CHAPTER 15

BIOLOGICAL CONTROL

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INTRODUCTION

Over 100 species of insects and mites are pests of cotton in the United States (see Chapter 2, this book). From 1980 to 1987, the aggregate damage attributed to these cotton insect and mite pests was about 7 to 14 percent despite the best control efforts (see Chapter 24, this book). In 1993, arthropod pests reduced cotton yields in the United States by about 6.9 percent resulting in a loss of 890 thousand bales from potential yield and $331 million in revenue (Hardee and Herzog, 1994). Moreover, $586 million were spent for pesticides to control these pests. So, the total direct cost of arthropod pests to United States cotton production was $917 million in 1993. Indirect costs not included are the value of the lost lint as it would have moved through the market place and the cost of environmental degradation caused by the application of about 1.6 pounds (active ingredient) of synthetic chemical insecticides and miticides applied per acre over 10 to 14 million acres of cotton in the United States each year (Chapter 24, this book).

Obviously, the cost to United States cotton growers, consumers, and the environment for arthropod pest control in cotton is unacceptably high, and there is an urgent need to develop less expensive pest management techniques. Perhaps even more importantly, United States cotton producers will be forced to consider non-chemical control measures more strongly because of public concern about synthetic chemical pesticides (see Chapter 28, this book; King *et al.*, 1988a). For example, concern in California about the need for safe drinking water resulted in Proposition 65, the "Safe Drinking Water and Toxic Enforcement Act of 1986," empowering the governor of that state to declare any chemical to be a health hazard if it is a carcinogen or reproductive toxicant. Moreover, where pesticides may be used, and therefore where cotton may be economically grown, is impacted by The Endangered Species Act of 1973, requiring the United States Environmental Protection Agency (EPA) to protect endangered and threatened species under the Federal Insecticide, Fungicide, and Rodenticide

Act. Finally, the number of effective pesticides for cotton insect and mite pests is decreasing. This decrease is related to obsolescence resulting from resistance (see Chapters 8, 9, and 13, this book), high cost of research and development (estimated over $50 million to acquire the first label for registered use of one single pesticide), and the requirement that all pesticide uses registered prior to November 1984 must be re-registered under EPA requirements because of putative chronic health effects and ground water leaching.

INTEGRATED PEST MANAGEMENT

The integrated pest management (IPM) concept fully emerged in the 1960s (Newsom and Brazzel, 1968) and became the dominant approach to arthropod pest control in cotton as well as other crops during the 1970s and early 1980s (Frisbie and Adkisson, 1985). Its development was in response to the control failures of insecticides and miticides (due to the development of resistant populations) as well as public concerns relative to the impact of these synthetic pesticides on non-target animal populations.

IPM has been defined as a system in which all available techniques are evaluated and consolidated into a unified program for managing pest populations to avoid economic damage and minimize adverse side effects on the environment (National Academy of Sciences, 1969). The evolution of this concept in cotton beginning in the early 1900s to date is reviewed in Chapter 1, this book.

BIOLOGICAL CONTROL STRATEGIES

Biological control is an integral component of cotton IPM strategy in the United States. It involves managing natural enemies (predators, parasites and pathogens) to reduce pest populations and their effects. Other non-chemical control strategies, such as genetic or autocidal control and host plant resistance or cultural control, are discussed in other chapters of this book.

Three strategies are often identified for encouraging and using natural enemies (Figure 1). First, exotic species may be introduced and established on pest species potentially reducing the pest population permanently to a lower level — this is classical biological control. Second, means may be developed to protect and spare natural enemies — conservation. Finally, efforts to increase the number of natural enemies, or their effectiveness, within a defined area may be undertaken—this is augmentation.

Importation — Some of the most important pests of cotton originated in other countries, including the boll weevil, *Anthonomus grandis grandis* Boheman, the pink bollworm, *Pectinophora gossypiella* (Saunders), and the sweetpotato whitefly, *Bemisia tabaci* (Gennadius). Consequently, these pests are not associated in the United States with co-evolved, selective natural enemies. Attempts to import and establish co-evolved natural enemies from the site of origin for these pest have not been success-

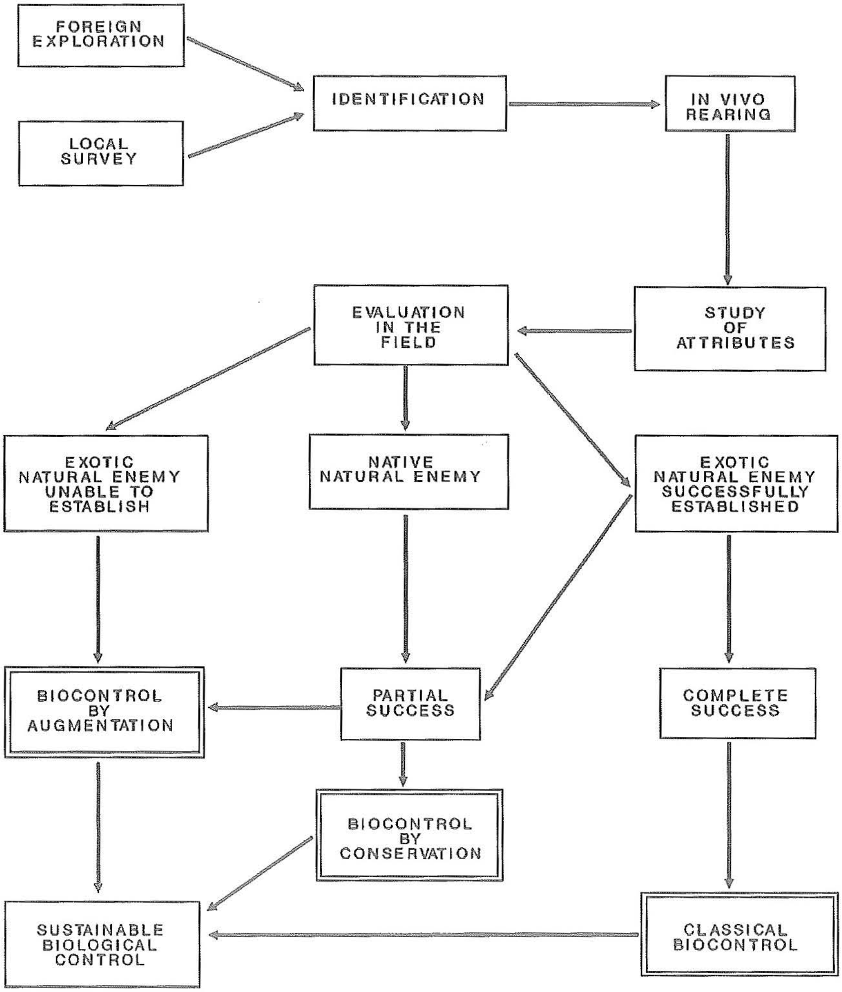

Figure 1. Biological control strategies for using entomophagous arthropods to reduce insect/mite populations and their effects.

ful. This biological control strategy is discussed in more detail on a pest-by-pest basis later in this chapter.

Conservation — Current cotton IPM strategy emphasizes minimizing insecticide and miticide usage to spare natural enemies and maximize their pest suppression action (King, 1986). Avoidance of pesticide usage has often been cited as precluding the buildup of pest populations, such as the bollworm, *Helicoverpa zea* (Boddie), and tobacco budworm (*Heliothis virescens* (F.)), aphids, whiteflies and mites because of pesticide-related mortality to the natural enemies (Bottrell and Adkisson, 1977).

Literally hundreds of species of arthropod predators, parasites and pathogens are associated with cotton arthropod pests (van den Bosch and Hagen, 1966; Whitcomb and Bell, 1964; Falcon, 1971; also see Chapters 3 and 5, this book). Perhaps the best evidence of the importance of these natural enemies in suppressing pest populations is the resurgence of treated pest populations to levels equal to or greater than pretreatment levels, and outbreaks of pests other than those against which the insecticides were directed resulting from insecticide overuse (Newsom and Brazzel, 1968). For example, the cotton aphid, *Aphis gossypii* Glover, became a serious pest of cotton as a consequence of using calcium arsenate for control of the boll weevil (Folsom, 1928). Indications are that this phenomenon occurred because of destruction of predators. Likewise, there is good evidence that the emergence of spider mites, as pests in the West and Southwest regions of the Cotton Belt is related to destruction of effective predators by pesticides used to control other pest species. Lingren *et al.* (1968) correlated a reduction of about 50 percent in predator populations after foliar applications of several organophosphate insecticides for control of the cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter), and a subsequent buildup of damaging bollworm and tobacco budworm populations.

Augmentation — There are two basic approaches to augmentation: periodic release and environmental manipulation. The most direct approach is through propagation and release or application of the natural enemy. These augmentations are classified as inoculative or inundative releases. Excellent reviews of this technology for crops in general may be found in Ridgway and Vinson (1977), Rabb *et al.* (1976), Stinner (1977), and King (1993). King and Powell (1992) reviewed the state of technology for mass propagating and augmentatively releasing predators and parasites for control of insect and mite pests of cotton. Additionally, parasites and predators have been augmented by environmental manipulation, including the provision of supplemental resources such as food or semiochemicals (naturally occurring, behavior-modifying substances that mediate interactions between organisms). For example, Hagen *et al.* (1971) reported that a dairy product composed of the yeast *Saccharomyces fragilis* and its whey substrate sprayed on cotton increased the effectiveness of the common green lacewing, *Chrysoperla carnea* Stephens, against bollworm eggs and larvae. Nordlund *et al.* (1985) provide some evidence for and suggest that semiochemicals from plants and/or hosts or prey may be applied to crop fields for retention and concentration of predator and parasite populations. (See Chapter 11, this book, for a comprehensive review of the use of semiochemicals to manage pest and natural enemy populations).

