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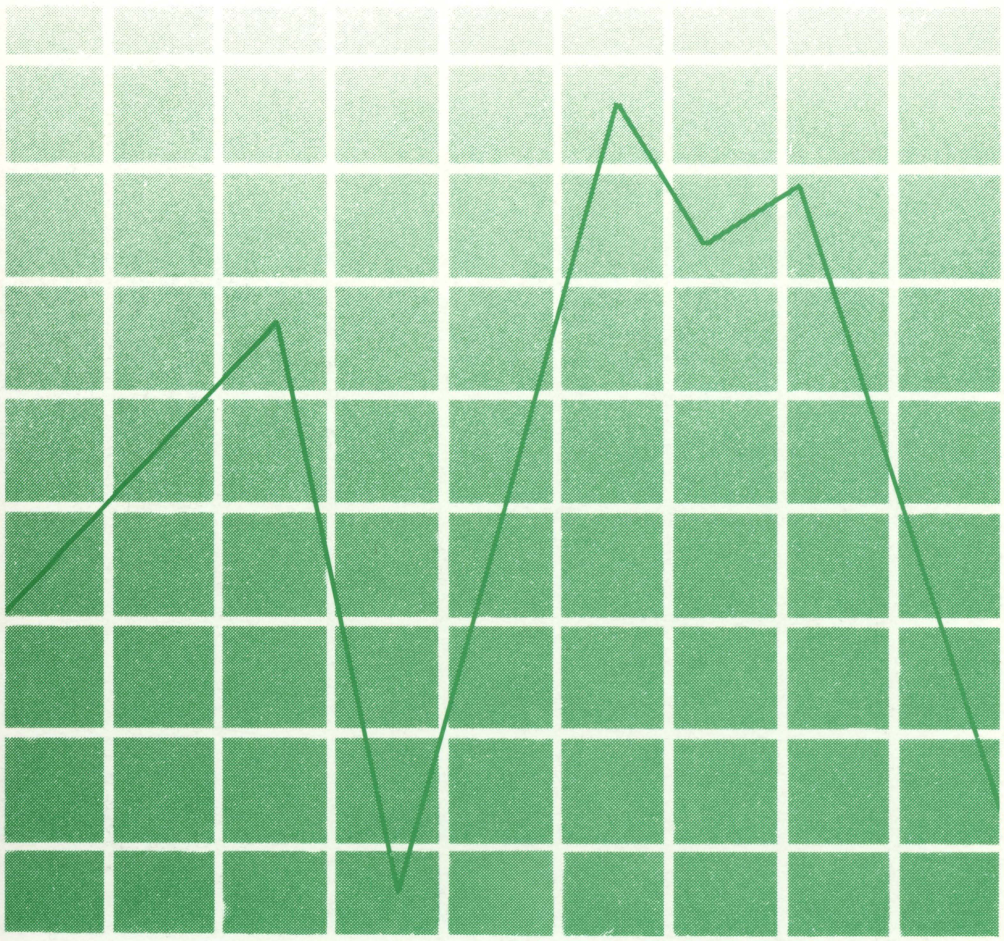
Action & Inaction Levels in Pest Management



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Action and Inaction Levels in Pest Management

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Introduction

The usefulness of a pest control concept can be evaluated by its effectiveness in solving actual problems (13). In this regard, the economic threshold concept (137, 138) has been extremely useful. Contemporary pest management systems that have been developed for insect pests of cotton and other crops, usually use the economic threshold concept or some modification of it in the decision-making process. However, the economic threshold concept is not without some conceptual and practical limitations. For example, the concept as currently conceived and applied in pest management situations is used to make decisions that call for emergency actions, primarily the use of insecticides. It is seldom used in conjunction with biological, cultural, or any other management tactics that are essentially curative. Additional difficulties are encountered in attempting to use the term "economic threshold" to indicate the densities of natural enemies needed to maintain pests below intolerable loss levels. One solution to this problem would be to use the term "action level" as a replacement for the term "economic threshold" and the term "inaction level" for the critical natural enemy densities (134). These terms are more fitting because economic and ecological factors are both important in pest management decisions. Also, the word "threshold" implies that the pest population density is projected to increase to an intolerable loss level when in actuality it may decrease. Thus a decision to take action at the threshold level may be in error and the concepts of "action and inaction levels" avoid some of these problems.

Many factors involved in the establishment of the action levels have been reviewed in other reports (37, 134, 137, 120). In this paper those factors that are believed to be of importance in calculating the most effective action levels are reviewed. Although the discussion is limited to decision-making in the management of arthropod pests of cotton, many of the same concepts should apply to other pests such as weeds, plant diseases, nematodes, and arthropod pests of other commodities.

Systems Analysis in Decision-Making

Systems analysis and computer models can improve pest management systems and can unify and guide research (18). "Consider the ecosystem" is the first principle of pest control, around which all other principles revolve (84). The key to the term 'agroecosystem' is the component *eco* (also found in ecology, economics, and ecumenical) which is derived from the Greek oikos, meaning house or household (161). In current usage, *eco* implies the wisdom and authority to manage, that is, decision-making and decision-following in the best interest of the household. In 'agroecosystem' the idea of orderly household is expanded to include the managed environment (161). Ecosystems are self-sufficient habitats where living organisms and the nonliving environment interact to exchange energy and matter in a continuing cycle (84).

The cotton ecosystem is a complex ecological unit. The cotton field is part of an ecological system that includes associated crop systems, pastures, woods, streams, and more. The major components of the cotton field include the plants, the soil and its biota, the physical and chemical environment, pest species with their natural mortality factors including disease and native enemies, arthropod competitors for food and space, and overall conditioning of man including his management of the system (20).

However, the cotton agroecosystem (compared to other natural systems) is a simplified ecosystem frequently interrupted and prevented from undergoing natural succession that would lead toward the climax state. It is often a high-technology, capital-intensive agricultural production system. In developed countries the cotton agroecosystem often requires a continuing energy input of fertilizer, herbicide, fungicide, defoliant, insecticide, and fuel for farm machinery (7).

Many of the components of any agroecosystem are interdependent, so that management decisions affecting one component have side effects that may have a detrimental relationship with other components. An improved understanding of these side effects should be very useful in developing more rational pest management tactics and decision-making techniques for the future. The warning that "we can never do merely one thing" in ecological systems (43) might well be remembered when we attempt unilateral tactics against a single pest.

A dioristic model of the cotton agroecosystem can be used as a guide for future modeling efforts (7). The master model can be divided into plant growth, pest management, grower management, and technological and harvest-gin modules, each containing a series of submodules needed to calculate the desired results of the model. Inputs detailing energy and environmental parameters and periodic updates of information on plant, arthropod, and economic dynamics should produce information of value to the decision-making process.

In this bulletin, it is not possible to discuss all the components of future pest management and decision-making models. However, a synopsis of the relationship of particular components to this concept of decision models is attempted.

Ecological Disasters

The need for improved pest management decisions is most obvious where poor decisions have resulted in total economic and environmental disasters. A recurrent pattern of cotton production throughout the world has been classified into six phases (20,119) as follows: (a) the subsistence phase, which uses minimal technology; (b) the exploitation phase in which the use of irrigation, fertilizers, insecticides, and high-yield varieties is begun; (c) the crisis phase in which the elements of the exploitation phase are used more intensely; (d) the disaster phase in which pests develop resistance to insecticides and the cotton industry may collapse; (e) the integrated control phase in which there is a de-emphasis on chemical insecticides and a search for optimal management tactics, if the industry survived the disaster phase; and (f) the deterioration phase during which integrated control is abandoned in favor of short-term economic advantages that then lead back to the disaster phase.

Major insecticide-related disasters in cotton have occurred in a number of areas including Mexico, the Rio Grande Valley of Texas, the Imperial Valley of California, the Cañete Valley of Peru, Central America, and the Ord River of Western Australia (145). The mechanisms of incipient disaster have been clearly detailed for the Ord River area (Figure 1) (50, 162, 163). As farmers strived for higher and higher yields and profits by increasingly greater inputs of irrigation, fertilizers, and insecticides, the trends up to 1970 suggested few limits to yield and profit potential. However, by 1972 the American cotton bollworm, *Heliothis armigera* (Huebner), developed resistance to DDT, toxaphene, and methyl parathion. Up to 125 kg of insecticide per hectare failed to control the pest. Thus, in only 10 years, since the start of large-scale commercial cotton production in the Ord, a total disaster resulted, largely due to the inability to control the American cotton bollworm with insecticides. Since no cotton is now being produced in the Ord, it is an example of an ecosystem that reached the disaster phase but has yet to evolve into the integrated control phase.

