include a class called the pyrroles containing a compound with the proposed name of Pirate® and a class called the nitromethelene guanocycles which includes a material called imidacloprid with the proposed name of Admire®. Pirate® shows promise for control of a broad spectrum of insect pests in cotton, particularly lepidopterous larve. Admire® is a systemic insecticide that is extremely efficacious against a wide range of sucking insect pests.

With the current regulatory climate, increasing environmental awareness, the cost of registration of new chemicals and the high cost of reregistration of existing materials, new products are not being developed as rapidly as in the past. Additionally, during the last decade there has been a trend toward the reduction in the number of agricultural chemical industries that remain in business. This has occurred as a result of corporate mergers or from industries being purchased by other chemical companies. There appears to be a commensurate reduction in the testing and development of new insecticides. Thus, resistance to currently used insecticides poses an even greater threat to the viability of the cotton industry in the United States. Newsom and Brazzel (1968) stated that "there is evidence that populations of *Heliothis* spp. and *Tetranychus* spp. are becoming completely intractable to control by any currently available insecticide". Although new chemicals became available shortly thereafter, that threat still exists perhaps with even more certainty. Chemical control of insect pests in cotton still is the first line of defense against economic damage, but resistance remains the greatest threat to the demise of this highly effective tool. Borlaug (1972) stated that if pesticides were completely banned, crop losses would probably soar to 50 percent and food prices would increase four to five fold. The outlook appears similar if resistance to insecticides by major pests of cotton precludes control.

EVOLUTION OF CHEMICAL CONTROL

SOUTHEASTERN UNITED STATES

The production of cotton in the southeastern United States provided economic stability to the region during a long period of historical development. The establishment of the boll weevil, however, brought crop devastation and economic disaster to most of the cotton growing areas in this region.

Arsenicals — Calcium arsenate was first tested in 1916 and was found to effectively control the boll weevil, but profitability was diminished due to added production costs. As calcium arsenate was more widely used, the disruption of biotic control factors involved in regulation of other insect pests allowed secondary and occasional pests to be elevated to primary pest status. Cotton aphid, *Aphis gossypii* Glover, and bollworm/tobacco budworm outbreaks were common following the use of these inorganic insecticides. Cost of control became prohibitive in much of the area; thus, producers began searching for alternative crops. Alternatives such as peanuts, soybeans, vegetables and livestock increased in popularity thereby dramatically reducing the acreage planted to cotton.

Organochlorines — The introduction of the organochlorine insecticides ushered in a new era of cotton insect control. These broad spectrum materials were effective in controlling virtually all insect pest problems in cotton. These materials created a renewed interest in cotton production; however, it was found that costs for control were too high even in light of the unprecedented yields that were obtained. A major drawback to their use was the increased incidence of spider mite problems. Producers that continued to grow cotton found that, in view of the heavy pest infestation levels and the overlap of populations experienced in much of the southeastern United States, it was expedient to apply controls on a scheduled basis. This approach lead to extensive use of the available chemicals bringing about serious problems with resistance (Tippins and Beckham, 1962; Snow, 1965). By the late 1960s many of the organochlorine compounds were found to be ineffective against boll weevil and bollworm/tobacco budworm populations. A mixture of toxaphene-DDT was still used to some extent until the cancellation of DDT registration by the Environmental Protection Agency in 1972.

Organophosphates — The late 1950s and early 1960s ushered in the era of the extensive use of organophosphate insecticides. These materials provided excellent control of bollworm/tobacco budworm and boll weevil. The systemic nature of several of the organophosphates also afforded excellent control of plant bugs, spider mites and several species of thrips. A wide array of organophosphate products was developed. Many of them had a broad spectrum of activity, while others offered selective control of some pests.

The organophosphate compounds were not unlike their predecessors—resistance began to develop in several pest species to several products (Canerday, 1974; Sparks, 1981). However, the boll weevil appears to be an exception as it is currently as susceptible to methyl parathion (Metaphos®, Penncap-M®), malathion (Cythion®) and azinphosmethyl (Guthion®) as when these compounds were introduced over thirty years ago. The selection pressure being placed on this species by the Boll Weevil Eradication Program in the Southeast should reveal organophosphate resistance mechanisms—barring mutations—if they are present in the population. Nevertheless, after completion of the eradication program in over one million acres of cotton in six southeastern states, no indication of increased resistance or tolerance has been documented or even suspected.

Carbamates — Carbamate insecticides were introduced into the marketplace for cotton insect control beginning in the late 1950s with the registration of carbaryl (Sevin®). It took only about ten years for resistance to this compound to develop in bollworm/tobacco budworm populations (Sparks, 1981). Methomyl (Lannate®, Nudrin®) was introduced in the early 1970s. Although not effective against boll weevil, it provided broad spectrum activity against other cotton insect pests. It was particularly useful in the control of insecticide-tolerant armyworms, *Spodoptera* spp. The major drawback to its use was the reddening of cotton foliage that occurred when high rates or repeated applications were made. Methomyl was also found to be a very effective contact ovicide against bollworm/tobacco budworm eggs when used at low rates (Pitts and Pieters, 1980). Resistance to methomyl (Lannate®, Nudrin®) followed similar patterns to other materials (Sparks, 1981). Thiodicarb (Larvin®) was registered in the mid-1980s for use in cotton insect control. It has proven to be extremely effective against beet armyworm and fall armyworm, *Spodoptera frugiperda* (J. E. Smith), that are tolerant to most other insecticides. It also provides good control of bollworm/ tobacco budworm but is ineffective against the boll weevil. Low rates of thiodicarb have been shown to have contact ovicidal activity against bollworm/ tobacco budworm eggs.

Aldicarb (Temik®), a systemic carbamate insecticide, has been used extensively since the early 1970s as an in-furrow treatment at planting for the control of early season pests of cotton. It is particularly effective against thrips, aphids and spider mites in seedling cotton. It has been shown to control other insects, including boll weevil, when applied at high rates as a side-dress application (Hopkins and Taft, 1965). Resistance has not become a problem with this compound in target species.

Formamidines — A formamidine insecticide, chlordimeform (Fundal®, Galecron®) has been used extensively through the 1970s and 1980s. Its primary activity is as an ovicide against bollworm/tobacco budworm (Dittrich, 1967). It exhibits contact and vapor activity against eggs of this group of pests and has a unique adverse effect on adult moths (Phillips, 1971). It was also demonstrated that there is an adverse effect from chlordimeform residues on larvae infesting treated foliage (Treacy *et al.*, 1987).

Plapp (1976) reported that chlordimeform synergized compounds against resistant bollworms/tobacco budworms. In fact, chlordimeform proved to be effective in the field when used against resistant tobacco budworms. Nevertheless, it was voluntarily removed from the market by the manufacturers following the 1989 crop year because of toxicological problems regarding safety to manufacturing employees. Several alternatives have received federal registration as ovicides for control of bollworm/tobacco budworm eggs, including another formamidine, amitraz (Ovasyn®), methomyl (Lannate®, Nudrin®), thiodicarb (Larvin®) and profenofos (Curacron®).

