Chapter 25

Cotton arthropod IPM

Steven E. Naranjo and Randall G. Luttrell

Cotton is the world's most important natural source of fiber, accounting for almost 40% of total worldwide production. The rich history of cotton and cotton production is closely linked to expanding human civilization (Kohel & Lewis, 1984; Frisbie *et al.*, 1989). Cotton belongs to the genus *Gossypium* and four species are cultivated worldwide. Levant cotton (*G. herbaceum*) and tree cotton (*G. arboreum*) are primarily grown in Asia, while the long staple sea island (American Pima, Creole, Egyptian) cotton (*G. barbadense*) is cultivated in Egypt, India, the West Indies and parts of the western USA and South America. Upland cotton (*G. hirsutum*) is the most common species cultivated throughout the world. Cotton is a perennial plant, but is grown as an annual through manipulation of irrigation, defoliants and cultivation. The harvestable portions of the plant are found in the cotton fruit. The primary product, fiber, arise from the growth of single cells on the seed surface, while the seeds are further used as animal feed or in the production of oil found in many food products.

Cotton is grown in more than 75 countries with a total production in 2006 of 116.7 million bales (~25 400 million kg: National Cotton Council, 2007a). The current top five producing countries, in order, are China, India, the USA, Pakistan and Brazil. In the USA, cotton is grown in 17 states grouped into four major production regions (Fig. 25.1) with a total production of 21.7 million bales in 2006. Total USA harvested cotton hectares and total production of lint has increased about 10% and 22%, respectively, from the ten-year period 1986–95 to the period 1996–2005 (Table 25.1). Crop loss to insects and mites has generally declined in the past ten years which represents a marked improvement in crop protection technologies and IPM practices.

Cotton farmers in the USA have a long history of organized support from public and private research and education efforts. The National Cotton Council coordinates a wide range of initiatives and policies for the cotton industry with a defined mission to ensure the ability of all USA segments of the cotton industry to compete in national and international markets. They also sponsor an annual industry-wide meeting (Beltwide Cotton Conferences). Cotton Incorporated is an organization funded through per-bale assessments on producers and importers. It is a major source of funding for cotton IPM and it has a mission to increase the demand for and profitability of cotton through research and promotion. Public support through various extramural and intramural programs of the US Department of Agriculture (USDA) continues to be a critical resource for research and extension efforts.

Integrated Pest Management, ed. Edward B. Radcliffe, William D. Hutchison and Rafael E. Cancelado. Published by Cambridge University Press.

Table 25.1 | **Summary of cotton production (bales/ha) and insect control costs ($US) in the four major USA production regions over the past 20 years (1986–2005)**

	West		Southwest		Midsouth		Southeast	
	1986–1995	1996–2005	1986–1995	1996–2005	1986–1995	1996–2005	1986–1995	1996–2005
Harvested ha (× 1000)	604	451	2143	2110	1444	1453	607	1261
Production (bales × 1000)[a]	3538	2862	4747	5583	5052	5802	1918	4376
Percent production (lint)	23.2	15.4	31.1	30.0	33.1	31.2	12.6	23.5
Percent crop loss to insects and mites	6.3	4.4	6.1	8.0	9.1	5.9	9.0	5.4
Control cost per ha[b]								
Insecticides and application	131	168	49	47	36	141	124	77
(Insecticides, application, scouting, eradication and technology fees)		(205)		(74)		(220)		(133)

[a] Cotton bale = 218 kg of lint.
[b] The data from 1996 onward is more complete, including costs ($US) associated with scouting, eradication of boll weevil and technology fees for growing transgenic cotton, in addition to insecticide and application costs. This more inclusive figure is presented within parentheses. None of the cost figures are adjusted for inflation.
Source: Summarized from *Cotton Insect Losses*, a database compiled by the National Cotton Council (2007b).

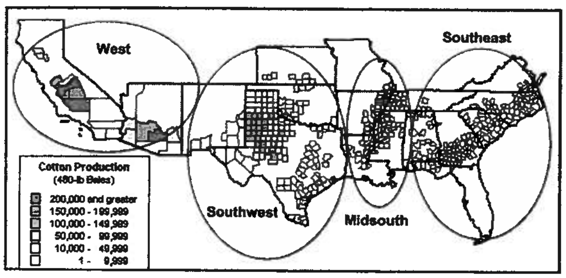

Fig. 25.1 Major cotton producing regions of the USA (modified from National Cotton Council, 2007a).

In many ways, cotton arthropod IPM both exemplifies and has shaped many of the general principles, control tactics and integrated strategies covered with great detail throughout this textbook. Numerous reviews have previously summarized cotton insect pest management in the USA (Gaines, 1957; Bottrell & Adkisson, 1977; Ridgway *et al.*, 1984; Frisbie *et al.*, 1989; El-Zik & Frisbie, 1991; Luttrell, 1994; King *et al.*, 1996b). Here we summarize current and recent past efforts in cotton IPM that continue to build upon more than a century of scientific research and innovation based on ecological principles and understanding.

25.1 | Arthropod fauna

25.1.1 Pest species and damage

Rainwater (1952) stated "cotton is a plant that nature seems to have designed specifically to attract insects." Over 1300 herbivorous insects are known from cotton systems worldwide (Hargreaves, 1948) but many fewer are common inhabitants and still fewer are of economic importance. Roughly 100 species of insects and spider mites are pests of cotton in the USA but only 20% of these are common and likely to cause damage if left uncontrolled (Leigh *et al.*, 1996) (Fig. 25.2). The remaining 80% are sporadic or secondary pests that become problematic in some years due to changing environmental factors or the misuse of insecticides or other disruptions of natural controls. Pest species vary from one production area to the next. Bollworm (*Helicoverpa zea*) and tobacco budworm (*Heliothis virescens*) are major pests of cotton in the USA from Texas eastward while the pink bollworm (*Pectinophora gossypiella*) is the dominant bollworm in the western USA. Various species of *Lygus* and other mirid plant bugs affect cotton throughout

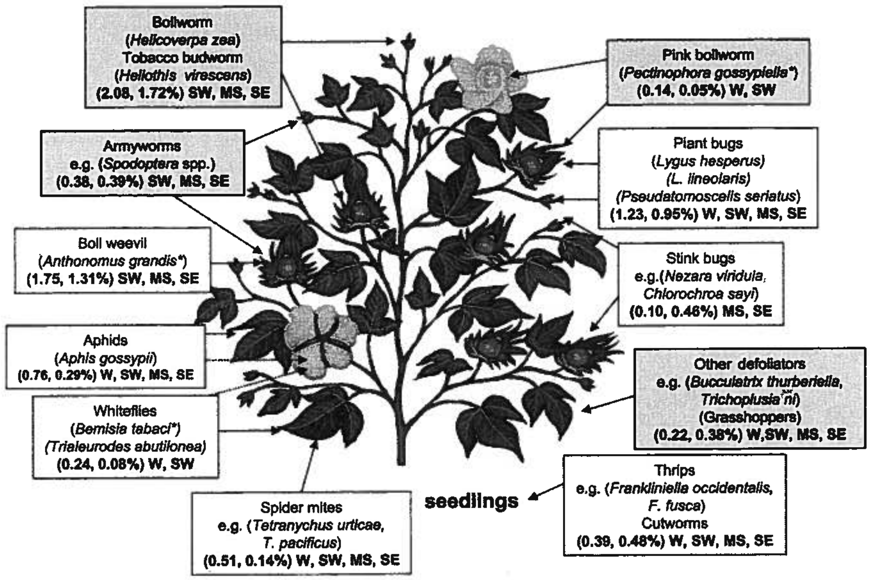

Fig. 25.2 Summary of major insect and mite pests of cotton in the USA, Numbers in parentheses indicate the average percent yield loss for the periods 1986–95 and 1996–2005, respectively, for each pest group across the entire USA. Bold letters denote the major production regions where the pest group primarily impacts cotton production; W, West; SW, Southwest; MS, Midsouth; SE, Southeast. Insects attacking cotton bolls (fruit) generally attack squares (flower buds) as well. Dotted lines pointing to lint indicate that whiteflies and aphids can affect yield quality through the deposition of honeydew. Asterisks next to species names denote exotic pests and shaded boxes indicate pests which are affected significantly by *Bt* cotton. Loss figures summarized from *Cotton Insect Losses*, a database compiled by the National Cotton Council (2007b).

the world. The pink bollworm, the cotton aphid (*Aphis gossypii*) and sweetpotato whitefly (*Bemisia tabaci*) are significant pests of cotton throughout the world while the boll weevil (*Anthonomus grandis*) is only found in the Americas. Some pests such as the bollworm, tobacco budworm and plant bugs are native insects that have expanded their ranges as cotton production grew, while the sweetpotato whitefly and pink bollworm are exotic invaders. The exotic boll weevil's movement into the USA was associated with the expansion of cotton production.