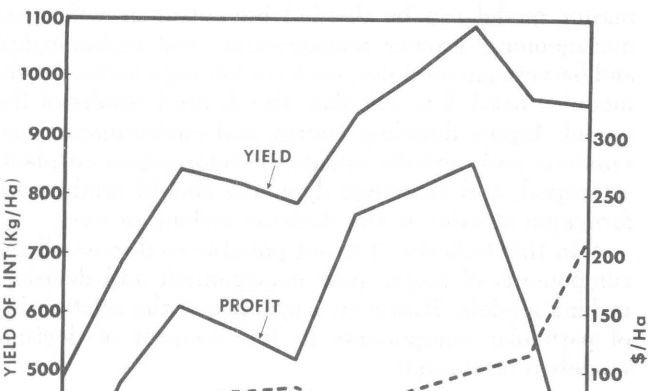

Figure 1. History of cotton production in the Ord River of Western Australia.

Van den Bosch (145) paints a rather bleak picture of the cotton agroecosystem as he contends that "cotton today is one of the world's most 'bugged' crops, victimized by an ecological backlash to heavy insecticide drenching. The sad state of the cotton ecosystem stands out as an example of the worst in pest control. The heavy use of pesticides has created an entomological nightmare, bringing in its wake economic ruin, human illness and death, and gross environmental pollution" (145).

He adds (144) "virtually no ecological consideration has gone into the development and use of modern insecticides. In some places disregard for insect ecology has resulted in a zooicidal overload which not only kills target pests but also decimates populations of arthropod species including natural enemies of the pest species. Elimination of these natural enemies creates a biotic vacuum that promotes the resurgence of the target pest and the eruption of previously innocuous species."

Although broad spectrum, chemical insecticides have repeatedly been implicated in these agroecosystem disasters, they are not exclusively at fault. Many other elements of the technologically intense cotton production system have contributed to these disasters. A few of these contributing elements may include monoculture production systems and excessive use of fertilizers, irrigation, herbicides, fungicides, and potentially high-yielding crop varieties.

Action Levels

The mere sight of a boll weevil, *Anthonomus grandis* Boheman, a cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter), or bollworm *Heliothis zea* (Boddie), may automatically trigger decisive action on the part of some growers and other decision makers. The decisive action is often the massive use of insecticides, whether needed or not (144). The economic threshold, as envisioned in the classical paper of Stern et al (138), was developed as a partial solution to the problem of unwarranted use of chemical insecticides. Figure 2 depicts the elements of the system as modified for *Heliothis* species. The relationship between the general equilibrium position (GEP), the action level (AL), and the intolerable loss level (ILL) is evident over the ten year period. The ILL should be based on population models predicting that pests at the AL will reach the ILL and not on the assumption that pest populations always increase in abundance. Resurgence of *Heliothis* spp. after insecticide application results in a modified average density (MAD) that may increase, depending largely on intensity of insecticide use. With the termination of insecticide use, the pest density may return to the GEP. Note that in the absence of insecticides the density of *Heliothis* spp. fluctuates about the GEP and only occasionally reaches the ILL. However, once insecticides are used, the ILL is reached more frequently.

The GEP was defined (138) as "the average density of a population over a period of time (usually lengthy) in the absence of permanent environmental change." The economic-injury level was defined as "the lowest popula-

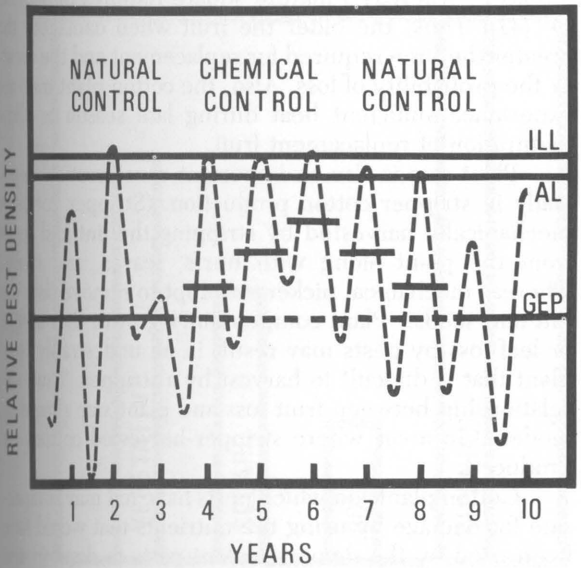

Figure 2. *Schematic of change in the modified average density of* Heliothis *species due to the use of insecticides: (MAD = modified average density; ILL = intolerable loss level; GEP = general equilibrium position; AL = action level) Modified from Stern et al. (138).*

tion density that will cause economic damage" and the economic threshold as "the density at which control measures should be taken to prevent an increasing pest population from reaching the economic-injury level." Many other definitions of the economic threshold have been advanced (35, 37, 45, 46, 84) that somewhat modify the definition of Stern et al (138). Most of these definitions pay major attention to economics, and relatively little attention to ecological consideration. Thus, the terms "economic threshold" and "economic injury level" may be replaced by the more inclusive terms "action level" and "intolerable loss level," respectively. Also, little attention has been paid to the economics of action tactics other than insecticides.

The action threshold is another related concept defined (84) as "the level of pest population at which action must be taken to prevent the population from rising to the economic threshold where significant damage occurs."

Also, the visual threshold was defined (84) as "the population level at which individuals of the pest species are obvious." Since it is difficult to place a definitive monetary value on the aesthetics of ornamental plants, the aesthetic injury level concept was introduced (93).

Economic thresholds have been divided into pragmatic types, based on experience and field observations that produce the desired results and, definitive types, based on carefully planned and executed experiments (134). Thus, there has been a proliferation of terms that tend toward confusion. To avoid much of the confusion, the term "action level" is suggested and is defined as the number of pests and/or injury level at which supplementary action tactics will optimize profits and minimize detrimental side effects. Ideally, action tactics used will not eliminate natural enemies, which will provide supplementary pest suppression in addition to that provided by the actions taken.

Methods used to establish economic thresholds have been summarized (68, 104, 136), as have assessments of plant damage and potential crop loss (60, 118). The empirical evidence, i.e. replicated observations and the experience of specialists, can be used to establish a provisional economic threshold (137). This same evidence can be used in the calculation of provisional action levels; these can be tied to a sampling method such as sequential sampling and can be evaluated in practical pest management programs (129, 135). Improvement in profits, yields, environmental stability, reduced risks, less pollution, and conserved energy will indicate the value of the provisional action levels. When necessary, these action levels can be modified by a definitive empirical approach. The adjustment of economic thresholds should be a continuing endeavor (35).

The Cotton Crop as an Example

The focus of any crop protection program must be the crop, and thus a crop growth and developmental model should be the central feature of any systems approach to crop protection (115). Cotton crop models have been developed (10, 38); SIMCOT II, a single plant model (81) was modified to make it more useful in pest management modeling efforts (38).

Action or Action Level Models

Improved cotton crop models can be employed in predicting action levels (i.e. action level models) and in determining the need to take action (i.e. action models). In the evolution of these models, it would intuitively appear that "action level" models will precede "action" models, since action level models can be verified by field decision sampling and can be of value in operational pest management programs as the models are improved. Our ultimate objective should be to develop "action" models where pest management decisions are made without the need for field decision sampling to verify computer model predictions. The requirement for precision and reliability in "action" models will be much greater than in "action level" models, since the computer makes decisions based on action models, whereas the field scout or farmer makes decisions using action levels. Thus, errors made by action models are less likely to be detected before actions are taken. But, the modules or sub-routines used in the "action level" models should be useful in the development of the "action" models.

Plant Compensation

Until the sixteenth century, cotton was grown as a perennial (57). Since the seventeenth century it has been grown as an annual crop, though it retains its perennial growth capacity (109). Thus, due to its perennial, indeterminant growth, the plant is often able to compensate for fruit and leaves lost to pests (109). The cotton plant normally produces an excess of vegetative and reproductive parts. For a variety of reasons, the plant is often unable to produce sufficient photosynthate to mature all the fruit that the plant attempts to set. Thus, fruit loss attributed to insect damage might have occurred naturally as a result of plant stress. Fruit that can be lost to pests without affecting yields or profits is referred to as "surplus fruit" (121).

In spite of a wealth of information on cotton plant compensation, there is still a widespread inability among growers and professional agriculturists to distinguish between actual crop damage and economic damage (35). Often, any perceptible crop damage is viewed as reflecting losses of yield or quality. The amount of fruit retained and its contribution to harvestable yield should be of greater concern than fruit damage (1).