Pyrethroids — Pyrethroids were among the last groups of insecticides to be developed and marketed for control of insect pests of cotton. They were first used commercially in 1978 under FIFRA Section 18 emergency use program and have since gained widespread acceptance as the materials-of-choice for control of bollworm/tobacco budworm populations. Use rates of these materials is roughly one-tenth or less that of organophosphate or carbamate insecticides. One consideration in the use of these products is their propensity to induce secondary pest outbreaks. Outbreaks of spider mites, cotton aphids and western flower thrips, *Frankliniella occidentalis* (Pergande), frequently occur following pyrethroid applications. Pyrethroids have not been reliable materials for control of armyworms, *Spodoptera* spp., particularly larger larvae, in cotton. There appears to be a preadaptive tolerance to the pyrethroids in these species (Herzog, 1988).

The soybean looper, *Pseudoplusia includens* (Walker), has been a sporadic pest of cotton in the southernmost areas of the southeast United States during the 1980s and early 1990s. It was effectively controlled with applications of permethrin (Ambush®, Pounce®) until 1988 when resistance to these pyrethroids began to appear. A 22-fold level of resistance to permethrin was documented in this pest during 1988-1989 (Herzog, 1988) making permethrin virtually useless for control of this pest.

Recently, there has been considerable concern that pyrethroid resistance in tobacco budworm populations already identified in Arkansas, Louisiana, Mississippi and Texas—may be spreading to the Southeast. One cotton growing area of north Alabama reported unexplained difficulty in achieving control of tobacco budworm beginning in late 1987. Adult moth vial tests (Plapp *et al.*, 1987) indicated that some resistant individuals may have been present in that population (Herzog, 1988). Standard laboratory bioassays using topical application on bollworm/tobacco budworm larvae indicate no change in pyrethroid susceptibility in either species in Georgia (Herzog *et al.*, 1987). There have been no reports of unexplained field failures in other areas of the Southeast.

The loss of these valuable compounds to resistance would certainly be a critical setback to cotton production in the Southeast. Cotton acreage in this region has experienced a steady increase over the last several years. This expansion may be attributed, in part, to the dependable control provided by the pyrethroids. Resistance, at least at some level, appears to be inevitable.

The success of the Boll Weevil Eradication Program in elimination of the boll weevil in much of the southeastern United States has provided significant opportunities for the return to a more biologically-based system of insect pest management. There has been a dramatic reduction in the amount of insecticide used in areas where sprays for boll weevils are not required. Natural enemies of pest species are more able to regulate populations to at least some extent reducing the number of insecticide applications appreciably. This reduction in insecticide use may delay pyrethroid resistance, however, the increased acreage of cotton with the accompanying exposure of a greater proportion of the tobacco budworm population to these compounds may portend a more rapid development of pyrethroid resistance.

MID-SOUTH AND SOUTHWEST UNITED STATES

Until the boll weevil entered the United States in 1892, only the cotton leafworm, *Alabama argillacea* (Hübner), cotton aphid and bollworm/tobacco budworm were recognized as occasional pests of cotton in the Mid-South and Southwest United States (Newsom and Brazzel, 1968). The boll weevil became a perennial pest of cotton (Metcalf and Luckmann, 1975) since populations exceeding recognized economic thresholds usually occurred annually due to insufficient natural control from climatic and biotic factors. In 1918, Coad demonstrated for the first time that a chemical, calcium arsenate, could be used to effectively control the boll weevil. The widespread use of calcium arsenate from the 1920s through the mid-1940s resulted in the cotton aphid and bollworm/tobacco budworm becoming severe pests (Lincoln and Graves, 1978).

The advent of DDT and other organochlorines in the mid- to late-1940s revolutionized cotton insect pest control since they exhibited a broad spectrum of activity against practically all arthropod pests. However, most organochlorines induced spider mite outbreaks. Development of insecticide and acaricide resistance in numerous arthropods, resurgence of arthropod pests following pesticide applications, and induced arthropod pest problems resulted in rapid shifts to new pesticide chemistry as it became available.

Use of organophosphates and carbamates became widespread in the late 1950s and continues to the present. However, the pyrethroids, which became available in 1978 are now being used extensively for control of bollworm/tobacco budworm, boll weevils and other insect pests of cotton. Outbreaks of cotton aphids, spider mites and western flower thrips have been associated with the use of pyrethroids. Other classes of insecticides useful in managing arthropod pest populations on cotton are formamidines (chlordimeform [Fundal®, Galecron®]) and insect growth regulators such as diflubenzuron (Dimilin®).

Arsenicals — Prior to Coad's (1918) demonstration that calcium arsenate could be effectively and economically used to manage boll weevil populations, there was no appreciable use of insecticides on cotton in the Mid-South or Southwest United States. During this period producers relied mainly on cultural and biological approaches, but they proved to be unreliable and inadequate.

From the early 1920s until the mid-1940s, calcium arsenate was used extensively for boll weevil control. Early recommendations for its use followed modern concepts of insect pest management. Emphasis was placed on cultural controls with calcium arsenate to be used only after other methods had failed. Dusting was recommended when 10 to 15 percent of the cotton squares were damaged (Hunter and Coad, 1923; Isely and Baerg, 1924); however, the treatment level later was increased to 25 percent in the Mississippi Delta (Gaines, 1944). Isely found that automatic early-season applications of calcium arsenate failed to control boll weevils effectively or increase yields; whereas, scouting and treating as needed proved quite effective (Isely and Baerg, 1924). Isely (1926) also introduced spot-dusting for control of emerging first-generation adults. From the early work of Isely, an insect pest management system was developed, its major components being scouting, spot dusting and early maturity of the cotton crop (Lincoln *et al.*, 1975).

Repeated applications of calcium arsenate, which were necessary in areas of heavy boll weevil pressure, usually induced cotton aphid outbreaks. Folsum (1928), Smith and Fontenot (1942) and Isely (1946) reported that these aphid outbreaks resulted from the detrimental effects of calcium arsenate on the biological control system that ordinarily controlled this insect. Furthermore, disruption of the biological control system plus the abundance of honeydew (from aphids) as a food source for adults of bollworm/tobacco budworm often led to outbreaks of these species (Lincoln and Graves, 1978). Nicotine, a plant product insecticide, was used to control aphids, but control of bollworm/tobacco budworm with available insecticides was virtually impossible. Meanwhile, the widespread use of calcium arsenate greatly reduced the pest status of the cotton leafworm.

Organochlorines — The advent of DDT and other organochlorines beginning in the mid-1940s revolutionized cotton insect pest control. These broad spectrum and relatively long residual insecticides were so effective against boll weevils; bollworms/tobacco budworms; aphids; cotton leafworms; thrips (primarily tobacco thrips, *Frankliniella fusca* [Hinds]); tarnished plant bugs, *Lygus lineolaris* (Palisot de Beauvois); cotton fleahoppers, *Pseudatomoscelis seriatus* (Reuter); and, other occasional pests of cotton that yields resulting from their use approximately doubled that obtained with calcium arsenate and other inorganic insecticides (Newsom and Brazzel, 1968).

DDT was the first truly effective insecticide for control of bollworm/tobacco budworm. DDT was soon followed by BHC, dieldrin, endrin and toxaphene, which were shown to be highly efficacious against boll weevils and most other cotton insect pests (Anonymous, 1947-71). Unfortunately, use of organochlorines released spider mites from their biological control agents and outbreaks became widespread (Anonymous, 1947-71; Boyer and Bell, 1961). Thus, mixtures of insecticides, including sulfur to suppress spider mites, were commonly used to control the insect pest complex attacking cotton, (Lincoln and Graves, 1978).

