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Comparison of strategies for bollworm control in Texas cotton using a heuristic simulation model

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The economic evaluation of pest control strategies was undertaken through a stochastic simulation experiment. A four-component model was constructed including a weather generator, a cotton plant growth model, a bollworm insect model, and a model of the pest control strategies. Alternative pest control strategies were encoded as rules in an expert system. On each sampling day, the rule-based system determined the next sampling date and whether or not to spray an insecticide or microbial the following day. The weather generator and the bollworm model were stochastic. Profit distributions for each of the three strategies were produced by combining results from 100 simulated growing seasons and were compared by stochastic dominance.

INTRODUCTION

Crop management operates within two complex systems, biological and economic. The ideal farmer makes decisions based on complete knowledge of these systems, their variability, and the available control options. In practice farmers make decisions without having complete knowledge. They follow relatively simple decision rules that in most cases lead them to make proper decisions. The economic threshold and sequential sampling plans are examples of simple decision rules. Farmers will develop their own decision rules based on their experience, judgement, and understanding. Researchers and extension agents likewise develop their own heuristics. Still, the overwhelming variation of the natural system virtually insures that no individual will experience enough of the real world to develop stable heuristics. The fundamental problem is determining and demonstrating that a particular set of rules or strategy is best.

Traditionally, alternative crop managment strategies are compared trough field experimentation. Field experimentation has difficulty to satisfactorily address independence of experiments, and sufficient number of repeated seasons. An alternative to field experiments is to use a computer simulation in place of the natural system (LAZARUS & SWANSON, 1983; GREENE *et al.*, 1985; BELLOWS, 1987). If a stochastic simulation model can be constructed that captures the variability in key factors affecting the success or failure of a pest management program, the model can be run repeatedly to produce hundreds or thousands of potential field situations. Management strategies, when encoded and linked to the simulation model, can then be tested and compared over a statistically reasonable number of years, but in a fraction of the time. The performance of each strategy can then be compared under perfectly controlled conditions ensuring independence between alternative strategies. This approach of stochastic simulation encompassing the heuristics of control strategies is used here to compare bollworm control strategies.

MATERIAL AND METHODS

Bollworm Management in Texas Cotton

Heliothis virescens FABRICIUS (Lepidoptera, Noctuidae), and *H. zea* BODDIE, form a pest complex recognized as the principal insect pest complex of cotton in the United States (STERLING *et al.,* 1989). Nevertheless, bollworms must be considered secondary pests in Texas short season cotton (WALKER *et al.,* 1979). Bollworms can damage cotton during most of the growing season. In most cases, bollworm populations are controlled naturally by beneficial insects. However, when the system has been disrupted by insecticide applications this natural control breaks down, requiring the chemical control of bollworms. Control by beneficials can also be insufficient to control large migrating bollworm populations. Bollworms are strong fliers and tend do be carried by wind over long distances (HARTSTACK *et al.,* 1982). Hence, cotton farmers must make a very difficult decision when faced with a bollworm in their fields. Additional factors that affect the control decision are the price of cotton, resistance to insecticides in the bollworm population, and the effectiveness of the application of insecticide. Clearly, many factors that are unpredictable and out of the control of the farmer affect the success of management decisions.

Modeling the Bollworm/Cotton System

The biological system was represented by four linked models, developed independently. These were: 1) a random weather generator, WGEN (RICHARDSON & WRIGHT, 1984), which produces daily maximum and minimum temperatures, rainfall and solar radiation based on longitude and latitude; 2) the cotton model developed by GUTIERREZ *et al.* (1984) and modified to simulate short season cotton cultivars under Texas conditions (SEQUEIRA *et al.,* 1989); 3) a stochastic model of bollworm migration and population dynamics; and 4) a rule-based model of the heuristic strategy of the decision maker.

When one is trying to predict, one uses the best estimate of what the weather will be. Typically mean values are used as expected values. But the average season is not a reasonable representation of a particular season's weather. For example, there can be no unusual cold spills, droughts, or storms. In our approach, however, we want to test the performance of a management strategy over a whole range of realistic simulations. Each simulation should behave as much as possible as an actual season, without worrying whether it is a good prediction of a particular season. Hence, randomly generated weather will perform better than mean weather.

