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OPTIMAL PESTICIDE APPLICATION FOR CONTROLLING THE BOLL WEEVIL ON COTTON

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Introduction

The rise of energy and pesticide costs for agricultural use, combined with growing ecological and social concerns about pesticide use, has recently attracted more attention in economic literature. While biologists concentrated on the understanding of interaction between plant and pests with or without pesticide control, many economists have focused their attention on the economics of pest control. Headley gave an economic interpretation to the entomologists' term "economic threshold"; further refinements and extensions were offered by Hall and Norgaard, and Talpaz and Borosh. The economic problem of pest resistance was dealt with by Hueth and Regev, and Taylor and Headley. A significant development was made by Regev, Gutierrez and Feder in optimizing an economic objective function subject to a biological plant-pest system. However, they were forced to compromise by simplifying the system when it came to obtaining a solution due to limitation of the solving algorithm. Furthermore, for the same reason, this solution is further simplified by considering a steady-state solution which avoids the complexity of a truly dynamic system (Regev, et. al., p. 191). Another way of avoiding complexities was the empirical approach taken by Talpaz and Frisbie.

The objective of this paper is to describe an economic optimization model incorporating a detailed plant-pest interactive system with a pesticide control scheme, keeping all the complexities intact under dynamic conditions.

This study is concerned with the optimal policy of a single decisionmaker. Indeed, externalities related to these policies are minimal. No resistance problems have been discovered, and no effective natural predators are known to exist (as described below). So, aside from negligible environmental effects and intraseasonal population dynamics, the policies for the single entrepreneur can be regarded similar to those of society.

The next section describes the biological system as an interaction between the cotton plant and boll weevil subsystems operating under certain approximate realistic environment. The following section relates pesticide applications to insect mortality, describing and defining economic measurements. The optimization process is briefly discussed, and finally a demonstration is presented which includes some sensitivity analyses.

Boll Weevil-Cotton Model

Components

The boll weevil is a key pest of cotton. It has essentially no predators and no effective parasites (the branconid wasp Bracon mellitor Say has been observed to cause minor mortality in the first immature generation (Barfield, *et*. *al*.). The major crop damage is caused by the female adults who lay single eggs in the cotton flower buds (squares) or less frequently in the small bolls. (These structures are hereafter called fruit.)

The adult weevils are mobile but mainly migrate into and out of the cotton field only during early or late season. Thus, the field populations are almost totally determined by the earlier season immigration and subsequent in-field growth. The adult female is capable of laying 250-300 eggs during her life time; the quantity is a function of temperature as depicted in Figure 1. The male adult also feeds on squares and bolls. They infrequently change feeding sites, and, hence, the female egg-laying process contributes the major portion of the damage to the crop.

The immature weevil develops completely within the attacked fruit and emerges as an adult generally from two to three weeks later. This immature developmental emergence time is a strong function of temperature as is depicted in Figure 2. The emergence of a cohort exhibits a wide, but consistent, variability about the mean developmental time (Figure 3). (See Sharpe, *et*. *al*., 1977, for a detailed discussion of stochastic boll weevil emergence.) The infested cotton squares or bolls are generally abscised by the plant and fall to the ground from 3 to 7 days (averaging around 4 days) after attack. Once the fruit are abscised from the plant, they begin to dry out. Depending on the micro-climate of the fruit, the fruit can dry out before the immature weevil reaches a critical size for survival. Thus, immature weevil survival becomes a race between the micro-climate controlled processes of development and fruit drying (DeMichele, _et al_., 1976). Immature weevil mortality as a function of temperature and relative humidity is depicted in Figure 4. One of the most important aspects of immature survival is the distribution of fruit sizes on the cotton plants within the weevil preference range (approximately 7/32" to 13/32" diameter fruit).