Because of their effectiveness, many cotton producers began to use the organochlorines on a preventative basis rather than when economic thresholds were exceeded (Lincoln and Graves, 1978). This "automatic" system, which was based on a fixed schedule of applications, was successful in its primary objectives of controlling insect pests and increasing cotton yields. However, subsequent problems of environmental pollution by the long-residual organochlorines and development of resistance to organochlorines by several cotton insect pests dictated a return to cotton insect pest management systems based on scouting, economic thresholds and timing of insecticide applications.

The boll weevil developed resistance to such organochlorines as BHC, toxaphene, endrin and dieldrin in less than a decade after their introduction (Roussel and Clower, 1957). Though first documented in Louisiana (Roussel and Clower, 1957), resistance to organochlorines developed rapidly throughout the range of the boll weevil (Graves and Roussel, 1962; Brazzel and Shipp, 1962; Tippins and Beckham, 1962). Nevertheless, mixtures of toxaphene and DDT still effectively controlled weevils even though weevils were resistant to toxaphene alone or DDT alone. Also, calcium arsenate again was used to effectively control boll weevils.

Other species of cotton insect pests also developed resistance to organochlorines. Resistance to DDT in the tobacco budworm occurred in Texas in 1961 (Brazzel, 1963) and soon was reported from across the Cotton Belt (Graves *et al.*, 1964, 1967; Pate and Brazzel, 1964; Snow, 1965; Lingren and Bryan, 1965; Harris, 1970). Graves *et al.* (1963) first reported organochlorine resistance in bollworms from Louisiana. Resistance to DDT and other organochlorines in the bollworm was soon reported from across the Cotton Belt (Graves *et al.*, 1963, 1964; Lincoln *et al.*, 1967; Brazzel, 1964; Snow, 1965; Lingren and Bryan, 1965). As with the boll weevil, mixtures of toxaphene and DDT remained effective against DDT-resistant bollworms/tobacco budworms. However, the removal of the DDT registration on cotton by the United States

Environmental Protection Agency in 1972 not only ended the use of the toxaphene-DDT mixture, but also signalled an end to the organochlorine era.

Organophosphates — Organophosphate insecticides were first developed in the late 1940s and early 1950s. Parathion was recommended for emergency use on cotton in 1951. Also TEPP (tetraethyl pyrophosphate) was recommended for aphid control in 1951. By the mid-1950s several compounds (malathion [Cythion®], demeton [Systox®, Metasystox®], methyl parathion and EPN) were registered on cotton and exhibited broad spectrum activity against most arthropod pests. Malathion and methyl parathion remain highly effective today on the boll weevil. In 1958, carbophenothion (Trithion®) was registered for control of cotton aphids and spider mites. During 1959, naled (Dibrom®), trichlorfon (Dylox®) and ethyl parathion were used to control several cotton pests. Ethyl parathion was used to control a wide variety of pests including organochlorine resistant bollworm/tobacco budworm populations.

Methyl parathion was recommended for bollworm/tobacco budworm control in the early 1960s. Shortly thereafter methyl parathion was mixed with endrin, carbaryl (Sevin®), strobane (Strobane®) and DDT for bollworm/tobacco budworm control. In 1962, phosphamidon (Swat®) was shown to provide effective control of cotton aphids, tarnished plant bugs and other mirids (small plant bugs that feed mainly on plant juices). Dicrotophos (Bidrin®), recommended in 1963, gave excellent control of cotton fleahoppers, cotton aphids, spider mites and tarnished plant bugs. Azinphosmethyl (Guthion®) was recommended in the mid-1960s for control of boll weevils, aphids, thrips and armyworms. Azinphosmethyl (Guthion®) still remains very effective against boll weevils. In the mid-1960s, dimethoate (Cygon®) and dicrotophos (Bidrin®) were used to control *Lygus* spp., cotton fleahoppers and thrips. Both are still recommended for the control of early season pests of cotton (except for spider mites). Monocrotophos (Azodrin®) was also registered during the mid-1960s for control of: boll weevils; bollworms/tobacco budworms; cabbage loopers, *Trichoplusia ni* (Hübner); cotton aphids; cotton fleahoppers; tarnished plant bugs; thrips; and spider mites. Monocrotophos (Azodrin®) was recommended for control of the majority of these pests but was voluntarily removed from the market by the manufacturer following the 1989 growing season.

In 1969 the bollworm began to develop resistance to methyl parathion in Arkansas and Oklahoma. During the early 1970s bollworm/tobacco budworm populations began to develop resistance to most recommended organophosphates used alone (Lukefahr, 1970). At that time several mixtures of organophosphates were used on populations that were difficult to control. Among these were: EPN + methyl parathion; EPN + methyl parathion + methomyl (Lannate®, Nudrin®); toxaphene + methyl parathion + chlorpyrifos (Lorsban®); and, EPN + methyl parathion + chlorpyrifos (Lorsban®). These mixtures provided effective control for several years.

Acephate (Orthene®) was registered for use in the mid-1970s for control of bollworms/tobacco budworms as well as loopers, cotton aphids, cotton fleahoppers, tarnished plant bugs and the bandedwinged whitefly, *Trialeurodes abutilonea* (Haldeman). Also during the late 1970s and early 1980s, sulprofos (Bolstar®) and profenofos (Curacron®) were registered for control of the bollworm/tobacco budworm and armyworm complexes.

Several organophosphate insecticides including disulfoton (Di-Syston®), phorate (Thimet®) and acephate (Orthene®) are recommended as seed treatments or in-furrow applications at planting for systemic control of thrips in seedling cotton.

The development of resistance in bollworm/tobacco budworm populations to organochlorines (Brazzel, 1963) made it necessary to rely on organophosphate insecticides for control (Adkisson, 1968). However, as early as 1970, Cantu and Wolfenbarger (1970) recommended that insecticides with different modes of chemistry were needed because of resistance to methyl parathion and monocrotophos (Azodrin®) that was found in larvae of the tobacco budworm collected in the Mante-Tampico, Mexico area and at Brownsville, Texas. Also, Whitten and Bull (1970) reported the tobacco budworm to be resistant to organophosphate insecticides. Plapp (1972) recognized that bollworm/tobacco budworm were becoming resistant to methyl parathion and immediately began looking for alternative insecticides. He reported that chlordimeform (Fundal®, Galecron®) worked as a synergist with many insecticides to control resistant populations of tobacco budworm (Plapp, 1976). Watve *et al.* (1977) reported high levels of resistance in bandedwinged whitefly to methyl parathion and monocrotophos (Azodrin®). However, Bottrell *et al.* (1973) reported that the boll weevil had failed to develop resistance to malathion (Cythion®) after several years of exposure.

