Chapter 7

TOWARD COMPREHENSIVE ECONOMIC THRESHOLDS FOR CROP MANAGEMENT

W. L. Sterling, A. W. Hartstack and D. A. Dean
Department of Entomology
Texas A&M University
College Station, Texas

INTRODUCTION

Simple economic thresholds (Pedigo *et al.*, 1986; Poston *et al.*, 1983) focus primarily on the numbers of pests or their injury sufficient to cause economic loss to some commodity. These simple economic thresholds usually constitute two-dimensional verbal or graphical models consisting of pest numbers (or injury) and yields (or profits). Notable attempts have been made to add variables to the basic model (Benedict *et al.*, 1989; Brown *et al.*, 1979b; Gutierrez and Wang, 1984; Headley, 1972; Onstad, 1987; Pedigo *et al.*, 1986; Ring *et al.*, 1989, 1993; Southwood and Norton, 1973; Sterling, 1979; Sterling, 1984; Sterling *et al.*, 1992; Stern *et al.*, 1959; Stern, 1973; Wilson, 1985). The trend is to include more and more variables in the calculation of economic thresholds with the goal of developing comprehensive economic thresholds (Pedigo *et al.*, 1986), that may ultimately account for all variables influencing costs, benefits and profits of a crop management tactic.

Many factors play a role in determining comprehensive economic thresholds. Pedigo *et al.* (1986) modified the equation of Southwood and Norton (1973) to include market value of the crop, management costs, injury per insect density, host damage per unit of injury and proportionate reduction of the insect population. Onstad (1987) suggests the need for multiple and multidimensional economic injury levels for each of several control tactics if they are available. Stern (1973) showed that economic thresholds need to be qualified in terms of local climatic conditions, time of year, stage of plant development, crop involved and its purpose, plant variety, cropping practices, the desire of people, and economic variables. Unfortunately, these authors did not have a multitrophic, multipest, multifactor, dynamic computer model at their disposal with which to integrate these multiple factors, so in practice, most economic thresholds developed for use in pest management programs have been simple economic thresholds. The models of Nordh *et al.* (1988), Pedigo *et al.* (1986) and Onstad (1987), provided important new concepts for understanding the economic criteria of Stern (1973). They emphasize the importance of the multidimensional needs of decision systems, however, they focus on dynamic pest injury thresholds. In contrast, control costs or benefits of control are the focus of TEXCIM for Windows. Thus, TEXCIM overcomes a major limitation (Pedigo *et al.*, 1986) of simple economic injury levels that cannot integrate multiple criteria of pests and environments.

When expanding the simple economic threshold from one focused narrowly on pests to all factors affecting the profitability of crop management, a flaw in the conceptual basis of the simple economic threshold becomes apparent. The simple economic threshold attempts to filter the flow of information through pest numbers (or pest injury) to reach a management decision (Figure 1). Because of the profit motive

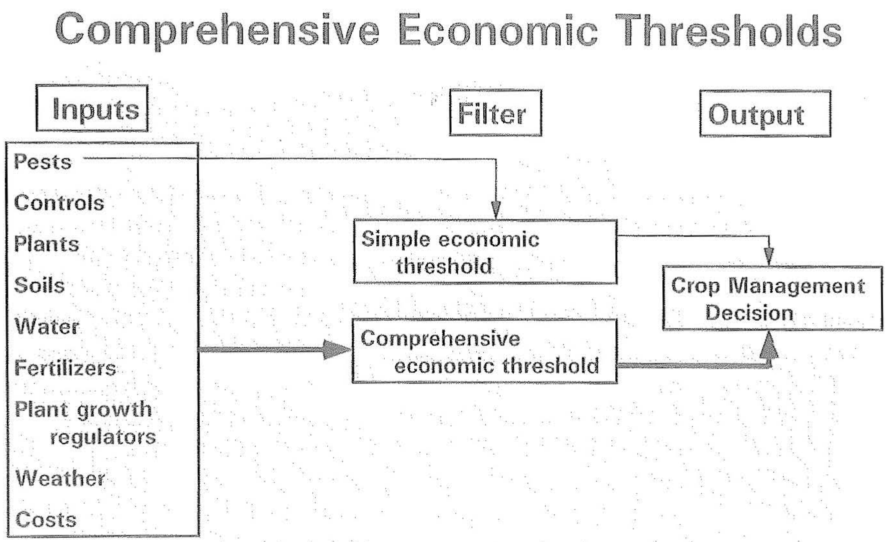

Figure 1. Filtering information inputs through a simple and comprehensive economic threshold to make dynamic crop management decisions.

of cotton crop production systems, economics provides a foundation through which all other components of the system can be filtered. Management decisions are fundamentally economic, so it makes little sense to force the flow of information through a feedback loop containing pests or injury to reach a management decision. Because of its focus on pests, the simple economic threshold has not been useful for making other crop management decisions such as irrigation, fertilization or application of plant growth regulators.

Building on the multidimensional foundation, we suggest an economically and ecologically based, dynamic, economic threshold as a further improvement of comprehensive economic thresholds for use in making tactical cotton crop management decisions. We define the economic threshold in economic terms rather than in numbers of pests or their injury. The economic threshold is reached when the forecasted marginal costs of a management tactic equals the forecasted marginal benefits accruing from the application of a crop management tactic. This definition is consistent with that of the National Academy of Sciences (1969) for a critical pest density at which "... the loss caused by a pest equals in value the cost of available control measures," except that the focus of this definition is still on the pest. "The cost of the control measure balanced against the increased value of crop that can be recovered or protected" is the ideal way to determine when to apply a pesticide (Stern, 1973). Using multidimensional models such as TEXCIM50 (Sterling *et al.*, 1992), TEXCIM for Windows (Sterling *et al.*, 1993), TEXCOT (Unpublished data, J. A. Landivar, Texas A&M University, Corpus Christi, Texas) or ICEMM (Landivar *et al.*, 1991), it is possible to simulate the effects of many variables simultaneously, rather than focusing on a single pest density or its injury. If we assume that costs and the economic thresholds are fixed, then the comprehensive economic threshold is reached if future benefits increase to equal the economic threshold (Figure 2). In other words, profits minus losses equal zero. If benefits increase so that they exceed the costs, treatment is justified. If costs exceed benefits, treatment is not justified.

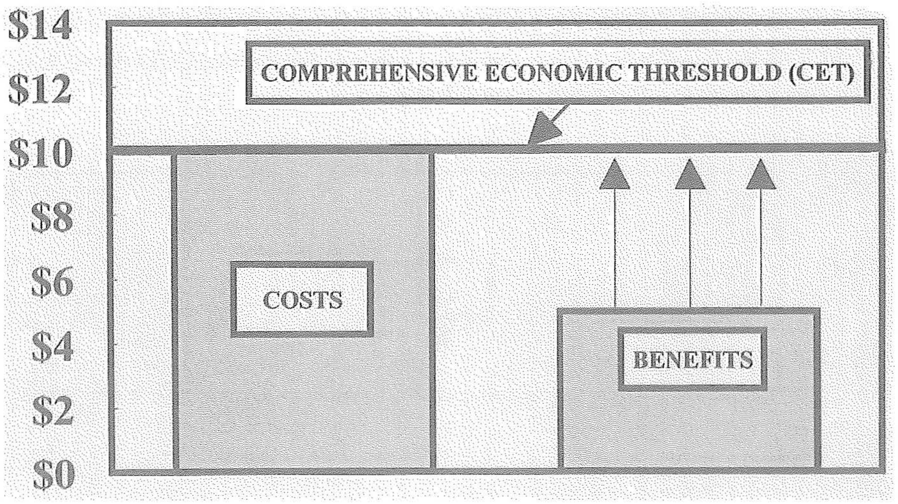

Figure 2. The comprehensive economic threshold has been reached when future benefits of a crop management tactic equal the cost of applying the tactic.

Neither costs, benefits, nor comprehensive economic thresholds are fixed; they are all dynamic. They change constantly as pests, economics, plant growth, control tactics and weather change (Figure 3). Costs, benefits, and the economic threshold may not increase or decrease simultaneously. Any one or two may increase while the others decrease. Models, such as TEXCIM, estimate these variables by making forecasts of insect and plant dynamics and translating numbers into economics. Benefits that exceed the comprehensive economic threshold constitute the profit of control (Figure 4).

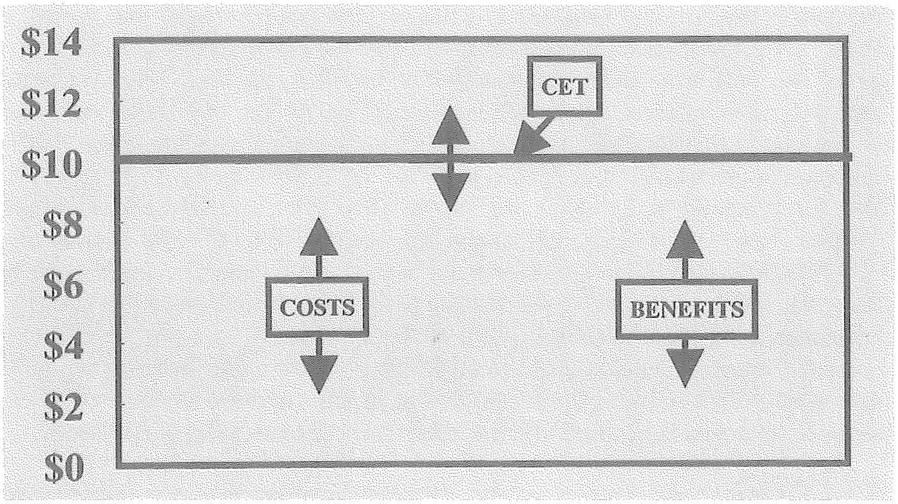

Figure 3. Costs, benefits and comprehensive economic thresholds (CET) are not fixed, they may increase or decrease independently.

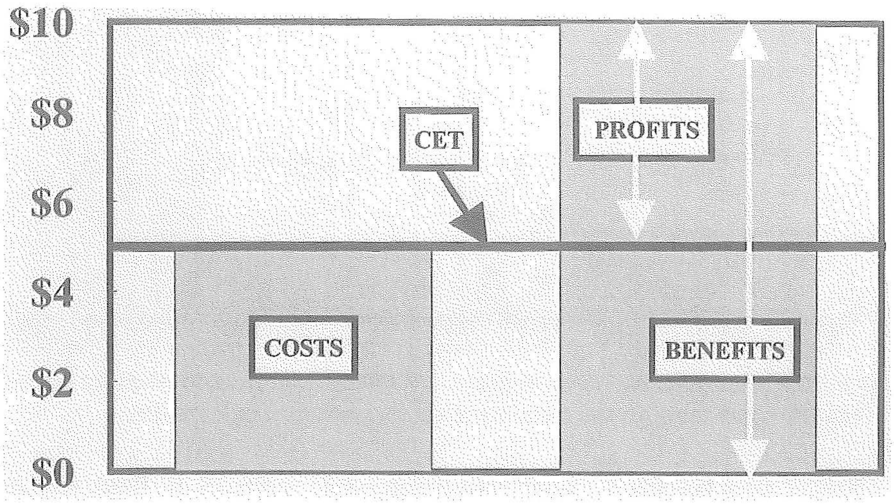

Figure 4. When benefits exceed costs, the difference is expected profit.