BIOLOGICAL CONTROL WITH PREDATORS AND PARASITES

This review of biological control of cotton arthropod pests will be largely restricted to those pests normally enumerated in the annual report on "Cotton Losses to Insects" (e.g., Hardee and Herzog, 1994). About one-half of the cotton insect losses in 1993 were attributed to three pest species: the boll weevil, the bollworm and the tobacco budworm. The remainder of the loss is attributed largely to plant bugs (*Lygus* spp. and the cotton fleahopper), spider mites, thrips, the sweetpotato whitefly and armyworms. The loss attributed to the pink bollworm is relatively low in most areas, but may be substantial in California and Arizona. The pink bollworm is included in this review because of its historical importance as a key pest.

BOLLWORM/TOBACCO BUDWORM

Biological control of the bollworm and tobacco budworm, as well as other *Helicoverpa/Heliothis* species has been extensively reviewed for cotton and other crops, worldwide. King and Jackson (1989) organized a symposium resulting in a comprehensive publication on the systematics, distribution and biological control of *Helicoverpa/Heliothis*. Symposium information was updated and summarized in King and Coleman (1989). Johnson *et al.* (1986) comprehensively reviewed cultural and biological control of *Helicoverpa/Heliothis* across crops. Perhaps the most comprehensive review of *Helicoverpa/Heliothis* to date is the "Proceedings of the International Workshop on *Heliothis* Management" (International Crops Research Institute for Semi-Arid Tropics, 1982).

Importation — Hundreds of predators and parasites attack *Helicoverpa/ Heliothis*. Some of the world's most important parasites attacking *Helicoverpa/Heliothis* have been imported, propagated and released for establishment. Three species of predators have been imported. This subject was most recently reviewed by Powell (1989) for the United States and by King and Jackson (1989), worldwide. To date, no exotic parasites or predators have been established on the bollworm/tobacco budworm in the United States. Nevertheless, attempts to establish effective species continue because of the potentially high return that may be gained by reducing the pest status level of the bollworm/tobacco budworm. In fact, the braconid *Cotesia kazak* (Telenga), imported from Europe and released in New Zealand in 1977, was established. It now has altered the number of *Helicoverpa armigera* (Hübner) attaining damaging levels in New Zealand (Cameron and Valentine, 1989).

Cotesia kazak was imported and released in the United States, and recovered from field collected larvae. However, long term establishment has not been documented. Some other important parasites imported and released in the United States include *Campoletis chloridae* Uchida from India, *Microplitis demolitor* Wilkinson from Australia, *Microplitis rufiventris* Kok from Egypt, *Hyposoter didymator* (Thunb.) from Europe and *Palexorista laxa* (Curran) from Kenya (Powell, 1989).

Conservation — Kogan *et al.* (1989), using a database of 7,717 documents, said that for bollworm and tobacco budworm in North, Central and South America, there were reported to be: (a) 60 species of hymenopterous parasites in six families; (b) 61 species of dipterous parasites in four families; and (c) 142 species of predators from eight insect and two Arachnid orders.

In the United States, the most common egg parasites were *Trichogramma* spp. and the most common larval parasites were *Cardiochiles nigriceps* Viereck, *Microplitis croceipes* (Cresson), *Cotesia marginiventris* (Cresson) and several species of *Campoletis* and *Hyposotor*. Common tachinid parasites included *Eucelatoria bryani* Sabrosky and *Archytas marmoratus* (Townsend). Predominant predators included members of the: (a) Coleoptera order (especially the convergent lady beetle, *Hippodamia convergens* Guérin-Méneville, *Collops* spp., the spotted lady beetle, *Coleomegilla maculata* DeGeer, and *Scymnus* spp.); (b) Hemiptera order (especially bigeyed bugs, *Geocoris* spp.; pirate bugs, *Orius* spp.; damsel bugs, *Nabis* spp.; and soldier bugs, *Podisus* spp.); (c) Neuroptera order (primarily lacewings, *Chrysoperla* spp.); and (d) the spiders.

Most of the predators and parasites cited above have been recorded from cotton fields. Whitcomb and Bell (1964) recorded over 600 predators in Arkansas cotton fields and van den Bosch and Hagen (1966) estimated about 350 different predators and parasites in California. Other data citing the diversity of predators and parasites of bollworm/tobacco budworm and other pests in cotton are given in Chapter 3, this book.

In large measure the emergence of IPM in cotton was caused by the failure of insecticides to control the bollworm/tobacco budworm, particularly the tobacco budworm, and other cotton arthropod pests (Bottrell and Adkisson, 1977). The conservation and maximum use of naturally occurring biological control agents is a key component of the IPM strategy. The potential effect of naturally occurring predators and parasites is generally recognized in cotton insect control guides (King, 1986; see Chapters 20, 21, 22, and 23, this book). On the other hand, explicit instructions for incorporating predators and parasites into decision-making regarding action versus nonaction are generally lacking.

Most state cotton insect control guides provide a listing of the predators that may be encountered while surveying insect pest infestations. Parasitic insects are usually mentioned but not by name. Some guides provide picture sheets to illustrate key natural enemies and some discuss techniques for quantifying predators. Rarely do the guides provide instructions for deciding on treatment versus no treatment based on abundance of natural enemies (King and Coleman, 1989).

The complexity of sampling for predators and parasites, and interpreting what these numbers mean relative to the vast array of biotic and abiotic factors affecting bollworm/tobacco budworm populations make the development of computer based decision-making technology imperative. Wagner *et al.* (see Chapter 6, this book) review the various models that have been developed in an attempt to describe the interaction between bollworm/tobacco budworm populations, their natural enemies and other components of their biotic and abiotic environment. One computer model, MOTHZV, predicted survival of late-instar bollworm/tobacco budworm larvae based on the effects of different densities of total predators (Hartstack and Witz, 1983). Ables *et al.* (1983) describe in detail the concepts underlying the use of predator-prey ratios to make decisions regarding IPM on a field-by-field basis but admit the inability to correlate increase or decrease of predator populations with varying densities of bollworm/tobacco budworm populations. Regardless, articles were cited and data presented demonstrating the efficacy of predators on bollworm/tobacco budworm life stages.

Direct evidence of predator efficacy consists of observations (Fletcher and Thomas, 1943; Whitcomb, 1967a, 1967b) and cage experiments (Lopez *et al.*, 1976; van den Bosch *et al.*, 1969; Tejada, 1971). Indirect evidence of predator efficacy is persuasive and has emerged as a consequence of first eliminating natural enemies followed by bollworm/tobacco budworm population outbreaks (Lingren *et al.*, 1968, van den Bosch *et al.*, 1971; and van Steenwyk *et al.*, 1976).

MOTHZV has been incorporated into the highly useful management model, TEXCIM (described in detail in Chapter 7, this book). In brief, "TEXCIM is a multipest, multitrophic, multicomponent computer model that uses field counts of cotton fleahopper, bollworm, tobacco budworm and boll weevil, ten groups of predators, insecticides, cotton fruit and local weather to forecast the expected benefits of control."

Other models also contain natural enemy components, e.g., HELSIM (Stinner *et al.*, 1977) and CIM-HEL (Brown *et al.*, 1979; McClendon and Brown, 1983). The decision making model, DEMHELIC, proposed by Hopper and Stark (1987) made explicit use of natural enemy populations. This model has structures for bollworm/tobacco budworm feeding, the impact of natural enemies on bollworm/tobacco budworm feeding and survival, cotton plant growth, mortality of bollworm/tobacco budworm and predators and parasites from insecticides and the economics of insecticide inputs and returns.

Augmentation: Parasites — The principal parasites that contribute to mortality of bollworm and tobacco budworm eggs and larvae are *Trichogramma* spp., *Microplitis croceipes*, *Cardiochiles nigriceps* (tobacco budworm only) and *Cotesia marginiventris*. Of these parasites, primary attention has been given to augmentation of *Trichogramma* populations. Recently, major emphasis has been placed on the development of augmentation technology for the larval endoparasite *Microplitis croceipes*. Other efforts have been placed on the development of rearing and augmentative release technology for the tachinid *Archytas marmoratus*.

Egg Parasites. Biological control of bollworm/tobacco budworm in cotton by releases of egg parasites like *Trichogramma*, particularly *Trichogramma pretiosum* Riley, in the United States is comprehensively reviewed in King *et al.* (1985a). All aspects are reviewed including: (a) rearing (Morrison, 1985a, 1985b); (b) transport, storage and parasite release technology (Bouse and Morrison, 1985); (c) behavioral manipulation (Lewis *et al.*, 1985); (d) parasite movement (Keller and Lewis, 1985); efficacy (King *et al.*, 1985b; Lopez and Morrison, 1985); (e) pesticide effects (Bull and Coleman, 1985); and (f) modeling (Goodenough and Witz, 1985). A recent popularized review of the state-of-the-art technology for identifying, propagating and augmenting *Trichogramma* populations is given by Olkowski and Zhang (1990).

Olkowski and Zhang (1990) list seven commercial producers of *Trichogramma* in the United States. These parasites are released over a total of about 200,000 acres. The parasite most commonly reared and released in cotton is *Trichogramma pretiosum*. The Angoumois grain moth, *Sitotroga cerealella* (Olivier), is the host generally used in the mass rearing/production system for this parasite. The technical feasibility of suppressing bollworm/tobacco budworm populations in cotton by inundative releases of *Trichogramma* has been repeatedly demonstrated in the United States. Aerial releases of 49,980 to 99,960 adult *Trichogramma* per acre resulted in an average 51 percent parasitism of bollworm/tobacco budworm eggs on five Texas cotton farms (Ridgway *et al.*, 1977). Stinner *et al.* (1974) evaluated the technical feasibility of reducing bollworm/tobacco budworm larval populations in cotton by releasing *Trichogramma pretiosum*. Parasite release rates were high (up to 387,293 per acre), but bollworm/tobacco budworm larval populations were suppressed. King *et al.* (1985b) reported three years of data following releases of *Trichogramma pretiosum* in cotton. In each year egg parasitism was increased as a consequence of the released parasites, but these parasitism rates could not be correlated with larval suppression. Regardless, in the third year, yields in release fields were significantly higher than in non-release, untreated control fields; though this amounted to 77 percent as much lint as in the insecticide-treated plots.