Carbamates — Carbaryl (Sevin®) was the first of the carbamate insecticides to be recommended for use in the control of insect pests of cotton. By 1958 it was recommended for the control of boll weevils, bollworms/tobacco budworms and plant bugs. About ten years later the bollworm showed signs of resistance to this compound in Texas (Adkisson and Nemec, 1966) and Louisiana (Graves *et al.*, 1964). Methomyl (Lannate®, Nudrin®) was recommended for control of bollworms/tobacco budworms and plant bugs in the early 1970s. Methomyl-resistant bollworm/tobacco budworm larvae were found, however, in Louisiana (Clower, 1980) and Mississippi (Furr, 1978) as early as 1976. Carbofuran (Furadan®) showed promise as an in-furrow treatment for controlling tarnished plant bugs, cotton fleahoppers, bandedwinged whiteflies and thrips. Aldicarb (Temik®), used at high rates, was shown to control overwintering boll weevils (Hopkins and Taft, 1965; Bariola *et al.*, 1971). However, researchers reported that increases in bollworm/tobacco budworm populations occurred following use of aldicarb at high rates, one to two pounds of active ingredient per acre (Cowan *et al.*, 1966; Coppedge *et al.*, 1969). Scott *et al.* (1985) reported little effect on total predator populations and no increase of bollworm/ tobacco budworm infestations when aldicarb was used at 0.25-0.5 pounds active ingredient per acre. Aldicarb currently is used widely across the Cotton Belt to control early-season pests in cotton. Oxamyl (Vydate®) was registered on cotton for control of several insect pests in the late 1970s but has not been widely used. Thiodicarb (Larvin®) was registered in the mid-1980s for cotton insect control. It has been especially effective against armyworms *Spodoptera* spp.; it provides good control of bollworm/tobacco budworm eggs and larvae; but, it is ineffective against the boll weevil.

Pyrethroids — Natural pyrethrins and early pyrethroids were recognized as excellent insecticides with a broad spectrum of activity against insects but relatively harmless to mammals (Barthel, 1961; Elliott, 1971). However, they were too unstable and expensive to efficaciously control pests of agricultural crops such as cotton (Elliott, 1976). Once permethrin was synthesized in 1972, pyrethroids which were photostable enough to be used on cotton and other agricultural crops started to become available (Elliott's *et al.*, 1973). Although pyrethroids exhibit a broad spectrum of activity against practically all cotton insects, they are especially toxic to the bollworm and tobacco budworm. For example, permethrin is approximately ten times more toxic to these pests than organophosphates and carbamates.

Pyrethroids became available for field use under a large-scale Section 18 program in 1977-1978. Conditional registration was granted in 1979 and they quickly became the insecticide of choice for controlling cotton insect pests, particularly the tobacco budworm, which had developed high levels of resistance to most organochlorines, organophosphates and carbamates (Clower, 1980). To reduce their usage and thus lessen the possibility of resistance development, pyrethroids usually were recommended only for control of the bollworm/tobacco budworm, although they were quite effective against boll weevil, tarnished plant bugs, cotton fleahoppers, cutworms and most species of thrips. Conversely, pyrethroids generally exacerbate aphid, spider mite and western flower thrips problems.

Pyrethroids became the most widely used insecticides on cotton during the early 1980s and remain so today. However, the development of problem levels of resistance to pyrethroids by the tobacco budworm in some locations in Texas in 1985 and in Texas, Arkansas, Louisiana and Mississippi during 1986 (Leonard *et al.*, 1987, 1988; Plapp *et al.*, 1987; Roush and Luttrell, 1987) threatens their continued usefulness. In response to the pyrethroid resistance problem in tobacco budworm, state and federal research and extension entomologists from Arkansas, Louisiana and Mississippi adopted and recommended a pyrethroid resistance management plan (Anonymous, 1986). This plan was widely accepted by cotton producers in the Mid-South and resistance monitoring data for 1987 indicates that resistant genotypes of tobacco budworm were reduced about 50 percent in Louisiana (Graves *et al.*, 1988a, 1988b).

Pyrethroid resistance problems in tobacco budworm have continued to increase through much of the Mid-South and Southwest United States. A number of field control failures using pyrethroids against tobacco budworm have been reported as a result of this resistance. This has made it necessary for growers to use tank-mixtures with other classes of chemistry or to switch to other classes altogether (Leonard *et al.*, 1993).

WESTERN UNITED STATES

Evolution of insecticidal control of pest insects in cotton grown in the irrigated deserts of the western United States followed a pattern similar to that in the southern and southeastern United States, except that the pest control scheme was dominated by the western lygus bug, *Lygus hesperus* Knight, and the bollworm (Reynolds *et al.*, 1982). More recently insecticide usage in cotton has been dictated by: (a) the pink bollworm, *Pectinophora gossypiella* (Saunders), which completed its spread across Arizona and southern California in 1965 (Noble, 1969); (b) the tobacco budworm beginning in 1972 in Arizona and subsequently into southern California (Watson, 1974); (c) the boll weevil in various parts of Arizona and southern desert valleys of California beginning in 1978 (Bergman *et al.*, 1982; Watson *et al.*, 1986a); and most recently by (d) the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Henneberry, 1993).

Prior to the establishment of the pink bollworm, insecticide treatments were generally initiated for control of lygus bugs and occasionally for control of the bollworm. Since 1966, when control of the pink bollworm required scheduled applications of insecticides, secondary pest outbreaks have occurred including the cotton leafperforator, *Bucculatrix thurberiella* (Busck), sweetpotato whitefly, and spider mites. Little insecticide was used in western cotton prior to the mid-1940s when the organochlorines became available. DDT and other organochlorines dominated the scene for the next two decades, ultimately being replaced by the organophosphates and carbamates beginning in the late 1950s and continuing to the mid-1970s, and then the pyrethroids in the late 1970s.

Organochlorines — DDT was first used experimentally in Arizona in 1943 and 1944; its first commercial use occurred in 1945, primarily against *Lygus* spp. (Ware, 1974). Subsequent outbreaks of other species such as the beet armyworm and saltmarsh caterpillar, *Estigmene acrea* (Drury), were also effectively controlled by DDT and other organochlorines (Ware, 1974). Because of severe insecticide-induced problems with secondary pests, developing in southern California in the late 1950s, the broad spectrum organochlorine insecticides were phased out in favor of a simple system of integrated pest control (Reynolds *et al.*, 1982). This system was centered on: (a) conserving the natural enemies of the target insect pest and secondary pest species and (b) using selective dosages of selected organophosphate insecticides.

During the mid-1950s, additional problems with organochlorine insecticides were beginning to surface. DDT was losing its effectiveness against the pests which were of greatest economic importance. Western lygus bugs could no longer be controlled with DDT in the San Joaquin Valley of California (Leigh, 1969). By 1966 the bollworm had become nine-fold more tolerant to DDT in Maricopa County, Arizona, than in the generally untreated area of Cochise County (Fadare, 1967).

In 1968, the United States Food and Drug Administration placed an embargo on 50,000 pounds of butter shipped from Arizona to California because of DDT residues present in amounts over the legal tolerance; in the same year, the University of Arizona Department of Entomology removed DDT from all of its agricultural pest control recommendations with the sole objective of reducing DDT residues in food and feed crops (Ware, 1974). This, of course, did not eliminate the use of DDT but paved the way for a one-year ban placed on its use in 1969 by the Arizona Board of Pesticide Control. This was repeated in 1970, 1971 and 1972. A federal ban on the use of DDT on cotton was declared by the United States Environmental Protection Agency, effective January 1, 1973 (Ware, 1974).

Organophosphates — The organophosphates, especially methyl parathion, were effective against bollworm and tobacco budworm in the western areas of the cotton growing region of the United States up to 1972. However, following the serious outbreak of tobacco budworm in 1972, it was found that these materials were becoming ineffective (Lentz *et al.*, 1974). During the tobacco budworm outbreak years of 1976-78, methyl parathion became virtually useless (Watson *et al.*, 1986b). The organophosphates, particularly methyl parathion and azinphosmethyl (Guthion®) were very effective against the key pest, the pink bollworm. Cotton leafperforators became an increasingly serious problem during this time as they became resistant to organophosphates and problems were in fact exacerbated by their use.