Computer models can now integrate many different factors simultaneously. Crop yield depends not only on pest numbers but also on any other factor that affects plant or pest growth and development. For example, a drought-stressed cotton crop might not profit from pest control. However, two inches of slow rain on drought-stressed cotton changes the economics of pest control. Any factor, such as rain, nitrogen application, pests, predators and parasites together with any combination of soil types, crop varieties, expected price of cotton and expected yield, will change the economics of pest control, and other crop management decisions. Thus, to focus on one factor only, such as the density of pests or their injury, cannot provide reliable forecasts of the benefits of pest control. We believe that a focus on economics and pests simultaneously constitutes the best foundation for the synthesis of a modified, comprehensive, economic threshold based on economics.

In this chapter, we investigated the effect of multiple variables and their interactions on the economics of managing cotton insect pests. We also expand the comprehensive economic threshold to include other crop management decisions such as irrigation, fertilization, application of plant growth regulators and pest control.

We focus on a revised definition of economic threshold because the TEXCIM family of models help define a modified concept of the economic threshold that is dynamic and based on economics. Only by having dynamic models of the pests, their natural and introduced enemies, and the plant, is it possible to accurately estimate comprehensive economic thresholds for any particular time and place.

MANAGEMENT DECISIONS

The function of the comprehensive economic threshold is to assist in making all crop management decisions. Although most of the following discussion uses pest examples, the process should be applicable to most crop management decisions. If benefits exceed costs, the correct decision is to treat. The magnitude of the difference between costs and benefits is not critically important in making pest management decisions as long as the major costs and benefits of control are included in the calculations. If benefits are less than costs, the correct decision is not to treat. Another function of the economic threshold is to determine the magnitude of profits or losses, as depicted in Figures 4 and 5.

When costs are subtracted from benefits, the difference is profits. The profit potential of pest control may be analyzed by comparing costs and benefits of a treatment (Sterling *et al.*, 1992). For example, if the cost of control is $4.00 and the benefit is $7.00, then profit is $3.00 ($7.00 - $4.00 = $3.00). This calculation appears simple. However, these costs and benefits are composed of many sub-costs and sub-benefits (Figure 6). Control costs are <u>not</u> exclusively the costs of an insecticide and its application. Control costs include investment in consulting, insurance premiums, interest charges, costs of pest resistance that develops from the use of insecticides, resurgence of pests after insecticides kill natural enemies, health costs, and environmental costs. All costs and benefits estimated by this model are internal (single farm) only and do not include external costs to others.

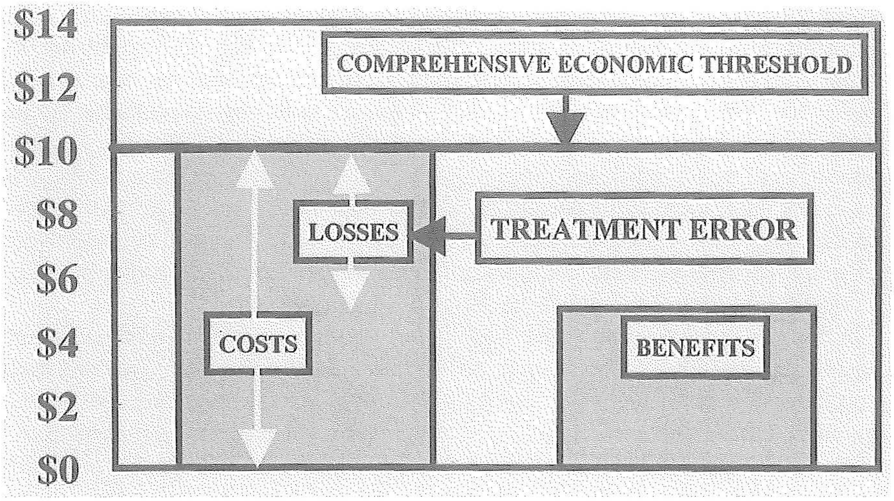

Figure 5. When costs exceed benefits of control, the difference is expected economic losses and indicate a treatment error.

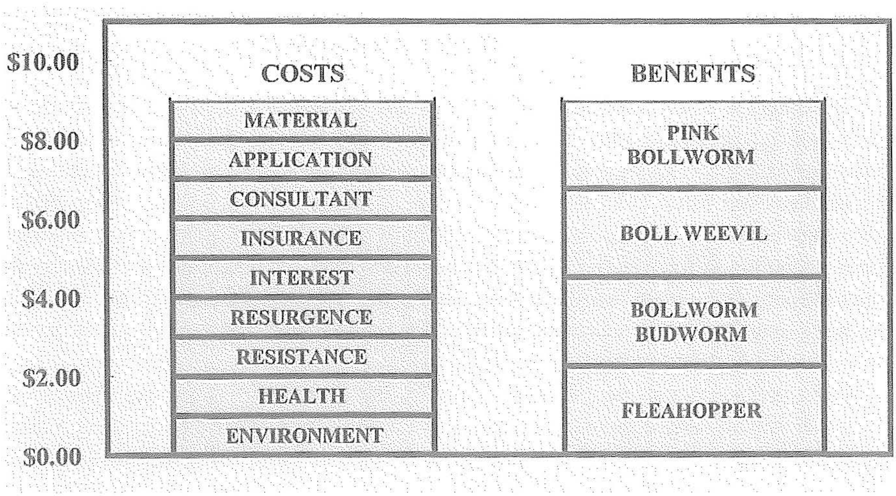

Figure 6. Allocation of costs and benefits for crop management.

COSTS

The costs of materials (usually insecticides) are often variable throughout a growing season. If an outbreak of pests expands the demand for a particular insecticide, the cost of this insecticide may increase if a shortage results. Thus, insecticides are not a fixed cost of cotton production. If pest control tactics other than synthetic insecticides are used, such as predator or parasite releases, their costs must also be considered.

Application costs may vary throughout the season and between years. Applications by ground rig may be cheaper than by air. Ultra-low-volume applications may be cheaper than high-volume rates. Thus, application costs are not usually fixed.

Another major cost is consulting. The farmer may hire a crop consultant to assist in making crop management decisions such as those related to irrigation, fertilization, plant growth regulators, or insect, disease, and weed control. To run TEXCIM, a consultant needs to sample pests, predators, parasites, plant fruiting rate and other items. The ICEMM model requires samples of soil hydrology, soil nitrogen, soil type, organic matter, fruit for plant maps and various cultural inputs, in addition to those parameters required by TEXCIM. Weather conditions should also be monitored. Reliable sampling should lead to more profitable management decisions or the investment in sampling information is not prudent.

If an insurance policy has been purchased to cover potential litigation from the movement of an insecticide to a neighbor's property, then this cost must also be added to the cost of control. Because an insurance policy may also cover other farm-related risks of litigation, only the fraction of the policy costs that applies to pest control should be considered.

The cost of interest depends on whether the money used for pest control is borrowed from a financial institution or supplied by the grower. Investments in pest control must at least make a return equal to the interest that could be generated by other investments such as bank savings accounts, stocks, bonds, etc. The interest that could be generated with other investments constitutes a cost of control. If one borrows money from a bank for pest control, the interest paid must be added to the cost of control.

Resurgence costs constitute the difference in profit or loss when natural enemies are present, compared with the loss of natural enemies after insecticide control. If an application of an insecticide triggers an outbreak of a target or non-target pest that would not have happened without an insecticide, the difference in cost is, in part, due to resurgence.

If a higher dose of an insecticide is needed in the second application than in the first application, the difference in cost may, in part, be attributed to the cost of resistance. Or, if the same dosage of an insecticide is used with a second application but increased losses result, some of these losses may be attributable to resistance. If more frequent applications are needed to control a pest, the difference in the cost of insecticides or loss in yield constitutes part of the cost of resistance.

If the farmer, his family or farm workers are exposed to agricultural chemicals, there may be a short- or long-term health cost to the farmer, his family or employees. Often the health-related costs of insect control are delayed so they do not appear for years after chemicals are applied. This is especially true of chemicals linked to cancer, or that disrupt the endocrine and immune systems, or lower resistance to disease (Misch, 1993). Because of delayed effects, it will be difficult to know the annual health costs of chemical control. Therefore, these costs cannot be known, but can be estimated.

Using the TEXCIM for Windows model, a self-imposed (by the farmer) environmental cost is designed to address the value of not using toxic insecticides. If the pest manager has limited concern for the environment, this cost can be set to zero. Otherwise, the farmer can choose $0.25 per acre or some other amount. This self imposed cost can be interpreted as a value to the farm of not applying toxic chemicals. Those who eschew the use of toxic chemicals could claim that it would be worth $0.25 per acre not to use toxic chemicals.

All these costs are variable throughout the growing season. Some, such as health costs and insurance, can be assumed to be constant. In many cases, some costs will not be present. For example, if no insecticides are used, many costs are eliminated.

It is critically important to understand that these costs will change between fields, farms and years. Consequently, to obtain the most accurate estimate of costs, each management unit (field or farm where conditions are similar but different from other locations) will need to be considered separately.

BENEFITS

The expected crop loss can be viewed as an expected benefit accruing to the farmer if the loss is prevented with pest control. Throughout the remainder of this paper, we use the term "benefit" rather than "cost" or "loss." At first this terminology may cause confusion because pests usually do not cause benefits. Benefits are obtained only if pests are controlled; if pests are not controlled then these benefits translate into costs or losses. We choose to use the term "benefits" to be consistent with conventional usage of cost/benefits among economists. Also, there is a precedence for this choice established by Stern, 1973; Headley, 1972; and Gutierrez and Wang, 1984.

Economic benefits of control include those obtained from controlling all injurious insects simultaneously. TEXCIM currently estimates the additive benefits of cotton fleahopper, bollworm, boll weevil and pink bollworm control. If an insecticide is applied that kills some of these pests and not others, then benefits will accrue only from those killed. An insecticide that is effective against one of these insects will not result in a benefit from control of all insects. TEXCIM for Windows partitions benefits accruing to each pest controlled.