Some pest damage to the cotton plant may actually be beneficial (26, 40, 42, 109). Figure 3 depicts a schematic of the effects of various pest densities on yield. A small amount of insect feeding may stimulate the plant, resulting in increased yields. Greater pest densities may result in either plant compensation, noneconomic loss, or economic loss (147).

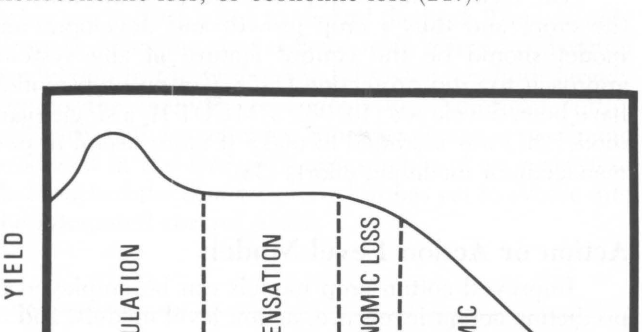

Figure 3. Schematic of crop yield and pest density (after van Emden 147).

Cultivated Acala cotton nomally sheds more than 70 percent of the fruit because the plants cannot meet their carbohydrate demand (40, 81). However, after bolls have reached their maximum growth rate the plant will retain them and shed smaller fruit during periods of carbohydrate stress. Bolls 12-14 days old are usually safe from damage by the boll weevil (95).

The size of fruit when damaged will affect the speed with which it can be replaced. For example, a square (a flower bud) can be replaced much more rapidly than a boll. A mature boll requires >2000 degree days (D°) >53.5°F, whereas a mature square requires only <900 D° (41). Thus, the older the fruit when damaged, the greater the time required for replacement and the greater the probability of loss. Also, the cotton plant may not experience sufficient heat during late season to allow maturation of replacement fruit.

Plant size is also an important consideration, especially in stripper cotton production. (Stripper cotton is mechanically harvested by stripping the lint and seeds from the plant along with burrs, leaves, and stems, whereas mechanical pickers attempt to remove only the lint and seeds.) Plant compensatory growth due to fruit or leaf loss by pests may result in an undesirably large plant that is difficult to harvest by a stripper. Thus, the relationship between fruit loss and plant size should be modeled in areas where stripper-harvested cottons are produced.

Cotton plants on which pests have fed may compensate for damage by using the nutrients that would have been used by the damaged plant parts to develop new leaves, fruit, stems, and roots and to increase the size of the remaining fruit (10). Prediction of the plant's ability to compensate at any point in time during the growing season should be an important component of an action level model. If the plant has reserves of nutrients and sufficient time remaining during the growing season to replace damaged fruit, then a higher action level might be set. The effect of leaf damage as related to the phenological stage of cotton plant growth is illustated in Figure 4. Removal of more than 25 percent of leaf area from the cotton plant during the boll growth stage may result in some yield reduction, whereas 100 percent leaf removal during the lint-ripening stage may result in no yield loss.

Although compensation provides us with a degree of latitude in pest management decision-making, there are also certain problems that must be addressed before we can readily accept pest damage and depend on compensation in cotton production. One problem is that as the cotton plant begins compensatory growth, neighboring plants increasingly shade each other. This shading reduces the amount of photosynthate produced (41). Dependence on compensation may also delay harvesting and thus expose the crop to more generations of pests and bad weather. Increased shading results in slower drying and a greater incidence of disease, such as boll rot. In gulf coast areas of the United States, the probability of heavy rains increases during September (10). Therefore, cotton not harvested before September may have rain-related harvest difficulties, and the crop will continue to grow and be damaged by pests. Several insect pests of cotton enter diapause at high rates during September and October. Thus, a delayed harvest may increase the numbers of overwintering pests available to invade future crops.

Plant injury by insect feeding provides a point of entry for pathogens so that, though the plant may compensate for the injury, it may become diseased and thus less vigorous. Also, plants suffering from other stress factors such as moisture or nutrient extremes may be slower to compensate than healthier plants.

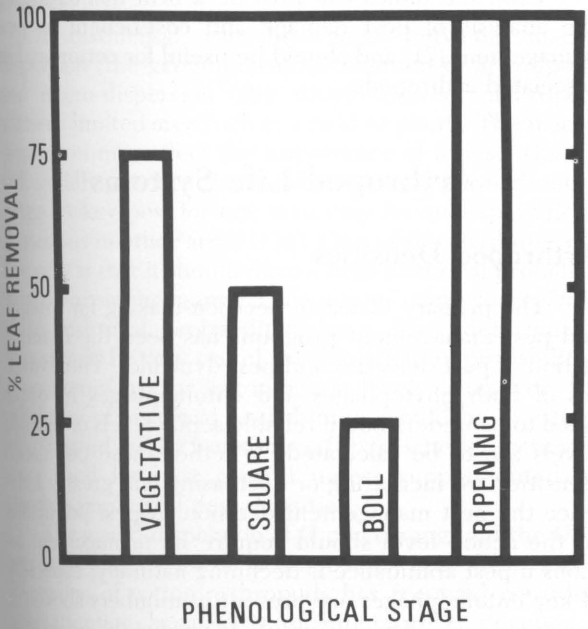

Figure 4. *Leaf loss causing no yield reductions = surplus leaf area (after Rahman, 109).*

If any chemicals such as fertilizers, insecticides, fungicides, nematocides, or herbicides are used in the cotton agroecosystem, the quality, chemical ingredients, frequency of application, and amount applied will influence the growth and development of plants, animals, or both (134). The use of pesticides may increase the nitrogen levels in treated plants and may lead to increased mite and aphid abundance (92). Thus, the direct action of pesticides may influence the role of plant compensation.

Plant Phenology

A truism for a crop such as cotton is that pests of leaves or fruit cannot cause damage until these plant parts are available. For example, the boll weevil may colonize pre-fruiting cotton fields, but effective colonization does not occur until squares are available for feeding and oviposition (160). Preliminary models of boll weevil population dynamics provided relatively poor predictions until the dynamics of the weevil was tied to the phenology of the cotton plant. When the weevil model was started at the time the cotton crop first began to set one-third grown squares, predictions of boll weevil dynamics improved considerably over what could be predicted by temperature alone (15). Logically, the colonization of cotton by both pests and the natural enemies of the pests should be related to plant phenology. Subroutines of plant phenology will be useful in action level models.

Host Plant Resistance

Cotton plant resistance to pests offers an ideal method of suppressing insect pests because most resistant characters are expressed under all weather conditions, while some weather may hamper other tactics (72). Maxwell (76) reviewed the major characters imparting resistance for several pests of cotton.

Cultivars of cotton may have three types of resistance: tolerance, nonpreference, and antibiosis. With tolerance the GEP of a pest may not be changed but the action level is raised. However, with nonpreference or antibiosis, the ability of the pest to reproduce is reduced and therefore the GEP is lowered (138).

Many varieties of cotton have been bred for pest resistance under a chemical insecticide umbrella. As a result, by breeding resistance characters into these cultivars, unknown natural plant defense mechanisms may have been unintentionally selected against and lost from the gene pool. Resistance mechanisms might be more fairly evaluated in the absence of insecticides. Resistant cultivars will undoubtedly affect the prediction of the action level.

Durational Stability of the Crop

Cotton as a crop may be considered to have low durational stability since it is usually destroyed at the end of the season and must be replanted at the beginning of each growing season (with the exception of ratoon [stub] and perennial cottons). However, long-season, indeterminant varieties have provided a durational stability to this crop in relation to the survival of the boll weevil (Figure 5). Use of long-season varieties has increased the synchrony of boll weevil and crop phenology so that the need for emergency action tactics, such as insecticidal use, has been increased. With the long-season crop, the spring suicidal emergence is minimized and production of diapausing individuals is maximized. The use of short-season, determinate varieties has lessened the durational crop stability. A short-season crop enables the pest manager to optimize planting dates—that is, to increase spring suicidal mortality while producing fewer diapausing individuals in the fall. The value of the short-season, minimal input system has been discussed in detail in other reports(12, 32, 97, 127, 151, 153, 160).

The short-season approach also provides reduced vulnerability to *Heliothis* spp. (151) and the pink bollworm, *Pectinophora gossypiella* (Saunders) (3, 164).