The boll weevil required insecticidal control measures in some areas of Arizona prior to the eradication effort in that area. Several organophosphate insecticides, such as methyl parathion, azinphosmethyl (Guthion®), malathion and encapsulated methyl parathion (Penncap-M®), as well as some of the pyrethroids, still effectively control the boll weevil. However, applications must be made at shorter intervals and for a much longer part of the growing season than for other pests. This results in excessively high control costs and the development of additional secondary pest problems.

Carbamates — During the early 1970s the introduction of the carbamate methomyl (Lannate®, Nudrin®) provided much needed relief for control of the resistant cotton leafperforator, a serious secondary pest caused by the use of organophosphate insecticides. Methomyl was also quite effective against tobacco budworm until the outbreak years of 1976-78 at which time resistance rendered it virtually useless.

Pyrethroids — During the tobacco budworm outbreak years of 1976-78, the pyrethroid insecticides were being developed and by 1979 had gained conditional federal registration. This group of insecticides had broad-spectrum activity and was extremely effective against the pink bollworm and tobacco budworm. Because of the need to conserve these materials for use against the bollworm/tobacco budworm complex, growers were cautioned against using them to control pests for which other effective materials were available. Specifically, they were encouraged to continue using the organophosphates for pink bollworm control.

During the next decade much of the chemical control of cotton pests in the West involved the use of pyrethroids, with the exception of the San Joaquin Valley of California. The result has been the development of higher levels of tolerance in certain localized populations of the pink bollworm (Miller, 1987). Additionally, a laboratory study in Arizona has shown that selective pressure on tobacco budworm at the LD_{80}[1] level will result in high levels of resistance after only twelve generations (Jensen *et al.*, 1984).

Because of increased spider mite populations following the use of pyrethroids, these materials are not recommended in California's San Joaquin Valley. In southern California and Arizona, there also is an association between sweetpotato whitefly outbreaks and the use of pyrethroids. Few effective materials are currently available for spider mite control and no really satisfactory insecticide is currently registered for sweetpotato whitefly control.

[1]LD80 is the dosage level which is lethal to 80 percent of the treated individuals.

In the highly fragile agroecosystem of the San Joaquin Valley, the western lygus bug is the key to the insect pest management program. Insecticide applications for lygus control can trigger outbreaks of bollworm/tobacco budworm, beet armyworm, cabbage looper and spider mites. Careful timing of insecticide applications and utilization of higher economic thresholds help prevent outbreaks of these secondary pests. This results in fewer insecticide applications in the San Joaquin Valley than in the lower desert areas of southern California and Arizona.

The sweetpotato whitefly has become an extremely serious pest problem not only in cotton but in a variety of other crops in the southwestern United States since the B-Strain became the predominant biotype (Henneberry, 1993; Henneberry and Toscano, 1993). Management and insecticidal control of this pest is extremely difficult because of: (a) its tolerance to most pesticides; (b) its wide and diverse host range; and (c) its biotic potential.

Several combinations of insecticides have shown promise for control of the sweetpotato whitefly provided that populations do not reach high levels before control programs are initiated. Fortunately, from the standpoint of insecticide resistance management, several classes of insecticides are included among those that are useful for control of sweetpotato whitefly. The materials that have shown the greatest activity against the whitefly include: (a) the pyrethroids–Capture® and Danitol®; (b) the organochlorine–endosulfan (Thiodan®, Phaser®); (c) the formamidine–amitraz (Ovasyn®); and (d) several organophosphates including Orthene® and Monitor®. Additionally, an insect growth regulator, buprofezin (Applaud®), and a systemic insecticide, imidacloprid, NTN-33893 (Admire® [proposed] have shown promise for sweetpotato whitefly control, however, it may be several years before their use is approved by the Environmental Protection Agency.

RELATIVE EFFICACY

Pesticide efficacy in relation to cotton pest control may be defined as "the ability of a compound, when applied to the crop, to reduce or eliminate the capability of a pest to cause crop damage". For purposes of this discussion, this is interpreted as resulting from pesticide-induced mortality or some other direct effect on the pest population.

There is no universal index of relative efficacy of insecticides. Labelling information required by state and federal agencies may be used to indicate general efficacy of a compound, at least at the time of registration (Table 1). However, because of the dynamic nature of insecticide efficacy in relation to individual pest species, label recommendations may not always reflect reality. Pesticide effectiveness is dependent upon a number of factors including: (a) the susceptibility of the pest species to the compound; (b) the density of insects per unit area; (c) the concentration of resistant genotypes in the population; (d) the type of resistance demonstrated in the population; (e) weather factors; (f) method of application; (g) timing of the pesticide application in relation to life stage of the target pest or time of day; (h) pH of the insecticide spray solution; (i) crop canopy density; (j) age of the plants; (k) plant uptake and transport; (l) pest behavior, and many other factors.

Table 1. Insecticides and acaricides fully registered for control (C) or suppression (S) of cotton arthropod pests as derived from actual labels or labels printed in <u>Crop Protection and Chemicals Reference</u> as of January 1993.

Insecticide/acaricide common name		Class	Cotton leafperforator	European corn borer	Yellowstriped armyworm	Beet armyworm	Fall armyworm	Tobacco budworm	Bollworm	Pink Bollworm	Cutworm	Cabbage looper	Saltmarsh caterpillar	Cotton leafworm	Boll weevil	Thrips*	Cotton aphid	Stink bug	Lugus bugs	Cotton fleahopper	Spider mites	Whiteflies**	Grasshoppers
Bacillus thuringiensis[1]	I	BIO	C		C	C	C	C	C		C	C											
Aldicarb	Sy	CAR	C												C	C	C		C	C	C	C	
Carbaryl	Ct	CAR	C		C		C		C	C	C			C	C	C	S	C	C	C			
Carbofuran	Ct,Sy	CAR														C							
Methomyl	Ct	CAR	C			C	C	C	C					C		C	C		C	C			
Oxamyl	Ct	CAR	C												C				C	C			
Thiodicarb	Ct,I	CAR	C		C	C	C	C	C	S	C	C		C	S				S	S			
Amitraz	Ct,F	FOR						C	C	C											C	C	
Diflubenzuron	Ct,I	IGR				C	C								C								
Dicofol	Ct	OCL																			C		
Endosulfan	Ct	OCL	C						C			C			C	C	C	C	C				
Acephate	Ct,Sy	OP			C		C	C	C	C	C	C				C	C	C	C	C		C	
Azinphosmethyl	Ct	OP							C	C				C	C	C		C	C	C			
Chlorpyrifos	Ct	OP			C	C	C	C	C	C	C		C		C	C	C		C	C	C		C
Dicrotophos	Ct,Sy	OP	C										C		C	C	C	C	C	C	C		C
Dimethoate	Ct,Sy	OP														C	C		C	C	C		
Disulfoton	Sy	OP														C	C				C		
Phosphamidon	Sy	OP														C	C		C	C			
Malathion	Ct	OP													C	C	C		C	C			C
Oxydemeton-methyl	Sy	OP														C	C		C	C	C		
Methamidophos	Ct,Sy	OP				C						C				C	C	C	C	C	C	C	
Methidathion	Ct	OP							C	C					C				C		C	C	
Methyl parathion	Ct	OP						C	C						C	C			C	C			
Naled	Ct,F	OP	C		C				C			C							C	C	S		
Phorate	Sy	OP									C					C	C				C	C	
Phosmet	Ct	OP													C							C	
Profenofos	Ct	OP	C			C	C	C	C								C		C		C	S	
Sulprofos	Ct	OP				C	C	C	C	C						C		C	C	C	S	S	
Trichlorphon	Ct,Sy	OP	C		C	C							C	C				C	C	C			
Bifenthrin	Ct	PY	C	C	C	C	C	C	C	C	C	C	C		C	C	C	C	C	C	C	C	
Cyfluthrin	Ct	PY	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C		S	C
Cypermethrin	Ct	PY	C		C	C	C	C	C	C	C	C	C		C	C	S		C	C		S	
Esfenvalerate	Ct	PY	C			C		C	C	C	C	C	C	C	C	C			C	C		S	C
Lamdacyhalothrin	Ct	PY	C	C		C	C	C	C	C	C	C	C	C	C	C	S	C	C	C	S	S	
Permethrin	Ct	PY	C			C		C	C	C	C	C	C				S		C	C		S	
Tralomethrin	Ct	PY	C			C	C	C	C	C	C	C	C	C	C	C	S	C	C	C	S	S	
Zetacypermethrin	Ct	PY	C	C	C	C	C	C	C	C	C	C	C			C	S		C	C		S	