The ability to forecast the economic benefits of pest control is one of the most powerful features of this model (Figure 7). By comparing the losses in a treated cotton field compared to an untreated one, the benefits of controlling all pests can be estimated. Forecasts are accomplished by using a multitude of factors that affect the reproduction, growth and death of each insect and cotton fruiting structures. The time required for an insect to complete development, or a fruit to mature, depends largely on temperature. Organisms generally grow faster and reproduce more rapidly in hot than cold conditions. They lay more eggs when their food quality is high, and

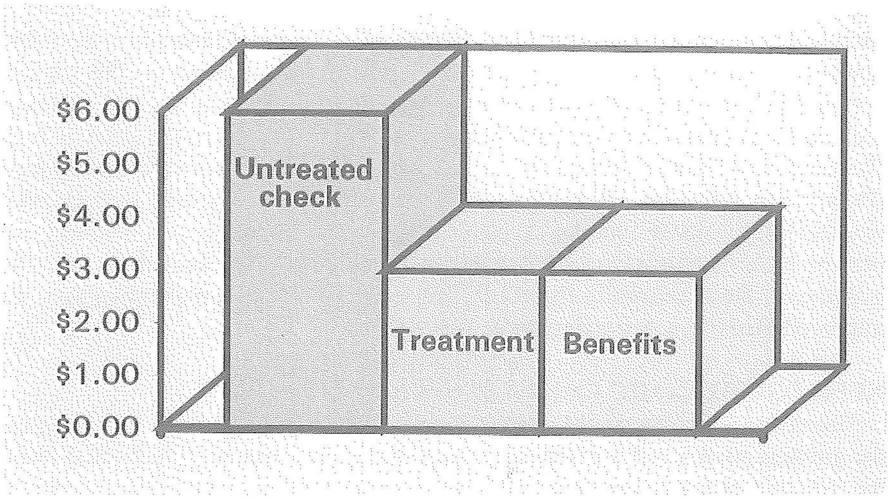

Figure 7. Forecasted benefits calculated as the difference between losses in an untreated check and a treated plot.

more die when their natural enemies are abundant. Temperature, rain, food quality and natural enemies are only a few of the many variables that operate within the model to make forecasts. It is virtually impossible for the human mind to simultaneously take all these factors into consideration in making management decisions. Computers are uniquely qualified to make these simultaneous calculations and forecasts.

MARGINAL COSTS, BENEFITS AND PROFITS

All the costs, benefits and profits mentioned are "marginal" in the sense that they are the consequences of making a future treatment and do not represent the cumulative consequences of multiple treatments in the past. For example, if two treatments have been made and we wish to estimate the economic consequences of an additional treatment, this third treatment is the "marginal" treatment. "Marginal" is a term with a long history of use in economics, which we have adopted to help explain the application of economics to pest management decisions.

ECONOMIC THRESHOLDS AND CURRENT MANAGEMENT

The economic threshold has been the cornerstone of integrated pest management (National Academy of Sciences, 1969). Unfortunately, reliable economic thresholds still exist more in theory than in practice. Some criticisms of economic thresholds are that they seldom: (a) consider the simultaneous interactions of multiple pests, (b) integrate the impact of multiple natural enemies of the pests, (c) are dynamic concerning plant development, or (d) change with expected lint prices. Consequently, economic thresholds in current use and those that have been proposed should be used with caution. On the other hand, the use of economic thresholds in pest management programs have shown potential in spite of their weaknesses. Six on-farm cotton IPM trials using economic thresholds reduced insect control costs, increased yield in 50 percent of the cases and reduced costs in 66 percent of the cases in Texas (Lacewell and Masud, 1985). The same trend exists in other agricultural systems (Frisbie and Adkisson, 1985). Thus, the economic thresholds used in these trials were an improvement over the exclusive reliance on calendar day insecticidal control and have functioned as useful "rules of thumb." However, as with any working hypothesis, these economic thresholds are subject to replacement when new and improved methods become available.

NEED FOR DYNAMIC CRITERIA

Simple economic thresholds have often been expressed as a constant throughout the growing season or for extended periods during the growing season. Because of the dynamic nature of the crop and insect numbers, dynamic economic thresholds have been recommended. Brown *et al.* (1979a) developed dynamic economic thresholds for bollworm, Curry and Feldman (1987) for boll weevil, and Gutierrez *et al.* (1979) for western lygus bug, *Lygus hesperus* Knight. These authors concluded that there is a need to replace static management criteria with dynamic ones but models capable of dynamically calculating these criteria have not generally been available or sufficiently user-friendly for use by crop managers or researchers. These authors apparently accept the notion that a dynamic economic threshold can be based on insect numbers or injury. We believe that replacing the economic threshold based on pest numbers or injury with comprehensive economic thresholds provides an analytical method for avoiding the limitations of the simple economic thresholds and will ultimately result in improved pest management decisions.

MULTIDIMENSIONAL ANALYSIS

Several models have been used to evaluate the impact of multidimensions on the economics of cotton production (Nordh *et al.*, 1988). Various control tactics such as pesticide timing, host plant resistance and natural predation and parasitism were analyzed by Curry *et al.* (1980) using an earlier version of the boll weevil model now incorporated into TEXCIM for Windows. They observed that relatively small reductions in the growth rates of boll weevil populations may provide economic control of this pest. Brown *et al.* (1979b) also evaluated the interactions of the cotton crop and insect pests. Gutierrez *et al.* (1975) investigated the interactions of plant age and beet armyworm, *Spodoptera exigua* (Hübner), injury and observed that the greatest injury primarily occurred during the early squaring period. Similar multiple-component studies have been conducted by Stinner *et al.* (1974a) and Wilson *et al.* (1982). Thus, there is a growing body of literature dealing with the importance of multicomponent models for improving the science of pest management.

MODEL VALIDATIONS

The TEXCIM model was first released for popular use by the Texas Agricultural Experiment Station and was made available through the Texas Agricultural Extension Service in 1988 with version 2.3 (Hartstack and Sterling, 1988b). It was followed by version 3.0 (Hartstack and Sterling, 1989), version 4.0 (Hartstack *et al.*, 1990), version 4.1 (Hartstack *et al.*, 1991), version 5.0 (Sterling *et al.*, 1992) and TEXCIM for Windows (Sterling *et al.*, 1993). These versions constitute multipest, multitrophic, multicomponent computer models. They increase in complexity until the latest versions use field counts of cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter), bollworm, *Helicoverpa zea* (Boddie), tobacco budworm, *Heliothis virescens* (F.), boll weevil, *Anthonomus grandis grandis* Boheman, pink bollworm, *Pectinophora gossypiella* (Saunders), 10 groups of predators, 10 groups of parasites, insecticides, cotton fruit, and local weather to forecast the expected benefits of control. The user's guides are accompanied by protocol for testing the model (Sterling *et al.*, 1989b, 1990b). Other specific methods used in the following simulations are provided as part of the results reported in this paper. An unpublished version currently under development includes ICEMM (Unpublished data, J. A. Landivar, Texas A&M University, Corpus Christi, Texas). In addition to the insects included in TEXCIM, ICEMM includes separate models for the tobacco budworm, the cotton aphid (*Aphis gossypii* Glover) and the sweetpotato whitefly (*Bemesia tabaci* Gennadius).

One important feature of models such as TEXCIM and ICEMM is that they provide a testable and falsifiable hypothesis. Often, models and their code remain in the tight control of their developers so that testing by other parties is very difficult. Versions of TEXCIM and its components have been tested in 26 separate experiments conducted by many different groups of scientists (Sterling *et al.*, 1993). This validation process has consisted of repeated development, testing, revision and retesting as an iterative process that is the essence of the scientific method. These validations lend credence to the value of using the TEXCIM model for the simulations presented in this paper, in commercial pest management, and as a basis for improving future models of this kind.

METHODS FOR ESTABLISHING COMPREHENSIVE ECONOMIC THRESHOLDS

Field experiments can be conducted that will explain the simultaneous effect of several pests (National Academy of Sciences, 1969). But, when all the permutations and combinations of pests (insects, weeds, diseases and nematodes), pest age, plant stage, fruit age, plant cultivar and weather are considered, it becomes virtually impossible to conduct such a field test that will incorporate all these components with each one varying in replicated, multifactorial experiments. The standard method used to determine simple economic thresholds is to use replicated field or caged plots so that a single variable, such as pest density, changes in each treatment while all other variables are held constant. Yields at the end of the year are then used as an index of the impact of different variables such as pest densities. "Because costs involved with developing economic thresholds can be substantial, a resultant effect is that experiments often have either insufficient replication or insufficient damage levels for deriving accurate economic thresholds. An alternative to conducting detailed field threshold trials is to use a crop-pest simulation model with simpler field trials" (Wilson, 1985).

Furthermore, field plot experiments to determine multiple pest effects are very complex. The permutations and combinations of variables in such studies make it unlikely that more than about three or four treatments can be changed in any single experiment. For example, the combinations of just three treatments with four replications each requires 24 plots and four treatments would require 96 plots. Coupled with the general inability to eliminate all variables but one in field plots, an accurate determination of the effect of each variable is unlikely. Also, because of multiple pest interactions the effect of several pests is not simply additive. The benefits of insecticidal control targeted against a specific pest can seldom be attributed to the control of that pest alone when several pests are present simultaneously. Thus, there is a need for multiple-pest decision criteria that are sensitive to plant growth stage and future insect and plant fruiting dynamics. Computer models can handle all these variables and make sense of multiple interactions of herbivores and fruit dynamics. These models can then be tested under commercial and experimental conditions and various components improved as evidence shows the need for such improvement (Breene *et al.*, 1989; Legaspi *et al.*, 1989; Sterling *et al.*, 1989b).

The problems of using field experiments to establish decision criteria are clear from work on *Helicoverpa/Heliothis* spp. conducted around the world. Different authors have found different criteria suitable for their conditions (Adkisson *et al.*, 1964; van den Bosch *et al.*, 1971; Wilson *et al.*, 1982). This evidence supports our hypothesis that benefit/cost ratios will not and cannot be precisely the same in different times and places. The most important observations from the simulations run in this paper is that no single factor such as pest density, lint value or time can be used alone to forecast benefits of control. All these factors must be considered simultaneously.

REDEFINING THE ECONOMIC THRESHOLD

"Economic thresholds can vary with stage of crop development, are modified by whether damage has occurred earlier in the season, vary depending upon the relative abundance of predators, and are affected by season length. They are dynamically associated with the market value of the crop and with management costs" (Wilson, 1985). The definitions of an economic threshold that focus primarily on pest density (Headley, 1972; Stern, 1973; Stern *et al.*, 1959) or pest injury (Onstad, 1987; Pedigo *et al.*, 1986) are approaching obsolescence and a new definition is in order. This is especially true if Pearson (1958) is correct when he asserts that neither pest numbers or their injury are valid indications of yield or quality of lint. A new definition must integrate not only pest numbers or their injury but their economic impact in association with other key factors that affect the economics of pest management decisions. Although all factors affecting the economics of decisions are not currently available in any model, sufficient factors are present in the TEXCIM model (Sterling *et al.*, 1993) to augment the new economic threshold concept.