The cotton model used has been well described elsewhere (GUTIERREZ *et al.,* 1984). It is a deterministic model of cotton growth and development as influenced by weather. Driving variables include temperature, rainfall and irrigation, nitrogen applications, and solar radiation. A cotton crop is modeled based on the predicted growth of a single plant with interplant competition modeled as a function of planting density. All rates are functions of physiological time. The plant is modeled as a series of submodels, one each for the leaves, fruit, stems and roots. The subpopulations are represented as arrays and are aged using a distributed delay algorithm (MANETSCH, 1976) that simulates variability in development rates deterministically. Subpopulations are linked through a single metabolic pool and a priority scheme for the allocation of carbohydrates and nitrogen. The model output includes daily numbers and weights for all fruit age classes.

The cotton model has been adapted to model cotton in several diverse growing regions including the San Joaquin valley of California (Gutierrez *et al.*, 1975), the irrigated desert regions of Arizona (Stone & Gutierrez, 1986) rain-irrigated cotton in Londrina, Brazil (Gutierrez *et al.*, 1984), and short season cotton cultivars in Texas (Sequeira *et al.*, 1989).

Various insect models have been linked with the cotton model in the past, and the linkage to the bollworm model (below) was accomplished based on linkages to lygus bug (Gutierrez *et al.* 1979), boll weevil (Gutierrez *et al.*, 1977), and pink bollworm (Stone & Gutierrez, 1986). Bollworm damage was reflected in the cotton model as a reduction in the number of fruit of the attacked age-classes. Cotton plant compensation for damage was modeled indirectly through decreased demand for carbohydrates by the attacked (and abscised) fruit increasing the metabolite supply available for other fruit growth and potentially for vegetative growth.

Bollworm Model

The model simulated two processes: immigration of bollworm into cotton fields, and development of bollworm within cotton fields subject to weather, natural enemies, and management actions. Development through age-classes is deterministic, modeled using a rate-summation algorithm, and a constant distribution describing the variation in aging rates.

Migration of bollworm into individual cotton fields was modeled stochastically, with the number of freshly laid eggs per plant on any given day of the simulation determined from a negative binomial probability density function in which the mean density and aggregation parameter were functions of time (Schaub & Stone, 1991). Fig. 1A shows the probability of finding any given number of freshly laid eggs per 25 plants throughout the cotton growing season. Fig. 1B shows the actual proportions of number of eggs per 25 plants found in 1988 in 600 fields in the Blacklands area of Texas. Other stochastic elements of the bollworm model included the original number of beneficial insects in each field and the effect of each insecticide application on the bollworm and beneficial insects.

Bollworm damage was modeled after Wilson & Gutierrez (1980). The probabilities of bollworm attack and larval feeding rates are determined as a function of the density and age-structure of both the bollworm population and the cotton fruit.

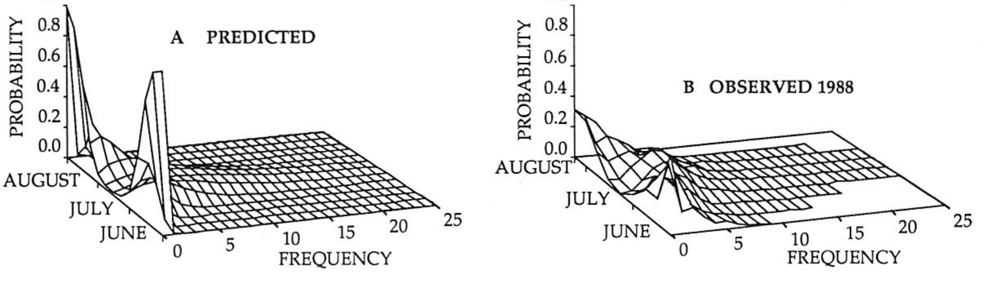

Fig. 1. The probability distributions of newly laid eggs per 25 cotton plants as a function of time of year. The distribution used in the stochastic model (A) is shown compared to the observed distribution from over 600 fields in the Blacklands area of Texas sampled in 1988.

Three pest management strategies were represented as rule-based expert systems: a simple economic threshold, the published recommendations of Texas Agricultural Experiment Station (TAEX), and the section of the COTFLEX pest management advisor (STONE *et al.*, 1987) dealing with bollworm. COTFLEX is a farm level expert system for cotton management. Each strategy made the following recommendations: whether or not to spray for the control of bollworm, what to spray (a pyrethroid, an organophosphate, or a microbal insecticide), and when to sample again.