Key: BIO - biological, CAR - carbamate, FOR - formamidine, IGR - insect growth regulator, OCL - organochlorine, OP - organophosphate, PY - pyrethroid, Ct - contact, Sy - systemic, I - ingestion, F - fumigant

*Western flower thrips are suppressed by only a few systemic insecticides.
**There is no effective compound for sweetpotato whitefly control in Arizona & California
[1]All current commercial products of *Bacillus thuringiensis* used in cotton include vars. Kurstaki, Aizawai, or a combination of the two.

Pesticide efficacy may be affected by previous use or misuse of insecticides which may induce pest resistance to the pesticide of choice (cross resistance). By the 1960s resistance to at least one insecticide was noted for every major cotton insect pest (Brazzel and Wilson, 1967). Insecticide efficacy for a specific compound and pest may vary among geographical areas. Factors that contribute to these variations include weather differences, differences in the pest insect gene pool caused by previous insecticide use, immigration of insects (gene flow) or other reasons. In addition, insecticides may stimulate the development of secondary pest populations by reducing natural control agents. Thus aphid and whitefly populations may increase drastically following repeated pyrethroid applications, and spider mite populations may build following applications of organophosphate or pyrethroid compounds.

Relative efficacy is related to the mode of entry of the insecticide into the insect—by contact, stomach (ingestion) or fumigant action. Insecticides which are taken into the plant's vascular system, and hence by feeding into the insect, are classified as systemic insecticides. In general, insects with a piercing-sucking method of feeding are best controlled by systemic insecticides. This is particularly true of aphids, spider mites, whiteflies and thrips which typically inhabit the abaxial (lower) leaf surface where deposition of insecticide by standard spraying systems is minimal. Usually, lepidopterous larvae which attack cotton fruit are controlled best with contact poisons that are transported through the insect integument (exoskeleton or enveloping layer) either when the spray falls on the insect or the insect contacts chemical residue on the plant's surface during movement. Leaf feeding insects are usually more susceptible to stomach poisons than insects which feed on more protected areas of the plant where there is less insecticide deposited. The fumigant activity of most insecticides is negligible and generally does not contribute much to efficacy of cotton insecticides. A notable exception is chlordimeform (Fundal®, Galecron®) which provides ovicidal activity in the vapor phase (Dittrich, 1967; Phillips, 1971) and affects mating behavior and fecundity (the ability to lay eggs and thus reproduce) of adult moths (Phillips, 1971).

Insecticide efficacy is also related to mode of action. In general, organophosphates and carbamates function as acetyl cholinesterase inhibitors, while pyrethroids function by altering ion permeability of nerve axons in a manner similar to that of early organochlorines. Endosulfan (Thiodan®, Phaser®), an organochlorine currently labelled for control of some cotton insects, blocks inhibitory nerve synapses. Insect growth regulators, pathogens and other biological or pseudobiological compounds used as insecticides function in various ways, many against specific insects or related groups of insects. For a more indepth discussion of mode of action of specific types of insecticides, readers are referred to Chapter 8 of this book.

Pyrethroids and organophosphates are the primary insecticides used on cotton. According to Luttrell and Reed (1986), field tests over a period of ten years indicate that control of larvae of the tobacco budworm and the bollworm collectively was significantly better with pyrethroids than organophosphates, and control of boll weevil, spider mites and aphids was significantly better with the organophosphates than with pyrethroids. Clower *et al.* (1987) reported that, over a period of several years throughout the Cotton Belt, pyrethroids were slightly more efficacious than carbamates or organophosphates for the control of bollworm/tobacco budworm.

The bollworm/tobacco budworm complex aptly demonstrates the difficulty in adequate insecticide efficacy evaluation. The larvae of the two species are so similar that identification in the field is difficult and reports of insecticide efficacy have generally referred to the population as a whole, rather than to populations of separate species. Because of the development of resistance in tobacco budworm larvae, the control of this species with pyrethroids is decreasing in the Arkansas, Louisiana, Mississippi and Texas. This continual decline in efficacy for control of larvae of the bollworm/tobacco budworm complex by two pyrethroids as used in several states from 1980 to 1986 is demonstrated in Figure 1. An increase in tobacco budworm resistance in 1986 (Leonard *et al.*, 1987; Luttrell *et al.*, 1987; Roush and Luttrell, 1987; Plapp *et al.*, 1987) may explain the drastic drop in efficacy of pyrethroids that year, 1986. In Mississippi, the percentage of field-collected bollworm/tobacco budworm eggs which developed into tobacco budworm was low in 1984 and 1985 (Pfrimmer, 1986). In Mississippi and Louisiana, the portion of adult pheromone-trapped male bollworm/tobacco budworm which were tobacco budworm also was low in 1984 and 1985 (Personal communication, E. A. Stadelbacher, retired, Greenville, Mississippi; Leonard, *et al.*, 1989) . If this trend was true in the rest of the Mid-South and Southwest United States, the increase in efficacy of the two pyrethroids during those years may be related to higher bollworm populations and lower tobacco budworm numbers. Stadelbacher (1979) ascribes a reversal in species dominance of these insects prior to 1979 to development of higher levels of resistance to insecticides in tobacco budworm than in the bollworm population. He attributes the general increase in tobacco budworm density to increased acreage of wild geranium, *Geranium dissectum* L. Thus, species identification, population densities, wild host availability and prior insecticide use all have played roles in efficacy evaluation for insecticides used to control bollworm/tobacco budworm larvae.

The relative efficacy of compounds used against resistant populations may be augmented or synergized by addition of other compounds. Field tests summarized over a period of several years indicate that pyrethroids, at one-half the recommended rate in combination with chlordimeform (Fundal®, Galecron®) at low rates, performed as well against bollworm/tobacco budworm as pyrethroids alone at full recommended rates (Luttrell and Reed, 1986). In addition to synergistic applications, compound mixtures may allow for concurrent control of secondary pests or as partial insurance against development of resistance.