Another major problem with economic thresholds currently in use is that multiple key variables have not been integrated into their calculations. Thus, the preliminary economic thresholds that were developed and used in pest management programs were simplistic and could not always be accurate in all places. Although it was obvious long ago that the economic threshold would be a function of local climate, time of year, stage of plant development, plant variety, cropping practices and economic variables, the methods and tools for calculating or forecasting such a level were not available (Smith, 1971). A comprehensive economic threshold concept has been slowly evolving so that factors such as control costs, crop phenology and multiple species are now sometimes considered in making management decisions. Southwood and Norton (1973) determined that economic damage was a function of yield, price per unit of yield, level of pest injury and control actions. These additions were only a beginning compared with the complexity needed to make consistently accurate pest management decisions.

TEXCIM provides information useful in making management decisions concerning the need for insect control. Field tests of an earlier version, TEXCIM30, showed that correct decisions were made greater than 95 percent of the time (Legaspi *et al.*, 1989) compared to simple economic thresholds. Whether the error is on the side of taking action when none is needed (treatment error) or taking no action when a need exists (no-treatment errors), dynamic models such as TEXCIM for Windows should prove useful.

Some of the first order components of the TEXCIM50 model are presented in mnemonic form (see Sterling *et al.*, 1989a for more details) where f is a function:

MGDC = management decisions
MGDC = f(BC,CET)

- 1.0 BC = benefits of pest control (forecasted cost of pest injury)
  BC = f(CVA,IIJ,CS)
  - 1.1 CVA = value of crop (see Sterling *et al.*, 1989a for multiple subcomponents)
  - 1.2 IIJ = injury by insects
    IIJ = f(HIJ,BIJ,WIJ,PIJ)
    - 1.21 HIJ = fleahopper injured fruit
      HIJ = f(HNU,HAG,CAG,HFP,HSF,HPF)
      - 1.211 HNU = numbers of fleahopper (includes 37 sub-components)
      - 1.212 HAG = fleahopper age
      - 1.213 CAG = crop age

1.214 HFP = fruit age preference of the fleahopper
1.215 HSF = number of susceptible fruit
1.216 HPF = probability of fleahopper finding a fruit
1.22 BIJ = bollworm-tobacco budworm injured fruit (See Sterling *et al.*, 1989a for multiple sub-components)
1.23 WIJ = boll weevil injury (See Sterling *et al.*, 1989a for multiple sub-components)
1.24 PIJ = pink bollworm injury (sub-components about same as for fleahopper).
1.3 CS = costs of pests surviving control
2.0 CET = comprehensive economic threshold
CET = f(INCO,IRS,IRE,INPO,ISCO,HECO,APCO)
2.1 INCO = insecticide cost
2.2 IRS = resurgence of insects
2.3 IRE = increased insecticide resistance
2.4 INPO = environmental pollution with insecticides
2.5 ISCO = insurance cost
2.6 HECO = health cost
2.7 APCO = application costs
APCO = f(LACO,EQCO)
2.71 LACO = cost of labor
2.72 EQCO = cost of equipment

Most of the components of the TEXCIM for Windows model can be found in a synthesis of TEXCIM40 (Sterling *et al.*, 1989a). This synthesis provides an abbreviated verbal description of the various components that play a role in forecasting benefits of pest control and references documenting mathematics and functions.

TEXCIM SIMULATIONS

The methods used here are a form of sensitivity analysis where a parameter or state variable is changed over a reasonable range to simulate expected benefits of controlling a particular pest or group of pests. A complete set of data on insect pests, predators, fruit, and weather is available from experiments conducted at Snook, Texas during 1989. These data, or parts of the set, were used for many of these sensitivity analyses. To determine the benefits of pest control, simulations were run using the TEXCIM50 model (Sterling *et al.*, 1992).

The following simulations are not designed to provide fixed benefits of value at any particular time or place, but to demonstrate the variability of control benefits that are conditional upon multiple factors. In order to determine these benefits for any particular time and place, it is necessary to enter current information on insect pests, predators, fruit counts and weather into the TEXCIM50 or TEXCIM for

Windows model and run it. An example of a complete data set used in these simulations is provided as example files provided with a copy of TEXCIM for Windows.

JUSTIFYING A CONTINUUM

The Texas Agricultural Extension Service cotton insect control guide (Knutson *et al.*, 1993) provides simple economic thresholds of the cotton fleahopper that vary from 10 to 15 fleahoppers per 100 plant terminals during the first three weeks of squaring. At the appearance of first bloom the threshold increases to infinity and the crop supposedly can tolerate any number of fleahoppers. There are two elements of these thresholds of interest: (a) they are dynamic in the sense that they change at least once during the growing season and (b) a range of thresholds (10 to 15 percent) is provided as an option for the pest manager. Testing with the TEXCIM40 model (Hartstack *et al.*, 1990) indicated that neither the 10 percent or 15 percent threshold was likely to be accurate for all cotton production systems. For example, the economic threshold is unlikely to change from 15 percent to 100 percent in one day (date of first bloom). This change is more likely a continuum of the type shown in Figure 8. Benefits change continuously over time, not in two discrete steps. Under

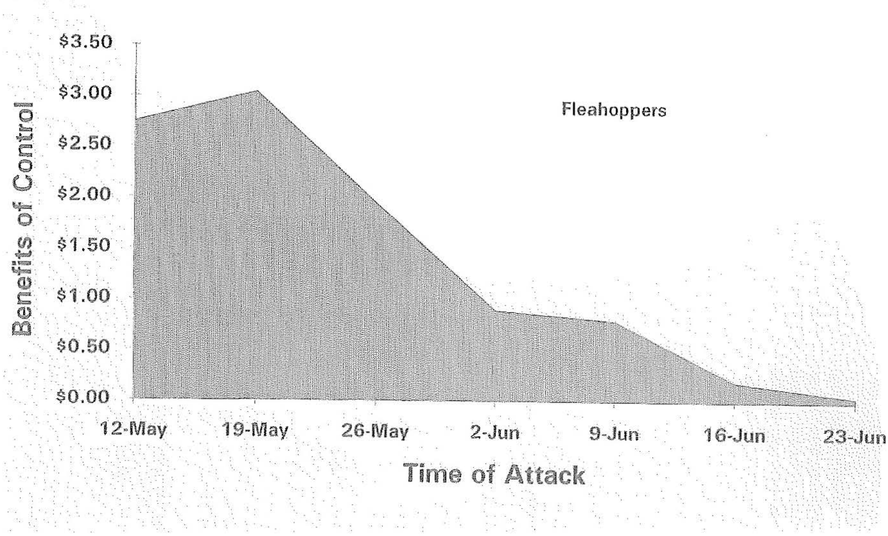

Figure 8. Benefits of cotton fleahopper control as a function of the time of attack during the growing season.

the scenario used in this example, the time of fleahopper attack was simulated on May 12 when a total of 15 fleahoppers per 100 plants were entered to mimic the lower economic threshold. The time of injury was then changed with all 15 fleahoppers entered on May 13, then on May 19 and so on until at last 15 fleahoppers were entered only on June 30. The same number of fleahoppers were entered at weekly intervals from the time of first square until after first bloom. The benefits of controlling these fleahoppers were highest at the time of first square and declined until about the time of first bloom. Thus, the decline in benefits of fleahopper control forms a continuum of costs from a high of over $3.00 per acre to $0.00 on June 23. The magnitude of benefits will vary in other cotton fields in other years, but changes should form a continuum similar to Figure 8. In other words, the benefits of controlling 15 fleahoppers per 100 plants changes continuously as a function of the time of attack on the cotton plant.

FACTORS DETERMINING THRESHOLD VALUES

Time of Insect Pest Attack — Onstad (1987), Ring *et al.* (1993) and Wilson (1985) emphasized the importance of including time in relation to numbers of pests changing over time. TEXCIM50 was used to test the hypothesis that time is important as it relates to other factors. Field counts of bollworm eggs and small larvae formed a pulse (a single peak) that lasted about one month during 1989 at Snook, Texas. This pulse, represented by peak abundance of 1.4 eggs and 0.3 larvae per 3.1 feet (1 meter of row) was entered into TEXCIM50 and run at 2-week intervals starting at the time of first square to simulate the change of control benefits as a function of time of attack. Data on other pests and insecticides were not included with this run of the model. All variables were held constant except time of attack. The price of lint was set at $0.62 per pound and the target yield at 1.2 bales per acre (dryland).

Under the above scenario, the benefits of controlling a single pulse of bollworms changed dramatically from $20.00 per acre to about $4.00 per acre, at different developmental stages of the cotton crop (Figure 9).

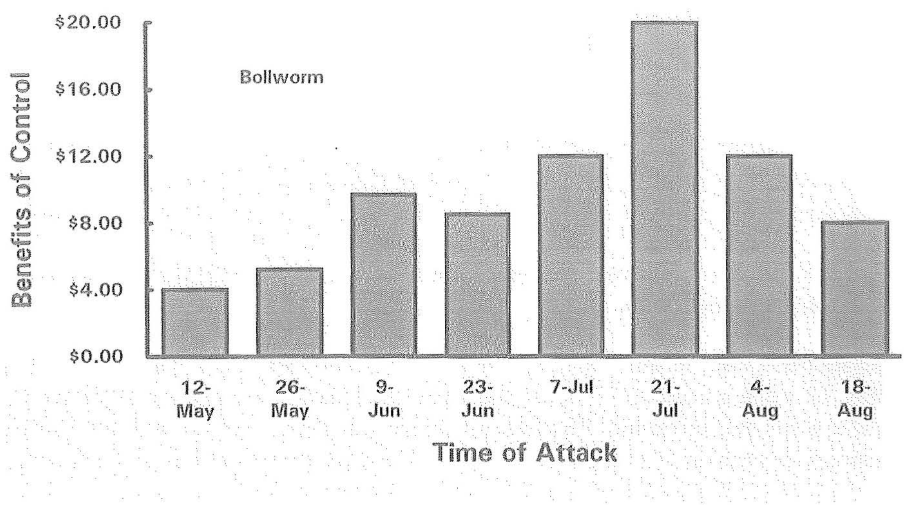

Figure 9. Forecasting the benefits of bollworm control when the time of attack varies during the growing season.

In general, developmental stage of the plant is an important factor in determining the benefits of bollworm control. It is clear from this simulation, that basing a decision on the presence of any pest would be inaccurate if the same criterion were entered at different stages of plant growth. Under other scenarios, including other insects or insecticide use, the pattern of benefits attributable to bollworm control would be different. However, based on this simulation it is reasonably certain that benefits of bollworm control will be, in part, a changing function of the time of bollworm attack. Only a dynamic crop-insect-predator model could begin to integrate changes over time in such a dynamic fashion to forecast benefits of control.