Although the levels of crop loss may appear small, the economic impact can be enormous. For example, in 2005 total yield reduction from arthropod pests in USA cotton was 4.47%, which represented a loss of >1.5 million bales of cotton valued at $US 1250 million in yield reduction and control costs (Williams, 2006). As will be discussed below, many factors have contributed to reductions in pest losses over the past 20 years including boll weevil eradication, transgenic cottons for control of caterpillar pests and improved overall IPM programs for various pests.

25.1.2 Beneficial arthropods

Many beneficial arthropod species are associated with cotton. In a seminal study, Whitcomb & Bell (1964) cataloged about 600 species of arthropod predators including ~160 species of spiders in Arkansas cotton fields. Van den Bosch & Hagan (1966) suggested that there may be nearly 300 species of parasitoids and arthropod predators in western cotton systems. Like cotton herbivores, only a fraction of these are common, with some of the more abundant groups including big-eyed bugs (*Geocoris* spp.), anthocorid bugs (*Orius* spp.), damsel bugs (*Nabis* spp.), assassin bugs (*Zelus* and *Sinea* spp.), green lacewings (*Chrysopa* and *Chrysoperla* spp.), lady beetles (e.g. *Hippodamia* and *Scymnus* spp.), ants (especially *Solenopsis* spp.), a wide variety of web-building and wandering spiders and both parasitic wasps (e.g. *Bracon* spp., *Cotesia* spp., *Microplitis* spp., *Hyposoter* spp., *Trichogramma* spp.) and flies (*Archytas* spp., *Eucelatoria* spp.). We continue to learn about the important role that these natural enemies play in cotton pest control but the most dramatic evidence of their impact comes from studies in which the destruction or disturbance of natural enemy communities by indiscriminant insecticide use is associated with pest outbreaks (e.g. Leigh *et al.*, 1966; Eveleens *et al.*, 1973; Stoltz & Stern, 1978; Trichilo & Wilson, 1993). Overall, arthropod communities in cotton are dynamic and largely driven by the wide diversity of management options discussed below.

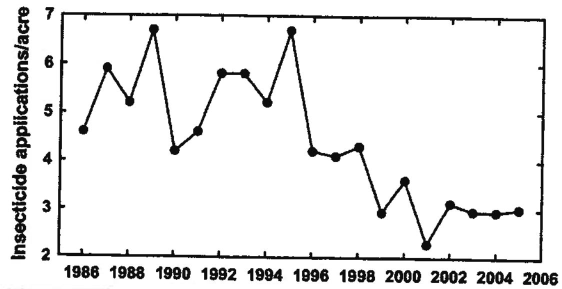

Fig. 25.3 Overall insecticide use patterns in USA cotton 1986–2005 summarized from *Cotton Insect Losses*, a database compiled by the National Cotton Council (2007b).

25.2 IPM tactics

25.2.1 Chemical control

Insecticide use has a long history in USA cotton pest control beginning with arsenicals for control of boll weevil in the early twentieth century and followed by a progression of synthetic insecticides (e.g. organochlorines, organophosphates, carbamates and pyrethroids) in the subsequent decades following World War II (Herzog *et al.*, 1996; Sparks, 1996). With each new introduction, periods of excellent pest control were generally followed by control failures due to the evolution of insecticide resistance. Many past and current insecticides have broad activity against pests and their associated natural enemies and pose hazards to the environment and human health. On a worldwide basis cotton accounts for about 22.5% of all insecticide use (Anonymous, 1995) and historically USA cotton has been the heaviest user of insecticides. That pattern has begun to shift (Fig. 25.3) with the introduction of transgenic *Bt* cotton in 1996 and the availability of a wide range of effective and safer insecticides registered in part through the US Environmental Protection Agency (EPA)'s Reduced-Risk Initiative over the past decade (Environmental Protection Agency, 2006) (Table 25.2). While a variety of many classes of insecticides continue to be used for cotton pest control throughout the USA (National Agricultural Statistics Service, 2006), adoption and use of reduced-risk insecticides has grown in recent years (e.g. Goodell *et al.*, 2006).

25.2.2 Resistance management

The development of resistance in pest populations to insecticides is a continual threat to successful implementation of chemical control and careful vigilance and proactive strategies are needed to preserve this important tactic (Castle *et al.*, 1999) (see Chapter 15). Around 550 arthropod pests have developed resistance to one or more insecticides, and currently a total of 34 cotton pests (19 in the USA) have developed resistance to as many as three insecticide classes (Whalon *et al.*, 2007). The mitigation of resistance is based on management of insecticide type and use that either attempts to reduce the fitness of resistant individuals or minimizes selection pressure on a pest population (Roush & Daly, 1990). Simply put, this means limiting insecticide use through adherence to economic thresholds, diversifying modes of action through rotations, mixtures and use of synergist, and partitioning of insecticide use in space and time by adoption of seasonal stages or crop-specific usage. Examples include the Australian IRM strategy for managing resistance in the Old World bollworm (*Heliocoverpa armigera*) through a three-stage plan which rotates pyrethroids with non-pyrethroids over the season (see Castle *et al.*, 1999), the Texas and Midsouth pyrethroid use window strategy for resistance in tobacco budworm (Plapp *et al.*, 1990) and the multi-crop resistance management plan for whitefly in the western USA in which various classes of insecticides are rotated depending on predominant crop mixtures within a region (Palumbo *et al.*, 2001, 2003).

25.2.3 Cultural control

The indeterminate nature of cotton plant growth and the influence of production practices such as cultivation, irrigation, fertilization, cultivar

Table 25.2 Insecticides registered for use on cotton through the EPA Reduced-Risk/Organophosphate Alternatives Program

Compound	Mode of action (IRAC MoA)[a]	Cotton target	Year registered
Spinosad	Acetylcholine receptor modulator (5)	Caterpillars	1997
Pyriproxyfen	Juvenile hormone mimic (7)	Whiteflies, aphids	1998
Tebufenozide	Molting hormone agonist (18)	Caterpillars	1999
Methoxyfenozide	Molting hormone agonist (18)	Caterpillars	2000
Indoxacarb	Sodium channel agonist (22)	Caterpillars	2000
Thiamethoxam	Acetylcholine receptor agonist (4A)	Whiteflies, aphids, thrips	2000/2001
Buprofezin	Chitin synthesis inhibitor (16)	Whiteflies, aphids	2001
Pymetrozine	Feeding blocker (9)	Whiteflies, aphids	2001
Bifenazate	Neural inhibitor (25)	Mites	2002
Acetamiprid	Acetylcholine receptor agonist (4A)	Whiteflies, aphids, plant bugs	2002
Etoxazole	Growth inhibitor (10B)	Mites	2003
Novaluron	Chitin synthesis inhibitor (15)	Whiteflies, thrips, caterpillars, plant bugs	2004
Fenpyroximate	Electron transport inhibitors (21)	Mites	2004
Dinotefuran	Acetylcholine receptor agonist (4A)	Whiteflies, thrips, plant bugs	2005
Flonicamid	Feeding blocker (9)	Aphids, plant bugs	2005
Spiromesifen	Lipid synthesis inhibitor (23)	Whiteflies, mites	2006

[a] IRAC MoA = *Insecticide Resistance Action Committee Insecticide Mode of Action Classification* (IRAC, 2007).

selection, weed control and planting date on the crop's susceptibility to damage and suitability for insect infestations remain an extremely important aspect of effective pest management (Ridgway *et al.*, 1984; El-Zik *et al.*, 1989; Matthews, 1994; Walker & Smith, 1996). For example, stalk destruction, field sanitation, efficient harvest, tillage and winter irrigation can effectively control or reduce populations of boll weevil and pink bollworm (Walker & Smith, 1996). Early planting and early crop termination are long-standing principles of cultural control and pest avoidance that are still relevant for many pest species. From eastern Texas to the Atlantic coast, timely planting and early harvest helps to avoid fall and winter rains and resulting in important economic advantages (Parvin & Smith, 1996). Delayed planting also may have benefits. For example, planting later so that no fruiting forms are present when pink bollworm adults emerge from the soil maximizes "suicidal emergence" and reduces pest populations throughout the season (Brown *et al.*, 1992). Cultivation can effectively reduce overwintering survival of bollworm and tobacco budworm, and Schneider (2003) suggested that recent trends for reduced tillage could accelerate resistance of tobacco budworm to insecticides and *Bt* toxins in transgenic cotton (see below). Deep tillage induces high overwintering mortality in pink bollworm (Watson, 1980).