When insecticide resistance has occurred, changing to a compound with a different mode of action has usually circumvented the problem. Thus control of boll weevil changed from organochlorine compounds to organophosphates in most areas. Similarly, the cotton leafperforator in the western United States developed resistance to organophosphates used for control of pink bollworm and was elevated from a minor pest to a primary pest. Introduction of chlordimeform (Fundal®, Galecron®) proved effective in regaining control of this pest.

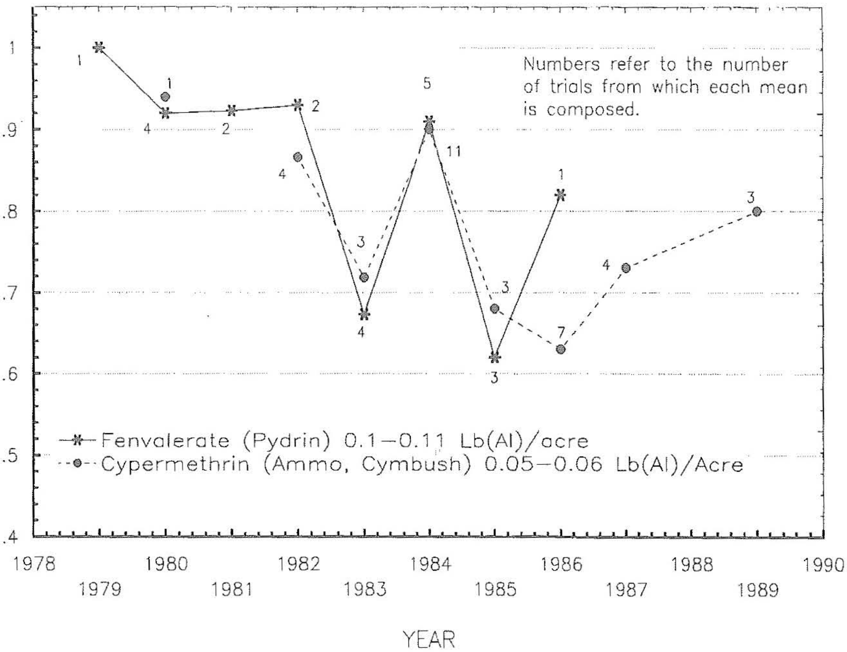

Figure 1. Downward trend of an efficacy index representing control of bollworm/tobacco budworm larvae by cypermethrin (Ammo®, Cymbush®) and fenvalerate (Pydrin®) as calculated from small plot field studies published in *Insecticide and Acaracide Tests* from 1979 to 1989. Data are from Mississippi, Louisiana, Texas and Alabama. The Efficacy Ratio is computed by dividing the larvae reported in treated plots by the number of larvae reported in untreated plots. An Efficacy Ratio of 1.0 indicates the same number of larvae are reported in the treated and the untreated plots. Negative efficacy ratios were not included in the graph.

Following a change in pesticide type, insect resistance to a previously used compound might decrease in time; but with the strong possibility that resistance in the insect population would build very rapidly if the insecticide were brought back into repetitive use.

As new chemistry is developed, there is a trend for compounds to be much more specific for the control of insects and less toxic to vertebrates. Early pyrethroids were used at a rate of approximately one tenth of a pound of active ingredient per acre; rates of three hundredths of a pound per acre or less are common with the newer pyrethroid insecticides. Such specificity is even more apparent in contrast to the organophosphates and organochlorines which were, or are, recommended for use at one pound or more active ingredient per acre. In addition to increased efficacy, there is a tendency for increased specificity, particularly in the case of experimental insect growth regulators and pathogens used as insecticides. These factors, however, have little bearing on the probability that pests may become genetically adapted to a chemical control agent. A major task of researchers and insecticide developers is to maintain an index of pesticide efficacies (insecticide resistance monitoring) in order to evaluate efficacy changes and to institute new procedures or compounds to insure maximum efficacy and longevity of compounds in common use.

INSECTICIDE RECOMMENDATIONS

Prior to the discovery that calcium arsenate could be used to effectively control the boll weevil (Coad, 1918), management of insect pests of cotton relied mainly on cultural and biological means (Lincoln and Graves, 1978). From the 1920s until the appearance of the organochlorines in the mid-1940s, insecticide recommendations were available only from bulletins published by either the USDA or agricultural experiment stations in the various states where cotton was grown. Typical of these early bulletins are: (a) "The Boll-Weevil Problem", a USDA publication by Hunter and Coad (1923), and (b) "The Boll Weevil Problem in Arkansas", an Arkansas Agricultural Experiment Station publication by Isely and Baerg (1924). These bulletins explained how and when to use calcium arsenate in concert with cultural controls to manage boll weevil populations.

The advent of the organochlorines in the 1940s and the organophosphates in the 1950s made available a large number of effective and economical insecticides and acaricides for use against arthropod pests of cotton. The sudden availability of so many pesticides that generally had a broad spectrum of activity was confusing and necessitated a more timely and a more formal approach to insecticide recommendations. The cooperative extension services of the various states producing cotton began publishing annual insecticide recommendations to fit their individual cotton insect pest problems and situations. Similarly, the National Cotton Council of America began publishing the annual Beltwide Conference Reports on Cotton Insect Research and Control starting in 1947 (Anonymous, 1947-1987; see Commemoration, this book).

The current process through which the cooperative extension services of the various cotton-producing states derive their cotton insect control recommendations varies greatly. However, the most common procedure involves an annual meeting of extension and research cotton specialists (primarily entomologists); private agricultural consultants, USDA cotton specialists, state regulatory officials, and cotton producers often are included. They discuss and decide upon additions, deletions and restrictions. To be recommended for a particular use, a pesticide must be registered by the United States Environmental Protection Agency and the state pesticide regulatory agency; it also must effectively control the pest(s) in question. The question of efficacy is answered by considering: (a) data made available by the registrant or manufacturer; (b) data obtained by state and federal scientists in that state; and, (c) data available from state and federal scientists in other states. Usually two to three years of efficacy data are required before new pesticides are added to official state recommendations. The most common reasons for deleting a pesticide from recommendations are: (a) the development of resistance to the pesticide; (b) cancellation of its registration by the Environmental Protection Agency or state regulatory agencies; and, (c) lack of availability.

In Louisiana, eight criteria are used in evaluating an insecticide for inclusion in the recommended list (Reagan, 1981). These are: (a) efficacy; (b) residual activity; (c) effect on important beneficial arthropods; (d) potential to cause buildup of secondary pests; (e) hazard to the applicator; (f) potential mortality to birds, fish, crustaceans and other nontarget animals; (g) potential for development of insecticide resistance; and, (h) ability to use the insecticide within the context of pest management so as to insure its availability for a longer period of time. Other states use most, if not all, of the criteria listed above as well as additional criteria that are pertinent to their cotton insect pest situations.

The most recent conference reports on Cotton Insect Research and Control published by the National Cotton Council of America contain a listing entitled "Changes in State Recommendations for Treatment of Arthropod Pests of Cotton". The list shows changes by states that are applicable to the upcoming season. The rates or rate ranges for each chemical recommended for controlling individual cotton pests are reported in the section titled "Cotton Insects and Spider Mites and Their Control". These annual conference reports serve as a national and international source of information on current cotton arthropod pest control recommendations.