Geographical Variation: Bollworm — Historical weather data from Lubbock, College Station and Weslaco, Texas were entered with the same bollworm pulse (same as the "time" simulation used above) to simulate the impact of weather at three locations on benefits of bollworm control. The same numbers of bollworm were entered for each geographical area and other factors were held constant. This simulation forecasts the benefits of bollworm control at three locations that exhibit different weather patterns. In general, location and its associated weather did not have a major impact in that benefits of bollworm control varied little among areas. In other words, TEXCIM50 was not very sensitive to weather differences at the three geographical locations under the conditions of this simulation. The greatest difference was only $1.65 between Weslaco and Lubbock with essentially no difference between Weslaco and College Station (Figure 10). In any given year, the economics of pest control between geographical areas is likely to be sufficiently different so that forecasts in one area are unlikely to be accurate in another, even with the same number of pests. This conclusion speaks to the importance of making independent pest management decisions for each field or management unit.

Geographical Variation: Boll Weevil — Studies designed to identify factors causing mortality of boll weevil in Texas produced a clear pattern of the impact of mortality resulting from heat and drying (Sterling *et al.*, 1990b; Sturm *et al.*, 1990; Sturm and Sterling, 1990). Average drying-caused mortality increased westward from the eastcoastal region to the midwestern region. Drying-induced mortality averaged 9 percent in the eastcoastal region, 30 percent in the northcentral region and 57 percent in the midwestern region of Texas. Benefits to the farmer from boll weevil mortality from drying can be calculated using the TEXCIM model. The greatest benefits of death caused by drying should occur in western regions of Texas. Benefits of boll weevil control at Snook, Texas were compared to benefits at Pecos, Texas. Snook characteristically enjoys high rainfall whereas Pecos is substantially dryer and hotter during the growing season. Therefore, it is intuitive to expect more boll weevil mortality caused by drying at Pecos than at Snook. Historical weather data were entered for each location, no predators were entered, and 15 percent weevil injured squares were entered three weeks after the first square. The benefits of boll weevil control was $70.37 more at Snook than in Pecos (Figure 11). This may be interpreted as a $70.37 potential benefit that farmers at Pecos enjoy because of

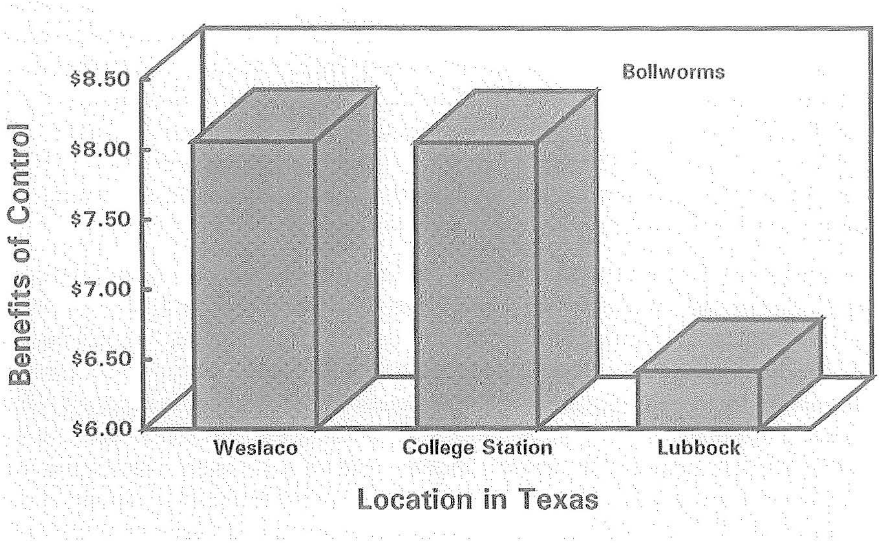

Figure 10. Simulated benefits of controlling identical numbers of bollworms at first bloom at three locations in Texas.

heat and drying if insecticides are not used. Of course this benefit may be offset by other costs of cotton grown in a dry climate.

Lint Value — The quality of lint affects its value and anything that affects the value of lint will change the economic threshold. If control measures are not undertaken at the appropriate time, there may be increased costs for washing, brushing, trimming, sorting or grading the crop at harvest. The value of fruit is a function primarily of time of the growing season and age of fruit (Hartstack and Sterling, 1988a; Stewart, 1987; Stewart and Sterling, 1987). As fruit mature they become more valuable because they are less likely to shed due to minor stresses. Thus, an open boll is more valuable than a square, bloom or green boll.

Field data for bollworm, predators and weather for Snook, Texas were again entered into TEXCIM50. Lint value alone was changed with each run. The benefits of bollworm control is a linear function of lint value (Figure 12). If lint was valued at $0.50 per pound, the pulse (peak) of bollworms realized a control benefit of only about $17.00 per acre. When the value of lint increased to $1.00 per pound, the benefits of bollworm control increased to about $33.00 per acre. Thus, decision criteria are dependent on lint value.

Planting Date — Simulations of the benefits of bollworm control were based on changes in planting date at 5-day intervals starting April 8 and ending June 3. All other factors including bollworm numbers and harvest date were held constant and based on field count data for the Snook, Texas untreated field during 1989. Numbers

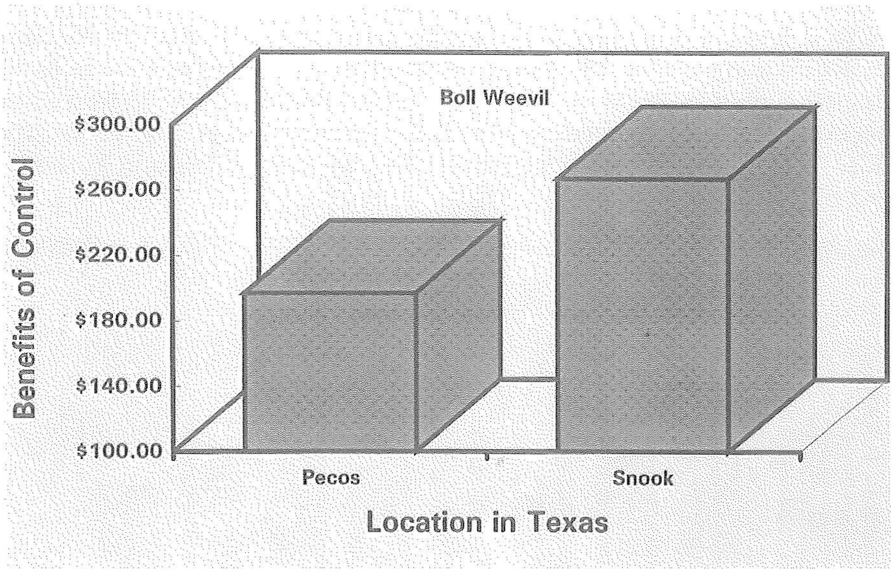

Figure 11. Geographical variation in benefits of boll weevil mortality caused by drying in Texas.

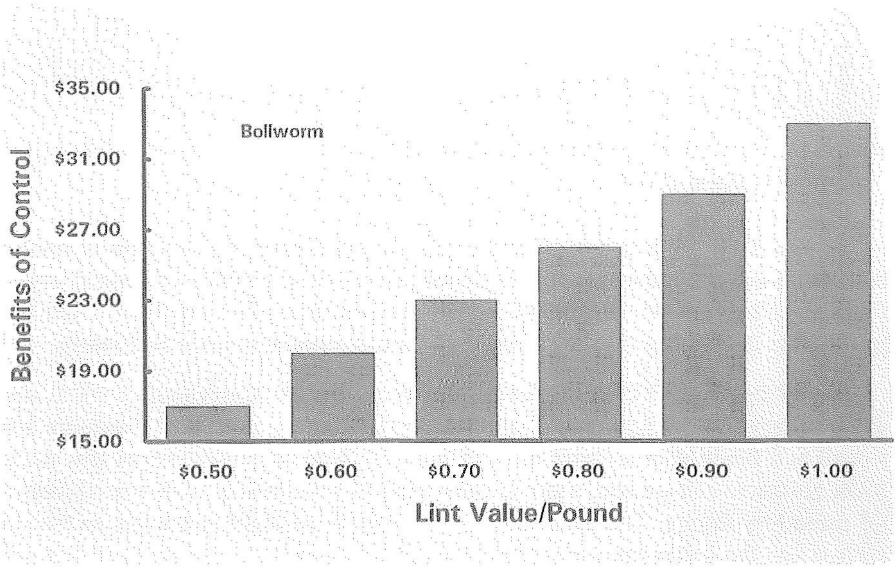

Figure 12. Benefits of controlling constant numbers of bollworms as a function of lint value.

of naturally occurring predators were included. Benefits of bollworm control were partly a function of planting date. Benefits varied little until May 20 then they declined rapidly (Figure 13). Data presented here should not be used to justify changes in planting date in any particular area since planting date will have a different impact on yield and crop value, in part as a function of area or geographical location. TEXCIM must be run using current data from each geographical location to provide reliable forecasts.

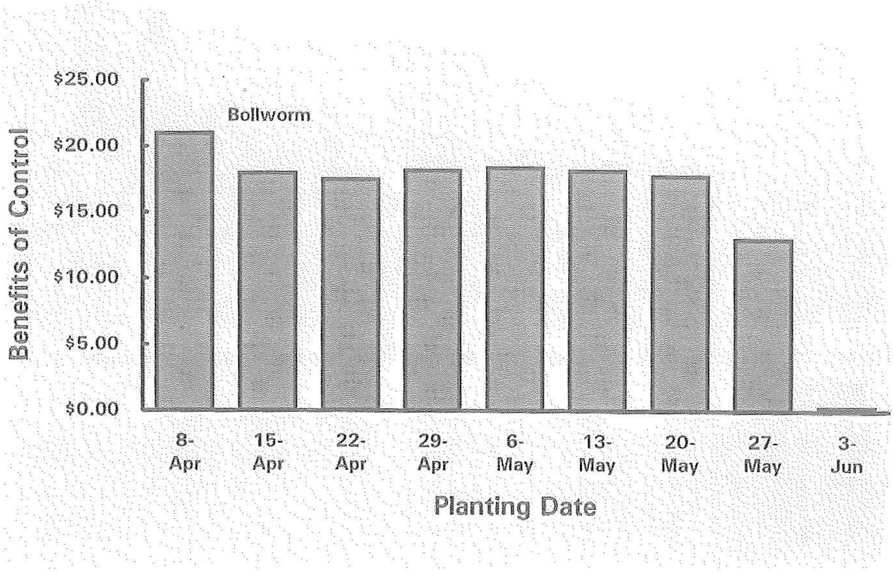

Figure 13. Benefits of controlling constant numbers of bollworms as a function of changes in planting date.

Harvest Date — Benefits of controlling the bollworm is a function of harvest date. With the particular scenario of Snook, Texas data, benefits of control were a function of harvest date (Figure 14). A later harvest date allows bollworm numbers to continue developing late in the growing season, causing greater boll injury.

Row Width — TEXCIM contains a boll weevil model (Curry *et al.*, 1982; Curry and Feldman, 1987; Schoolfield, 1983) that simulates mortality of immature boll weevil as a function of temperature and humidity. One of the features of this model is the ability to change row width to determine its relationship with weevil mortality caused by drying. The wider the rows, the more sunlight penetrates to the soil surface and the hotter the surface becomes. Weevils on hot soils die from heat and drying. The TEXCIM50 model was used to simulate the impact of 10- to 50-inch row widths, changed at 10 inch increments and holding all other factors constant. Temperatures entered were from historical average temperatures from Pecos, Texas.