There has been renewed interest in manipulating dispersal and crop colonization though trap crops, especially in the management of polyphagous plant bugs. The use of strip crops of alfalfa within cotton is the classic example of cultural control through the practical deployment of trap crops (Stern *et al.*, 1964). Most examples of trap cropping, including this classic example of strip harvesting alfalfa, have been only sporadically accepted and utilized in production agriculture because of the logistic impact on farming operations and the wide availability of effective chemical controls options (Shelton & Badenes-Perez, 2006). For example, only 4% of California growers reported using manipulation of alfalfa to control cotton pest insects (Brodt *et al.*, 2007).

Future management systems may need to examine incentives for grower adoption and expansion of cultural management tactics that may reduce pest populations across broad geographic regions.

25.2.4 Behavioral control

A suite of tactics are available that alter or manipulate the behavior of pest arthropods leading to population suppression or even elimination. Two examples, (1) pheromones and (2) sterile insect release, are discussed here.

Pheromones

A pheromone is a chemical that mediates behavioral interactions between members of the same species. The most common examples are sex pheromones which are involved in mating, but aggregation and alarm pheromones are also known from cotton pest species. As of 1994 sex pheromones have been identified in 15 major cotton pest species (seven species in the USA) including 14 moths and one beetle (Campion, 1994). The three main applications of pheromones are monitoring, mating disruption and mass trapping (see Chapter 21).

Traps baited with sex pheromones are routinely used for selective monitoring of pink bollworm, boll weevils, bollworm and tobacco budworm. Trapping information is useful in pest detection at low densities and tracking seasonal events such as adult emergence and the number and timing of generations. For pink bollworm, pheromone traps have even been used to monitor density for pest control decision making (Toscano *et al.*, 1974) and traps are a major component of the ongoing pink bollworm eradication program (see below). Pheromone traps continue to play an important role in ongoing boll weevil eradication efforts and as long-term monitoring tools in post-eradication areas of the USA.

Mating disruption is achieved by applying pheromone to a field, thereby making it difficult for potential mates to find one another and resulting in reduced mating and subsequent reproduction. This technology was first applied in 1978 for the pink bollworm and the method is still used today. Mating disruption is a major component of the ongoing eradication and exclusion programs for this pest and has been used in several past areawide programs in California and Arizona and in other countries (Campion, 1994). Mating disruption has been evaluated for other pests such as bollworm and tobacco budworm, but their polyphagous nature is problematic and results have been unsuccessful or ambiguous (Campion, 1994).

Mass trapping showed some promise for pink bollworm control in a three-year grower funded trial in Arizona (Huber *et al.*, 1979) and the method was used in some Arizona production areas into the mid-1990s. The approach is not currently in use for pest control in cotton.

Sterile insect release

The notion that mass release of sterile insects could be used to manage or eradicate a pest was first proposed by E. F. Knipling during the 1930s (Knipling, 1955) and was first successfully used to eradicate screwworm (*Cochliomyia hominivorax*) from the island of Curaçao during the 1950s (Baumhover *et al.*, 1955). The concept, known as the sterile insect release method (SIRM) or the sterile insect technique (SIT) has been attempted with several major cotton pests in the USA including the bollworm and tobacco budworm, the boll weevil, and most successfully with the pink bollworm. Various biological and operational factors precluded the successful application of SIRM to the two former species/groups (see Villavaso *et al.*, 1996) but the method has been used annually since 1968 to help mitigate the establishment of pink bollworm on cotton in the Central Valley of California (Miller *et al.*, 2000), and is a component of the current pink bollworm eradication program.

25.2.5 Host plant resistance

Host plant resistance is a fundamental management tactic (El-Zik & Thaxton, 1989; Gannaway, 1994; Jenkins & Wilson, 1996). Host plant resistance can be broadly categorized as antibiosis (reduced fitness or pest status), antixenosis (avoidance or behavioral factors) and tolerance (ability of plant to compensate for damage) (see Chapter 18). Plant resistance traits may include manipulation of the plant's genome or the resistance may be associated with indirect selections for traits like yield and fiber quality. Genetically controlled traits useful in cotton resistance to insects include: crop earliness, a range of plant morphological traits (nectariless, glaborous or pilose leaf surface, okra-shaped leaf, frego bract, red plant color, yellow or orange pollen) and varying concentrations of plant secondary compounds (high gossypol and tannin content). Relatively few of these traits have been incorporated into commercial cultivars.

The tools of biotechnology have provided new opportunities to enhance traditional approaches to host plant resistance (see Chapters 18 and 21). The impact of transgenic cottons producing insecticidal toxins from *Bacillus thuringiensis* (*Bt*), primarily for control of pink bollworm, tobacco budworm and bollworm has been enormous. The reduction in insecticide use in cotton over the past decade (Fig. 25.3) can be partly attributed to increased adoption of *Bt* cottons. Use of *Bt* varieties has expanded each year with 57% of all USA upland cotton hectares planted to *Bt* cotton in 2006 (Williams, 2007). In most areas of the Midsouth and Southeast where bollworm and tobacco budworm are historically important pests, adoption of *Bt* cotton approaches 80–90%. In 2006, Texas planted about 35% of its total cotton hectares to *Bt* varieties while California planted less than 20% (a large portion of California's hectares are planted to long staple Pima varieties that have not been transformed). In Arizona, *Bt* cottons are widely adopted because of their dramatic impact on pink bollworm.

Commercial transgenic cottons with insecticidal activity are currently limited to the transgenes from *B. thuringiensis*. Bollgard cotton (Monsanto Company, St. Louis, MO) was the first commercially available cotton in 1996. It expresses the Cry1Ac insecticidal protein. Bollgard II cotton (Monsanto) expressing Cry1Ac and Cry2Ab2 protein was commercially introduced in 2003, and Widestrike cotton (Dow AgroSciences, Indianapolis, IN) expressing Cry1Ac and Cry1F protein was launched in 2005. VipCot cotton (Syngenta Biotech, Jealott Hill, Berkshire, UK) will express the Vip3A vegetative protein from *B. thuringiensis*, probably along with a Cry protein, and is expected to be commercialized in the USA shortly.

One of the most hotly debated issues facing cotton insect management is the sustainability of transgenic *Bt* cottons. However, despite the high use of *Bt* crops there has been little or no increase in insect resistance over the ten years of commercial deployment (Tabashnik *et al.*, 2003). This success can be partly attributed to a EPA-mandated resistance management program that requires growers using *Bt* cotton to also plant non-*Bt* cotton refuges. The principle behind this mandated strategy is that non-*Bt* cottons produce susceptible target pests that can readily interbreed with any resistant pests that may arise from *Bt* fields, thereby diluting incipient resistant populations.

Bt cottons offer real environmental and economic advantages to conventional cottons sprayed more with insecticides. Frisvold *et al.* (2006) estimated global economic benefits of $US 836 million for *Bt* cotton in USA. The potential role of *Bt* cotton in reducing human exposure to toxic chemicals, especially in developing countries where insecticides are often applied manually, is large. Still, environmental risk issues such as effects on non-target organisms and ecosystem function and gene flow associated with transgenic crops in general continue to be debated and researched in the scientific community (e.g. Andow *et al.*, 2006; Romeis *et al.*, 2006).