Smaller abscised fruit dry out faster than their larger counterparts; the drying time for a 7/32" diameter fruit is only about 6% of the drying time, into the critical survival mass for the weevil, for 13/32" diameter fruit. This relative percentage increases, of course, with increasing fruit diameter (Figure 5). However, these percentages are constant for all practical environmental conditions although the drying time varies. Thus, drying time can be calculated for any size fruit by computing it for a standard (13/32" diameter) and multiplying by the appropriate percentage.

Since immature boll weevil survival is directly related to fruit drying, the size distribution of available fruit on the cotton plant is of critical importance in modeling the system.

This size distribution can change drastically over a period of two to three weeks (Walker, unpublished data). In addition, the cotton plant has a high compensation capability for replenishing lost fruit. Approximately 50% of the squares and 10% of the bolls are shed due to natural (non-pest related) causes. Thus, the plant-weevil interaction has a strong effect on weevil populations and, hence, on ultimate crop yields.

In addition to the boll weevil model, a model of the cotton plant fruiting characteristics which yields the dynamic fruit size distributions over time has been developed (Curry, et. al., 1977b). The model is temperature dependent and describes central Texas cottons fairly well (Figure 6).

Component Interactions

The composite model of the boll weevil-cotton crop system consists of a temperature dependent boll weevil population model (for details see Curry, et. al., 1977a), a mechanistic fruit drying model for immature weevil survival, and a cotton fruiting model. The composite model incorporates three independent developmental time scales: (1) weevil development, (2) fruit drying, and (3) cotton plant development. These developmental parameters are computed from hourly temperatures and accumulated for population count updates which occur at four-day time intervals.

The dynamics of the plant regrowth characteristics depend on the fruit structure on the plant. Plants which were attacked four days ago would have a different structure than those attacked eight days ago due to their associated regrowth time. To allow for these nonlinear regrowth characteristics, the model segments the field population into a maximum of 11 categories of plants. The categories are the average unattacked plant, the average plant attacked 4 days ago, the average plant attacked 8 days ago, etc., up to those plants attacked 40 days ago. The weevil then sees an average field plant, which is the weighted average of the various plant categories. The separation of the crop into various categories allows the delineation between natural abscision and weevil incurred damage. This distinction is hard to ascertain under field conditions, and natural abscision is easily misinterpreted as insect-caused damage.

When plants are attacked on a given day, the average fruit size distribution for the attacked plants is associated with the egg cohort laid that day. This distribution and subsequent climatic conditions determine the survival proportions for each specific egg cohort. In actuality, the weevil egg-laying preference, based on the available fruit size distribution, determines the attacked fruit distribution. The model of Jones, _et al._, 1975, is used to incorporate these preference aspects into the model.

Finally, the proportion of crop canopy closure throughout the season determines the probability that a fallen infested fruit will be exposed to direct sunlight. The temperature of the infested fruit and, hence, the encapsuled immature weevil varies from essentially ambient temperature (before abscision or, if left hanging, after abscision) to various degrees above air temperature depending on direct sunlight penetration. Fully exposed ground temperatures can range up to 140° F which is much beyond the lethal range for weevil immatures (Fye and Bonham, 1972). The model incorporates multiple immature weevil and fruit drying environments based on the percentages of the ground under the crop which is fully exposed to direct sunlight, covered by one plant canopy shadow, covered by two plant canopy shadows, etc. (for analytical treatment of light penetration of cotton crop canopies see Mann, *et*. *al*., 1975 and 1977).

All of the above model components have been computerized to simulate the cotton-boll weevil behavior.

Pesticide Kill Function

Theoretical studies of the dosage-response function yield a sigmoid shaped curve (i.e., Finney). This is based on the argument that the pest tolerance to variable pesticide dosage is a random variable with nonsymetric distribution skewed to the right. Following Talpaz and Borosh, a cumulative Weibull distribution function has been used to represent the proportion of killed pests of the existing population given by

$$(1)\quad K(x) = \begin{cases} 1 - \exp(-\beta x)^{\alpha} & \text{for } 0 \leq x \leq \infty \\ 0 & \text{for } x < 0 \end{cases}$$

where x is the amount of pesticide, α and β are the function's parameters to be estimated (Fishman, p. 211).