Larval Parasites. Larval parasites are an important part of the environmental resistance to increase of *Helicoverpa/Heliothis* populations. Unique complexes of hymenopterous and tachinid parasites have been recorded in the various regions of the world (King and Jackson, 1989). Cumulative rates of larval parasitism are often high but the predominant species vary between region of the country in the United States as well as crop (King *et al.*, 1982). One of the most important parasites of bollworm/tobacco budworm larvae in cotton and wild host plants in the United States is *Microplitis croceipes* (King and Powell, 1989).

The potential for releases of larval parasites has been indicated in small-scale tests. Lingren (1969) reported that *Cotesia marginiventris* had considerable potential for use in augmentation programs. Also, *Campoletis sonorensis* (Cameron) released at the rate of 680/day for 10 consecutive days in a 0.08 acre cage (13,760 wasps per acre equivalent) infested with tobacco budworm larvae resulted in 85 percent parasitization for nine consecutive weeks (Lingren, 1977). Jackson *et al.* (1970) reported that if the tachinids *Eucelatoria bryani* and *Palexorista laxa* were released at the rate of 2,500 female flies per acre on cotton containing 5,000 bollworm/tobacco budworm larvae per acre, about 50 percent parasitization should occur in two days.

Research on *Microplitis croceipes* has been extensive (Powell *et al.*, 1989). Basic biology including host relationship physiology was recently reviewed by Powell and Elzen (1989) and Vinson and Dahlman (1989). Behavioral aspects relating to habitat and host location, mate finding and mating were reviewed by Nordlund *et al.* (1989), Elzen and Powell (1989) and Jones (1989). Other research vital to development of the augmentation technology for *Microplitis croceipes* is effect of insecticides on the parasite (Bull *et al.*, 1989), genetic characterization and genetic improvement (Steiner and Teig, 1989), and the possibility of developing an *in vitro* rearing system for the parasite (Greany *et al.*, 1989).

Hopper (1989) surmised that augmentation of *Microplitis croceipes* for control of bollwom/tobacco budworm is technically feasible. Of the principal parasites of bollworm/tobacco budworm, across host plants, *Microplitis croceipes* has emerged as one of the most important (King *et al.*, 1985c; King and Powell, 1989). King *et al.* (1985c) hypothesized—based on dramatically higher rates of bollworm/tobacco budworm larval parasitism—that *Microplitis croceipes* was highly tolerant of many commonly used insecticides, particularly the pyrethroids. In general, the parasites are more tolerant of certain pyrethroids (e.g., esfenvalerate [Asana®] and cypermethrin [Ammo®, Cymbush®]) and carbamates (e.g., thiodicarb [Larvin®] and oxamyl [Vydate®]) and least tolerant of certain organophosphates (e.g., acephate [Orthene®] and profenofos [Curacron®]) (Powell and Scott, 1991). *Microplitis croceipes* prefers to parasitize third instar larvae, (Hopper and King, 1984a), but all parasitized instars move and feed less on the cotton plant (Hopper and King, 1984b). Consequently, less damage is caused by parasitized larvae. Hopper *et al.* (1991) report that releasing 809 female *Microplitis croceipes* per acre of cotton yielded 75 percent parasitized bollworm/ tobacco budworm larvae after six days, with an estimated 38 percent reduction in damage. Hopper (1989) suggested that releases over large areas, particularly during the time that bollworm/tobacco budworm are restricted on wild host plants (valid in the United States only for the Mid-South) might be an effective population suppressant tactic.

Augmentation: Predators — No predators are currently being released for controlling bollworm/tobacco budworm in the United States. Most management models do include predator-caused mortality, indirectly if not directly.

Releases of several hemipteran predators indicate that it might be feasible to augment their populations if economical procedures for mass producing them could be developed. Field-cage studies by Lingren *et al.* (1968), van den Bosch *et al.* (1969) and Lopez *et al.* (1976) with a bigeyed bug, *Geocoris punctipes* (Say), the common damsel bug, *Nabis americoferus* Carayon, and the spined soldier bug, *Podisus maculiventris* (Say), respectively, demonstrate their ability to suppress bollworm/tobacco budworm populations in cotton.

Ridgway *et al.* (1977) reviewed the technical feasibility of suppressing bollworm/tobacco budworm larval populations in cotton by periodic releases of the common green lacewing's eggs or larvae. Release of 2-to 3-day-old larvae consistently produced significant reductions of bollworm/tobacco budworm on cotton. Reductions in bollworm/tobacco budworm larval populations were obtained by releasing as few as 10,000 common green lacewing larvae per acre, and high levels of reduction were obtained in the field by releasing 100,000 to 200,000 thousand per acre.

BOLL WEEVIL

Importation — The boll weevil evolved on noncrop hosts, *Hampea* spp., in Central America (Burke *et al.*, 1986). Subsequent colonization of wild cotton by the boll weevil followed by cultivation of cotton along the eastern coastal lowlands of Mexico ultimately provided a "bridge" into the Lower Rio Grande Valley of Texas. Northward expansion by the weevil, coupled with the ability to overwinter as an adult in facultative diapause, allowed its "escape" from co-evolved natural enemies. In fact, some parasite species, e.g., *Bracon compressitarsis* Wharton, attack the boll weevil on *Hampea* spp. but not cotton. Consequently, the boll weevil is often viewed as a key pest that is largely invulnerable to biological control in the United States (Bottrell, 1976).

The earliest attempt to import and establish natural enemies involved a parasitic mite, *Pediculoides ventricosus* Newport (Hunter and Hinds, 1905). Cook (1904, 1905) imported the "kelep ant," *Ectatoma tuberculatum* (Oliver), from Guatemala, but it failed to establish in Texas. Two parasites, *Triaspis vestiticida* Viereck and *Bracon vestiticida* (Viereck), imported from Peru and Colombia, parasitized boll weevil larvae but failed to establish after field release (Berry, 1947). Two parasites, *Bracon kirkpatricki* Wilkinson from Africa and *Bracon greeni* Ashmead from India, imported for establishment on the pink bollworm, parasitized boll weevil larvae in the laboratory, but failed to overwinter in Mississippi (Cross *et al.*, 1969).

Some parasites attacking the boll weevil and a closely related species, *Anthonomus hunteri* Burke and Cate, in southern Mexico include *Catolaccus grandis* (Burks), *Catolaccus hunteri* Crawford, *Heterospilus annulatus* Marsh, *H. megalopus* Marsh, *Bracon compressitarsis*, *Urosigalphus schwarzi* Gibson, *Zatropis incertus* Ashmead, *Lelaps* sp., *Paracrias anthonomi* Woolley and Schauff, *Nealiolus* sp., *Phaneronoma* sp., and *Spilochalcis* sp. (Cate *et al.*, 1990). Several species have been reared in the laboratory (Cate, 1987).

Marsh (1982) reported that the two braconids, *Heterospilus annulatus* and *Heterospilus megalopus*, released at four Texas sites, apparently did not establish. *Catolaccus grandis*, was released during 1967 to 1969 in Mississippi resulting in high rates of parasitism and in-season recycling by the parasite (Johnson *et al.*, 1973). Cate *et al.* (1990) reported that a single release of 1200 female *C. grandis* provided economic control of the boll weevil in a cotton field for a six-week period. However, in both cases, the parasite did not establish.

Conservation — Numerous predators and parasites have been observed to attack the boll weevil in the United States (Pierce *et al.*, 1912; Cross and Chestnut, 1971). However, only in unique circumstances have they been documented as causing significant mortality. For example, Sterling and collaborators (Fillman and Sterling, 1983; Sterling *et al.*, 1984) report that, where the red imported fire ant, *Solenopsis invicta* Buren, exists in east Texas, it may be an effective predator of boll weevil larvae. Parasites, indigenous to the United States, that attack the boll weevil are typically polyphagous and utilize the boll weevil facultatively.

At least 55 indigenous entomophagous arthropods have been recorded as attacking the boll weevil in the United States (Pierce, 1908; Hunter, 1910; Pierce *et al.*, 1912; Chestnut and Cross, 1971). Of these, *Bracon mellitor* Say predominates, sometimes accounting for as much as 90 percent of the total parasitism (Marlatt, 1933). An oligophagous parasite, *Urosigalphus anthonomi* Crawford, has been detected in surveys near Brownsville, TX, parasitizing up to 50 percent of the boll weevil larvae collected (Pierce *et al.,* 1912; Summy, 1991). Other parasites occurring in significant numbers include *Aliolus curculionis* (Fitch), *Eurytoma gossypii* Bugbee, *Catolaccus hunteri*, *Zatropis incertus*, and *Eupelmus cyaniceps* Ashmead (Cate, 1985).

Indigenous parasites of the boll weevil characteristically have a wide host range (polyphagous or oligophagous), and, consequently, do not respond to boll weevil population dynamics as would a more host-specific parasite. For example, *B. mellitor* typically occurs too late in the season to maintain the boll weevil at subeconomic levels. Moreover, Adams *et al.* (1969) report that *B. mellitor* prefers to oviposit on weevil larvae in floral buds (squares) not completely abscised from the plant. However, present-day commercial cotton varieties typically shed their squares and the boll weevil larva completes its development to adulthood inside the fallen square. Moreover, *B. mellitor* development is poorly synchronized with development by the boll weevil (Morales-Ramos and Cate, 1993). The parasite *U. anthonomi* is of interest, but it has not been successfully reared in the laboratory. *Bracon thurberiphagae* is a primary parasite of the thurberia form of the boll weevil, but it is restricted to searching for hosts in *Gossypium thurberi.*

Augmentation — Pierce (1908) increased the percentage parasitism of boll weevil larvae by collecting parasites from one location and releasing them in another. Pierce *et al.* (1912) proposed encouraging the growth of plant species which attract and support hosts of polyphagous parasites, including the suggestion that these alternate host plants might then be destroyed thereby forcing the polyphagous parasites into cotton. Bottrell (1972) suggested the use of the synthetic pheromone Grandlure® to attract overwintering weevils into a portion of the cotton field thereby increasing the density of host larvae. The idea was to attract *B. mellitor* into cotton earlier in the season. McGovern and Cross (1976) increased the effectiveness of *B. mellitor* by use of the frego-bract character in commercial cottons; parasitism was increased from 7-56 percent.