There has been limited progress in the development of transgenic cottons for pests other than caterpillars. For example, Monsanto is in the very early stages of development of transgenic cottons targeting *Lygus* spp. based on *Bt* and non-*Bt* approaches. Focus on non-caterpillar pests remains a major goal of various biotech firms and basic researchers around the world, and it highlights the importance of a continued investment in traditional host plant resistance.

25.2.6 Biological control

The three major approaches to biological control include classical biological control, where exotic agents are introduced for permanent establishment against exotic and native pests, augmentation biological control, which involves the rearing and periodic release of natural enemies, and conservation biological control, which attempts to protect, manipulate and enhance existing natural enemies for improved control (see Chapters 9 and 12). Classical biological control programs have been carried out in the past for several pest groups including bollworm, tobacco budworm, boll weevil, pink bollworm and to a lesser extent for lygus bugs. These efforts have been largely unsuccessful in the cotton system as natural enemies have either failed to become established and/or their impacts have been minimal (King *et al.*, 1996a). The whitefly *B. tabaci* has been the most recent target of classical biological control, with numerous species of parasitoids released for establishment (Gould *et al.*, 2008); however, as with other classical efforts, the impact of these established agents have so far been minimal in the cotton system (Naranjo, 2007).

Likewise, augmentative biological control with predators and parasitoids has been researched and evaluated for several major cotton insect pests, but factors such as lack of efficacy, technical difficulties with natural enemy mass-production and cost relative to insecticides have combined to limit this approach from becoming a viable option in cotton pest control in the USA (King *et al.*, 1996a). Augmentation with microbial agents (viruses, fungi, bacteria) for control of bollworm, tobacco budworm, boll weevil, pink bollworm, whitefly and plant bugs (King *et al.*, 1996a; Faria & Wraight, 2001; McGuire *et al.*, 2006) has been examined; however, commercialized microbial products continue to have very small shares of the cotton pest control market.

In contrast to classical and augmentative biological control, conservation biological control continues to be a major focal area of cotton IPM that has been further stimulated by the many recent changes to cotton pest management systems. As noted, the cotton system in the USA harbors a diverse complex of native natural enemies, many of which are generalist feeders that opportunistically attack many insect and mite pests. Naturally occurring epizootics of some microbes also may significantly suppress pest species (Steinkraus *et al.*, 1995). The potential value of these natural enemies in pest suppression has been repeatedly demonstrated over many decades in the cotton system when broad-spectrum insecticides applied for one pest lead to resurgence of the target pest and/or outbreaks of secondary pests through the destruction of natural enemies (see Bottrell & Adkisson, 1977). This potential is also widely recognized in state recommendations for cotton IPM. Most guidelines call for sampling of natural enemies and emphasize their preservation through inaction or judicious use of insecticides, particularly those with selective action. Our understanding of the role and interaction of natural enemy species and complexes and how to manipulate them for improved pest control in cotton has a rich history that continues to grow (e.g. Sterling *et al.*, 1989; Naranjo & Hagler, 1998; Prasifka *et al.*, 2004).

25.2.7 Sampling and economic thresholds

A hallmark of all cotton IPM programs in the USA is monitoring of pest density or incidence combined with action or economic threshold to determine the need for control measures. In 2006, about 50% of USA cotton hectarage was scouted an average of 1.3 times per week at an average cost of $US 18.97/ha across the cotton belt (Williams, 2007). The intensity of scouting varies greatly by state. In Virginia and Kansas less than 5% of cotton hectarage was scouted but more than 90% was scouted in Arizona, Louisiana and South Carolina. In Texas, the largest cotton producing state, only 19% of the hectarage was reported as scouted.

The cooperative extension programs of each of the 17 cotton growing states produce recommendations for scouting, treatment thresholds and insecticides to help growers and consultants implement IPM.[1] The basic tools of sampling include sweep nets, beat cloths and beat boxes, traps and visual inspection of various plant parts, all of which require human labor and the associated cost. Sampling plans, which specify the general protocols for how samples should be collected and how many sample units should be taken, are

[1] Web links to sampling and threshold recommendations and individual state recommendations are available at http://ipmworld.umn.edu/textbook/Naranjo3.htm.

typically based on research to understand the distribution and variability of pest populations (see Chapter 7). Sequential sampling plans, which minimize the number of sample units that need to be taken, are often developed for cotton pest management application, but in practice it is more typical for a set sample size to be recommended and implemented. Many cotton pest sampling plans also use a presence/absence approach (e.g. percent infested) for monitoring rather than a complete count which allows for quicker sampling and decision making.

Thresholds tend to vary depending on production region and also may be dynamic, with critical pest densities being a function of plant development and prior management activity. For example, thresholds for bollworm and tobacco budworm are lower following an initial insecticide application during post flower bloom, while thresholds for plant bugs generally increase as the cycle of flower bud (square) production progresses. Thresholds in *Bt* cotton also may differ from non-*Bt* cotton for the bollworm which is not controlled completely in some transgenic cottons. Some of these thresholds are based on experimental study (see Chapter 3), but many are nominal thresholds developed on the basis of trial-and-error experience by researchers, extension agents, consultants and growers. Many state guidelines encourage scouting of natural enemy populations, but only a few have provided explicit information on how to use these counts to modify treatment decisions (e.g. Fillman & Sterling, 1985; Wilson *et al*., 1985; Conway *et al*., 2006). Nonetheless, the preservation of natural enemies through judicious use of insecticides is implicitly recognized as a key component of most management systems.

25.3 IPM programs and implementation

Despite the challenge of researching and compiling the necessary component tactics into a workable IPM strategy, the greatest difficulty may be in implementing and evaluating IPM programs because such tasks depend on logistical, sociological and economic factors (Mumford & Norton, 1994; Kogan, 1998) (see Chapter 38). Education is a key element in IPM implementation regardless of the crop and Cooperative Extension Services associated with land-grant universities generally take the lead in developing educational materials (circulars, bulletins, websites) as well as organizing training and even on-farm demonstrations and adaptive research. Private industry may also contribute educational and consulting activities, and depending on the scope of implementation, grower organizations and/or federal agencies such as USDA may be involved (Harris *et al*., 1996).

25.3.1 Areawide programs

Cotton entomologists have long recognized the importance of spatial scale of management activities for mobile pest species. Ewing & Parencia (1950) demonstrated effective control of boll weevil when coordinated early-season treatments were applied on a community basis. With the dramatic success of screwworm eradication, Knipling (1979) extended the areawide concepts of pest population suppression to cotton insects, especially the boll weevil and the tobacco budworm. Henneberry & Phillips (1996) provide an overview of the elaborate experiments and theoretical debates that followed.

Boll weevil eradication (see below) is perhaps the largest-scale example of areawide programs. Other examples include numerous attempts to manage bollworm and tobacco budworm through biological control and community management systems, a 40-year program to exclude pink bollworm from central California, successful control of whitefly in the desert valleys of the West, and emerging management systems for plant bugs and stink bugs in the Midsouth and Southeast.

25.3.2 Models and decision aids

A wide diversity of simulation models and decision support systems have been developed for USA cotton beginning in the 1970s with the NSF/EPA Integrated Pest Management Project (commonly known as the "Huffaker project"), continuing with the USDA/EPA Consortium for IPM project during the 1980s and many other cooperative state and federal projects thereafter (Mumford & Norton, 1994; Wagner *et al.*, 1996). Modeling efforts have focused on individual pests and groups of pests and some have included simple or detailed cotton plant models. In general, these models have been useful in structuring knowledge of the plant–pest system, studying and predicting population dynamics, examining alternative management scenarios and identifying areas needing further research. However, with few exceptions such models have found very limited application in guiding day-to-day pest and crop management activities.

In the 1990s, management tools based on expert systems and information management began to be developed for cotton insect management (Wagner *et al.*, 1996). Some of these decision aids were coupled with the more complex simulation models and others were based on broad generalizations of expert opinion and historical data. These systems included the expert systems rbWHIMS, COTFLEX, CALEX and CIC-EM for a range of cotton production systems. In general, none of these systems has seen wide-scale adoption. COTMAN, a more recent decision aid, emphasizes the synthesis of field samples rather than projection of information and has remained a component of practical cotton production in limited areas of the Midsouth, Southeast and Texas. The strength of COTMAN and its continued use may be due to the simplicity of the system and its close conceptual linkage to crop development.

