51
1cst copy

REPRINT

from

JOURNAL OF AGRICULTURAL ECONOMICS

Vol. XXXVII, No. 1
January, 1986

INFORMATION IN AGRICULTURAL PEST CONTROL

Spiro E. Stefanou, Marc Mangel and James E. Wilen*
Pennsylvania State University and University of California†

This paper develops a decision aid for agricultural producers regarding their pest scouting and spraying activities. The basic issue is how estimates of pest populations are computed and when the operator should act using that information. Scouting for pests, essentially a search operation, can lead to a change in the strategy for applying pesticide. An adaptive-scouting process is developed to unify the spraying and scouting activities. Some results, for the cotton-lygus bug system, are presented.

I. Introduction

It is commonplace for crops to be vulnerable to a range of pests whose population levels and period of infestation are more or less uncertain over the growing season. On an abstract level there are basically two ways to structure decision making in the face of these types of uncertainties. One way is to attempt one-shot *ex ante* forecasting and then implement a control strategy following some decision rule. Another way is to develop a monitoring procedure which allows for frequent sampling and updates decisions in an optimal, closed loop manner.

In the real world, a variety of institutions have arisen as a practical compromise between theoretically ideal decision making aides and the complexity and costs associated with such undertakings and simple heuristics, or "rules of thumb." For example, publicly supported extension units may report pre-season estimates of infestation levels and recommend control strategies. Where continuous monitoring is possible, public or private institutions, or both, may monitor and update the status of the pest as the season progresses. The latter procedure — pest scouting — is the subject of this paper.

Scouting for pests, essentially a search operation, can lead to a change in the strategy for pest control. The problem of controlling pests contains both dynamic and geographic elements. Pest control is dynamic since the longer the pest goes undetected, the greater the cumulative damage inflicted on the crop. Since the pest infestation is not necessarily uniformly distributed throughout the field, there is a geographic component. Information provided by scouting can help identify the more widely infested areas within the field and is a potentially valuable input into the operator's decision model if it leads to actions that differ from actions that would be taken without that information.

The objectives of this paper are: (a) to model the optimal scouting decision

*The work of SES was partially supported by a Statewide University of California Integrated Pest Management Grant. The work of MM was partially supported by NSF Grant MCS-81-21659.

†Address for correspondence: Department of Agricultural Economics and Rural Sociology, Pennsylvania State University, University Park, PA 16802, United States of America.

process for the operator who is gathering information about the incidence of a pest; (b) to determine when and with what set of controls the operator should act given the scouting information; and (c) to measure the value to the operator of obtaining pest information. In the next section a Bayesian model for processing scouting information is developed for both the single and sequential scouting cases. The third section presents an application of this model to the cotton-lygus bug system. The last section summarizes the main theories of the paper and proposes directions for further research.

II. A Model of the Scouting Decision Process

The economics of information acquisition regarding disease and pests has been receiving increasing attention in the literature (Carlson, 1970; Feder, 1979; Wetzstein, 1981; Zavaleta and Dixon, 1982). Most of the Bayesian theory approaches to disease have focused on the operator's attitude toward risk on control decisions (Webster, 1977; Mumford, 1981). Carlson (1980) models an information variable directly into the production relationship, but without regard to the mechanism by which the operator uses information to influence productivity.

Despite this considerable body of work, little consideration has been given to the problem of combining the pest scouting activity and the control programme in a dynamic context. The uncertain and dynamic nature of the decision with regard to the timing of the control measure needs to be considered in conjuction with the scouting activity.

Several assumptions are made to make the problem more tractable. The operator is assumed to maximize expected utility, where utility is a function of an uncertain profit level. The calculation of profit incorporates the magnitude of the pest infestation, and the optimized scouting the spraying activities. The time frame considered is a single season. It is assumed that the cost of scouting is constant and independent of the results of previous scouting and control decisions. The pest control method assumed in the remainer of the paper is chemical control. Finally, all other inputs for production are assumed to be applied at the optimal levels so that the operator need only focus on determining the optimal scouting and spraying decisions