The simple threshold of 5 percent damaged fruiting structures was implemented with seven rules. The simple threshold strategy always triggered sampling in an interval of 3 to 4 days and application of pyrethroid insecticide. The TAEX recommendations were translated into a set of 27 rules. The following excerpts from TAEX recommendations (ROBINSON & STEWART, 1987) illustrate some of the reasoning:

"SCOUTING PRIOR TO INITIAL CHEMICAL APPLICATION. ... If numbers of beneficials are low and an average of 12 or fewer small bollworms is found per 100 terminals, consider using one of the microbial insecticides... Otherwise, before bloom the economic threshold is reached when 15 to 25 percent of the green squares are worm damaged. After bolls are present, the economic threshold has been reached when 8 to 10 percent of the green squares have been worm damaged..."

Finally, the rules relating to bollworm control in the COTFLEX pest management advisor were modified to interact with the simulation models. This rule base was extracted from extensive discussions with a highly educated extension entomologist to mimic the reasoning of a cotton pest managment expert. The resulting rule-base consisted of 65 rules.

Analysis

For each simulated season, the weather generator was run once and the output was stored. Similarly, the random numbers used by the random factors immigration, beneficial insects and effect of insecticide application were produced for each day of the season and stored. Each strategy was run once using the generated weather file to drive the system and using common random numbers. Thus, the weather, the patterns of egglay and beneficial insects, and insecticide efficiency were identical for all strategies in each season, creating a perfectly controlled experiment.

On each day, the cotton plant growth was updated, taking account of the bollworm population and age structure as updated on the previous day. After the cotton fruiting arrays were updated by the cotton model, the bollworm model was run to update the bollworm population and age structure, as well as the number of fruiting structures damaged. If the day of simulation matched the date of the recommended sample, the appropriate rule-base was then activated to determine whether or not a spray should be made the next day and if so of what type. A subsequent sampling date was also generated by the rule-base and stored.

The activation of the rule-based system required that sampling data be extracted or calculated from the state variables of the models and asserted into the fact base.

One hundred simulated seasons were run for each strategy resulting in a 3 × 100 factorial design without replication. Summary statistics recorded for each run included the final yields per acre, the number of samples and the number of insecticide applications. Revenue was calculated by multiplying the yields by a price generated at random from a distribution of cotton prices for lint and seed. Profit per acre was calculated by subtracting the application and material costs of the sprays, the cost of sampling, and an estimate of the fixed costs of cotton production from the revenue. The nonexistence of an effect of strategy was tested by analysis of variance ($\alpha = 0.05$) using the strategy × season interaction as error term. A multiple comparison of strategy means was performed by a STUDENT-NEWMAN-KEULS test ($\alpha = 0.05$).

In addition, stochastic dominance analysis (ANDERSON *et al.*, 1977) was used to determine which of the strategies would be most attractive to farmers under assumption about the farmers risk preference (COCHRAN *et al.*, 1985). Stochastic dominance compares the cumulative probability density functions of alternative strategies. When one curve lies consistently to the right of another, it will be preferred for all levels of risk. When distribution curves intersect, risk preferences affect the decisions.

RESULTS

Fig. 2 shows the cumulative probability density functions for profit generated by the three strategies. The COTFLEX strategy was dominant because at all cumulative probability levels it gave a higher profit than the TAEX strategy. COTFLEX is thus preferred at all levels of risk. The worst strategy was clearly the simple threshold, which was consistently to the left in the figure. The TAEX strategy gave intermediate results. Tab. 1 shows the mean and standard deviations of profit generated by the three strategies. The analysis of variance showed that choice of strategy had a significant effect on profit. Each mean resulting from each strategy was significantly different.