Others surmised that it might be possible to mass propagate parasites and augmentatively release them for control of the boll weevil (Anonymous, 1958). In fact, Johnson *et al.* (1973) reported releases of *C. grandis* during 1967, 1968, and 1969, resulting in rates of parasitism ranging up to 72 percent as well as in-season recycling by the exotic parasite. Though they were unsuccessful in establishing the parasite, they suggested that it "might be used as part of an integrated control program...if the parasite can be mass reared...". Regardless, no determined attempts were made to suppress the boll weevil by augmentative releases of parasites until 1992 (Summy *et al.*, 1993).

King (1993) hypothesized in 1988 that some of the United States' most intractable key pests, such as the boll weevil, may be controlled through propagation and inoculative/augmentative releases of selective parasites. It was further hypothesized that failure to become established, as in the case of exotic parasites of the boll weevil, was not critical in an inoculative/augmentative release program. In fact, it was concluded that population densities of boll weevils tolerated by cotton growers, in season, are so low that they cannot support a naturally-occurring parasite population. These hypotheses are documented in two USDA Agricultural Research Service CRIS Work Projects (1988, 1989) and in the Proceedings of a Work Planning Session, September 19-20, 1989 (Memo, E. G. King/W. Klassen, ARS Associate Deputy Administrator, and others, 1990). As part of the Work Planning Session, E. F. Knipling developed a theoretical model postulating the suppressive effects of a selective parasite inoculatively/augmentatively released against the boll weevil; this model is elaborated on in Knipling (1992).

An outcome of the 1989 Work Planning Session was selection of *C. grandis* as the lead candidate for large-scale propagation and release for control of the boll weevil. This parasite apparently is well adapted to the in-season biotic and abiotic environment of the United States cotton agroecosystem based on results from attempts to establish it (Johnson *et al.*, 1973; Cate *et al.*, 1990). Though the parasite did not establish, these studies demonstrated that *C. grandis* effectively searches for boll weevil-infested squares on the ground as well as on the plant.

A series of experiments from 1992 through 1994 demonstrated the effectiveness of *C. grandis* augmentative releases. Summy *et al.* (1993, 1994) report on exceptionally high rates of parasitism of boll weevil larvae, as well as their population suppression, following inoculative/augmentative releases of *C. grandis*. Augmentative releases of *C. grandis* in Texas and Alabama cotton fields at rates of 500 to 1000 females/acre per week during early season resulted in 50 to 100 percent parasitism of boll weevil third instars during the release periods (Morales-Ramos *et al.*, 1994; Summy *et al.*, 1994). The parasite releases were made over a six- to eight-week period in Texas and a three-week period in Alabama. Lint yield from parasite-release fields in Texas did not differ significantly from the insecticide-treated IPM control fields, but the test was terminated prematurely in Alabama due to a lack of boll weevil immatures to rear the parasites.

Catolaccus grandis is highly fecund relative to its host, the boll weevil. During their most fertile ages the parasite is capable of producing several times more eggs than the boll weevil (Morales-Ramos and Cate, 1992; Gast, 1966). Weekly releases of the parasite during the F_1 and F_2 larval-pupal generations are projected to have a highly suppressive effect on the boll weevil population (Morales-Ramos *et al.*, 1993). So, parasite fecundity is not a limiting factor in biological control of the boll weevil. Moreover, this high fecundity facilitates mass propagation of the parasite, *in vivo* or *in vitro*.

The parasite prefers boll weevil third instars, but also oviposits in squares containing host prepupae and pupae and occasionally second instars. It apparently searches effectively for host larvae in shed squares, but a cage study (Tillman, 1993) demonstrated a preference for infested squares on the plant as opposed to abscised infested squares on the ground surface. Another study (Summy *et al.*, 1993) revealed a preference by field-released parasites for infested squares over infested bolls during early season. These findings affirm the strategy for using the parasite to attack and strongly suppress the F_1 and F_2 host larval/pupal generations, which are typically in squares on the soil surface, thereby reducing the third and fourth weevil generations to non-pest status.

At temperatures ranging from 16°C to over 36°C the development of *C. grandis* is well synchronized with its obligate host, the boll weevil (Morales-Ramos and Cate 1993). In contrast, development of the polyphagous parasite, *Bracon mellitor* is not well synchronized. The developmental time of *C. grandis* and the boll weevil from egg to adult at 30°C is about 12 days each.

Initial efforts to rear *C. grandis* required placing third instar larvae into hollowed cotton squares, sealing the hollowed square with artificial medium, and exposing the artificially implanted larvae to gravid *C. grandis* females (Johnson *et al.* 1973). Cate (1987) reported a simple but elegant process, encapsulating the third instar host larvae in Parafilm^{R} in lieu of artificially infesting hollowed squares. Morales-Ramos *et al.* (1992) modified and improved the encapsulation process. Further automation of the process described by Morales-Ramos *et al.* (1992) is given by Roberson and Harsh (1993). The potential for *in vivo* mass propagation of *C. grandis* exists because of the advances that have already been made in the mass propagation of the host (see Roberson and Wright 1984).

Catolaccus grandis has been reared from egg to adult on an artificial diet (Guerra *et al.*, 1993; Rojas *et al.*, patent pending/in manuscript), and the economic feasibility of the inoculative/augmentative release approach to areawide boll weevil suppression may be dependent on this technological advance. On the other hand, use of inoculative/augmentative releases of *C. grandis* in environmentally-sensitive areas as a component in the boll weevil eradication programs may be economically feasible using *in vivo*-reared parasites.

Two substantial limitations have been identified in attempts to develop a use pattern for releasing *C. grandis* in the cotton agroecosystem. First, this parasite is highly sensitive to the chemical insecticides that are likely to be used for control of the boll weevil as well as other pests (Summy *et al., 1994)*. However, if the application of these chemicals is strategically timed, they can be used for control of early-season pests, such as thrips and plant bugs. Moreover, at least one application of a relatively short residual chemical may be applied early to eliminate overwintering weevils invading the cotton fields.

The second limitation involves the ability of the parasite to detect infested squares on the ground that have been covered with soil. In one controlled test, infested squares were covered with about one millimeter of soil to simulate the likely effect of cultivation. The parasite females apparently could not detect and parasitize the host larvae. Consequently, mechanical cultivation at the time of, and following parasite release, will have to be curtailed to achieve maximum effectiveness by the parasite (Summy *et al.*, 1994).

The inoculative/augmentative release strategy of *Catolaccus grandis* for control of the boll weevil can be integrated into short-season, cotton-production systems. There are a number of attributes of this system that make it amenable to the parasite inoculative/augmentative release strategy. Shortening the growing season through management practices, including planting of rapidly maturing cultivars, escapes high, late-season weevil and other pest populations. Moreover, shortening the season allows earlier stalk destruction and plowdown thereby further reducing the number of weevils overwintering and dispersing into cotton fields the following year. Imposing insecticide applications early season, near pinhead square occurrence, to kill invading overwintered weevils reduces populations to their lowest seasonal density. Harvest-aid chemicals can be valuable in preparing the crop for earlier harvest, and indirectly, in suppressing diapausing weevils (Cleveland and Smith, 1964).

Release of *C. grandis* to parasitize and kill F_1 and F_2 weevil immatures imposes an additional mortality factor heretofore not possible in extant production systems. In fact, attainment of very high rates of parasitism by *C. grandis* during the F_1 and F_2 generations can practically eliminate in-field reproduction by the boll weevil, thereby precluding the need for subsequent insecticide treatments for control of the weevil (Summy *et al.*, 1994; King *et al.*, unpublished data).

Proper timing and use of short-residual materials prior to releases of *C. grandis* controls early season pests (including overwintered boll weevil), yet minimally impacts the parasite. Properly timed, this practice can greatly reduce or eliminate the need for boll weevil control later in the season (Walker, 1980a). Later, mid-season pests, such as the bollworm or tobacco budworm, may require insecticide treatments, which would curtail subsequent releases of *C. grandis*. However, avoidance of additional insecticide treatments for 30 to 45 days may allow predators and parasites to increase in sufficient numbers to curb damaging pest populations. In fact, during 1994 field tests with *C. grandis*, no insecticide applications were necessary for late-season pests such as the bollworm and sweetpotato whitefly in fields where *C. grandis* was released but were necessary in the IPM-treated control fields (King *et al.*, unpublished data). Often, late-season pests can be tolerated because the majority of the crop is of sufficient maturity that potentially harvestable bolls are no longer vulnerable to insect damage, and feeding or oviposition on other fruiting forms does not affect realized yield.

The role of mechanical cultivation in cotton is primarily for weed control. Yet, as reported earlier, covering infested squares with soil allows the immature boll weevil to escape parasitism. We have hypothesized that weed control in the narrow-row (30 inch), short-season system may be achieved with reduced herbicide and mechanical cultivation. Smart (1993) demonstrated experimentally that more rapid shading of interrow spaces occurs, correlated with increased canopy, in the narrow-row system as opposed to the conventional 40-inch system. So, the narrow-row system potentially may complement parasite release by reducing weed populations and the need for mechanical cultivation.

Early stalk destruction after harvest has long been touted as a means of reducing boll weevil and pink bollworm overwintering populations. Nevertheless, it was not until the 1950s that equipment became available to realistically accomplish timely stalk destruction and plowdown (Chapter 14, this book). Since that time it has become more apparent that early stalk destruction as well as many other pest control measures are most effective when practiced on an areawide basis because of the dispersal capability of these pests (Henneberry *et al.*, 1991).