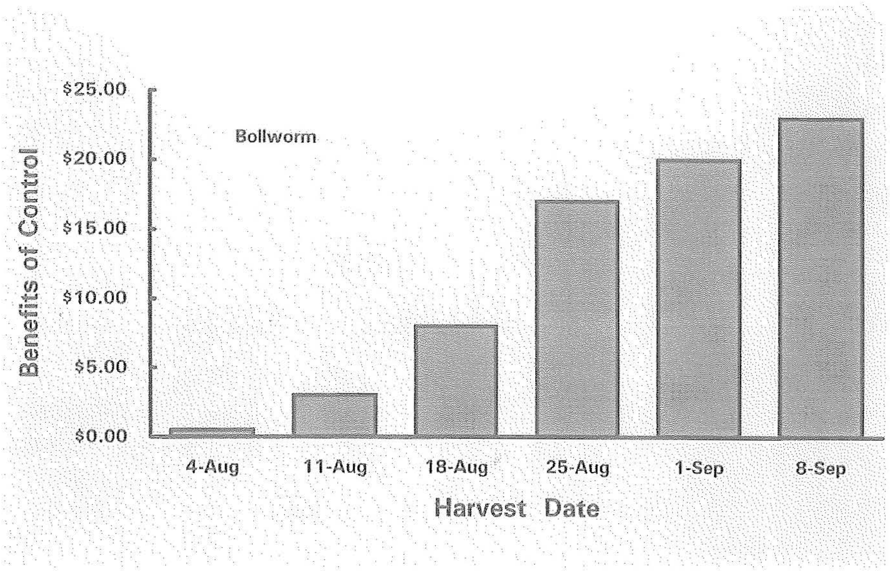

Figure 14. Benefits of controlling constant numbers of bollworms as a function of harvest date.

This location was chosen because some of the highest temperatures and lowest humidities in Texas occur at Pecos.

As row width changed from 10 to 50 inches, the benefits of boll weevil control decreased from \$35.20 to \$27.78 per acre (Figure 15). Thus, the potential benefit of increasing row width may be as much as \$7.42 per acre if boll weevil are abundant and in hot-dry climates. In areas where boll weevil are a problem in Central and West Texas, there may be some value in making a change in row width to take advantage of boll weevil mortality caused by drying.

Row Orientation — Row orientation may at times be important in relation to boll weevil mortality caused by drying. Drying is more important as a mortality agent of boll weevil in hotter, drier parts of Texas (Sturm and Sterling, 1990; Sturm *et al.*, 1990), so Pecos, Texas was chosen. Historical weather data from Pecos was entered but all rainfall was removed to insure maximum drying mortality. A short-season (160-day) cotton variety, no insecticides, and 15 percent damaged squares were entered two weeks after the appearance of the first square. Two row orientations, north-south (0 degrees) and east-west (90 degrees), were entered.

Benefits of boll weevil control were \$1.09 more per acre when rows were planted in an east-west direction than in a north-south direction. Thus, in dryland cotton production areas of West Texas, orienting the row direction so that sunlight falls on the soil surface between the rows enhances weevil mortality. This row direction results

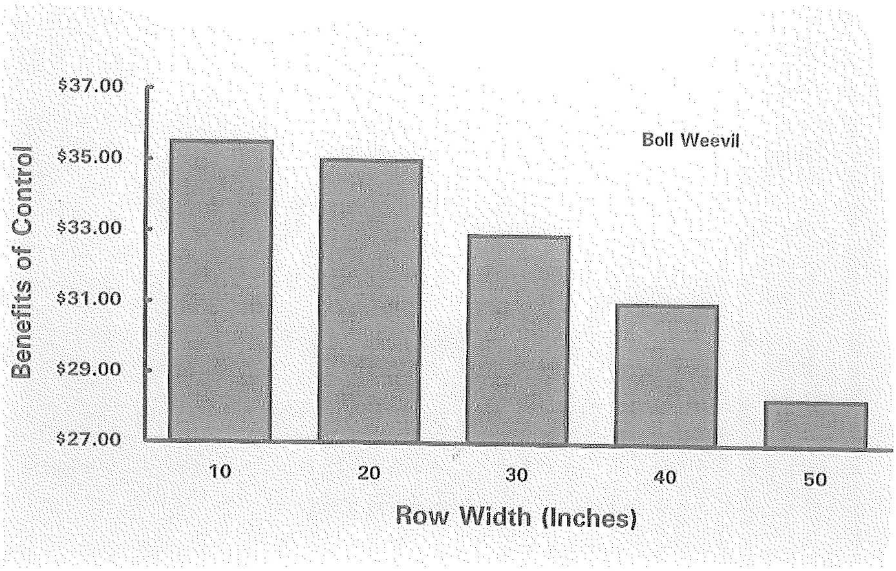

Figure 15. Benefits of boll weevil control as a function of row width.

in greater exposure of immature boll weevil in squares on the soil surface to the drying of solar radiation than if rows ran north-south. As temperature (Sterling *et al.*, 1990a) and solar radiation increase, boll weevil mortality also increases. However, TEXCIM50 was not very sensitive to row orientation as indicated by the low benefit of only $1.09 per acre.

Target Yield — Cotton fleahopper numbers were held constant (Snook, Texas 1989 data) and target yield was changed with each run of TEXCIM50. The target yield in TEXCIM50 functions to set limits on potential cotton yields per acre. With all other factors held constant, the benefits of controlling fleahopper increased from about $17.00 per acre at a target yield of 0.5 bales per acre to about $41.00 per acre when the target yield was increased to 1.5 bales per acre (Figure 16). If we expect a yield of 1.5 bales per acre, there is very little room for plant compensation of fleahopper injury. With lower expected yield, compensation is more likely. Apparently, plant compensation for fleahopper injury explains the difference in benefits.

Plant Variety — Different cotton varieties can be chosen in TEXCIM50 by changing the growth rate of the plant. Short-season varieties (<140 days) grow rapidly compared to very long-season varieties (>200 days). The user can change these values to calibrate the cotton model in TEXCIM50 to his own crop. The benefits of controlling fleahoppers is dependent on the variety of cotton grown (Figure 17). Under the conditions at Snook, Texas during 1989, long-season, slower fruiting varieties resulted in less benefit of controlling a constant number of fleahoppers than

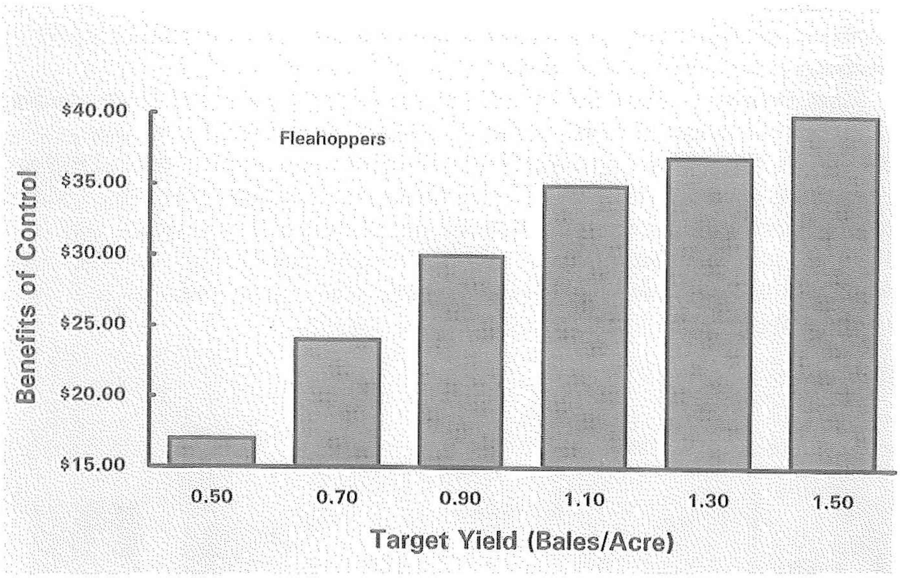

Figure 16. Benefits of controlling constant numbers of cotton fleahopper as a function of target yield.

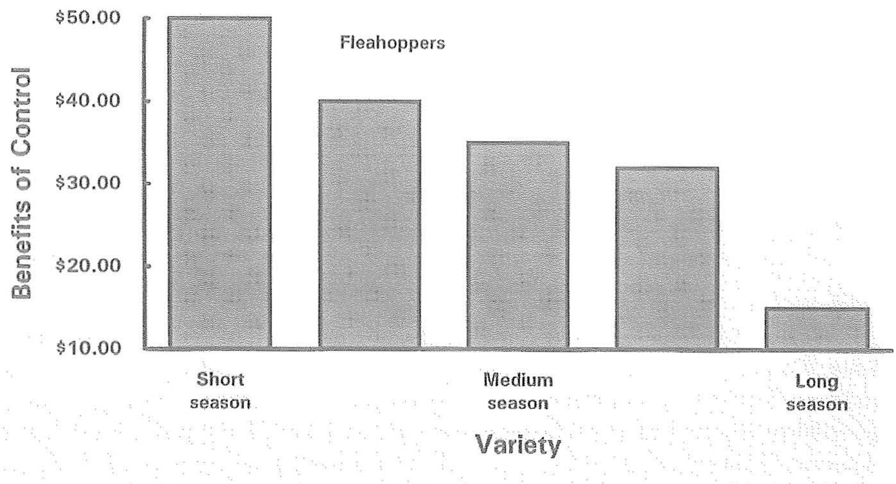

Figure 17. Benefits of controlling constant numbers of cotton fleahopper as a function of variety dependent on fruiting rate.

short-season, rapidly fruiting varieties. One reason for this difference is that long-season varieties generally have a greater ability to compensate for squares injured by fleahoppers than short-season varieties.

Plant Density — Plant density will also influence the amount of shade affecting immature boll weevil survival on the soil surface. To simulate the change in plant density, TEXCIM50 was run using Pecos, Texas historical weather data and 15 percent weevil injured squares entered three weeks after first square. Medium numbers of predators were entered together with average planting and harvest dates for Pecos. Plant densities were changed from 10 to 90 thousand plants per acre in TEXCIM50 while boll weevil numbers were held constant. This change increased benefits of boll weevil control by $12.97 per acre (Figure 18).