Empirical data for this function is quite scarce, unfortunately. With no other alternative, it was necessary to combine results from two independent studies in order to estimate α and β compatible to field conditions.[1/] Kill rates in the simulation were computed according to equation (1)'s estimated parameters.

The Objective Function

The economic problem for a single cotton producer is assumed to maximize the net returns from his cotton fields. A cotton crop is composed of lint and seed. Hence the gross revenue is defined by

$$(2)\quad R \equiv y_L P_L + y_S P_S$$

where y and P are yield (bu/acre) and Price (\$/bu.),respectively, and L and S denote lint and seed. Total cost of production can be divided into variable and fixed costs. In this case, only costs associated with the control of pests is regarded variable where all other costs like labor, machinery, fertilizers, land, etc. are assumed to be fixed (P_L and P_S are the product prices minus harvest cost). The total variable cost is defined by

$$(3) \quad C \equiv P_x \sum_{i=0}^{T} X_i + \sum_{i=1}^{T} S_i$$

where P_x is price of pesticide including cost of application ($/lb). X_i is the amount (lbs./acre) of pesticide applied at period i = 1, 2, ..., T, where each period is equal to four days. S_i is the setup cost per treatment ($S_i=0$ if $X_i=0$; $S_i=S$ if $X_i>0$). The net return is given by

$$(4) \quad \Pi = R - C$$

and our problem can be stated as

$$(5) \quad \max_{X_i \geq 0} \quad \Pi = R - C \quad , \text{ for } i = 1, 2, \ldots, T$$

subject to (2), (3), relations of the simulation model, which is capable of evaluating R and C as a function of any given set X_i. It is assumed that the single farmer is not large enough to affect the regional pest dynamics nor can he affect either price of cotton or price of pesticides.

In this study the assumption is made that the boll weevil is the only key pest threatening cotton. This assumption is reality in some major areas of cotton production in the Southwest (in other areas there is a greater probability that an outbreak of a secondary pest like the boll worm will take place as a result of pesticide applications aiming at the boll weevil).

To maximize eq. (5) it is necessary to satisfy

(6) $\Pi_{x_i} = 0 \quad , i = 1, 2, \ldots, T$

where Π_{x_i} denotes a partial derivative of net return with respect to x_i. However these derivatives are practically unobtainable analytically, due to the highly nonlinear behavior of R which, in addition, involves dynamic interrelationships among the X_i's. Regev, et. al., did obtain the partial derivatives analytically, but only because the alfalfa and its pests are by far simpler in their behavior than the cotton-boll weevil system and due to other simplifications imposed on this model. So, the method of obtaining the solution had to consider this difficulty.

The Solution Method

A modified version of the Fletcher-Powell-Davidon method has been adapted (see Talpaz, 1976, pp. 501-502). This algorithm calculates the gradient vector and the Hessian metrix numerically by repeated evaluations of the cotton-boll weevil simulation and then equation (5). The cotton growing season, potentially vulnerable to the boll weevil attacks, begins with emergence of the first fruit and ends at harvest time. Depending on variety and location, this season is approximately 100 days. Taking pest population dynamics, cotton growth rates, and management decisions into consideration, this season was divided into 25 time periods, each 4 days long. Hence, our problem is to find x_i, for $i = 1, 2, \ldots, 25$ such that Π is maximized. Initial guess for x_i is needed, and was set at 0.01 for all x_i.

The computer program is written in APL-SV language. It costs \$15-\$20 to obtain a solution on an AMDHAL computer.

Results of a Demonstration

A demonstration was carried out with the following assumptions fed to the computer, representing the "basic" run.

a. Weather conditions (temperature, humidity, and solar radiation curves for the season) comparable to the Brazos Bottom, Texas.

b. Cotton variety is Stoneville 213.

c. Pesticide is Methyl-Parathion, with a price of $4.00/lb. of pure substance (which includes spray costs); set up cost of $5 per application.

d. Cotton price; $0.45/lb. of cotton-seed; $0.55/lb. of cotton-lint. These are prices minus harvest costs.

e. Number of overwinter weevils is 110 per acre with immigration rate of 50 weevils per 4-day period throughout the growing season.