Based on tests conducted in 1992 (Summy *et al.*, 1993; and Morales *et al.*, 1993), apparently it is possible to virtually eliminate boll weevil reproduction in defined areas by augmentative releases of *Catolaccus grandis.* However, simulations of parasite releases demonstrate that boll weevil ingression into the test area and parasite egression from the test area limits the power of the augmentation approach. Experience with the boll weevil as well as with other dispersing insects has demonstrated that suppressive tactics applied over large areas and to all plants inhabited by the insect (areawide suppression) are more powerful than a field-by-field approach.

PINK BOLLWORM

Importation — Classical biological control efforts against the pink bollworm were initiated in Egypt during the period 1928 to 1935 with the importation of *Bracon kirkpatricki* from Kenya and Sudan (Alfieri, 1929) and *Bracon mellitor* from Hawaii (Kamal, 1935). Both of these parasites failed to become established (Clausen, 1978). The importation of *Bracon lefroyi* (D & C) in 1935 from India resulted in establishment, but no appreciable impact (Kamal, 1951). Initial efforts in the United States during the period 1932 to 1955 included the importation into Texas of the: (a) European corn borer strain of *Exeristes roborator* Fabricius and *Bracon brevicornis* Wesm. from southern Europe; (b) *Bracon kirkpatricki* from Africa; (c) *Bracon mellitor* and *Chelonus blackburni* Cam. from Hawaii; (d) *Bracon nigrorutum* (Cushm.) and *Chelonus pectinophorae* Cushm. from Korea; and (e) *Bracon brevicornis*, *Bracon gelechiae* Ashm., *Chelonus narayani* Rao, *Chelonus heliopae* Gupta and *Cotesia (=Apanteles) angaleti* Mues. from India (Noble and Hunt, 1937; McGough and Noble, 1955, 1957). Several of these parasite species were recovered during the season of release, although none became established (Clausen, 1978). More recently, Legner and Medved (1979) summarized attempts to establish 14 hymenopterous parasite species in the Lower Colorado Valley of California and Arizona. Included were: (a) *Goniozus* sp. from Ethiopia; (b) *Parasierola emigrata* (Rohwer) from Hawaii; (c) *Cotesia angaleti* Muesebeck from India; (d) *Cotesia (=Apanteles) oenone* Nixon from Australia; (e) *Bracon gelechiae* from India; (f) *Bracon kirkpatricki* from Kenya; (g) *Bracon mellitor* from Mississippi; (h) *Chelonus blackburni* from Hawaii; (i) *Chelonus curvimaculatus* Cameron from Africa; (j) two *Chelonus*. spp. from Ethiopia; (k) *Chelonus* sp. from Australia; (l) *Exeristes roborator* from Europe; and (m) *Pristomerus hawaiiensis* Ashmead from Hawaii. Reproduction during the season of release was documented for eight species. None of them became established (Legner and Medved, 1979). The most recent attempts involved the importation into California of *Goniozus aethiops* Evans from Ethiopia (Gordh and Evans, 1976), *Goniozus pakmanus* Gordh from Pakistan (Gordh and Medved, 1986) and *Trichogrammatoidea bactrae* Nagaraja from Australia (Hutchinson *et al.*, 1990). Establishment of the latter species has not been documented.

Conservation — In addition to the exotic parasites, pink bollworm is attacked by a large complex of native predators in the southwestern United States (Telford and

Hopkins, 1957; Wene and Sheets, 1962; van den Bosch and Hagen, 1966). Orphanides *et al.* (1971) suggested that pink bollworm eggs were the stage most vulnerable to predation, and noted that larvae of common green lacewing and adults of *Collops marginellus* LeConte, bigeyed bug, *Notoxus calcaratus* Horn, the common damsel bug, and the minute pirate bug, *Orius tristicolor* (White), may destroy substantial numbers of pink bollworm eggs under laboratory conditions. Irwin *et al.* (1974) quantified predation of pink bollworm eggs, placed under calyxes (bracts) of bolls, during 48-hour intervals, and noted that: (a) 75 percent of such eggs were detected and destroyed by common green lacewing larvae; (b) 45 percent by the western bigeyed bug, *Geocoris pallens* Stål; (c) 25 percent by the minute pirate bug: (d) 16 percent by *Spanogonicus albofasciatus* (Reuter); (e) 1 percent by the common damsel bug; and (f) 0 percent by *Collops marginellus*. Henneberry and Clayton (1985) quantified rates of egg predation by several predator species, and noted the highest consumption rate of 96 eggs per day by adult *Collops vittatus* (Say), followed by 63-67 eggs per day for mixed common green lacewing and convergent lady beetle larvae, 39 eggs per day for adult *Nabis* spp., 14 eggs per day for *Sinea confusa* Caudall, 8 eggs per day for *Geocoris* spp. and 5 eggs per day for the minute pirate bug. Henneberry and Clayton (1985) concluded that several predators commonly found on cotton in Arizona and California have the potential to reduce pink bollworm populations.

Attempts to evaluate the impact of native predators on field infestations of pink bollworm have produced variable results. Bryan *et al.* (1976) documented the occurrence of generally large predator populations on cotton during the production season, but also noted a significant decline in abundance of several species (particularly the common green lacewing, *Collops vittatus*, convergent lady beetle, minute pirate bug, *Noctoxus calcaratus* and ants) during mid-August, a period in which the abundance of various lepidopterous prey was generally increasing. Such trends suggested that predator populations tend to be more dependent upon populations of aphids than lepidopterous prey (Bryan *et al.*, 1976). Irwin *et al.* (1974) suggested that most native predators tend to be relatively ineffective against pink bollworm eggs except at relatively high predator densities. However, Henneberry and Clayton (1985) documented egg predation ranging from 95 percent in July to 35 percent in September. They suggested that native predators may have a significant impact against pink bollworm.

Augmentation — Despite their failure to become established in the United States, many of the exotic parasite species appear to be promising candidates for augmentation. The release of more than two million *Bracon kirkpatricki* and about 280,000 *Chelonus blackburni* into about 113 acres of Arizona cotton resulted in a significant reduction in the need for insecticidal treatment in release sites compared to controls (Bryan *et al.*, 1973a, 1973b). Parasitism by *Bracon kirkpatricki* ranged up to 25 percent, which the authors considered an underestimation, whereas *Chelonus blackburni* appeared to be largely ineffective, which the authors attributed to release of insufficient numbers. More recently, Bryan *et al.* (1976) documented parasitism of about 32 percent by *Bracon kirkpatricki* and about 9 percent by *Chelonus blackburni*, but concluded that such rates were insufficient to control pink bollworm. Inundative release of several parasite species in the Lower Colorado Desert of Arizona and California produced variable levels of pink bollworm control (Legner and Medved, 1979). Most effective was *Chelonus* sp. nr. *curvimaculatus* Cameron, which was credited with an adjusted 69.6 percent infested boll reduction at the equivalent release rate of 1,079 females per acre (Legner and Medved, 1979). Augmentation of exotic parasites appears to be a feasible approach to pink bollworm control, and has been enhanced considerably by the development of artificial diets for pink bollworm (Adkisson *et al.*, 1960; Stewart, 1984) and several parasite species (Bryan *et al.*, 1969, 1971).

Several augmentation strategies designed to enhance the impact of the native predator complex attacking pink bollworm appear to be feasible. The effectiveness of releases of the common green lacewing against bollworm/tobacco budworm on cotton has been clearly demonstrated (Ridgway and Jones, 1969). A second approach involves the generation of field "nurseries" of native predators in crops such as alfalfa and sorghum, which subsequently move into cotton (Stern *et al.*, 1967; Fye, 1971; DeLoach and Peters, 1972; Fye and Carranza, 1972; Robinson *et al.*, 1972). Field studies have generally suggested that native predators tend to be most effective against reduced pink bollworm infestations, which tends to promote a relatively high predator-prey ratio, and have therefore stressed the importance of cultural controls as an adjunct to biological control (Bryan *et al.*, 1976).

PLANT BUGS

Importation — The term plant bugs is commonly used to refer to several pest species in the family Miridae (see Chapter 2, this book, for a listing of species and their biology and ecology). For purposes of this discussion biological control efforts have focused on two species: the western lygus bug, *Lygus hesperus* Knight and the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois). Several efforts to import parasites of *Lygus* from Europe and establish them in North America have been made, but all have failed. The most intense effort involved the rearing and release of the braconid *Peristenus stygicus* Loan (Van Steenwyk and Stern, 1976, 1977). Lesser numbers of *Peristenus digoneutis* Loan and *Peristenus rubricollis* (Thomson) also were released (Hormchan, 1977; Coulson, 1987). A good review of the effort to establish *Lygus* parasites in North America is found in Coulson (1987). In 1985 two braconid parasites, *Leiophron schusteri* Loan and *Peristenus nigricarpus* (Szepligeti), were obtained from mirids in Kenya and successfully reared in the USDA, ARS Stoneville, Mississippi Research Quarantine Facility (Jones *et al.*, 1985) using nymphs of tarnished plant bug and western lygus bug. Releases of small numbers of adults of both species were made in Mississippi in 1987 (Snodgrass, unpublished data).

Conservation — Plant bugs are attacked by predators and parasites on cotton, other crops and on alternate or wild hosts. Numerous references are made in the literature to various arthropods feeding on plant bugs. However, little quantitative data is available on the importance of these predators in controlling plant bug populations. Most studies have been done in the laboratory using species of bigeyed bugs or damsel bugs. These have been studied since they are abundant in cotton and will feed on plant bugs. Crocker and Whitcomb (1980) observed that, under natural conditions, species of bigeyed bugs feed opportunistically on diverse small to minute arthropods and obtain additional nutrition by feeding on insect corpses and several herbaceous angiosperms. One of the small arthropods fed upon are pirate bugs. Pirate bugs are also important predators in cotton, and predation by bigeyed bugs is probably detrimental to total insect control of pests in cotton.