Other Factors

In a model of the cotton crop for use in the calculation of action levels, other factors must be considered. Fertilizer can speed up plant development (74) if used in optimal amounts. However, crop production systems using excessive amounts of fertilizer and irrigation can prolong growth and delay harvest (50). The importance of optimal amounts of nitrogen and water in minimizing damage from lepidopterous pests has been demonstrated (97).

Soil types may affect the action level through their effect on plant growth and development. The economic

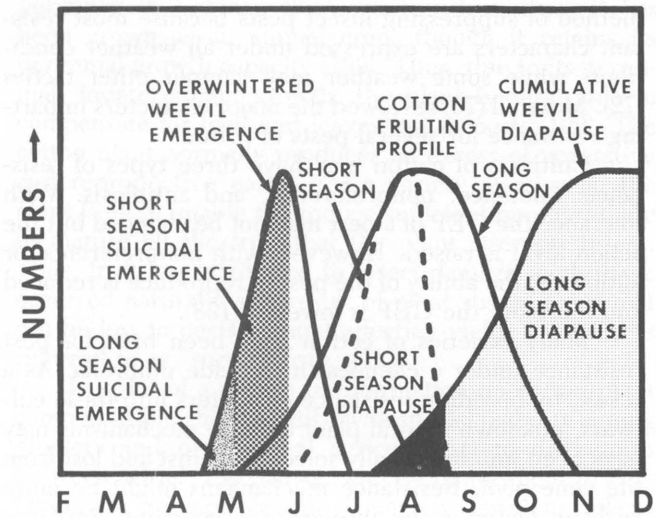

Figure 5. Schematic of boll weevil phenology in short and long-season cotton production systems.

returns due to boll weevil control were related to soil type and the soil's effect on plant growth (113). Plants growing on black soils are excellent producers of plant nectar; alluvial soils result in good nectar production most years; grey or red soils result in good nectar production only under favorable conditions; and sandy soils only occasionally result in nectar production (30). Nectar flow of the cotton plant influences the abundance of red imported fire ants, *Solenopsis invicta* Buren, (4) so soil type may indirectly influence the abundance of the fire ants. These ants are key predators of *Heliothis* spp. (78-80) and the boll weevil (58, 130). However, nectariless cotton is less attractive to some insects pests (76). Thus, the abundance of both phytophages and entomophages may be affected by nectar production of cotton on various soil types.

Weather factors generally used in modeling the cotton plant include daily rainfall, maximum-minimum temperature, solar radiation, and pan evaporation, which is an index of humidity (10). Most of the yearly fluctuations in cotton yield are caused by weather patterns and not by insects (41). Cotton farmers tend to overestimate yield potentials because they remember high production years without remembering the associated weather. In years of lesser yields, insects are often blamed instead of the weather. Weather patterns based on historical climatological data are currently being used as the best estimate of future weather in insect predictive models (44, 133).

Secondary plant substances have evolved as defenses against enemies of plants (107). These products are often toxic or repellent to animals and other plants. The term "allelopathy" is used to describe the biological inhibition of feeding or toxicity to plants or animals by the secondary plant substances such as gossypol or tannins in cotton plants.

Crop life tables can provide a firm foundation for the analysis of pest damage and cost/benefit in pest management (71) and should be useful for cotton and its associated arthropods.

Arthropod Life Systems

Arthropod Densities

The primary thrust in decision-making for integrated pest management programs has been the determination of pest densities and pest dynamics. The dynamics of both phytophages and entomophages in cotton need to be understood if reliable action levels or inaction levels are to be calculated. Whether these population densities are increasing or decreasing will greatly influence the pest management decision. A pest population at the action level should require no management actions if pest abundance is declining naturally, especially if key entomophages are present in numbers above the inaction level. Thus, the ability to predict the population dynamics will be critical in future pest management systems.

Simulation models have been developed for the boll weevil (15, 59, 154), *Heliothis* spp. (44, 96, 140), *Lygus* spp. (41), and the cotton fleahopper (133). These models simulate the dynamics of these insects through parts of their seasonal cycles, usually during the cotton growing season.

Pest management decisions made for one season may affect future seasons (54). In cotton this concept is very important because both the boll weevil and the pink bollworm can often be managed by tactics used during one year that effect pest numbers in future years. Both insects have few host crops in he United States other than cotton on which they can rapidly reproduce. Thus, management tactics designed to minimize overwinter survival have been very effective. Destruction of the cotton crop before these insects enter diapause in the fall is a key management tactic in some areas. In the case of the boll weevil, supplementary suppressive actions in the fall using insecticides have been an accepted and effective tactic (116).

Pest management systems will benefit from models that consider the dynamics of insects throughout the year, and from year to year. Winter mortality can be especially critical for the suppression of some insects below the action level during the following season.

Dispersal

The importance of dispersal in pest management systems has been reviewed by Rabb and others (108,148). Single night flights of *Heliothis* spp. up to 16 miles and 4-day movement of 45 miles have been observed (126). Computer simulation models of *Heliothis* spp. (44, 140) include the dispersal of moths between crops as a function of crop attraction.

Predictions of pest and entomophage dispersal and crop colonization will be of great value in developing future pest management models.

Dispersion

A distinction can be made between macro-dispersion (the geographical distribution of arthropods) and micro-dispersion (the distribution of arthropods within a limited area such as a field or plant). The macro-dispersion may affect the importance of a pest, since it will usually not occur in a uniform density throughout its range. A key pest for one area may be only sporadic or innocuous in other areas (134). One of the attributes of a key pest is that it should have a high historical probability of recurrent economic damage over many years. Once these historical probabilities have been determined, they should be very useful in calculations of probabilities of economic loss for use in action levels. However, the reliability of historical probabilities would be questionable if based on the frequency of years when insecticides were used for pest control unless supplemented by careful sampling of pest densities.

The macro-dispersion of *H. zea* throughout the USA was reviewed by Snow & Copeland (122). The micro-dispersion of cotton arthropods has received considerable attention because it is important in developing improved research or pest management sampling techniques (63). Also, "spatial aspects of populations are difficult to model, and it is very rare to find both spatial and temporal dynamics included in a single model (114).

Instar, Size and Sex

Traditionally, emergency actions taken for *Heliothis* spp. have been designed to prevent the development of large numbers of large larvae. These large larvae cause much more fruit damage than small larvae (143). Also, large larvae remove larger fruit that require a longer replacement time than smaller fruit. Removal of large fruit also results in a greater loss of plant photosynthate than removal of smaller fruit.

Size and sex of *Lygus hesperus* Knight may also cause different amounts of damage. Adult females cause approximately twice as much damage as males, whereas the average for third to fifth instar nymphs is near that of males (40).

Simultaneous Damage by a Complex of Pests

Is the damage caused by two or more pest species additive, synergistic, or antagonistic? What should be done when the crop is infested by species A, B, C, and D, none of which has reached the action level but each of which may be within one-half to three-fourths of it (35)?

In calculating an action level for a single pest when a complex of pests is present, a cotton plant model may be essential for calculating the cumulative damage from all the pests that can be tolerated and the amount of fruit that can be expected to survive the attack. When two pests such as the boll weevil and *Heliothis* spp. feed on squares, the cumulative damage might possibly be less than the additive damage of either alone, since *Heliothis* spp. will consume weevil-infested squares, which results in simultaneous damage to some squares. Definitive data on the subject is not available but one simulation study showed that reduction in yield from simultaneous damage by two pests was larger than the sum of the yield losses when the damage was caused by each species separately (77). The interactions of the boll weevil and the bollworm have been considered in establishing an economic threshold based on the ratio of fruit production to the rate of cumulative fruit damage caused by both pests (38).

Each species may not affect the action level of the other species if each species feeds on a different plant part and if their cumulative plant damage does not result in plant stress. Also, the decision to take action against a group of pests, all below the action level, is complicated by the need for different action tactics for each pest species (134). This helps account for the popularity of broad spectrum insecticides among cotton farmers. Also, the presence of the tobacco budworm, *Heliothis virescens* (Fabricius), in the *Heliothis* complex will dictate the need for more toxic insecticides or higher dosages, since *H. virescens* is generally more resistant to many insecticides than *H. zea* (88).