The components of total cost are: (1) the value of the crop yield lost due to the physical damage inflicted by the pest, (2) the cost of spraying, and (3) the cost of scouting. The operator can try to control the physical damage the pest inflicts upon the crop by applying the pesticide at selected points in time. The extent of the physical damage depends on the pest population levels throughout a season of length T. Let $D(\underline{S}_T, \underline{y}_T, \underline{z}_T)$ be the damage to the physical yield done by the pest. Here $\underline{S}_T = (S_1, S_2, \ldots, S_T)$, $\underline{y}_T = (y_1, y_2, \ldots, y_T)$ and $\underline{z}_t = (z_1, z_2, \ldots, z_T)$ where S_t denotes the pest population at time t, y_t denotes the level of a spray applied at time t, and z_t denotes exogeneous factors affecting crop development for $t = 1, 2, \ldots T$. If the cost of the pesticide application is $c_1(y_t)$, and the cost of scouting at any time is c_2, then the total cost at the terminal period is

$$TC(\underline{S}_T, \underline{y}_T, \underline{Z}_T, \underline{e}_T) = p.D(\underline{S}_T, \underline{y}_T, \underline{z}_T) + \sum_{t=1}^{T} c_1(y_t) + c_2 \sum_{t=1}^{T} e_t \qquad (1)$$

where p is the fixed (known) price per unit of physical yield, $e_t = \begin{cases} 0 & \text{if do not scout in period t} \\ 1 & \text{if do scout in period t} \end{cases}$ and $\underline{e}_T = (e_1, e_2, \ldots, e_T)$. If Q is the physical crop yield when no pests are present, the profit is

$$\pi = p \cdot Q - TC. \tag{2}$$

The utility function of profit at the end of the terminal period is assumed to be separable with the cost of scouting being independent of other production decisions and is expressed as

$$U(\underline{S}_T, \underline{y}_T, \underline{z}_T, \underline{e}_T) = U_1[p.Q - pD(\underline{S}_T, \underline{y}_T, \underline{z}_T) - \sum_{t=1}^{T} c_1(y_t)] - u_2[c_2 \sum_{t=1}^{T} e_t]. \tag{3}$$

The function $U_1[\ ]$ reflects the impact of the pest population level and the spray strategy on the operator's utility, while $U_2[\ ]$ reflects the loss in utility the operator incurs for collecting information.

Processing Scouting Information

In order to incorporate the scouting procedure into the decision process a Bayesian approach is used to update the probability distribution of the true pest population through observations which are the result of present and past scouting. The benefits from the scouting must then be balanced against the cost of learning. Unfortunately, the operator never observes the true pest population level in the field; but scouting for pests can reduce uncertainty about the level of pest infestation. If the operator chooses to scout, these results can be used to determine a spray strategy. If the operator chooses to not scout, the spray strategy is based upon an *a priori* estimate of the true pest population.

Let X be the number of pests observed by scouting and let the true state of nature, S, be the actual pest population in the operator's field. Thus, the probability that $X = x$ is observed depends on the true pest population. Suppose that the field is divided into subunits called plots, and that each of these plots constitutes a habitable site and is a natural sampling unit. The sampling time is assumed to be small enough to ignore the possibility of the pest migrating from one plot to another.

The pest population estimates are characterized by a matrix of conditional probabilities of the likelihood specification consistent with the partitioning of the pest population into ranges. The likelihood matrix is presented in Table 1. Scouting information is perfect if all of the diagonal entries in the likelihood matrix are equal to one and all other elements are zero (i.e., $\sigma = 1$). Scouting provides no information when observed pest counts are independent of the true pest population. This occurs when all elements of the likelihood matrix are equal (i.e., $\sigma = 1/3$). Table 1 possesses the symmetry property which implies that if the pest counts resulting from scouting are wrong, they are as likely to be wrong on the low side as on the high side. Thus, the parameter σ reflects the accuracy of scouting information. Values of σ less than 1/3 are not considered since scouting information would be negatively correlated with the true pest population. The accuracy of scouting information increases within the interval [1/3,1].

Sequential Scouting

Sequential scouting requires the selection of a sequence of scoutings over time. To do this, the operator uses past information and the pest dynamics, which are assumed to be

$$S_{t+1} = z_t(y_t) + (1 - K(y_t))\, S_t, \tag{4}$$

where $z_t(y_t)$ represents the net immigration plus any change in the pest population as a result of a spray killing the predators of the pest, and $K(y_t)$ is the fraction of pests killed if the spray level is y_t. Although the exact form of the kill function is not needed in what follows, it is reasonable to assume that $K(0)=0$ and $\lim_{y_t \to \infty} K(y_t) = 1$.