Plant bugs and bigeyed bugs also prey upon each other (Champlain and Butler, 1967; Dunbar and Bacon, 1972; Leigh and Gonzalez, 1976). Tamaki *et al.* (1978) found the large bigeyed bug, *Geocoris bullatus* (Say), to be an effective predator of early instar nymphs. Gupta *et al.* (1980) found that the large bigeyed bug preferred the pea aphid, *Acyrthosiphon pisum* (Harris), over plant bugs and had trouble capturing late instar plant bugs. Leigh and Gonzalez (1976) found western bigeyed bug to be an effective predator of eggs and nymphs of western lygus bug. Predation between western lygus bug and bigeyed bugs is thought to be related to developmental time of nymphs as related to temperature. Champlain and Sholdt (1967) found that the western lygus bug developed faster than bigeyed bugs at the cool temperatures which are found in early spring. The more rapidly developing western lygus bug population could depress bigeyed bugs by predation of the smaller slower developing bigeyed bug nymphs. Cohen (1982) confirmed that the bigeyed bug required higher temperatures than the western lygus bug for optimum development.

Damsel bugs and bigeyed bugs also prey on each other. Atim and Graham (1984) found that *Geocoris punctipes* and the western damsel bug, *Nabis alternatus* Parshley, would feed on each other, and that size was the determining factor as to which species was predator and which was prey. Thus, there is a complex relationship between *Lygus* and its predators in cotton. How these predators interact with *Lygus* and other prey is largely unknown. Assessing the value of predators in control of *Lygus* in cotton will be difficult, especially if the spiders, which are usually one of the bigger groups of predators in cotton, are also considered.

The main nymphal parasites of *Lygus* in North America are the braconids *Peristenus pallipes* (Curtis), *Peristenus pseudopallipes* Loan, and *Leiophron uniformis* (Gahan). *Peristenus pallipes* is found in most areas of the United States but not in the Southwest (Clancy and Pierce, 1966). *Leiophron uniformis* is found from the Southwest to the East coast and Canada, while *Peristenus pseudopallipes* is found mainly in Canada. *Peristenus pallipes* and *Peristenus pseudopallipes* are univoltine while *Leiophron uniformis* produces two to four generations each year (Loan, 1965; Clancy and Pierce, 1966; Lim and Stewart, 1976).

Eggs of *Lygus* are parasitized by the mymarid, *Anaphes iole* Girault. It could be the most important parasite of *Lygus* in the United States, since it is found in most areas of the country and is multivoltine (produces several broods per year) (Clancy and Pierce, 1966; Romney and Cassidy, 1945; Sillings and Broersma, 1974; Scales, 1973; Graham *et al.*, 1986).

Few studies have ever determined the rate of parasitism of *Lygus* in cotton. Graham *et al.* (1986) found that *Anaphes iole* parasitized western lygus bug eggs in cotton in Arizona at rates as high as 36 percent from May through August. They found no parasites from nymphs collected in cotton. Most studies of the parasitism of *Lygus* have been conducted in crops other than cotton—crops which receive few or no insecticide treatments, and in which *Lygus* produces higher populations for a longer period of time. Parasitism of *Lygus* on wild host plants near crops has also been frequently studied. In Canada rates of parasitism of tarnished plant bug by *Peristenus pallipes* and *Peristenus pseudopallipes* range from 8 to 60 percent in alfalfa, forage legumes and weeds (Loan, 1965, 1970, 1980; Lim and Stewart, 1976; Loan and Craig, 1976). Shahjahan and Streams (1973) reported parasitism averaging 20 to 30 percent for tarnished plant bug on weed hosts. Scales (1973) reported parasitism of tarnished plant bug as high as 62 percent in weeds in the mid-delta of Mississippi. Clancy and Pierce (1966) found the pale legume bug, *Lygus elisus* Van Duzee, was parasitized by *Leiophron uniformis* at rates of 25 to 50 percent on goosefoot grass, *Chenopodium* spp. Rates of parasitism are usually higher in areas undisturbed by agricultural practices (Sillings and Broersoma, 1974).

In addition to agricultural practices, other factors can influence rates of parasitism of *Lygus*. One or more species of the weeds commonly called fleabanes in the genus *Erigeron* have been identified in several different geographical areas as being important wild hosts of *Lygus* (Tugwell *et al.*, 1976; Latson *et al.*, 1977; Cleveland, 1982; Anderson and Schuster, 1983; Snodgrass *et al.*, 1984; Fleischer and Gaylor, 1987). Streams *et al.* (1968) found *Peristenus pallipes* parasitized tarnished plant bug nymphs on plants in the genus *Erigeron* while mostly ignoring nymphs on other plant species in a field in Connecticut. They thought that volatile semiochemicals (naturally occurring behavior modifying chemicals) from *Erigeron* attracted the parasite, and this was confirmed by Shahjahan (1970).

In most areas of the United States where cotton is grown, rates of parasitism of *Lygus* have not been studied. It is not known how much control they presently exert on *Lygus* populations, or what their potential is for control if agricultural practices such as insecticide use are modified to favor them. Consequently, designing strategies for *Lygus* control in cotton that better utilizes *Lygus* parasites is difficult. The information that is available suggests that additional parasites are needed. Where studied in the Southeast, the main nymphal parasite of the tarnished plant bug is *Peristenus pallipes* (Scales, 1973; Hormchan, 1977). This parasite is univoltine (produces one brood per year) and is not present to parasitize the tarnished plant bug during several of its generations on wild or alternate hosts during the year. A multivoltine parasite that could overwinter in the Southwest could have a major impact on western lygus bug populations. The multivoltine egg parasite *Anaphes iole* is present in the Southeast (Scales, 1973); however, very little is known about its impact on tarnished plant bug populations in this area.

Augmentation — The development of an artificial diet for western lygus bugs (Debolt, 1982) has made production of large numbers of nymphs and eggs possible.

This greatly increases possibilities for biological control of western lygus bugs since large numbers of nymphal or egg parasites also might be reared in the laboratory for release in the field. The potential for using inundative releases of parasites to control *Lygus* is discussed in Debolt (1987) and holds promise for *Lygus* control in the future.

Too little is known about the biology and behavior of *Lygus* predators and parasites to estimate their effects on *Lygus* populations. More information is needed on the control they exert on *Lygus* on wild or alternate hosts as well as on cotton. In many areas where cotton is grown, the parasites present have not been determined. The presence of *Lygus* on wild or alternate host plants throughout the year presents good opportunities to control this pest prior to its movement into cotton by reducing the size of the overwintering generation or reducing the size of the first and/or second generation produced in the spring. This could be done by a variety of methods. Some methods, such as the use of insecticides or herbicides, could also harm parasite and predator populations. Better information on the value of *Lygus* parasites and predators is needed in order to make the proper control decisions, and make better use of the amount of control provided by these beneficial arthropods.

BIOLOGICAL CONTROL WITH MICROBIALS

The use of insect pathogens for biological control of insect pests is generally accepted as a safe and efficacious method. Except in some recent cases where genetically altered microorganisms have been opposed (Ferguson, 1988), insect pathogens have not provoked the adverse reactions from the general public as have chemical insecticides. The microbials that are under serious study for use in insect pest management systems are usually known to be environmentally safe and to have almost no adverse effect on the crop or on non-target species. Except for the genetically altered microorganisms, insect pathogens are naturally occurring in the insect populations. In that sense, they may already exist and interact in the crop ecosystems as limiting factors of some populations. When pathogens are applied as a management component, the attempt is to exploit the specific disease processes of the individual pathogens in order to maximize their effectiveness in the biological control of insect pests. The following discussion summarizes: (a) the microbial agents available either for research or for on-farm use; (b) reports of efficacy of microbials in the management or control of cotton insect pests; and (c) some various tactics being studied to increase their effectiveness. A more in-depth review of the pathogens found in cotton insects and mites and their effects on populations, regardless of their commercial amenability, is presented by Harper and Carner (see Chapter 5, this book).

The insect pathogens studied for possible use in the management of cotton pests include representatives of the viruses, bacteria, fungi, protozoa and nematodes. The ecology of the pest species and the traits of the pathogen often indicate innate factors that determine which pathogen has the best chance of success in individual management systems. One important consideration is usually the feeding habit of the target pest. Although some pathogens may be transmitted in or on the egg (Hamm and

Young, 1974), most viruses, bacteria and protozoa are transmitted by the insect ingesting the pathogen along with its food. Therefore an insect larva such as the cabbage looper feeding on leaves, is more likely to consume and thus become infected by those pathogens than a pink bollworm larvae, feeding inside the squares or bolls. Since the immature stages of the boll weevil develop entirely within the cotton fruit, it is even more protected from pathogens which must be consumed. An analogy may be drawn comparing the bacteria, viruses and protozoa to the stomach poison-type chemical insecticides and the fungi and nematodes to contact-type insecticides. The entomopathogenic fungi and insect nematodes, which may invade the host without being ingested, often have other traits which make them less attractive as microbial agents for use in exposed areas such as on cotton foliage because they are often very sensitive to variation in microhabitat. Even after the target insect population is infected with the pathogen, crop protection still depends upon the disease processes of the particular microbial organisms.