FUTURE AREAS OF RESEARCH

Historically, insecticides have been the primary means of managing arthropod pests of cotton. However, the continued availability of effective and economical chemicals is in question because of: (a) rapid development of resistance by arthropods to chemicals used for control; (b) the increasingly stringent and costly federal and state registration requirements; (c) the relatively short patent life of new chemicals; and (d) the difficulty in discovering new leads for insecticides with novel modes of action. Increased research concerning the best utilization of available chemicals (i.e. mixtures, alternations, rates, timing and resistance management) is required to prolong the use and effectiveness of currently available compounds and insure continuing adequate control of cotton insects and mites.

There is a current research thrust to "focus on the unique aspects of insect-specific physiological processes, thereby increasing the margin of safety for nontarget animals" (Adams, 1986). This biorational approach to insecticide synthesis and screening offers, long term, great promise since it capitalizes on knowledge of insect physiology and biochemistry which emphasizes differences between pests and nontarget organisms (Williams, 1967; Sparks and Hammock, 1983). There is current interest in insect endocrinology, especially juvenile hormones, hormone inhibitors, biologically active peptides (Ross *et al.*, 1986a, 1986b, 1987) and other regulators of insect growth and development. These would include insect specific hormone or pheromone inhibitors such as anti-juvenile hormone agents (Staal, 1986).

Synthetic aggregation and "sex" pheromones or close mimics are commonplace in monitoring programs for boll weevil, bollworm, tobacco budworm and pink bollworm. They have been used for increasing the efficacy of pathogens on other crops, or to increase insecticide efficacy by attracting the pests to insecticide treated areas.

Entomopathogens have been developed and marketed. Nuclear or cytoplasmic polyhedrosis viruses and various strains of *Bacillus thuringiensis* have been utilized with varied success for insect control on cotton or other crops. Further research has resulted in bacterial exotoxins which are pesticidal and show promise of efficacy where resistance has developed to standard pesticides (Roush and Wright, 1986). Added to these are the little exploited entomophagus fungi (Samson, 1981; King and Humber, 1981; Bland *et al.*, 1981; Wilding *et al.*, 1986) which are active in nature and often reduce populations of aphids and spider mites.

Recently, the entomophagus fungus, *Beauveria bassiana* (Balsamo), has been shown to suppress populations of boll weevil and sweetpotato whitefly as well as other pest arthropods (Wright, 1993; Wright *et al.*, 1993). A commercial formulation of this fungus, Naturalis-L®, has been granted an Experimental Use Permit by the Environmental Protection Agency on various crops including cotton. The registration and successful use of this fungus may provide an additional biorational tool for control of several insect pests of cotton.

Allelochemicals are yet another possibility for insecticide research. These compounds occur in nature, originating in individuals of one species but affecting individuals of another species. Terpenes, tannins, gossypol and similar allelochemicals of cotton or other plant species may be found useful in future insecticide-related concepts such as predisposing cotton pests to insecticide susceptibility.

Genetic engineering developments that permit incorporation of foreign genes into bacteria, viruses, plants (Marvel, 1985) and insects (Maeda *et al.*, 1985) offer new vistas for imaginative researchers. Toxin producing genes have been transferred from bacteria to plants and shown to produce plants possessing insect tolerance (Fischhoff *et al.*, 1987; Vaeck *et al.*, 1987). Similarly, Hammock (1985) has proposed that genes for bioactive molecules could be transferred to pest insects through an appropriate viral or bacterial vector. Adaptation of the insect populations to genetically altered monocultures is a possibility, and although this elicits questions concerning longevity of the benefits (Gould, 1988), genetically engineered crops remain a viable hope for future crop protection.

The possibilities of light-activated compounds which are toxic to insects primarily in the presence of light have been explored (Heitz, 1987). Rebeiz (1988) recently researched entomological applications of the light-sensitive porphyric insecticides which cause insect mortality by uncontrolled biosynthesis of a protoporphyrin within the insect. The future of such compounds remains to be decided, but if perfected, they may contribute to the arsenal of insect-specific insecticides.

Abamectin (Zephyr®), which is as toxic to tobacco budworm as permethrin in laboratory tests and field trials on flue-cured tobacco (Wolfenbarger *et al.*, 1985), represents a new class of insecticides, avermectins, which are revolutionizing animal health care. Because the avermectins act on the peripheral nervous system rather than the central nervous system, there is no anticipated cross-resistance present from previous use of organochlorines, organophosphates or pyrethroids (Roush and Wright, 1986). The avermectins offer great promise in controlling insect pests of cotton. However, many of those now available are too labile (unstable) to be efficacious under field conditions.

Thus there are many possibilities for future insecticide research, but few promises of functional breakthroughs with an impact comparable to the development of pyrethroids in the 1970s. Research is being slowed by the burdens of increased cost and registration requirements. Although some functional advances in bioengineering and chemistry are expected in the near future, they probably will not be frequent and may be designed for specific pests or related pest groups rather than as broad spectrum insecticides.

SUMMARY

R. L. Metcalf (1980) indicated that the "Age of Pesticides", beginning with the introduction of DDT in 1946, had undergone three distinct phases in the thirty years leading up to 1976. Those phases were: (a) the Era of Optimism, 1946-1962; (b) the Era of Doubt, 1962-1976; and (c) the Era of Integrated Pest Management beginning in 1976. Cotton entomologists and producers have experienced the first two of those cycles on several occasions. Those cycles coincide with the introduction of new classes of insecticides and then their eventual loss due to resistance. First there was the "optimism" that the arsenicals would provide the needed relief from boll weevil invasion. Then came the period of "doubt" when secondary pest infestations became overwhelming problems. With the introduction of the organochlorines came the period of "optimism" that all of their pest problems had been solved. Reality of resurgent pest populations and later resistance brought about the second cycle of "doubt". Organophosphate and carbamate insecticides brought "optimism" that finally control would be achieved without worry, but "doubt" returned when resistance removed many products from recommendations. Finally, "optimism" was high upon the introduction of the pyrethroids. But now "doubt" is beginning to return as secondary pest problems become more significant and reports of resistance in tobacco budworm and pink bollworm populations become more widespread.

Looking back at the history of insecticide use in cotton, it becomes evident that a new class of insecticides has a life expectancy of only about ten years. After that time resistance usually has negated the use of many or most products of this type at least for some important uses. Changes in use patterns of a new class of insecticides also occurs in a predictable manner. First, there is careful and judicious use of the materials in insect pest management systems followed by a period when applications are made on a preventative or scheduled basis. This latter period is inevitably followed by a period of decreasing effectiveness, elevation of secondary pests to primary pest status and often resurging pest populations.

Should another highly effective class of insecticides for use in cotton be discovered and registered, past experiences make it imperative that their use be carefully managed in order to maintain a viable cotton industry throughout the Cotton Belt. Following the basic principles of insect pest management, i.e. monitoring pest populations, utilizing established economic thresholds, and timing necessary applications to achieve maximum long term benefits, is the obvious and logical approach to conserving such a valuable resource as a new class of insecticides. In addition, resistance management systems such as those now being recommended for pyrethroids in the Mid-South United States (Anonymous, 1986) and Texas (Plapp, 1987) must be designed and implemented as part of an overall insect pest management system when new classes of insecticides become available.