Action Levels for Cotton Pests

The action levels for *Heliothis* spp. on several crops and alternate host plants have recently been reviewed (131). Four chapters in SCSB 231 relate to *Heliothis* spp. on cotton (10, 99, 104, 151). Graham et al (37) also reviewed pioneering research leading to the establishment of economic thresholds of ca. 0.5-0.6. larvae per meter (2, 111). These thresholds provided guidance for making pest management decisions for *Heliothis* spp., but many modifications have been made in the various cotton-growing states. A major improvement was the recognition that the threshold must be dynamic during the growing season (47, 54). For example, after broad spectrum insecticides have been applied, few entomophages will survive, which often results in a pest resurgence. Thus, the economic threshold decreases after insecticide applications have been initiated and/or as the season progresses (5). The need for dynamic thresholds was demonstrated by determining that relatively heavy infestations in mid- and late-season were required to reduce yield and that 1.2 larvae/m throughout the season significantly reduced yields (61). Cotton was able to tolerate seasonal densities of ca. 0.6 larvae/m. In Texas a seasonal average of 0.9 larvae/m significantly reduced yields (2).

Action levels are reviewed for other pests of cotton such as the boll weevil (134), *Lygus* spp. (41, 137), pink bollworm (32), and the cotton leafworm, *Alabama argillacea* (Huebner) (31). Current pragmatic action levels for cotton arthropod pests may usually be obtained from local Extension entomologists.

Soils and Fertility

The effect of boll weevil control on yields is related to soil type and soil fertility (113). Also, fertile soils such as river "bottoms" may force determinant cotton varieties into indeterminant growth patterns. Thus, action levels established on soils of a certain level of fertility may not be applicable for soils with other levels of fertility (134). Infertile soils with a low yield potential, in the absence of pest control, may show only a negligible profit increase when control measures are applied (14). Ecosystems enriched with plant nutrients often result in the development of dominant pest species, whereas systems with lower concentrations of plant nutrients have no or fewer dominant species, and thus the the system is more stable (98, 128). Cotton fields that receive moderate amounts of nutrients might be expected to have fewer dominant pests than fields that receive heavy concentrations of plant nutrients.

Contamination of soils with pesticides, salts, and even over use of fertilizers will have some influence on the soil microflora, soil fauna, and their relation to soil and plant health and may be important in the calculation of action levels.

Insecticide Resistance

In modeling for predictive purposes, time frames of greater than a single season should be considered. One reason is that the gene pool of the various pest and entomophage populations changes over time. This change is apparent in the development of insecticide resistance, but it may also be expected in other physiological and behavioral adaptions to changes in cotton production practices. Thus, if insecticides are to be used as a pest management tactic in future years, predictive models of resistance should be developed for key arthropods of the cotton agroecosystem.

Prediction of susceptibility to insecticides will be useful in decisions regarding choice and dosage of insecticides. The total susceptibility of a particular species to currently used pesticides has been referred to as "biological capital" (54). A genetic model dealing with the developmental rate of insecticide resistance suggests means of minimizing selection pressure (105).

Insects may also develop resistance to other management tactics such as resistance varieties and predators (55). Since insects can develop a resistance to their own hormones (149), it would not be surprising if they could also develop resistance to autocidal methods, pheromones, cultural controls, mechanical controls, host plant resistance, and others. Thus, there is a need to determine the risks of these events and the rate of development.

Yield Losses

Definitive evaluation of crop losses is one of the most complex problems facing the researcher. The literature of economic entomology is replete with examples of yield increases resulting from the use of various pest management tactics. Often these experiments have been conducted in small-plot, randomized plot designs where some replicated plots were treated with broad spectrum, chemical insecticides while certain randomized plots were left untreated as a control. The differences in yield between the treated plots and the control were used as an estimate of pest damage. Experiments of this type have often demonstrated cotton yield "increases" of 100-500 percent. However, the difference in yields is often due to the destruction of natural enemies in the control plots by the insecticides drifting from the treated plots. Without their natural enemies, and with insufficient amounts of drifted pesticide to kill the pests, much damage was realized from the pests. Also, these studies were and are still frequently being conducted in communities where large amounts of insecticides are being applied to neighboring cotton fields, upwind from the test plots.

The effects of patchy applications of insecticides in a community on the abundance or change in behavior of natural enemies in the untreated areas is largely unknown, but it would be foolish to assume no effect. Though the randomized experimental method may be a fair evaluation of the relative efficacy of the various chemical insecticides in the experiment, it is not a fair evaluation of yield losses without insecticides. As a result, yield losses due to insects tend to be overestimated.

Estimates of crop losses to pests can only be fairly evaluated in areas where minimal insecticides are present in the soil, on the plant, or in the air and where they have little chance of drifting into the area. Isolation of several miles from treated areas may be essential for these loss estimates. Also, insecticides used over large areas may reduce the abundance of natural enemies, so that 2-3 years may be necessary for the effective recovery of these natural enemies (6, 87, 100.) Thus, crop loss estimates should be obtained in areas where insecticides have not been used for several years, so that the true effectiveness of natural enemies can be realized. In these experiments, the optimal cultural and biological crop management tactics should be employed to maximize the probabilities of producing acceptable yields and profits in both the control and treatment plots.

A distinction can be made between direct and indirect damage (118). Direct damage results when the pest directly attacks the part utilized by man, whereas damage to other plant parts results in indirect damage. In cotton, higher levels of indirect damage can be tolerated than direct damage. The key pests of cotton, i.e. plant bugs, boll weevils, bollworms, and tobacco budworms, all cause direct damage by attacking the fruit. The secondary pests are generally leaf feeders. However, this distinction is simplistic because those pests that cause direct damage may also cause indirect damage. All the key pests of cotton will occasionally cause damage to plant parts other than the fruit. For example, *Heliothis* spp. feeding on pre-fruiting cotton terminals can delay plant growth (52).

Despite increased use of insecticides in the United States, crop losses continue to increase. The changes in our agricultural production system that have contributed to this increased crop loss are (a) use of crop varieties susceptible to pests, (b) continuous culture of certain crops with less rotation and diversification, (c) reduced crop sanitation, (d) reduced tillage, (e) growth of crops in areas where they are more susceptible to pest attack, (f) increased pesticide resistance in pests, (g) destruction of natural enemies of pests. (h) use of pesticides that alter the physiology of plants, and (i) reduced tolerance by the Food and Drug Administration, and increased cosmetic standards by processors and retailers for crops (102).

Crop losses due to insect pests have increased from 9.8 percent in 1904 to a present high of 13 percent (101). In part, these increased loss trends are due to high "cosmetic standards" in fruits and vegetables now sold on the US market. They also result from planting varieties that are more susceptible to pests and eliminating crop rotations and other sound ecological practices from crop culture.

Cosmetic standards are of little or no importance in cotton except for the spotting of the lint that may result from insect feeding in the green boll. For example, feeding by the green stink bug, *Nezara viridula* (L.), or the pink bollworm can cause reductions in lint quality. However, feeding by *Heliothis* spp. or boll weevil does not generally reduce lint quality, because if only a small section of the boll is damaged, the lint from the damaged section is not harvested (152).

Inaction Levels

Pest management decisions should be based not only on the abundance of pest species but also on the abundance of natural enemies of the pest. Obviously, greater numbers of pests can be tolerated if an abundance of effective natural enemies are present. Thus, the abundance of natural enemies will affect the action level. However, before reliance can be placed exclusively on natural enemies, a working understanding of the most efficient enemies and the numbers needed to maintain pests below the action level is needed. The presence of greater numbers of a complex of predators than of pests does not ensure the maintenance of pests below economic levels (112). The term *inaction level* for the density of natural enemies sufficient to maintain the pests below the action level is suggested (29). McDaniel & Sterling (79) provided an example of an inaction level. They proposed a ratio of one key predator for each *Heliothis* spp. egg. When 15-20 percent of the terminal buds of cotton contain a predaceous black fleahopper, *Rhinacloa forticornis* Reuter, 80-100 percent of *Heliothis* spp. eggs will be consumed (53). No chemical insecticides were recommended if "beneficials" were present at 20 or more per 56 row feet of terminals (5). Inaction levels for a key predator of the boll weevil have been established (29) and evidence supporting these levels is available (28, 132). Inaction levels have not been established for natural enemies of most insects pests.

Key Predators

Any predator species or stage of a predator species that provides predictive value for forecasting future prey population trends and is capable of providing irreplaceable (indispensable, sensu Southwood [125], p. 374) mortality leading to prey population regulation may be considered a key predator. Irreplaceable mortality is that portion of the total generation mortality contributed by a particular agent and not replaced by other natural enemies. Thus, removal of an agent providing irreplaceable mortality would result in greater survival of the prey species. The concept of the key predator should be distinguished from the concept of an index predator. An index predator provides value in forecasting future prey population trends but may or may not regulate the prey population. For example, if the numbers of prey are highly inversely correlated with the abundance of a predator species, then the predator may be included as an index predator. If later evidence supports the conclusion that the index predator is causally related to the decline of prey numbers and actually provides irreplaceable mortality, then it is clearly a key predator.