Of the microbials, the viruses and bacteria currently are considered to have the greatest potential for commercial development and use as biological control agents. More than 1000 virus-host relationships in over 700 species of insects and mites (about 370 baculoviruses) have been reported (David, 1975; Martignoni and Iwai, 1981) and this is considered by some to be just a small fraction of the actual numbers present (Kurstak and Tijssen, 1982). Although many of the reported viruses have been found to affect pests of agricultural importance, few have offered control potential to date. Of those viruses, the baculoviruses (nuclear polyhedrosis viruses and granulosis viruses) have the most desirable properties. These properties include their safety, relative stability and virulence. They are considered among the safer pathogens for study since they are uniquely associated with invertebrates, and usually have a limited host range. They also have a potential infectivity such that the LD_{50} may be as low as a single polyhedron per bollworm/tobacco budworm larva (Burges, 1981). The negative aspects of their use as biological control agents in cotton include their relatively long incubation period, problems related to the target insect ingesting the virus, and deactivation of the virus by environmental factors (Bullock, 1967; Ignoffo *et al.*, 1972; Yearian and Young, 1974; Young and Yearian, 1974; Jacques, 1977; Bell, 1983). Since viruses must be produced in live tissue, industry generally views their production as somewhat difficult, however several efficacious production procedures are known (Ignoffo, 1966; Shapiro, 1982; Sheih and Bohmfalk, 1980). Research has shown that many of these problems can be overcome. Ingestion of the virus by the target insect may be increased by improved application and formulation techniques that place more of the pathogen in the target area (Smith *et al.*, 1977, 1978; Smith and Bouse, 1981), or by the use of formulations containing feeding stimulants that increase feeding on the pathogen (Bell and Kanavel, 1975, 1977, 1978; Luttrell *et al.*, 1982, 1983). Problems with environmental deactivation of the virus may be overcome by the use of protectants which increase field persistence of the virus (Bull, 1978; Ignoffo and Batzer, 1971; Smith and Hostetter, 1982). Despite their good traits, only the baculovirus from the bollworm is registered for use on cotton in the United States, and none are in present commercial production. Sandoz, Inc. mass produced the bollworm/tobacco budworm virus from 1976 until about 1982 under the trade name Elcar®. Bohmfalk (1982) discussed some possible explanations for its lack of acceptance. Primarily, application of the virus did not result in a rapid kill desired by the growers. The problems associated with the relatively long period between ingestion of the virus and the expression of the disease symptoms (incubation period) have yet to be overcome and are due to the pathological characteristics innate to the disease. Basically, the virus may appear within the nuclei of certain tissues of the insect host within 24 hours after ingestion, but external appearance and behavior may not be noticeably changed during the incubation period. After the symptoms are noticed, the larvae usually die within about three days.

Of the bacterial candidates for biological control of cotton insects, by far the most promising are strains of *Bacillus thuringiensis* Berliner (B.t.). Research uses and commercial sales of B.t.-based products have been steadily expanding. This bacterium persists worldwide and natural variation is widely observed. Many varieties, or serovars, have been recognized in the hundreds of isolates (Martin and Dean, 1981; Luthy *et al.*, 1982; DeLucca *et al.*, 1981), and their pathogenicity to various insects differs widely from very active to none (Dulmage, 1981). As a biological control agent in cotton, B.t., unlike the baculovirus, can be used to rapidly affect caterpillar pest populations and reduce crop injury. Again, this is due to the specific pathological characteristics of the microbial. When B.t. and its associated toxins are ingested, the gut cells of larvae of susceptible species are affected in such a way as to immediately inhibit feeding (Faust and Bulla, 1982). The bacteria themselves, unlike the viruses, may be inefficient as infective agents, but produce effective toxins that serve as narrow-spectrum toxins of many crop insect pests (Kurstak and Tijssen, 1982). These include a thermolabile (changes with heat) toxin (δ-endotoxin) contained within a crystal produced within the cell, and a thermostable toxin (*a*-exotoxin). Strains producing the exotoxin are not presently registered for use in the United States. As with the viruses, the effectiveness of this microbial depends largely on feeding activity of the target pest which results in ingestion of the microbial. Also, the activity of the B.t. is adversely affected by the environment and repeated applications at two- to three-day intervals may be necessary for control (Beegle *et al.*, 1981). Probably one of the main advantages of bacteria in comparison to the viruses as control agents is that they may be mass produced by fermentation procedures. Consequently, they are easier to produce and less expensive.

Several cotton insect pest species are killed by fungi, either individually or in epizootics (outbreaks involving several species). The reason cited for the lack of widespread use of fungal agents is that there are too many variable conditions which make their application unreliable and which would require the proper conditions for every combination of fungus and pest insect (Weiser, 1982). Of the fungi tested as biological control agents, only deuteromycete fungi have been produced in somewhat large scale (e.g., species of *Beauveria, Metarrhizium, Nomuraea, Verticillium, Hirsutella*). Some of these have been field tested against cotton pests (Ferron, 1978, 1981; Ignoffo, 1981). Although several of these fungi have potential as biological agents of cotton pests, especially in the areas of cotton with normally high humidity, only two fungi are being seriously researched as possible control measures for the sweetpotato whitefly in cotton.

There are numerous reports of nematode parasitism in insect populations, but most are from observations made in host plants other than cotton. Members of the Steinernematidae and Heterorhabditidae families have a mutualistic association with specific bacteria that can rapidly kill insect hosts, thus there has been much interest in their use as biological control agents (Woodring and Kaya, 1988).

Many species of insects, including several cotton pests, are known to be hosts of protozoans. However, few protozoan pathogens of insects have been field tested as biological control agents, perhaps because the incubation period is so long that crop damage usually is not controlled. They tend to cause slow, debilitative symptoms that do not lead to the rapid mortality needed in most crop protection systems, including cotton. Since the protozoans usually produce chronic rather than acute diseases, they are considered as being more useful as long-term control agents for the suppression of insect populations.

TOBACCO BUDWORM AND COTTON BOLLWORM

There are presently two registered pathogens for use in the management of tobacco budworms and bollworms, the bollworm nuclear polyhedrosis virus and the δ-endotoxin of *Bacillus thuringiensis* (B.t.). Of these, only B.t. is in commercial production at present. The last commercial production of bollworm nuclear polyhedrosis virus was registered and sold as Elcar® for use against bollworm/tobacco budworm in cotton by Sandoz, Inc. Sandoz ceased production by 1982, due primarily to competition from the new pyrethroid insecticides. Although B.t. is registered for use against bollworm/tobacco budworm in cotton, relatively little is used for control of population outbreaks.

Field studies have shown that applications of B.t. at dosages of 3.6-7.3 X 10^9 International Units (IU) of potency per 0.16 acre will suppress a bollworm/tobacco budworm larval population and result in increased cotton yield over an untreated check (Bell and Romine, 1980; Pfrimmer *et al.*, 1971; Pfrimmer, 1979). However, the degree of control generally was less than that obtained using effective chemical insecticides. The control obtained with B.t. has been more consistent than that with the bollworm/tobacco budworm nuclear polyhedrosis virus, primarily due to the respective characteristics of the pathogens after ingestion by the larval host as previously described. Whereas the virus is slow acting and the larva continues to feed, the ingestion of B.t. acts to immediately reduce feeding. Larvae are known to grow at a slower rate after feeding on B.t., but they tend to recover, continue their feeding and emerge as adults after a period of time (Dulmage *et al.*, 1978; Bell and Romine, 1986). Although control comparable to that obtained with chemical insecticides was reported using B.t., the quantity of formulation necessary was too great for such applications to be economically feasible (McGarr *et al.*, 1970). The level of control of bollworm/tobacco budworm on cotton produced by multiple applications of the bollworm/tobacco budworm nuclear polyhedrosis virus has been erratic. In some tests, the control was shown comparable to that obtained with chemical insecticides (Ignoffo *et al.*, 1965; Allen *et al.*, 1967a, 1967b; Andrews *et al.*, 1975), whereas others showed a 10 to 40 percent yield increase compared to check plots (Shieh and Bohmfalk, 1980), or marginal to no control when used alone in field tests (McGarr, 1968; Pfrimmer, 1979). Burges (1981) discussed the use of the nuclear polyhedrosis virus in 150 to 200 field trials for control of bollworm/tobacco budworm in cotton as well as other field crops. Control of "light" to "moderate" infestations with the virus was reported as comparable to a chemical standard, but at higher infestations, control by the virus was inferior.

Other nuclear polyhedrosis viruses isolated from bollworm/tobacco budworm and other species have been reported to be efficacious for control of bollworm/tobacco budworm on cotton. Although it has a very diminished effect on bollworms, the nuclear polyhedrosis virus from the alfalfa looper, *Autographa californica* (Speyer), was shown to be very virulent against the tobacco budworm and other cotton pests (Vail and Jay, 1973; Vail *et al.*, 1970). The nuclear polyhedrosis virus isolated from *Helicoverpa armigera* was field tested and demonstrated control in one of two years tested (Roome, 1975). Several of these nuclear polyhedrosis viruses are also known to exhibit broader host ranges than the isolate registered for use.

Several attempts have been made to increase the effectiveness of the nuclear polyhedrosis virus and B.t. against bollworm/tobacco budworm in cotton. These include the development of formulations to protect the microbial from deactivation by sunlight and to increase ingestion through feeding stimulants (Bull *et al.*, 1976; Ignoffo *et al.*, 1976; Patti and Carner, 1974; Bell and Kanavel, 1978). In most instances, the addition of these materials to nuclear polyhedrosis virus or B.t. sprays increased the effectiveness of the microbial. Two feeding-type spray adjuvants were marketed for commercial use with nuclear polyhedrosis viruses and B.t.; Gustol® was developed and manufactured by Sandoz, Inc. and COAX®, manufactured by Traders Oil Mill Co. Both were shown to increase feeding by bollworm/tobacco budworm larvae and to increase the persistence of nuclear polyhedrosis virus on cotton (Bell and Kanavel, 1978; Smith and Hostetter, 1982). In most reported studies, the addition of these adjuvants generally increased the effectiveness of the microbials (Bell, 1983). In one field test, treatment with a mixture of B.t. with the nuclear polyhedrosis virus from the alfalfa looper and COAX® resulted in less than 10 percent square damage compared to up to 60 percent damage in untreated cotton and an increase in yield from 292 pounds per acre seed cotton to 1,270 pounds per acre (Bell and Romine, 1980).