The optimized strategy for this "basic" run resulted from pesticide applications on periods 4, 6 and 10 which are equivalent to 16, 24 and 40 days after the emergence of first fruit, with quantities of 1.1, 0.95 and 0.7 lbs./acre of pure substance, respectively, and net income (as defined above) of $230/acre.

In addition to this information, the program provides for each period a detailed account of pest population of weevils according to their age groups and cotton fruit population.

Two additional sensitivity runs were made. In run II, a doubled price of pesticide was assumed, i.e. $8.00/lb., keeping all other assumptions unchanged. Results show a decrease of pesticide to the levels of 1.0, 0.8, 0.6 lbs./acre applied at the same periods as before. This represents a decline of pesticide use of 12.7%. Net income is down to $221/acre.

In run III, the price of cotton was increased by 50% leaving everything else the same as in the "basic" run, i.e., $P_L = 0.825$ and $P_S = 0.625$ (\$/lb.). Optimal policy, in this case, calls for the same three applications with quantities 2.0, 1.4, and 1.5 with two additional mini applications which can be practically ignored at periods 8 and 12. This nearly doubles the amount of pesticide use compared to the "basic" run. Net income is \$356/acre.

Discussion of Results

Results of the three runs seem to be reasonable, economically and biologically. It is increasingly recognized among entomologists that the boll weevil causes damage to cotton yield only at a "time window" which takes place before fruiting reaches the halfway point. Due to the plant's enormous capacity to compensate for early injuries, there is no significant damage caused at that time. Since the weevil cannot attack the set bolls, it always "prefers" the younger and juicier squares which are being reproduced during late stages and have no change to mature even under a pest-free situation. It is somewhere around midseason when damages can be economically significant. The optimizing algorithm appears to aim these treatments at that critical "window". Due to setup costs, it pays to treat at certain intervals instead of smaller doses at each period in the "window".

The sensitivity analysis shows that timing of pesticide applications is robust, moderately sensitive to a change in pesticide price, and highly sensitive to a change in price of cotton. These conclusions could be expected. Pesticide costs still remain marginal compared to total costs which leads to a small adjustment, as a response to a considerable increase in price. Changes in cotton price are far more important, leading producers to protect their higher value yield by increasing pesticide use. If the biological-environmental assumptions representing central-eastern Texas can represent the cotton belt regions (highly doubtful), then these results may indicate that severely high taxes imposed on pesticide will not be effective in reducing their use, and the only alternative is to look for alternative control practices <u>if</u> for some external reasons pesticides should be banned or curtailed.

Concluding Remarks

A detailed model of a cotton plant-boll weevil system has been built. Optimized policy for pesticide application has been achieved through a dynamic nonlinear optimization technique. There was no need to simplify the model to obtain control optimization. The model is so flexible that if additional detailing is necessary in the future, it can be easily introduced where the only consideration would be the computer memory capacity and/or computer time.

Future research is needed to establish first the biological relationships between boll weevil and other pests, which will make the model more general and applicable. However, once completed, extensions to this model seem to be straightforward. More testing and applications from different regions and cotton varieties is needed to build confidence in its use. This may lead to extension of this methodology to other crops and pests. An important extension of this model would be to obtain an optimal strategy under risk conditions. This will be possible when more information about the random behavior of the system becomes available.

FOOTNOTES

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1/ The estimated values are: $\hat{\alpha} = 0.08605$, $\hat{\beta} = 1.00727$. Data from Shipp, et. al.,was used to estimate the function. X is in terms of unit per cage in their experiment. To convert X to a lbs./acre unit, a multiplier of 0.0314 is used which was calculated from a study by Mistrie and Gaines.

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