Thus, an index predator may also be a key predator, but the difference is that there is no field evidence that the index predator causes any irreplaceable mortality. An index predator may be an excellent predictor of the numbers of the real, but unknown, key predators. A hypothetical example of an index predator might be a ladybeetle that does not feed on a bollworm egg, but numbers of the ladybeetle increase at the same time as the real key predators that actually regulate the bollworm eggs. In this case the abundance of the index predator might be correlated inversely with the abundance of the bollworm eggs, but the correlation is spurious.

A key predator might be expected to fit a modified definition of a key factor as proposed by Solomon (123), i.e. one of the main controlling factors affecting a population, implying that key factors cause the mortality but is not spuriously correlated with it. An index predator would more closely fit Morris's (83) definition of a key factor, i.e. any biological or environmental condition associated with mortality that is useful in predicting a future trend in a population but lacks evidence of causation. Spurious correlations may have predictive value even though changes in one may not cause the changes in the other.

More than 600 species of predators have been observed in Arkansas cotton fields (159), but only a few species are responsible for most of the predation. In field studies, the order of importance for *Heliothis* spp. eggs was as follows: ants, lady beetle larvae, adults of the spotted ladybeetle (*Coleomegilla maculata* DeGeer), adults of *Hippodamia convergens* Guerin-Meneville, spiders, predaceous mites, and green lacewing larvae (*Chrysopa* spp.). In later studies (158) *Orius* spp. and *Geocoris* spp. adults were added to the list. Similar results were obtained in east Texas using ^{32}P labeled *Heliothis* spp. eggs (78, 79). Dominant egg predators were ants (mostly *Solenopsis invicta*), *Orius insidiosus* (Say), *Geocoris* spp., *H. convergens*, *Cycloneda sanguinea* (Linnaeus), *C. maculata*, *P. seriatus*, and the spiders *Chiracanthium inclusum* (Hentz), *Phidippus audax* (Hentz), and *Oxyopes salticus* (Hentz),. The average seasonal egg mortality due to predators was 93 percent after 72 hrs. Many of these same species are important larval predators of *Heliothis* spp. with the notable exception of the large lady beetles (80). As a result of this high level of predation, *Heliothis* spp. seldom caused economic damage except where insecticidal perturbations had occurred.

The efficiency of many of these predators when reared or field collected and released has been evaluated (69, 70, 110, 111, 146). A maximum of 90 to 99.5 percent reduction of *Heliothis* spp. was observed as a result of these releases, the efficiency depending on the numbers of predators released. A review of inundative releases (139) is a valuable reference on this subject.

No more than a dozen key natural enemies of pests are of importance on cotton (112). The species and their importance may vary between geographical areas. Thus, their efficiency should be evaluated in many cotton production areas and for all key and secondary pests.

Of course, predators are not the only natural enemies of cotton pests. Parasites and pathogens may also play a major role in the regulation of pest abundance. The identification and relative importance of *Heliothis* spp. parasites has recently been reviewed (112), and a manual is provided for pathogen identification (106).

Colonization

To predict the colonization of entomophages and pathogens in cotton, their sources should be known. For example, a major source of predators in south Texas is grasses (34). Certain entomophagous species exhibit superior dispersal-colonizing abilities and are characteristically dominant in disturbed habitats such as agroecosystems (22). However, there is usually a trade-off between the reproductive-dispersal abilities of a species and their competitive abilities. Species exhibiting high reproductive-dispersal abilities have been labelled r-strategists and those with high competitive abilities, k-strategists (73). Ehler & Miller (22) contend that r-pests may be controlled by r-strategist natural enemies in disturbed systems and in habitats of low durational stability.

Since the cotton field is essentially a pauperized, ecological desert before the crop is planted, most entomophages must disperse into and colonize the field before they can effect control of pests. To predict the efficiency of natural enemies in the management of pests, a knowledge of their dispersal and colonization rates may be essential.

Switching

Polyphagous predators may switch from feeding on a key pest species to secondary pests or innocuous species, resulting in greater survival rates of the key pest. In field cages, bollworm eggs survived at a rate 16 times greater when *Orius* spp. and aphids were both present as compared to eggs alone (25). However, noneconomic densities of aphids, thrips, spider mites, lepidopterous eggs and larvae, and innocuous species attract, hold, and increase predator and parasite abundance (89).

Models

Preliminary models of natural enemies that could be used in action level models are available (44, 142).

Economics

Mid-season chemical insecticide applications to cotton often necessitate subsequent treatments later in the season to protect the crop from resurgence of the treated pest or an outbreak of a secondary pest (137). Thus, the first insecticide application perturbs the cotton agroecosystem by causing a decrease in the effectiveness of natural enemies. Frequently, this perturbation results in a virtual ecosystem addiction to the insecticides (145), so that a "treadmill" of applications is essential to protect the crop. Each additional application of insecticide does not ensure the protection of the crop at potential yield present when the application was made. Much of the crop may remain susceptible to pest damage, so that very large losses may be suffered if the applications are terminated. Economic analysis of cotton production should definitely consider this "treadmill" effect.

Insecticides

Of the pest management tactics available for analysis by economists, pesticides have been universally attractive because they are "easier to cost" and easier to put into practice than other methods (94). However, in nine separate, large-scale pest management programs in Texas, an average 44.2 percent reduction in the use of insecticides resulted (64) when greater dependence was placed on native entomophages for pest control. Net returns increased by an average of 77 percent. Thus, the economics of alternate action tactics, which have largely been neglected in the past, should receive a fairly high research priority in the future.

Cost-Benefit Ratios

Cost-benefit ratios are of value because they are easily understood by growers (35). In practical agriculture, a simple cost-benefit ratio is the best "first approximation" of potential crop yield (137). The grower may understand this ratio more easily than marketing fluctuations and commodity prices on a regional, national, or international basis.

When the concept of social cost/social benefit ratios is introduced, the modeling problem becomes more complex. The concept of social benefit (welfare) is vague and controversial (66). As in other areas of modeling, there is a need for definitive data in order to calculate the costs and benefits to all individuals in the society, rather than basing calculations on estimates or theory. The impact of pest management decisions on the health, wealth, and nutrition of individuals is one of the important elements that needs to be quantified.

Production Costs

Costs of contemporary pest management systems in Texas have been reported (12, 32, 91, 97, 127). In evaluating costs of pest management systems, production, management, sampling, set up, and application of tactics should not be overlooked (134).

Insect Losses

Losses due to cotton insect pests have been reviewed (17, 39, 85). Care should be observed in evaluating loss estimates. If pest damage were eliminated, the true value of the product would decline on a per unit basis (except in the case of price supports) because of the greater yields and supplies that would result. Thus, loss figures are often exaggerated. For example, boll weevil eradication benefits to the cotton producer are nebulous. Consumers benefit from large-scale management programs such as boll weevil eradication because of lower cotton prices, but landowners lose because land values fall (65).

Supply and Demand

In order to calculate an action level of value to the producer, some estimate of the short-term value of the crop is required. The supply-demand relationship of cotton and its value has been reviewed (47). Information on the current status of world cotton production, US Department of Agriculture (USDA) loan levels, and deficiency payments may be obtained from several sources such as the National Cotton Council, Cotton Incorporated, and the Economic Research Service of the USDA.

Ecology And Society

Ecologically sound management practices should also be economically sound. However, ecological measures such as soil and natural enemy conservation, or ecosystem stabilization, may be of economic value primarily over the longterm, which may extend to several human generations. An awareness of the need to preserve nonrenewable resources and to leave the earth as healthy as we found it is an ethical legacy that we must pass on to future generations (92). In the case of ecologically sound practices, optimal profits often may not coincide with maximum profits. In the search for maximum profits, little regard may be given to such concepts as conservation and stability of systems. Thus, boom or bust cycles are commonplace in cotton production. When the price of cotton is high every possible acre of farmland may be planted to cotton. From the air the gullied and eroded soils across the cotton belt of the USA lie as a testament to the failure of this strategy. The top soils of much of this once fertile land now lie in river beds and ocean floors. Thus, this potentially rich inheritance of fertile soils lies wasted and of no value to future generations whose fathers attempted to make quick profits, that are now denied to their offspring.

Soil erosion is not the only example of the deterioration of our valuable natural resources. Reduction or elimination of natural enemies of plant-feeding insects because of misuse of broad spectrum insecticides and pollution of soils with salts of irrigation waters, insecticides, fertilizers, and herbicides may have greatly affected the stability and long-term profitability of many systems. The history of cotton production around the world is replete with examples of financial disasters resulting largely from a failure to understand certain basic ecological and economic principles (145).