25.3.3 Case studies

There are many examples of operational IPM programs for cotton pests throughout the USA that involve many of the component tactics discussed. Here we highlight two representative programs, (1) whiteflies in Arizona and (2) plant bug and stink bug management in the Midsouth and Southeast.

Whitefly IPM strategy in Arizona

Since the early 1990s the polyphagous sweetpotato whitefly (*B. tabaci*), Biotype B, has had major impacts on most agricultural production in the West (Oliveira *et al.*, 2001). In response, a multi-component research and educational plan was launched that resulted in a successful IPM program which continues to be expanded and refined today (Ellsworth & Martinez-Carrillo, 2001; Naranjo, 2001; Ellsworth *et al.*, 2006). The overall program can be envisioned, and is taught to growers and consultants, as a pyramid with multiple, overlapping layers and components (Fig. 25.4). The broad base of the pyramid, founded on research, emphasizes tactics and strategies that can be implemented to reduce overall pest populations including various crop management practices and selection of well-adapted, smooth-leaf varieties which are generally less attractive to whiteflies. The foundation also emphasizes natural enemy conservation through the use of selective control methods for whitefly and other pests and an array of areawide tactics like crop placement and arrangement to reduce pest movement, destruction of crop residue and weeds and coordinated use of insecticides among all affected crops to manage resistance.

The two upper layers of the pyramid outline pest monitoring through an efficient binomial sampling scheme (Ellsworth *et al.*, 1996; Naranjo *et al.*, 1996), and the timing of effective control methods based on economic threshold and a three-stage insecticide use system which emphasizes selectivity (i.e. safety to beneficial arthropods) in the initial stages (Naranjo *et al.*, 2004; Ellsworth *et al.*, 2006). Follow-up treatments are rarely needed if these selective options are used first because the conserved natural enemies and other natural forces are then able to suppress whitefly populations long term (Naranjo, 2001). The three-stage system also implicitly encourages the rotation of insecticides with differing modes of action in order to mitigate resistance. Operationally, the IPM plan has significantly reduced insecticide use for all cotton pests in Arizona from a decades-long high of over 12 applications in 1995 at a cost of $US 536/ha to a decades low application rate of 1.4 at a cost of $US 77/ha in 2006.

Plant bug and stink bug management in the Midsouth and Southeast

A plant bug complex, including tarnished plant bugs (*Lygus lineolaris*), cotton fleahoppers (*Pseudatomoscelis seriatus*) and clouded plant bugs

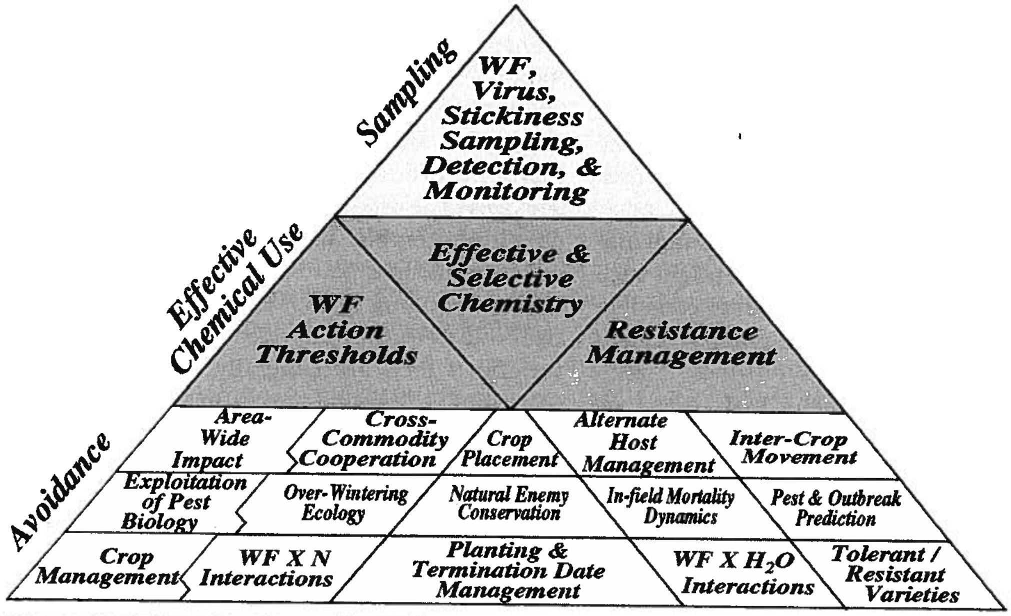

Fig. 25.4 Conceptual diagram of the Arizona Whitefly (WF) IPM program showing the three main components of effective IPM: avoidance, effective use of insecticides and sampling. (Reprinted from Ellsworth & Martinez-Carrillo [2001] with permission from Elsevier.)

(*Neurocolpus nubilis*), has been a long-standing pest problem in Midsouth and Southeast cotton. Plant bugs typically attack cotton at early squaring but can persist as a pest problem through boll development. A complex of seed-feeding stink bugs (brown stink bug [*Euschistus servus*], green stink bug [*Acrosternum hilare*] and southern green stink bug [*Nezara viridula*]) also attack maturing bolls later in the growing season. Both plant bugs and stink bugs are increasing in status but these tend to be more important in the Midsouth and Southeast, respectively. The elevated importance of these polyphagous and mobile insects reflects success in eliminating boll weevil (through eradication) and tobacco budworm (by *Bt* cotton) as major pests. In 2006, crop loss and insecticide use for these bug pests were twice to three-fold those of other pests across the Midsouth and Southeast (Williams, 2007).

Designing effective control measures for the bug complex has been a challenging and difficult task. Plant bugs are now resistant to several insecticides (Snodgrass, 1996). The USDA in Stoneville, Mississippi has developed an areawide approach to the removal of early-season broadleaf hosts of tarnished plant bug (Snodgrass *et al.*, 2005). This research approach has been evaluated by extension entomologists across the Midsouth and is being adopted on limited hectares by growers in some regions. Additional testing is needed to confirm the broader impacts on other pest and beneficial species in the system. Extension entomologists in the Southeast are developing treatment thresholds and monitoring procedures for the stink bugs (Greene *et al.*, 2001), and those in the Midsouth are studying sampling and management options for plant bugs.

25.4 Pest eradication

Pest eradication involves the complete elimination of a pest from its current range and generally focuses on invasive pest species (Chapter 10). Significant debate continues over the value of pest eradication as a substitute for or as a complement to pest management (Myers *et al.*, 1998). Nonetheless, eradication programs are currently under way for two key cotton pests in the USA and they will be briefly discussed here.

25.4.1 Boll weevil

Effective removal of boll weevil as a key pest of USA cotton is an important biological and social achievement covering a half-century of scientific and strategic effort (Cross, 1973; Smith & Harris, 1994; Dickerson *et al.*, 2001; Hardee & Harris, 2003). Interest in a coordinated effort to eliminate this invasive cotton specialist began in the late 1950s and the eradication program was initiated in earnest by the late 1970s. Incipient populations were eradicated in Arizona, California and northwest Mexico in the 1980s, and the nationwide effort began in North Carolina and successfully expanded through South Carolina, Georgia, Florida and south Alabama. In the early to mid-1990s boll weevil was eradicated from central and north Alabama, middle Tennessee and the Texas Southern Rolling Plains. During the late 1990s, boll weevil eradication expanded to the Midsouth and Texas, with only a few isolated regions still infested. It is anticipated that the USA will be weevil free by 2009. Reductions in cotton insect losses (Table 25.1) can be directly and indirectly related to removal of this key USA cotton pest. In the past, early-season treatments were necessary to keep weevil populations from expanding, but they also triggered many additional pest outbreaks. The basic components of the program include monitoring with pheromone (grandlure)-baited traps to time early-season applications of insecticides that reduce establishment in cotton, late-season "diapause" treatments to reduce overwintering weevils and early crop maturity and crop destruction to enable a host-free period coordinated across large geographic zones.