Table 1. The Symmetric Likelihood Matrix, PR{X|S}.

Observed Lygus Population, X	*True Lygus Population, S* Low	Medium	High
Low	σ	(1-σ)/2	(1-σ)/2
Medium	(1-σ)/2	σ	(1-σ)/2
High	(1-σ)/2	(1-σ)/2	σ

An assumption consistent with the application in section III is that the individual pests are assigned independently and at random to the available plots, resulting in a random spatial pattern of the pest (Wilson and Room, 1983). Under these conditions the number of pests per plot is a Poisson random variable. The probability that a plot contains s_1 individuals in the first period is given by

$$\Pr\{S_1 = s_1 | \mu\{ = \mu_{s_1} \exp(-\mu)/s_1! \tag{5}$$

$s = 0,1,2,3,\ldots$ where $\mu > 0$ is the mean number of pests per plot, as well as the variance.

The probability that a plot contains s_2 individuals in the second time period is found from the Poisson and the pest dynamics (4); that

$$\Pr\{S_2 = s_2|\mu;\, y_1\} = \Pr\{S_1 = (\frac{s_2 - z_1}{1-Ky})\,|\mu;y_1\} \tag{6}$$

$$= \frac{e^{-\mu}\mu \quad (\frac{s_2 - z_1}{1-Ky_1})}{(\frac{s_2 - z_1}{1-Ky_1})!}$$

for $s_2 = z_1,\, z_1 + (1 - K\,y_1),\, z_1 + 2\,(1 - K\,y_1), \ldots$

Equation (6) provides a complete description of the pest population at the start of the second period. According to (6), S_2 may take fractional values. This is not a major difficulty since (a) it is simply a modelling quirk and (b) for decision making, ranges of the pest population are used.

However, as Pielou (1976) notes, the plots may be dissimilar. Some may provide more favourable environments than others so that the parameter varies from plot to plot. For simplicity, treat μ as a continuous random variable. A candidate for the probability distribution for μ is the gamma density with parameters α and β, where the mean is α/β and the variance is α/β^2. Thus

$$\Pr\{\mu(m,m+\Delta m)|\alpha,\beta\} = \gamma(m;\alpha,\beta)\Delta m \tag{7a}$$

where

$$\gamma(m,\alpha,\beta) = (\beta_\alpha/(\alpha-1)!)m^{(\alpha-1)}\exp(-\beta m). \tag{7b}$$

By repeatedly applying Bayes theorem, one can derive the probability distributions required to determine scouting and spraying strategies at later periods within the season. A presentation of the details can be found in Stefanou (1983).

For sequential scouting, the observation distribution is independent of the results of previous scouting results and depends on the parameter through the value of the true state. The optimal scouting decision at a given stage using the Bayesian updating procedure just described is the solution to a stochastic dynamic programming problem. This problem can be formulated as follows. Consider the decisions to be made in the terminal period T. If the operator chooses to scout in this period, the spray decision is determined by

$$\max_{y_T} E_{\mu|\underline{X}_T;\underline{y}_{T-1}} E_{S_{T-1}|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} E_{S_T|X_T,\mu;\underline{y}_{T-1}} \cdot \underline{U}_1(\underline{S}_T,\underline{y}_T,\underline{z}_T). \tag{9}$$

Since the true pest population in the T−1 previous periods are not ever known with certainty at the beginning of the terminal period, the operation $E_{\underline{S}_{T-1}|\underline{X}_T,\mu;\underline{y}_{T-1}}$ in the previous period is revised using the sampled pest population in the terminal period. If the operator chooses to not scout in the terminal period, that period's spray decision is determined according to

$$\max_{y_T} E_{\mu|\underline{X}_{T-1};\underline{y}_{T-1}} E_{S_{T-1}|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} E_{S_T|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} \cdot U_1(\underline{S}_T,\underline{y}_T,\underline{z}_T). \tag{9}$$