Side Effects of Management Actions

Economists refer to some of the side effects of actions taken as "externalities," or the benefits and costs accruing to persons other than the producers or consumers of the agricultural commodities involved (66). The identification of externalities is nebulous (66) because these secondary effects are not signalled to the decision-maker either from the market or from the ecosystem and are therefore not considered in his decision-making (67). It is possible for externalities to cause a major divergence between management strategies optimal for the grower and those optimal for society. A decision model has been developed to estimate the external costs and quantify the costs of pesticide side effects (21).

According to Norgaard (90) the misuse of pest management actions is a social problem. He claims that social objectives such as nourishment, health, and environmental quality are not being met and that solutions to this social problem lie in changing the behavior of men. Thus, farmers need to use fewer and narrower spectrum pesticides and biological controls consistent with the dynamics of the agroecosystem. Or, farmers should plant less vulnerable plants in better patterns and places at better times.

Because of the externalities inherent in pesticides, their use should be reduced to the extent that their marginal social costs (including all side effects) approximate their marginal benefits (27). Marginal costs or benefits are the total costs or benefits of cotton production that result from each additional input such as each additional application of insecticide.

Some of the side effects of pest management actions have been summarized (92). These side effets relate primarily to chemical pesticides and their detrimental effects on the crop and nontarget organisms; they include long- and short-term effects on human and ecosystem health. A review of the side effects of insecticides, herbicides, and fungicides on some of the flora and fauna of plant, soil, and aquatic ecosystems has been provided (9).

Management tactics such as cultural practices, hormonal regulation of plant growth, host plant resistance, mechanical control, pheromonal control, pathogens, classical biological control, and the augmentation and conservation of natural enemies of plant pests are generally considered to have less detrimental side effects than broad spectrum insecticides. This may be because management tactics other than insecticides have been poorly evaluated for these side effects. For example, foreign parasites introduced for the classical biological control of pests are usually screened for hyperparasites but not for new pathogens that could be a hazard to native natural enemies of pests. However, even with pesticides, "inadequate data and the necessity of subjective evaluation of damage to wildlife and threat of risks subvert detailed, quantifiable, cost-benefit analsysis of overall liabilities and benefits of pesticide use" (92).

Uncertainty in Pest Management

Uncertainty because of lack of information on the part of the farmer is an additional factor encouraging pesticide use. Feder (27) investigated the impact of uncertainty on farmers' decisions regarding pesticide use and the way it affects reaction to various changes. Given risk aversion on the decision-maker's part, Feder's improved optimization model introduced random elements into several components of the pest-pesticide-crop system and used Bayesian decision rules and dynamic programming to reproduce the farmer's decision-making process. Feder (27) also evaluated the impact of improved information regarding old and new technologies, as well as information acquisition. The cost of information and its effect on pesticide use was evaluated, and a market for management information was established.

Insecticide Decomposition

A simulation model of the rate of insecticide loss from a terrestrial ecosystem was developed (150) that was based largely on soil surface temperature and moisture fluctuations. This type of model could prove useful in predicting the residual side effects of pesticide use. Also, the model ecosystem approach, along with the use of radiolabeled insecticides, is an informative and convenient experimental technique for studying the environmental effects of insecticides (82).

Policy Decisions

Some farm policies and practices have been counterproductive. Nearly four billion dollars was spent by the US government to retire productive land from cultivation (103). This land restriction encouraged high crop yields on fewer acres, resulting in some cases in increased reliance on pesticides. Thus, one trend in crop production has been the use of more pesticides and less land. Any program that indirectly encourages the substitution of pesticides for land should be critically examined (103).

A computer model predicted that future costs of cotton production without insecticides would be slightly greater than the cost of producing cotton with insecticides in the absence of a government land retirement program (103). With a land retirement program, the cost of producing cotton would be greater with insecticide use. Restrictions on land use appear to play a greater role in price increases than do restrictions on insecticide use.

The farmer's income is often supported through a guaranteed government price; thus his gross income is proportional to his output. This is a form of insurance that is of value to the farmer only if there is no crop failure. Thus, the farmer often sees the use of chemical pesticides as a means of reducing the risk of being unable to take advantage of price supports. This type of policy thus tends to subsidize the use of chemical pesticides (92). Davidson & Norgaard (16) have suggested both income or output insurance as a solution to this problem.

Marketing standards are determined by government policy. High marketing standards dictated by regulatory agencies may have little bearing on the nutritional value of the product. Thus, for largely cosmetic reasons, action levels have been reduced to near zero, resulting in a greater use of pesticides, higher production costs, higher environmental costs, and an increased cost of the final product (35). Consequently, the flame of inflation, which is often fueled by policy decisions and is reasonably predictable, should be considered in establishing action levels.

The passage of the Occupational Safety and Health Act, which requires a hazard-free environment for workers, has transferred some of the costs of pesticide side-effects from society to the farmer. Farmers may also be legally liable for damage or contamination of neighboring farms from spray drift (92).

The federal government compensated bee keepers an average of $1.5 million per year in the early 1970s (86) for losses due to "pesticide accidents." "When the public picks up the tab for negligence, there is little incentive to be careful" (92).

Thus, the effects of government policy are often counterproductive to the minimization of the detrimental side effects of pesticides. Policy decisions will probably play an important role in the calculation of action levels in future pest management models. The need for the quantification of externalities resulting from pesticide use as they might affect policy decisions is suggested by Headley and others (48, 67). For an excellent review of economic research on pesticides for policy decision making see the proceedings of the 1970 symposum of the Economic Research Service (11, 19).

Strategies and Tactics

Pest management decisions can be made at either the strategic or tactical level. A pest management strategy is a scientifically determined plan in which potential management tactics and other pertinent contingencies have been optimized for the management of pests in the ecosystem [modified from *Encyclopedia Britannica* (23)]. The three basic strategies are (a) prevention or eradication, (b) containment, and (c) doing nothing (56). Other factors that should be considered in developing a strategy of cotton production include the selection of a planting date, crop variety, and methods of weed control, fertilization, irrigation, etc. These decisions can be made before the crop is planted and thus are part of the crop production strategy.

Obviously, anyone who produces cotton has developed a production strategy. However, one objective of optimized strategies may be to avoid the creation of new pest problems and to try to remedy those situations from which present-day problems have arisen (13). Koenig and Tummala (62) contend that systems science techniques should be used to redesign agroecosystems. Crop production practices can be evaluated by systems science to produce improved ecosystem strategies less susceptible to pests.

Tactics were defined as the "specific methods or supporting techniques required to carry out a basic strategy" (56). Pest management tactics include plant resistance and cultural, biological, mechanical, pesticidal, autocidal, pheromonal and plant growth regulators (8, 36, 71). These tactics were categorized as follows: (a) chemical pesticides and (b) bioenvironmental controls (102). Bioenvironmental control was defined as "any nonchemical control method utilized to reduce pest populations by environmental manipulations and biological control" (102). Bioenvironmental controls are employed on more acres of crops (9%) than insecticidal control (6%) in the United States (102).

The efficiency of a management tactic may affect the selection of the action level. A tactic yielding 98 percent reduction of a pest should generally have a higher action level than a tactic yielding only 50 percent reduction. If the action level has erroneously been set too high, or sampling fails to accurately detect the action level, a highly effective tactic can still be used to "clean up" and recover from these mistakes. However, a less effective tactic would be of less value in recovering from decision errors. Thus, the tendency is to set the action level at a conservatively low point (134).

Risks

Farmers often appear to be risk-adverse. To lessen risks, knowledge is needed not only of the expected value of return for decisions but also of the variance of the value of possible outcomes. This information can be used in models that yield not only the expected outcome but also the probability of all possible outcomes (18). However, until these predictive models are available, new methods of minimizing decision risks will depend on the traditional experimental methods.

One production method that has shown much promise in reducing the risk of pest damage to cotton is the short-season, reduced input systems that many of the farmers in Texas have been quick to adopt (151). Where highly fertilized, indeterminant cottons are grown in Texas, investment risks may be greater than with the short-season systems.

The major risk in cotton insect pest management is that pests will cause unacceptable losses to the crop. However, there are many other risks associated with decisions made in pest management. The risks of taking management actions when they are not needed and the risks of taking no action when actions are needed (i.e. type I and type II errors, respectively) must both be considered (135). Current concerns regarding the risk to human health due to agricultural chemical pesticides are resulting in legislative sanctions against their misuse. The prime risk appears to be to those who apply the pesticides (103). Thus, the farmer-applicator should have grave concerns for the risk he takes in using certain tactics.