25.4.2 Pink bollworm

Like the boll weevil, the pink bollworm is an exotic cotton specialist that successfully invaded in USA in the early 1900s and became firmly established in the West by the mid 1960s following various attempts to contain and suppress populations throughout the first half of the twentieth century (Henneberry & Naranjo, 1998). The cooperative eradication program involves growers, and state and federal agencies. The program is being implemented in phases beginning with west Texas, New Mexico and northern Chihuahua, Mexico in 2001 and continuing through Arizona to southern California and northern Sonora, Mexico in 2007 with the total program completed by 2010. The basic elements of the program include mapping and monitoring of all cotton fields within each region and the use of a combination of *Bt* transgenic cotton, mating disruption with pheromones, sterile insect release, and follow-up insecticides as needed. The sterile insect release in this case serves both to augment population control and as a substitute for the required non-*Bt* refuge for resistance management which was relaxed in Arizona and southern California to allow for 100% production of *Bt* cotton. Pink bollworm populations in the Phase I regions have been reduced by >99% from 2001 to 2005 (El-Lissy & Grefenstette, 2006), but it is too early to gauge the overall success of the eradication effort.

25.5 Conclusions

IPM is based on an ever-changing foundation of improved scientific knowledge, economic circumstances, and societal issues and demands. Several significant technological advances (e.g. transgenic crops) have occurred in the past decade that have dramatically lowered pest losses and significantly lowered insecticide use in a system that has historically been associated with insecticide over-reliance and misuse. Undoubtedly, future advancements will continue to improve the sustainability and environmental quality of cotton production in the USA and worldwide. Environmental issues will continue to grow, especially as urban areas expand and become more closely integrated with crop production areas.

Current IPM programs in cotton like many other crop systems are largely focused on what Kogan (1998) characterizes as "Level 1 IPM," or IPM of single pest species in individual fields. This is contrasted to "Level 2 IPM" which focuses on interactive effects of multiple pest species within whole farms or "Level 3 IPM" which involves management of multiple pests on perhaps multiple crops within entire agroecosystems. Some of the areawide programs summarized above have begun to view and manage cotton pests within a broader landscape perspective, but much additional research will be needed to understand the simultaneous and multiple impact of all pests (insects, weeds, pathogens) on plant health and to develop efficient decision aids and control methods for managing multiple stressors at multiple spatial scales. This task will be an even greater challenge for polyphagous and mobile pests such as aphids, mites, whiteflies, plant bugs, bollworm and tobacco budworms.

Meeting these challenges will likely call upon the increased use of models, risk assessment tools and information technology at both the grower and regulatory level to better understand, predict and manage systems behavior. This is going to require information managers and more user-friendly systems for storing, mining, analyzing and applying this information to farm-level decisions. Transgenic cotton conferring either insect or herbicide resistance or both has been widely adopted by growers to manage risk from caterpillar and weed pests and that trend is likely to continue. Current commercial cultivars of insecticidal transgenic cotton are based on one or more of three Cry toxins and one vegetative insecticidal protein but other proteins like snowdrop lectin (GNA) and protease inhibitors are being examined in other crop species (Christou *et al.*, 2006), and over 170 distinct δ-endotoxins as well as many other toxins are known from *B. thuringiensis* (Glare & O'Callaghan, 2000) providing much to be mined for future transgenic plant development targeting multiple pests. The technologies associated with precision agriculture (GIS, remote sensing and GPS) are likely to expand (Shaw & Willers, 2006). Such technologies may reduce overall inputs like fertilizers, herbicides and insecticides by selectively allowing growers to apply these only as needed within specific areas of a single field.

Overall, the long tradition of pest management research and practice in the cotton system will continue to expand, leading to reduced risk and greater predictability for producers, and greater sustainability and environmental stewardship benefiting society as a whole.

Acknowledgements

We thank Drs. Pete Goodell (University of California), Peter Ellsworth (University of Arizona) and John Ruberson (University of Georgia) for their insightful comments on an earlier draft of this manuscript.

References

Andow, D. A., Lovei, G. L. & Arpaia, S. (2006). Ecological risk assessment for *Bt* crops (response to Romeis). *Nature Biotechnology*, **24**, 749–751.

Anonymous (1995). Cotton: the crop and its pesticide market. *Pesticide News*, **30**, 1.

Baumhover, A. H., Graham, A. J., Bitter, B. A. *et al.* (1955). Screw-worm control through release of sterilized flies. *Journal of Economic Entomology*, **48**, 462–466.

Bottrell, D. G. & Adkisson, P. L. (1977). Cotton insect pest management. *Annual Review of Entomology*, **22**, 451–481.

Brodt, S. J., Goodell, P. B., Krebill-Prather, R. L. & Vargas, R. N. (2007). California cotton growers utilize integrated pest management. *California Agriculture*, **61**, 24–30.

Brown, P., Silvertooth, J., Moore, L. & Watson, T. (1992). Revised planting window for full season cotton varieties. In *Cotton: A College of Agriculture Report*, pp. 240–251. Tucson, AZ: University of Arizona Press.

Campion, D. G. (1994). Pheromones for the control of cotton pests. In *Insect Pests of Cotton*, eds. G. A. Matthews & J. P. Tunstall, pp. 505–534. Wallingford, UK: CABI Publishing.

Castle, S. J., Prabhaker, N. & Henneberry, T. J. (1999). Insecticide resistance and its management in cotton insects. *ICAC Review Article on Cotton Production Research, International Cotton Advisory Committee*, **5**, 1–55.

Christou, P., Capell, T., Kohli, A., Gatehouse, J. A. & Gatehouse, A. M. R. (2006). Recent developments and future prospects in insect pest control in transgenic crops. *Trends in Plant Science*, **11**, 302–308.

Conway, H. E., Steinkraus, D. C., Ruberson, J. R. & Kring, T. J. (2006). Experimental treatment threshold for the cotton aphid (Homoptera: Aphididae) using natural enemies in Arkansas cotton. *Journal of Entomological Science*, **41**, 361–373.

Cross, W. H. (1973). Biology, control, and eradication of the boll weevil. *Annual Review of Entomology*, **18**, 14–46.

Dickerson, W. A., Brashear, A. L., Brumley, J. T. *et al.* (2001). *Boll Weevil Eradication in the United States through 1999*, Cotton Foundation Reference Book Series No. 6. Memphis, TN: Cotton Foundation.

El-Lissy, O. A. & Grefenstette, W. J. (2006). Progress of pink bollworm eradication in the U.S. and Mexico, 2005, In *Proceedings of the Beltwide Cotton Conferences*, pp. 1313–1319. Memphis, TN: National Cotton Council.

El-Zik, K. M. & Frisbie, R. E. (1991). Integrated crop management systems for pest control. In *Handbook of Pest*

Management in Agriculture, vol. 3, ed. D. Pimentel, pp. 3–104. Boca Raton, FL: CRC Press.

El-Zik, K. M., Grimes, D. W. & Thaxton, P. M. (1989). Cultural management and pest suppression. In *Integrated Pest Management Systems and Cotton Production*, eds. R. E. Frisbie, K. M. El-Zik & L. T. Wilson, pp. 11–36. New York: John Wiley.

El-Zik, K. M. & Thaxton, P. M. (1989). Genetic improvement for resistance to pests and stresses in cotton. In *Integrated Pest Management Systems and Cotton Production*, eds. R. E. Frisbie, K. M. El-Zik & L. T. Wilson, pp. 191–224. New York: John Wiley.

Ellsworth, P. C. & Martinez-Carrillo, J. L. (2001). IPM for *Bemisia tabaci*: a case study from North America. *Crop Protection*, **20**, 853–869.

Ellsworth, P. C., Diehl, J. W. & Naranjo, S. E. (1996). *Sampling Sweetpotato Whitefly Nymphs in Cotton*, IPM Series No. 6, Publication 196006. Tucson, AZ: University of Arizona, Cooperative Extension. Available at http://cals.arizona.edu/crops/cotton/insects/wfsampl.html.

Ellsworth, P. C., Palumbo, J. L., Naranjo, S. E., Dennehy, T. J. & Nichols, R. L. (2006). *Whitefly Management in Arizona Cotton 2006*, IPM Series No. 18, Publication AZ1404. Tucson, AZ: University of Arizona, Cooperative Extension. Available at http://ag.arizona.edu/crops/cotton/insects/wf/ipm6.html.