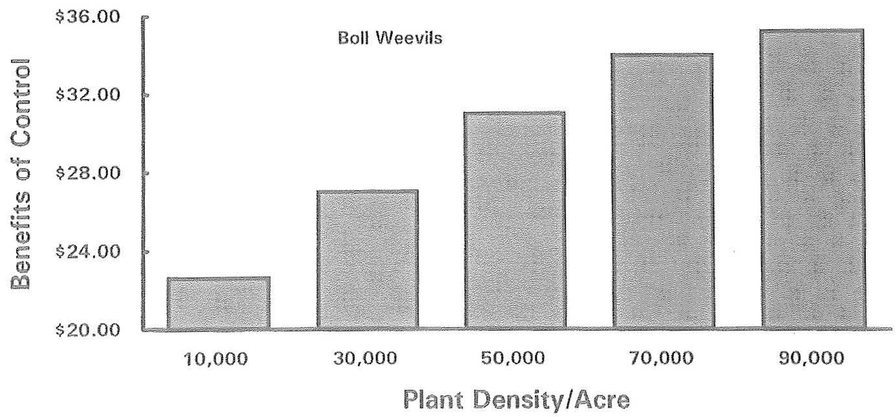

Figure 18. Benefits of controlling constant numbers of boll weevil as a function of plant density at Pecos, Texas.

Predator Numbers — The number of predators capable of checking the abundance of a pest and preventing economic loss has been called the inaction level for predators (Sterling, 1984). Inaction levels in current use in Texas include the density of predators able to prevent economic losses on boll weevil and bollworm-tobacco budworm (Knutson *et al.*, 1993). Models that consider the impact of predators include the various versions of TEXCIM, and another by Gutierrez and Baumgaertner (1984). The economic impact of native predators on cotton fleahoppers was estimated by Sterling *et al.* (1992).

By changing both the numbers of bollworm eggs and predator numbers, the benefits of bollworm control can be calculated. As predator numbers increase, the benefits of natural control also increase (Figure 19). However, predators alone do not determine the benefits of bollworm control. This benefit of control is, in part, a function of bollworm egg density and all other factors used by TEXCIM50 for forecasting benefits. Thus, an inaction level based on predator numbers alone is no more valid for forecasting benefits of control than pest numbers alone. Predators are simply one more component necessary for accurate forecasts.

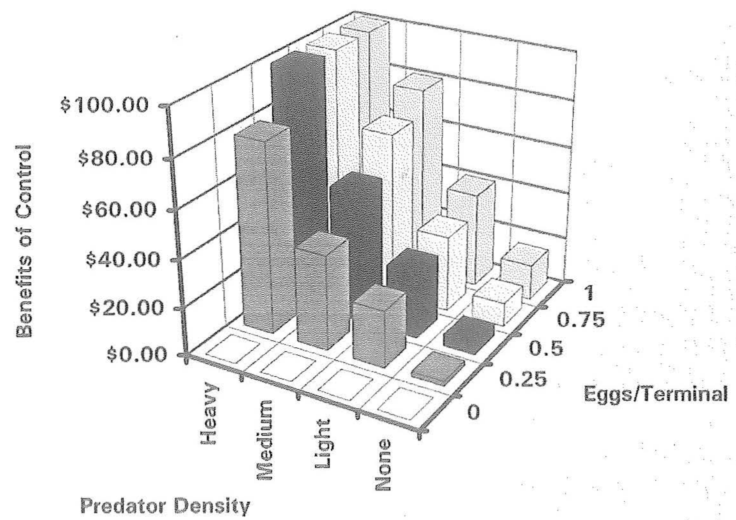

Figure 19. Benefits of controlling changing bollworm egg numbers as a function of predator density.

Pest Abundance — The abundance of an insect (or its injury) are imperfect predictors of yield loss (Pearson, 1958). However, insect numbers and injury are important components of a model designed to forecast benefits of control.

Using weather and predator data from Snook, Texas, fleahopper numbers were varied from one to eleven in increments of two. These fleahoppers were entered at the time of first square only. Under the conditions at Snook, the benefits of fleahopper control increased dramatically from about $10.00 per acre with one fleahopper per 3.3 feet to about $75.00 with 11 fleahoppers per 3.3 feet (Figure 20). Under the conditions of this simulation, TEXCIM50 was very sensitive to fleahopper abundance.

Multiple Pests — Using single species economic thresholds in cotton fields containing multiple pests results in a theoretical situation where a single fruit may be destroyed by several species concurrently. This is a case of contemporaneous (occur-

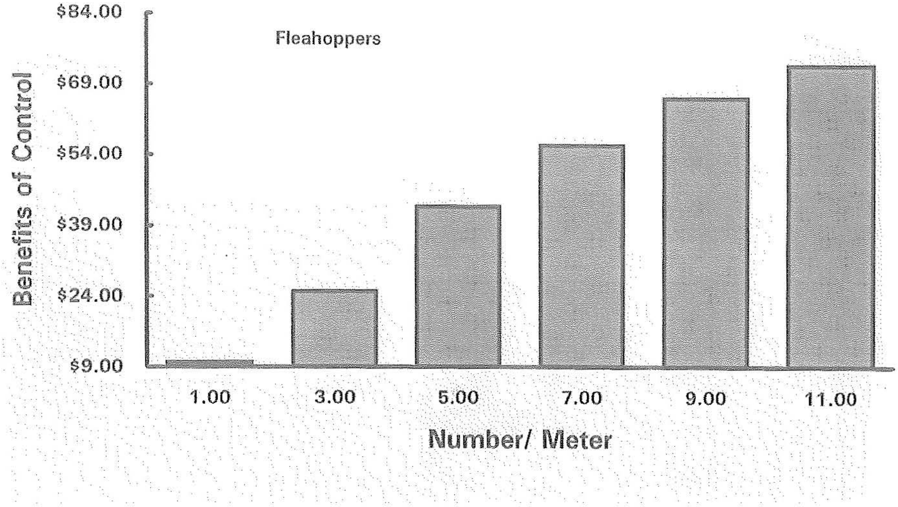

Figure 20. Benefits of cotton fleahopper control as a function of changing fleahopper densities.

ring at the same time) fruit mortality (Morris, 1965; Royama, 1981) where there is a tendency to overestimate concurrent injury caused by each pest (p. 491, National Academy of Sciences, 1969).

Using Snook, Texas data, when bollworm are run by themselves, the seasonal benefits of control were $20.72. When they were run simultaneously with fleahopper and boll weevil, the benefits of controlling the bollworm was $9.47. This suggests that simple economic thresholds based on single pests may tend to overestimate economic loss by that pest. The benefits of controlling a single pest is also a function of the damage caused by other pests. Part of the explanation for this phenomenon is that fruit feeding insects compete with each other so that when several are present, each one injures less fruit resulting in a lower benefit of control.

Most of the simple economic thresholds are based on research or practical experience designed to assess the effect of a single pest on yield. Methods to assess the impact of each of several pests simultaneously have not been available for use by farmers in cotton crop production. TEXCIM50 and TEXCIM for Windows currently provide essentially the only practical method for partitioning the economic benefits of controlling each pest in a multipest situation.

Insecticide Resistance or Insecticide Efficacy — Using TEXCIM50, cypermethrin (Ammo®, Cymbush®) insecticide was entered in a single application on June 3, 1989 on naturally occurring bollworms in the Snook, Texas, untreated cotton field. The efficacy of cypermethrin was changed in 5 percent increments starting at 80 percent and ending at 100 percent. For simplicity, the assumption was made that cypermethrin was equally effective on eggs, small larvae and large larvae. The benefits of controlling bollworm as resistance to cypermethrin increases was simulated by reducing its efficacy. The efficacy of cypermethrin against predators was held constant at 95 percent.

A reduction in efficiency from 100 percent to 80 percent resulted in an increased benefit of bollworm control of $15.18 per acre (Figure 21). Thus, benefits of bollworm control from a single application of cypermethrin had a dramatic effect under conditions at Snook, Texas when the level of efficacy changed. The benefits of bollworm control declined rapidly as a function of increased insecticide efficacy. These results are counterintuitive and no ready explanation for them is available.

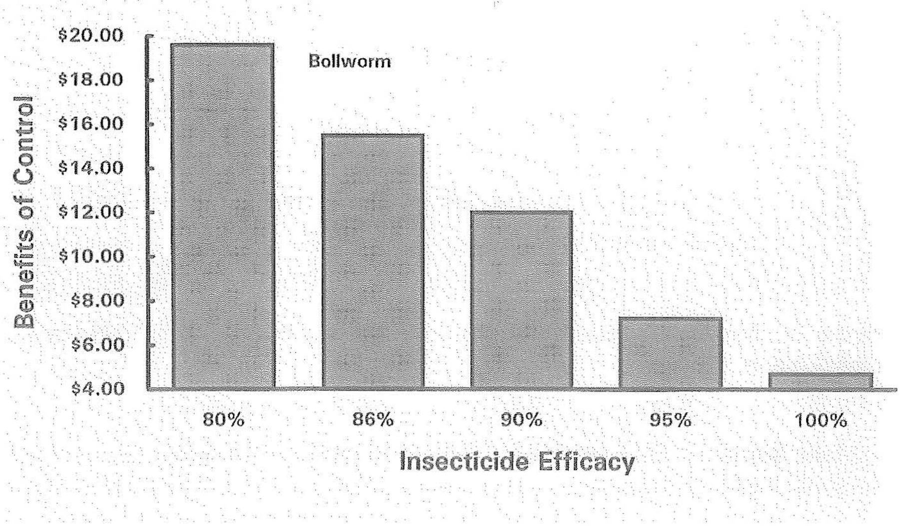

Figure 21. Changes in the benefits of bollworm control as a function of changes in the efficacy of cypermethrin.

Timing of Insecticide Applications — The use of models to evaluate different insecticidal application regimes has been conducted on an earlier version of the boll weevil component of the TEXCIM50 model (Talpaz *et al.*, 1978). The timing of insecticides to coincide with susceptible stages of pests is critical in pest management programs. As the efficiency of an insecticide changes when applied at different times, the benefits of control must also change. When a single application of cypermethrin was made at different times starting on June 19 and ending on July 14, the benefits of bollworm control changed (Figure 22). Bollworm egg and larval numbers peaked on July 7 at Snook, Texas.

If the efficiency of an insecticide was reduced through improper timing, the benefits of control increased. Conversely, if efficiency increased, the economic benefits decreased.

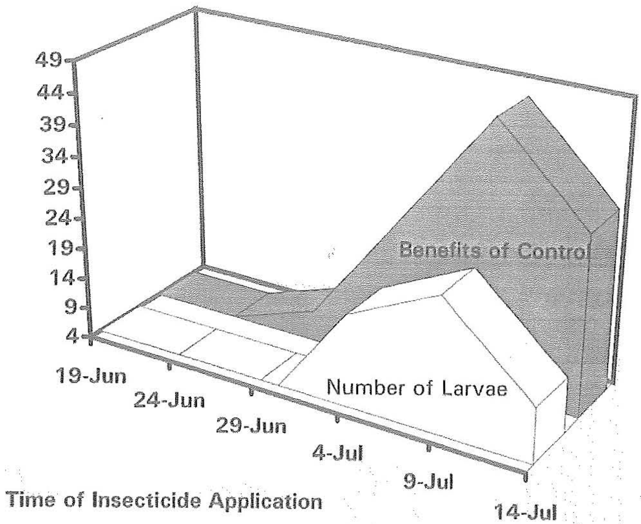

Figure 22. Benefits of bollworm control as a function of the time of cypermethrin application.