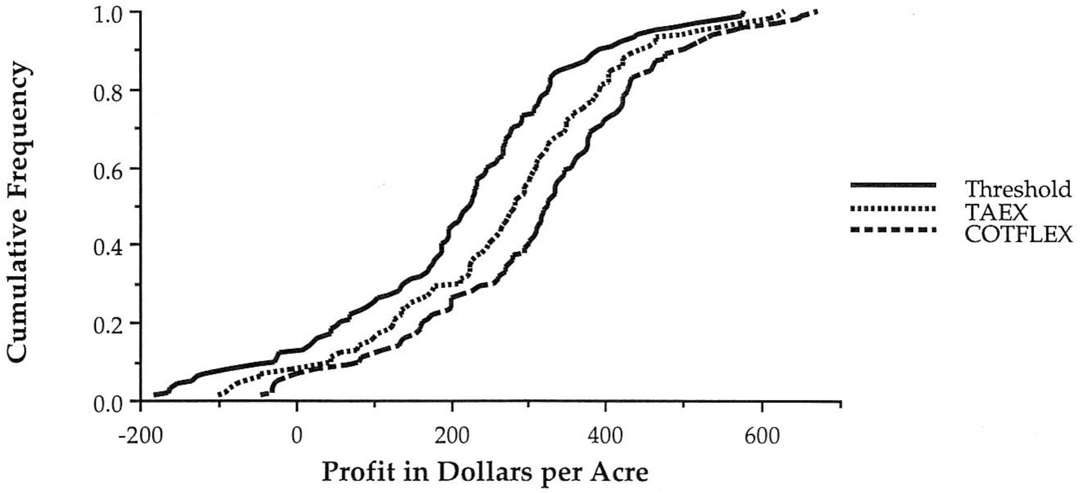

Fig. 2. The cumulative probability density functions for profit (in US Dollars per acre) from the three strategies tested. The preferred distribution for all risk preferences is the one furthest to the right.

Tab. 1. Mean and standard deviation of profit (in US Dollars per acre) generated from 100 simulations of the model with three pest control strategies.

Strategy	Average Profit*	Standard Deviation
Simple Threshold	205.5[a]	167.1
TAEX	266.9[b]	161.9
COTFLEX	311.5[c]	161.2

* Strategy average followed by different letters are significantly different by a STUDENT-NEUMAN-KEULS test ($P < 0.05$).

Based on this analysis, any farmer ought to prefer the COTFLEX strategy. Without access to the expert system he does better by following the guidelines of TAEX than using a simple threshold.

DISCUSSION

Simulation models have been integrated with knowledge-based systems for many purposes. Most examples of such linkages in agriculture have been for the purpose of supplying the reasoning system with some quantitative information selected from the model output. In some cases, notably the COMAX system (LEMMON, 1985), the reasoning system acted as a controller to modify model input as an aid in crop management. Here, however, the integration was undertaken to help validate an expert system under realistic and perfectly controlled conditions.

The COTFLEX strategy was the most complicated and information intensive of the three strategies tested. Since it was the most preferred strategy we can conclude that the reasoning of the extension entomologist was economically advantageous and that the added costs of obtaining more sampling information was worth the cost. It is also possible to estimate if it is economical for a farmer to acquire the capability of running the COTFLEX expert system. The cost of the expert system should be smaller than the difference of the mean profit of the COTFLEX and the TAEX strategy.

Clearly, the validity of this analysis is dependent on the assumption that the model used is an accurate representation of the real world. In particular, it is essential that the model reflect the same variability and range ofdriving variables seen in nature. Stochasticity is central to this approach, therefore. However, because models are never completely accurate or true representations of nature, this short of analysis should not be used alone to evaluate strategies. Additional evidence, such as experimental proof that the model performs at the level of experts, should supplement simulation results.

Here we compared entirely different rule-bases, representing different pest management strategies. The same analysis could be used to test very small differences in rule-bases. One could determine, for example, what is the impact of adding a set of rules or of modifying the contents of individual rules. This technique might even be combined with a search strategy to seek nearly optimal rule-bases.

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ZUSAMMENFASSUNG

Schädlingsbekämpfungsstrategien wurden mit Hilfe eines stochastischen Simulationsexperimentes evaluiert. Ein Modell mit vier Komponenten wurde entwickelt: ein Wettergenerator, ein Baumwollpflanzenmodell, ein Insektenpopulationsmodell von *Heliothis/Helicoverpa* und ein Modell der Schädlingsbekämpfungsstrategien. Die verschiedenen Schädlingsbekämpfungsstrategien wurden als Regeln in einem Expertensystem kodiert. Das Expertensystem bestimmte an jedem Stichprobenentnahmetag den nächsten Stichprobenentnahmetag und ob und welches Insektizid angewendet werden soll. Der Wettergenerator und das Insektenmodell waren stochastisch. 100 Simulationen erzeugten Verteilungen des Profites jeder Strategie, die mit stochastischer Dominanz verglichen wurden.

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