Community Strategies

A distinction can be made between local (producer level) and regional (community-wide) strategies (125). Considering the vagility of both phytophages and entomophages, it is small wonder that community-wide strategies have some distinct advantages over individual producer stategies. Community-wide strategies minimize the problem of recolonization of pests from fields not included in a management program to fields included in such a program. However, in community-wide insecticidal applications there is a high risk that some fields will be treated where no treatment is needed, unless each field is sampled separately.

Pesticidal Tactics

Of the currently available and effective tactics, chemical insecticides remain an important component of pest management systems. Thus, pest control models such as the one by Talpaz and Borosh (141) are needed to evaluate strategies for pesticide use. They applied a mathematical-numerical optimization that selected frequency of applications and dosages designed to minimize control costs and crop damage. Watt (156) also used a computer to evaluate alternative insecticidal programs.

Insecticides should only be used on an "as needed" basis. Sampling is generally recommended to determine the need for management actions. However, preventative actions have been suggested as a valid option if the risk of economic losses is almost certain every year when actions are not taken. In south Texas, the risk of unacceptable boll weevil loss was so high every year that a preventative strategy was incorporated into the pest management program (51).

The use of insecticides where they are not needed can be very expensive insurance. For example, controlling *Lygus* spp. with insecticides tended to reduce yields of Acala cotton in simulation studies (41). Thus, "farmers were spending money to lose money" (41). The use of pesticides rarely increases yields; rather, use prevents loss of yields (71).

Of all the chemicals used to produce cotton, insecticides have the most serious side effects (92). About 80-90 percent of human cancer may be caused by chemical contamination of the environment and food (75). Also, there is evidence that aldrin (24) and DDT (49) cause cancer and possible birth defects and genetic mutations.

The history of chemical pesticide use in a field or community may indicate the current availability of natural control agents. Up to three years may be required for a normal balance of predators to return after the use of persistent insecticidal chemicals over broad areas (6).

Cultural Tactics

Some of the cultural tactics used in cotton pests management include planting and harvest dates, tillage, crop rotations, water management, and trap crops (155). Cultural control is defined as "the use of farming or cultural practices associated with farm production to make the environment less favorable for survival, growth and reproduction of pest species" (155).

Other Tactics

Tactical decisions can be separated into emergency actions or preventative actions. Emergency actions are taken as a result of failure to accurately predict events leading to emergency pest situations and requiring immediate amelioration. The unexpected development of economic injury because of an outbreak of pests, resulting in emergency applications of insecticides, is an example. The tactics frequently used in emergency action situations are insecticides and plant growth regulators.

Curative actions are designed to prevent pests from reaching the action level where emergency actions are needed. Plant resistance, cultural, biological, autocidal, and regulatory tactics are all examples of curative actions. Usually two or more of these tactics are used simultaneously. For example, certain varieties and planting dates designed to minimize pest density are used together with chemical methods.

Action levels are used primarily to determine when to take emergency actions but probably find little use in determining when to implement curative actions.

Discussion

Definitive predictions of action levels are likely to be based on a clear understanding of the relation between the plants, arthropods, economy, and ecology. The failure to consider any of these factors and their interactions may result in erroneous management decisions that are not in the long-term best interests of the producer, consumer, or others in our society.

Computer Models and Simulation

Brown et al. (10) reviewed the use of computer simulation in establishing economic thresholds. Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behavior of the system or evaluating various strategies for the operation of the system (117).

Adequate economic thresholds and economic injury levels have been established for relatively few of the most important pests of the world, in spite of the long recognized need (35). None of the action levels currently used are based on precise estimates that integrate the host, the pest, enemies of the pest, the economy, and the ecology. This multiplicity of factors needed in calculating precise action levels is too complex for most human minds to comprehend simultaneously. Computers can store, recall, evaluate, simulate, and calculate rapidly using large quantities of data; thus their potential for calculating precise dynamic action levels is excellent. Some of the variables used in the calculation of the action level are more important than others. The initial models may include a wide range of variables that can be evaluated through the simulation process; unimportant variables and relationships can be eliminated, leaving only the variables of key importance for prediction.

We should also be able to predict when occasional pests will be present in outbreak numbers. This will eliminate unnecessary and environmentally disturbing "insurance" treatments (138). According to Clark et al. (13), "Forecasts can be required for a variety of purposes, such as: evaluating the variability of a pest's injuriousness in time; preparing for possible increases in the injuriousness of a pest; and timing the application of recurrent control measures." All of these objectives can be used in either "action" or "action level" models.

An optimization model for the calculation of the economic threshold of *L. hesperus* was developed (41). Even programmable calculators have been used to calculate economic injury levels (157). User inputs into this program are the approximate growth stage, estimated price of crop, control costs, and an estimate of damage-free yield.

Models and Pest Management

Figure 6 depicts how models might be used in pest management programs. Updates of weather and economics together with current plant and arthropod dynamics would be used to calculate forecasts, strategies, tactics, and their side effects. From these, action levels could be predicted and used in decision sampling, or action decisions could be calculated directly by the computer with or without field validation. The decision to sample or not to sample might be based on the calculated reliability of action decisions. If the decision to take action has a high degree of reliability, field validation sampling may not be necessary. However, if the action level cannot be calculated because of low reliability, then either decision or validation sampling may be needed. Also, if the areawide update sampling reveals a very low or very high risk situation, then again decision or validation sampling may be unnecessary. When decision or validation sampling becomes necessary, the sampler will enjoy the benefit of possessing computer tactic recommendations, calculated action levels, and computer management decisions to assist in making the final, in-field, decisions.

There is the need to make a careful distinction between decisions that should be made in the field and decisions that can be made by computer. As the reliability of computer models increases, more and more decisions should be made by computer to decrease the labor and expense of field sampling. However, some field validation or decision sampling may be needed for the foreseeable future.

Conclusions

The essential value of the action level and the inaction level is that their use improves the probability that increases in yield, as a result of decisions made regarding the choice of tactics and strategies employed, will justify the costs of pest management. Yield may also include the value of the commodity to agribusiness as well as to the consumers of the commodity. A change in the action level may be detrimental or beneficial to either group.

The costs of pest management are not simply the

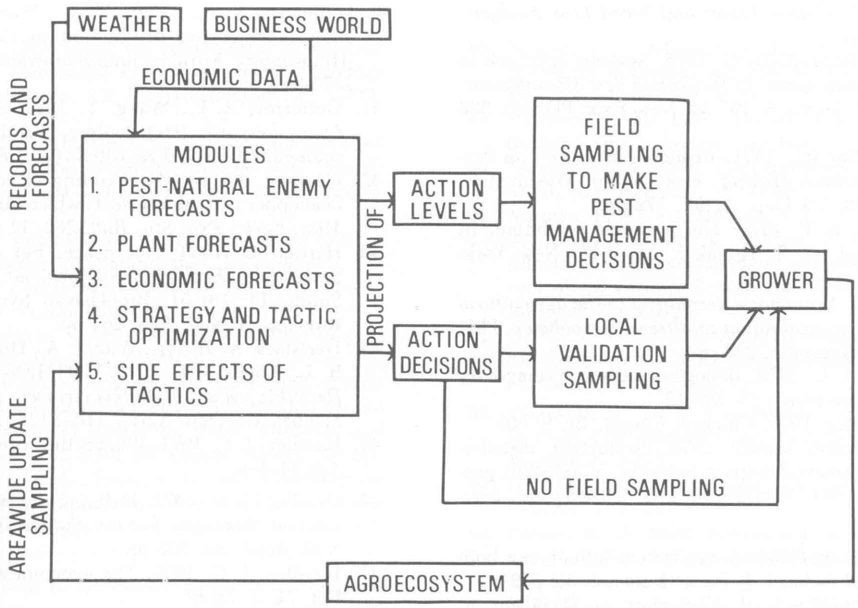

Figure 6. Schematic of the basic components of an action level system with options (Modified from Ruesink 114).

costs of control tactics (e.g. chemicals, parasite releases, pheromones, application costs, etc.); they also include the ecological costs that are the result of deterioration of the ecosystem which in turn is associated with monoculture cropping, pesticide application, and the misuse of fertilizers and irrigation.

However, the long-term goal of pest management research should be to develop nondisruptive, preventative strategies that totally eliminate the need for action levels, since the latter are useful only in conjunction with emergency action tactics rather than with the preferred preventative strategies.

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