Environmental Protection Agency (2006). *Reducing Pesticide Risk*. Washington, DC: US Environmental Protection Agency. Available at www.epa.gov/pesticides/health/reducing.htm.

Eveleens, K. G., van den Bosch, R. & Ehler, L. E. (1973). Secondary outbreak induction of beet armyworm by experimental insecticide application in cotton in California. *Environmental Entomology*, **2**, 497–503.

Ewing, K. P. & Parencia, C. R. Jr. (1950). *Early-Season Applications of Insecticides on a Community-Wide Basis for Cotton Insect Control in 1950*, Bureau of Entomology and Plant Quarantine Publication No. E810. Washington, DC: US Department of Agriculture.

Faria, M. & Wraight, S. P. (2001). Biological control of *Bemisia tabaci* with fungi. *Crop Protection*, **20**, 767–778.

Fillman, D. A. & Sterling, W. L. (1985). Inaction levels for the red imported fire ant, *Solenopsis invicta*, a predator of the boll weevil, *Anthonomus grandis*. *Agriculture, Ecosystems and Environment*, **13**, 93–102.

Frisbie, R. E., El-Zik, K. M. & Wilson, L. T. (eds.) (1989). *Integrated Pest Management Systems and Cotton Production*. New York: John Wiley.

Frisvold, G. B., Reeves, J. M. & Tronstad, R. (2006). *Bt* cotton adoption in the United States and China: international trade and welfare effects. *AgBioForum*, **9**, 69–78.

Gaines, J. C. (1957). Cotton insects and their control in the United States. *Annual Review of Entomology*, **2**, 319–338.

Gannaway, J. R. (1994). Breeding for insect resistance. In *Insect Pests of Cotton*, eds. G. A. Matthews & J. P. Tunstall, pp. 431–453. Wallingford, UK: CABI Publishing.

Glare, T. R. & O'Callaghan, M. (2000). Bacillus thuringiensis: *Biology, Ecology and Safety*. New York: John Wiley.

Goodell, P. B., Montez, G. & Wilhoit, L. (2006). Shifting patterns in insecticide use in California, 1993 to 2004. In *Proceedings of the Beltwide Cotton Conference*, pp. 1367–1373. Memphis, TN: National Cotton Council.

Gould, J., Hoelmer, K. & Goolsby, J. (eds.) (2008). *Classical Biological Control of* Bemisia tabaci *in the United States: A Review of Interagency Research and Implementation*. New York: Springer-Verlag.

Greene, J. K., Turnipseed, S. G., Sullivan, M. J. & May, O. L. (2001). Treatment thresholds for stink bugs (Hemiptera: Pentatomidae) in cotton. *Journal of Economic Entomology*, **94**, 403–409.

Hardee, D. D. & Harris, F. A. (2003). Eradicating the boll weevil (Coleoptera: Curculionidae): a clash between a highly successful insect, good scientific achievement, and differing agricultural philosophies. *American Entomologist*, **49**, 82–111.

Hargreaves, H. (1948). *List of the Recorded Cotton Insects of the World*. London: Commonwealth Institute of Entomology.

Harris, F. A., Canerday, T. D., Henry, L. G. & Palmquist, D. L. (1996). Working together: roles of private consultants, industry, researchers, extension, and growers. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 843–851. Memphis, TN: Cotton Foundation.

Henneberry, T. J. & Naranjo, S. E. (1998). Integrated management approaches for pink bollworm in the southwestern United States. *Integrated Pest Management Review*, **3**, 31–52.

Henneberry, T. J. & Phillips, J. R. (1996). Suppression and management of cotton insect populations on an areawide basis. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 601–624. Memphis, TN: Cotton Foundation.

Herzog, G. A., Graves, J. B., Reed, J. T., Scott, W. P. & Watson, T. F. (1996). Chemical control. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 447–469. Memphis, TN: Cotton Foundation.

Huber, R. T., Moore, L. & Hoffman, M. P. (1979). Feasibility study of areawide pheromone trapping of male pink bollworm moths in a cotton insect pest management program. *Journal of Economic Entomology*, **72**, 222–227.

Insecticide Resistance Action Committee (2007). *MoA Resources*. Brussels, Belgium: IRAC. Available at www.irac-online.org/.

Jenkins, J. N. & Wilson, F. D. (1996). Host plant resistance. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 563–600. Memphis, TN: Cotton Foundation.

King, E. G., Coleman, R. J., Morales-Ramos, J. A. *et al.* (1996a). Biological control. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 511–538. Memphis, TN: Cotton Foundation.

King, E. G., Phillips, J. R. & Coleman, R. J. (eds.) (1996b). *Cotton Insects and Mites: Characterization and Management*. Memphis, TN: Cotton Foundation.

Knipling, E. F. (1955). Possibilities of insect control or eradication through the use of sexually sterile males. *Journal of Economic Entomology*, **48**, 459–462.

Knipling, E. F. (1979). *The Basic Principles of Insect Population Suppression and Management*, US Department of Agriculture Agricultural Handbook No. 512. Washington, DC: Government Printing Office.

Kogan, M. (1998). Integrated pest management: historical perspectives and contemporary developments. *Annual Review of Entomology*, **43**, 243–270.

Kohel, R. J. & Lewis, C. F. (eds.) (1984). *Cotton*, Monograph No. 24, Agronomy Series. Madison, WI: American Society of Agronomy.

Leigh, T. F., Black, H., Jackson, C. E. & Burton, V. E. (1966). Insecticides and beneficial insects in cotton fields. *California Agriculture*, **20**(7), 4–6.

Leigh, T. F., Roach, S. H. & Watson, T. F. (1996). Biology and ecology of important insect and mites pests of cotton. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 17–85. Memphis, TN: Cotton Foundation.

Luttrell, R. G. (1994). Cotton pest management. II. A US perspective. *Annual Review of Entomology*, 39, 527–542.

Matthews, G. A. (1994). Cultural control. In *Insect Pests of Cotton*, eds. G. A. Matthews & J. P. Tunstall, pp. 455–461. Wallingford, UK: CABI Publishing.

McGuire, M. R., Leland, J. E., Dara, S., Park, Y. H. & Ulloa, M. (2006). Effect of different isolates of *Beauveria bassiana* on field populations of *Lygus hesperus*. *Biological Control*, **38**, 390–396.

Miller, E., Lowe, A. & Archuleta, S. (2000). Evaluation of different release strategies for use in pink bollworm sterile release programs. In *Proceedings of the Beltwide Cotton Conference*, pp. 1368–1370. Memphis, TN: National Cotton Council.

Mumford, J. D. & Norton, G. A. (1994). Pest management systems. In *Insect Pests of Cotton*, eds. G. A. Matthews & J. P. Tunstall, pp. 559–576. Wallingford, UK: CABI Publishing.

Myers, J. H., Savoie, A. & van Randen, E. (1998). Eradication and pest management. *Annual Review of Entomology*, **43**, 471–491.

Naranjo, S. E. (2001). Conservation and evaluation of natural enemies in IPM systems for *Bemisia tabaci*. *Crop Protection*, **20**, 835–852.

Naranjo, S. E. (2007). Establishment and impact of exotic aphelinid parasitoids in Arizona: a life table approach. *Journal of Insect Science*, **7**, 63 (abstr.).

Naranjo, S. E. & Hagler, J. R. (1998). Characterizing and estimating the impact of heteropteran predation. In *Predatory Heteroptera: Their Ecology and Use in Biological Control*, eds. M. Coll & J. Ruberson, pp. 170–197. Lanham, MD: Entomological Society of America.

Naranjo, S. E., Flint, H. M. & Henneberry, T. J. (1996). Binomial sampling plans for estimating and classifying population density of adult *Bemisia tabaci* on cotton. *Entomologia Experimentalis et Applicata*, 80, 343–353.

Naranjo, S. E., Ellsworth, P. C. & Hagler, J. R. (2004). Conservation of natural enemies in cotton: role of insect growth regulators in management of *Bemisia tabaci*. *Biological Control*, 30, 52–72.