Another area of research to increase efficacy has been in the study of application methods. Yearian and Young (1982) reviewed some of the aspects associated with the formulation and application methodology as it applied to efficacy of nuclear polyhedrosis virus. In general, although the viruses and bacteria may be applied utilizing equipment designed for chemical insecticides, it was shown that some droplet sizes and density were more desirable than others (Smith *et al.*, 1977). Since the activity of these pathogens depends upon ingestion, methods of application that result in more thorough coverage may increase effectiveness (Falcon, 1978).

Finally, one of the more promising new technologies with exciting possibilities for use in microbial control, including cotton insect pests, is through genetic manipulation (or genetic engineering) of known pathogens. The aspect of these altered microbials led to the beginning of several companies based on the ideas that these new pathogens can compete with chemical insecticides. Research to date by these companies has been focused mostly on the development of new products based on B.t. As more information is developed, these studies might lead to varieties of increased stability, host range and potency, and thus to increased effectiveness of microbials (Martin and Dean, 1981; Geiser, 1986). Several constructs of the B.t. gene have been inserted into advanced cotton strains and commercial varieties are now available (see Chapter 17)..

BOLL WEEVIL

Pathogens infecting boll weevils include: the sporozoans *Mattesia grandis* McLaughlin and *Glugea gasti* McLaughlin; the bacterium *Serratia marcescens* Bizio; the fungi *Mettarrhizium anisopliae* (Metschnikoff) Sorokin, *Nomuraea rileyi* (Farlow) Sampson and *Beauveria bassiana* (Balsamo); and, the nonoccluded *Chilo* iridescent virus (McLaughlin, 1965, 1969; McLaughlin *et al.*, 1972; Bell, 1983; Wright and Chandler, 1991). None are registered for use at this time. Although several entomopathogenic fungi are known, and field testing was conducted with protozoan pathogens, none resulted in levels of economic control that encouraged commercial possibilities (McLaughlin, 1962; McLaughlin *et al.*, 1969). While boll weevils were shown to be susceptible to a nonoccluded (not enclosed) *Chilo* iridescent virus (McLaughlin *et al.*, 1972), none of the viruses isolated to date have shown promise for use as field control agents of that pest. There is hope for future microbial insecticides of the boll weevil through the ever-increasing varieties of *Bacillus thuringiensis.* A variety (MYX 1806) is presently being produced by Mycogen Corporation, under an Emergency Use Permit. It has activity against another coleopterans (beetles). A variety having activity against adult weevils would be needed to be useful as a control agent due to their feeding habits.

PINK BOLLWORM

Although pink bollworms are susceptible to *Bacillus thuringiensis* and some measure of control has been shown (Bullock and Dulmage, 1969), the level of control has not been reproducible and no microbials are recommended for control of pink bollworm. The nuclear polyhedrosis virus isolated from the alfalfa looper infects pink bollworms as well as several other lepidopteran pests of cotton (Vail *et al.*, 1972) and was field tested for possible control applications. In field tests, only about one percent of the larval population was infected, presumably because the larvae did not ingest the virus. Although the use of a feeding stimulant formulation significantly increased the incidence of infection (Bell and Kanavel, 1975, 1977), the degree of control was not deemed practical because of the quantity and cost of materials. The results did, however, indicate that an early-season application of the formulation might be useful as a population suppression method.

The entomopathogenic nematode, *Steinernema riobravis* Poinar, Cabanillas, and Raulston, is a highly virulent and heat tolerant species that was discovered attacking bollworm pre-pupae and pupae in corn fields in the Lower Rio Grande Valley of Texas (Cabanillas *et al.,* 1994). Methods have been developed for small scale field testing and efficacy monitoring (Lindegren et al., 1994). They showed that when applied as a water suspension to soil in cotton fields, nematode rates as low as 10 infective juveniles per cm^2 resulted in greater than 90 percent parasitism of pink bollworm larvae. *Steinernema riobravis* may have a potential role for managing cotton insect pests (bollworm/tobacco budworm, pink bollworm, boll weevil and others) that spend a portion of their life cycle in or at the soil surface. This species and others are commercially available, EPA exempt, and can be delivered with conventional ground, air, or irrigation systems.

Other pathogens infect the pink bollworm and can be considered potential control agents. For example, a cytoplasmic polyhedrosis virus found in a laboratory culture (Ignoffo and Adams, 1966) produces chronic and debilitative effects on the insect. At present, the pathogen is not considered a promising candidate due to the quantity of virus required and problems associated with production (Bell and Henneberry, 1980).

OTHER COTTON INSECTS

The nuclear polyhedrosis viruses of the cabbage looper and the beet armyworm occur naturally in larval populations and are important in the regulation of their respective hosts. Further, varieties of B.t. are commercially available for their control when needed. Since the feeding behavior of these two species favors ingestion of the applied microbials, they are more easily controlled by the virus and bacterial pathogens compared to the more specific feeders. Both species are also susceptible to a broad range of known pathogens including the nuclear polyhedrosis virus from the alfalfa looper (Vail and Jay, 1973).

The cotton leafperforator, *Buccalatrix thurberiella* Busck, is considered a sporadic pest of cotton in the western United States. Vail *et al.* (1977) obtained partial control with multiple applications of the alfalfa looper nuclear polyhedrosis virus, and multiple applications of the HD-1 variant of B.t. at normal recommended rates resulted in an acceptable level of control (Bell and Romine, 1982). Although such microbial control methods probably would not be used against this pest, treatments directed against other pest insects could reduce the populations of this pest as well.

Many efforts are being made to increase the effectiveness and the uses of microbials in cotton insect control and management programs. The use of microbials remains very appealing from an environmental safety standpoint. However, either for operational or economic reasons, their use at present and in the near future appears limited. The development of more virulent strains of B.t. over a broad host range of pest species should aid in increased utilization of products based on that bacterium. The development of other pathogens as commercial products for cotton insect control may depend upon identifying specific areas for their use, or increased public involvement in environmental concerns.

SUMMARY

In 1994, administrators of the United States' Environmental Protection Agency, Food and Drug Administration, and the Department of Agriculture presented joint testimony stating their intent to focus efforts on "...reducing overall risks from the use of pesticides through integrated pest management programs (IPM) which lead to more sustainable agricultural production strategies and reductions in the use of pesticides." Reducing "pesticide risks" can be most expeditiously achieved by changing from chemically-intensive pest management to systems emphasizing biologically-based or other nonchemical-control strategies.

Over the last three to four decades cotton insect and mite pest management has evolved from the use of long-residual, broad-spectrum organochlorine insecticides and miticides, applied at predetermined intervals based on a pre-specified time interval, calendar date, or plant growth stage, to IPM systems that prescribe chemical treatments when damaging populations of the insects and mites are present—based on scouting. Importantly, the use of pest presence or damage thresholds as criteria for chemical treatment in lieu of other pre-determined criteria often spares predators and parasites and reduces the overall amount of chemical insecticides and miticides used. The development and use of computer-based decision-making technology that makes explicit (qualitatively and quantitatively) use of natural enemy populations is growing, and promises to further reduce "pesticide risks."

On the other hand, the United States' most intractable cotton insect pests are lacking in effective natural enemies; two of these pests are exotic, viz., the boll weevil and pink bollworm. And, attempts to introduce natural enemies that co-evolved with them in their site of origin have been unsuccessful—leading to the prevalent belief that these pests cannot be biologically controlled. Also, plant bugs often function as key pests by causing early-season insecticide treatments for their control. Plant bugs are effectively attacked by numerous predators and parasites in wild host habitats but not in cotton fields. Chemical treatments for these key pests often induces the occurrence of other pests, such as whiteflies, aphids, bollworms, tobacco budworms, loopers, and armyworms, by killing their natural enemies.

The technical feasibility of augmenting natural enemies through mass propagation and strategically timed releases or applications is being practiced on a limited commercial basis in the United States. Pathogens, particularly a nuclear polyhedrosis virus for control of bollworms and tobacco budworms, and the delta-endotoxin from the bacterium, *Bacillus thuringiensis*, have been marketed in the United States on a limited basis. The egg parasite, *Trichogramma* spp., and lacewings, *Chrysoperla* spp., are also occasionally sold to cotton producers, but the high cost for producing and releasing them in numbers and times required to be effective, is prohibitive.

The ectoparasite, *Catolaccus grandis*, effectively suppressed boll weevil populations in cotton fields. The parasite is easily reared on artificial diet-reared boll weevil third instars, but this approach probably is not economically feasible except in extenuating circumstances, e.g., elimination of the boll weevil from environmentally-sensitive areas as part of the boll weevil eradication programs. However, preliminary results indicate that the parasite can be reared on artificial diet and perform in the field as well as weevil-reared parasites. Development of this mass propagation technology has potential for opening the path toward operational and economic feasibility of the augmentation approach for areawide suppression of the boll weevil. Release of the parasite during early season in previously eradicated areas that have been reinvaded by boll weevils may be a cost-effective and environmentally-rational approach for eliminating rare individuals while they are still in the immature stage.

Development of biologically-based IPM systems in cotton maximizes the value of predators and parasites. Often, these natural enemies maintain pest populations at subeconomically important levels. Management guidelines should make explicit use of natural enemy populations in making control decisions. Regardless, seasonally-disrupted system such as cotton production can be expected to intrinsically limit natural enemy numbers, diversity, and effectiveness. Consequently, natural enemies often appear too few and too late. Moreover, exotic pests such as the pink bollworm, the boll weevil, and sweetpotato whitefly often are lacking in co-evolved, selective natural enemies. Failure to establish co-evolved natural enemies from the pest site of origin does not preclude the mass propagation and seasonal introduction and augmentation of these natural enemies. Biological control of early-season pests and the avoidance of chemical insecticides and miticides spares naturally occurring and augmented beneficial organisms thereby opening the path to reducing "pesticide risks", increasing production profitability and achieving sustainability.