Plant Stress — Graham *et al.* (1972) recommended changing the economic threshold based on variations in plant susceptibility to insect injury. Other factors affecting plant stress such as weeds, diseases, nematodes, water and nitrogen will interact with all other factors that affect economic decisions. Multiple component, pest management models of the future will require attention to other factors to improve the accuracy of forecasts. TEXCIM for Windows does not currently include weed, disease or nematode components that impose a stress on the plant. However, the ICEMM model (Landivar *et al.*, 1991) can evaluate stresses due to nitrogen, water and plant growth regulators simultaneously with pest injury.

Sampling Method — The sampling method used to provide information on pest numbers, fruit numbers, predators and weather can have an impact on the accuracy of economic forecasts. In general, field counts of bollworm larvae result in less forecasting error than counts of eggs (Figure 23). Counts of bollworm (BB) moths or boll weevil (WV) adults monitored in pheromone traps result in higher forecasting

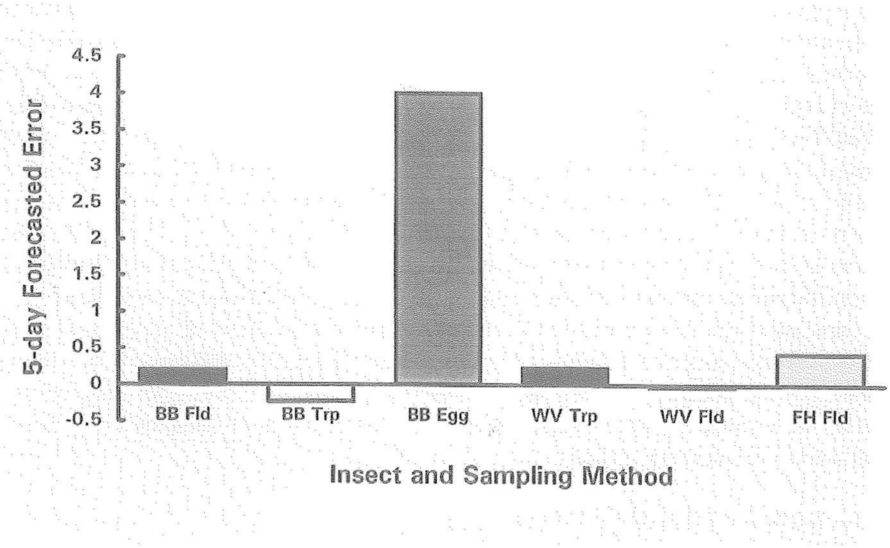

Figure 23. Forecasting errors based on initializing TEXCIM50 with counts of pests based on different sampling techniques. Abbreviations are BB = bollworm/ budworm, FLD = field, TRP = trap, WV = bollweevil and FH = fleahopper.

errors than field counts of fruit injury and immatures (Sterling *et al.*, unpublished). Thus, a very accurate model may produce forecasts with considerable error if based on data obtained from unreliable samples.

Relation Between Sampling Method, Forecasts and the Economic Thresholds — The decision to control pests is a function of the sampling method and time. For example, the purpose of sampling boll weevil in pheromone traps is to forecast the consequences of immediate boll weevil control to prevent economic injury one or two months into the future. The idea is to control overwintered boll weevils in the spring before they have a chance to reproduce. Thus, the growth rate of boll weevil populations is reduced so that, after one or two generations, insufficient numbers of boll weevils are present to require control during mid-season. Thus, economic thresholds based on trap catches function as a forecasting model. For all models, forecasting error increases with distance into the future. However, when considering the alternatives of using the boll weevil trapping index or the TEXCIM50 model to forecast current benefits of control, the limitations of the trap index as a forecasting model become obvious. Since the trap index does not consider weevil mortality, weather and plant growth, etc. it cannot possibly provide consistently accurate forecasts and thus should be used with considerable caution. With continuous testing and revision, the TEXCIM50 approach should ultimately lead to much improved forecasts and management decisions.

In taking field counts of fleahoppers during the growing season, the goal may be to make a control decision based on a forecast in the next 5 or 10 days. However, when sampling bollworm with pheromone traps, the goal may be to make a decision based on a longer forecast of 10-15 days, depending on how long it takes the moths to colonize the field and lay eggs that produce large larvae. Thus, a crop manager would not make a decision to treat today based on pheromone trap catches of moths taken today. However, he could plan to take actions in about 10 days based on forecasts of 10 to 15 days. The decision to control boll weevil depends on the management strategy. If the strategy is to control overwintered boll weevil to prevent them from increasing to numbers that would cause injury in the third or fourth generation, then long-term forecasts of much more than 25 days may be necessary. However, if a forecast of the first generation is adequate, then a forecast of 25 days may be sufficient. The main point is that at times, moderately long-term forecasts may be desirable, but the accuracy of forecasts declines over time (Sterling *et al.*, unpublished data). The most accurate decisions are obtained with field samples of insects or injury rather than trap catches.

EXTERNALITIES AND THEIR COSTS

When insecticides are used in a cotton field, the farmer does not pay all the costs of application. Pesticides often enter the ground or surface water where they may affect the health of others who may drink the water. These are the so-called "side effects" of insecticide use. DDT apparently moves in wind and water currents over much of the surface of the world causing harm to many biological organisms. TEXCIM50 currently makes no attempt to include external costs as part of the costs of pest control. Currently, farmers are paying some of the costs of these externalities with higher taxes to support agencies such as the Environmental Protection Agency and through higher insurance premiums to cover potential litigation resulting from the use of chemical control. We assume that farmers pay only a small fraction of the true external costs. Estimates of external costs of applying a single insecticide range from $0.91 to $4.67 per acre (Higley and Wintersteen, 1992). These costs include costs to surface water, ground water, aquatic environment, birds, mammals, beneficial insects, human acute toxicity and human chronic toxicity. These costs can be expected to vary from field to field depending on many factors. It will be very difficult to accurately calculate these costs for each cotton field. However if such an estimate is available it can be included in the total costs of control. Also, all of these costs are not external. A fraction of these costs are borne by the farmer. Because the farmer, his family or his employees either live or work in close proximity to the application site, they are most likely to receive major exposure to insecticides. Thus, the farmer is paying for some of this exposure in higher medical bills or in the reduced efficacy of natural enemies, whether he knows it or not. It is probably not valid to assume that the farmer pays no part of these costs.

SIMPLICITY

One of the major advantages of the simple economic threshold is its simplicity (Pedigo *et al.*, 1986). However, there are other criteria such as reliability, value and objectivity that may be of considerable importance. Granted, many pest managers may refuse to use a system because of its complexity, but pest managers may also lose confidence in systems with high failure rates over the long term. Failure of pest management systems may frequently be due to a shortage of reliable information. However, systems which are accurate and provide a satisfactory return on the investment in labor will be used if they are consistently reliable. Farmers make money by either increasing yields more than costs or reducing costs and holding yields at near the same level. Thus, knowing when to treat and when not to treat can both return a profit. If this profit is sufficient it will cover the cost of acquiring knowledge and models such as TEXCIM50 will prove to be a good investment. Since farmers tend to be averse to risk (Norgaard, 1976), objective, accurate systems will soon gain the confidence of farmers if the known risks are lower than subjectively perceived risks and if consistent profits result from using the models. A distinguishing feature of these models is that they introduce greater objectivity into the decision-making process.

LIMITATIONS OF TEXCIM

The plant model contained in TEXCIM50 and TEXCIM for Windows is a simple fruit dynamics model that is not based on plant physiology. It is designed to produce fruit as a function primarily of temperature. Each fruit is assigned an economic value that changes as the fruit grows and matures or is injured and lost from the crop. Integrating insects into this system that function as stand reducers, leaf-mass consumers, assimilate sappers or turgor reducers would be difficult using this fruit model. TEXCIM for Windows has been integrated with (TEXCOT) (Unpublished data, J. A. Landivar, Texas A&M University, Corpus Christi, Texas) a version of the GOSSYM physiologically based plant model (Baker *et al.*, 1983) to form the ICEMM model (Landivar *et al.*, 1991). This model facilitates the linkage of these pests to carbon, nitrogen and water contents (pools) in the plant.

SUMMARY

Pest numbers or pest injury alone cannot provide consistently accurate forecasts of costs, benefits and profits of pest control. Thus, the simple economic threshold that depends on pest numbers or pest injury alone cannot be consistently reliable in making pest management decisions. Using the TEXCIM for Windows and related models, pest management decisions are based on a profit analysis of potential management tactics. If forecasted benefits of control equal the costs of control, then the economic threshold has been reached. Anything that changes plant growth rates, yield potential, or economics of crop production will change the economic threshold. Because plant growth rates, yield potential and economics of crop production are different in every cotton field, management decisions based on a single criterion, such as pest density cannot provide accurate decision criteria in all cotton fields. As used in TEXCIM, the comprehensive economic threshold does not depend on pest numbers or their injury alone, it is a function of all costs, benefits and profits of control. Evidence is provided of the need for many factors — time of attack, geographical location, lint value, planting date, harvest date, row width, row orientation, target yield, plant variety, plant density, predator numbers, pest numbers, multiple pests, resistance, timing, stress and sampling — in determining forecasted benefits of pest control. No single factor such as pest numbers, lint value and predator numbers can provide accurate criteria for making management decisions. The TEXCIM model provides an example of an analytical tool useful in forecasting the profitability as needed for scientific pest management and for partitioning the economic benefits of controlling each pest when multiple pests are simultaneously attacking the crop.

Although forecasting the profitability of insect control separately for each cotton field may result in more reliable decisions than extrapolations from a single run for a community, in practice the forecasts for a single variety planted simultaneously on a farm or fraction of a community may sometimes be practical. Errors in long-term forecasts are greater than in short-term forecasts so economics should be most reliable with short-term forecasts. Ultimately, the use of this information will be based on its value to the farmer or his crop manager. The crop manager will ultimately make management decisions based on returns exceeding the investment in pest control. Improvements in the accuracy of economic thresholds should result in sufficient benefit to the farmer to more than justify the cost of data acquisition (sampling) needed to run the model. This information may serve to reduce the cost of other technologies, such as insecticides, to provide an acceptable return on the investment in sampling to obtain the information. Accurately determining costs, benefits and profits of control may play a key role in reducing the risks of making unprofitable treatment decisions or unprofitable decisions not to treat.

ACKNOWLEDGMENT

Special thanks to Larry Pedigo, Dennis Ring, Merle Shepard, George Teetes and Myron Zalucki for helpful suggestions for improving this manuscript. The support of the National Science Foundation, USDA, CSRS Southern Regional IPM, and the Texas Department of Agriculture is gratefully acknowledged. Approved for publication as TA 31353 by Director, Texas Agricultural Experiment Station.