National Agricultural Statistics Service (2006). *Agricultural Chemical Usage: 2005 Field Crops Summary*. Washington, DC: US Department of Agriculture. Available at http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC/2000s/2006/AgriChemUsFC-05-17-2006.pdf.

National Cotton Council (2007a). *Crop Information: Data bases*. Memphis, TN: National Cotton Council. Available at www.cotton.org/tech/pest/index.cfm.

National Cotton Council (2007b). *Pest Management. Cotton Pest Loss Data*. Memphis, TN: National Cotton Council. Available at www.cotton.org/tech/pest/index.cfm.

Oliveira, M. R. V., Henneberry, T. J. & Anderson, P. (2001). History, current status, and collaborative research projects for *Bemisia tabaci*. *Crop Protection*, **20**, 709–723.

Palumbo, J. C., Horowitz, A. R. & Prabhaker, N. (2001). Insecticidal control and resistance management for *Bemisia tabaci*. *Crop Protection*, **20**, 739–765.

Palumbo, J. C., Ellsworth, P. C., Dennehy, T. D. & Nichols, R. L. (2003). *Cross-Commodity Guidelines for Neonicotinoid Insecticides in Arizona*. IPM Series No. 17, Publication AZ1319. Tucson, AZ: University of Arizona, Cooperative Extension. Available at http://cals.arizona.edu/pubs/insects/az1319.pdf.

Parvin, D. W. Jr. & Smith, J. W. (1996). Crop phenology and insect management. In *Cotton Insects and Mites:*

Characterization and Managements, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 815–829. Memphis, TN: Cotton Foundation.

Plapp, F. Jr., Jackman, J., Campanhola, C. *et al.* (1990). Monitoring and management of pyrethroid resistance in the budworm (Lepidoptera: Noctuidae) in Texas, Mississippi, Louisiana, Arkansas and Oklahoma. *Journal of Economic Entomology*, **83**, 335–341.

Prasifka, J. R., Heinz, K. M. & Minzenmayer, R. R. (2004). Relationships of landscape, prey and agronomic variables to the abundance of generalist predators in cotton (*Gossypium hirsutum*) fields. *Landscape Ecology*, **19**, 709–717.

Rainwater, C. F. (1952). Progress in research on cotton insects. In *Insects, The Yearbook of Agriculture, 1952*, pp. 497–500. Washington, DC: US Department of Agriculture, US Government Printing Office.

Ridgway, R. L., Bell, A. A., Vetch, J. A. & Chandler, J. M. (1984). Cotton protection practices in the USA and world. In *Cotton*, Monograph No. 24, Agronomy Series, eds. R. J. Kohel & C. F. Lewis, pp. 266–361. Madison, WI: American Society of Agronomy.

Romeis, J., Meissle, M. & Bigler, F. (2006). Transgenic crops expressing *Bacillus thuringiensis* toxins and biological control. *Nature Biotechnology*, **24**, 63–71.

Roush, R. T. & Daly, J. C. (1990). The role of population genetics in resistance research and management. In *Pesticide Resistance in Arthropods*, eds. R. T. Roush & B. E. Tabashnik, pp. 97–125. New York: Chapman & Hall.

Schneider, J. C. (2003). Overwintering of *Heliothis virescens* (F.) and *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) in cotton fields of Northeast Mississippi. *Journal of Economic Entomology*, **96**, 1433–1447.

Shaw, D. R. & Willers, J. L. (2006). Improving pest management with remote sensing. *Outlooks on Pest Management*, **17**, 197–201.

Shelton, A. M. & Badenes-Perez, E. (2006). Concepts and applications of trap cropping in pest management. *Annual Review of Entomology*, **51**, 285–308.

Smith, J. W. & Harris, F. A. (1994). Boll weevil: cotton pest of the century. In *Insect Pests of Cotton*, eds. G. A. Matthews & J. P. Tunstall, pp. 228–258. Wallingford, UK: CABI Publishing.

Snodgrass, G. L. (1996). Insecticide resistance in field populations of the tarnished plant bug (Heteroptera: Miridae) in cotton in the Mississippi Delta. *Journal of Economic Entomology*, **89**, 783–790.

Snodgrass, G. L., Scott, W. P., Abel, C. A. *et al.* (2005). Tarnished plant bug (Heteroptera: Miridae) populations near fields after early season herbicide treatment. *Environmental Entomology*, **34**, 705–711.

Sparks, T. C. (1996). Toxicology of insecticides and acaricides. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 283–322. Memphis, TN: Cotton Foundation.

Steinkraus, D. C., Hollingsworth, R. G. & Slaymaker, P. H. (1995). Prevalence of *Neozygites fresenii* (Entomophthorales: Neozygitaceae) on cotton aphids (Homoptera: Aphididae) in Arkansas cotton. *Environmental Entomology*, **24**, 465–474.

Sterling, W. L., El-Zik, K. M. & Wilson, L. T. (1989). Biological control of pest populations. In *Integrated Pest Management Systems and Cotton Production*, eds. R. E. Frisbie, K. M. El-Zik & L. T. Wilson, pp. 155–189. New York: John Wiley.

Stern, V., van den Bosch, R. & Leigh, T. F. (1964). Strip cutting alfalfa for lygus bug control. *California Agriculture*, **18**, 5–6.

Stoltz, R. L. & Stern, V. M. (1978). Cotton arthropod food chain disruption by pesticides in the San Joaquin Valley, California. *Environmental Entomology*, **7**, 703–707.

Tabashnik, B. E., Carrière, Y., Dennehy, T. J. *et al.* (2003). Insect resistance to transgenic *Bt* crops: lessons from the laboratory and field. *Journal of Economic Entomology*, **96**, 1031–1038.

Toscano, N. C., Mueller, A. J., Sevacherian, V. & Sharma, R. K. (1974). Insecticide applications based on hexalure trap catches versus automatic schedule treatments for pink bollworm moth control. *Journal of Economic Entomology*, **67**, 522–524.

Trichilo, P. J. & Wilson, L. T. (1993). An ecosystem analysis of spider mite outbreaks: physiological stimulation or natural enemy suppression. *Experimental and Applied Acarology*, **17**, 291–314.

van den Bosch, R. & Hagen, K. S. (1966). *Predaceous and Parasitic Arthropods in California Cotton Fields*, California Agricultural Experiment Station Bulletin No. 820. Berkeley, CA: University of California.

Villavaso, E. J., Bartlett, A. C. & Laster, M. L. (1996). Genetic control. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 539–562. Memphis, TN: Cotton Foundation.

Wagner, T. L., Olson, R. L., Willers, J. L. & Williams, M. R. (1996). Modeling and computerized decision aids. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 205–249. Memphis, TN: Cotton Foundation.

Walker, J. K. & Smith, C. W. (1996). Cultural control. In *Cotton Insects and Mites: Characterization and Management*, eds. E. G. King, J. R. Phillips & R. J. Coleman, pp. 471–510. Memphis, TN: Cotton Foundation.

Watson, T. F. (1980). Methods for reducing winter survival of the pink bollworm. In *Pink Bollworm Control in the Western United States*, ed. H. S. Graham, pp. 24–34. Oakland, CA: US Department of Agriculture, Science and Education Administration, Western Region.

Whalon, M. E., Mota-Sanchez, D., Hollingsworth, R. M. & Duynslayer, L. (2007). *IRAC Arthropod Pesticide Resistance Database*. East Lansing, MI: Michigan State University. Available at www.pesticideresistance.org/.

Whitcomb, W. H. & Bell, K. (1964). *Predaceous Insects, Spiders and Mites of Arkansas Cotton Fields*, Bulletin No. 690. Fayetteville, AR: Arkansas Agricultural Experiment Station.

Williams, M. R. (2006). Cotton insect losses 2005. In *Proceedings of the Beltwide Cotton Conference*, pp. 1151–1204. Memphis, TN: National Cotton Council.

Williams, M. R. (2007). Cotton insect losses 2006. In *Proceedings of the Beltwide Cotton Conference*, pp. 974–1026. Memphis, TN: National Cotton Council.

Wilson, L. T., Gonzales, D. & Plant, R. E. (1985). Predicting sampling frequency and economic status of spider mites on cotton. In *Proceedings of the Beltwide Cotton Conference*, p. 168. Memphis, TN: National Cotton Council.