If the operator chooses to scout in the terminal period, the value of this option is

$$V_S^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1}) = E_{\mu|\underline{X}_{T-1};\underline{y}_{T-1}} E_{S_{T-1}|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} E_{X_T|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} J_S^{(T)}(\underline{X}_T,\underline{y}_{T-1},\mu,\underline{S}_{T-1}) - U_2(c_2) \tag{10}$$

where

$$J_S^{(T)}(\underline{X}_T,\underline{y}_{T-1},\mu,\underline{S}_{T-1}) = \max_{y_T} E_{S_T|\underline{X}_T,\mu;\underline{y}_{T-1}} U_1(\underline{S}_T,\underline{y}_T,\underline{z}_{T-1}). \tag{11}$$

Notice that the results of scouting in all periods and the previous spray decisions also influence the T th period spray decision via the probability distribution over which $U_1(\underline{S}_T,\underline{y}_T,\underline{z}_T)$ is averaged. If the operator chooses to not scout in the terminal period, the value of this option is

$$V_{NS}^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1}) = E_{\mu|\underline{X}_{T-1};\underline{y}_{T-1}} E_{\underline{S}_{T-1}|\underline{X}_{T-1},\mu;\underline{y}_{T-1}} J_{NS}^{(T)}(\underline{X}_{T-1},y_{T-1},\mu,\underline{S}_{T-1}) \tag{12}$$

where

$$J_{NS}^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu,\underline{S}_{T-1}) = \max_{y_T} E_{S_T|X_{T-1},\mu;y_{T-1}} U_1(\underline{S}_T,\underline{y}_T,\underline{z}_T) \tag{13}$$

The decision to scout in this period is determined by the policy associated with $\max\{V_S^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1});\ V_{NS}^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1})\}$.

Now that the operator knows how to act in the final period with respect to scouting and spraying, it remains to be determined how to develop the (T−I) st period scouting and spraying strategies. If the operator chooses to scout in period (T−1), the spray decision is made according to

$$\max_{y_{T-1}} E_{\mu|\underline{X}_{T-1},\underline{y}_{T-2}} E_{\underline{S}_{T-2}|\underline{X}_{T-1},\mu;\underline{y}_{T-2}} E_{\underline{S}_{T-1}|\underline{X}_{T-1},\mu;\underline{y}_{T-2}} \cdot V_*^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu,\underline{S}_{T-1}) \tag{14}$$

where

$$\begin{aligned} &V_*^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu,\underline{S}_{T-1}) = \\ &\max\{E_{X_T|\underline{X}_{T-1},\mu;y_{T-1}} J_S^{(T)}(\underline{X}_T,y_{T-1},\mu,\underline{S}_{T-1}); \\ &J_{NS}^{(T)}(\underline{X}_{T-1},\underline{y}_{T-2},\mu,\underline{S}_{T-1})\}. \end{aligned} \tag{15}$$

In order to optimally select the (T−1) st period scouting and spraying decisions, the consequences of that spray upon the terminal period decisions must also be taken into account. By similar reasoning, if the operator chooses to not scout in the (T−1) st period, the spray decision is determined by

$$\max_{y_{T-1}} E_{\mu|\underline{X}_{T-2};\underline{y}_{T-2}} E_{\underline{S}_{T-2}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} E_{S_{T-1}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} \cdot V_*^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu,\underline{S}_{T-1}) \tag{16}$$

where in this case $\underline{X}_{T-1} = (X_1, X_2, \ldots, X_{T-2}, X_{T-1} = x_0)$ and x_0 denotes no scouting in the (T−1) st period. That is, in this case $\underline{X}_{T-1}$ and $\underline{X}_{T-2}$ are equivalent in an information context.

The (T−1) st scouting decision is determined by the policy associated with

$$\begin{aligned} &\max\{E_{\mu|\underline{X}_{T-2};\underline{y}_{T-2}} E_{\underline{S}_{T-2}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} E_{X_{T-1}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} \\ &\cdot J_{(S)}^{(T)}(\underline{X}_{T-1},\underline{y}_{T-2},\mu,\underline{S}_{T-2}) - U_2(c_2); \\ &E_{\mu|\underline{X}_{T-2};y_{T-2}} E_{\underline{S}_{T-2}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} J_{NS}^{(T-1)}(\underline{X}_{T-1},\underline{y}_{T-2},\mu,\underline{S}_{T-2})\} \end{aligned} \tag{17}$$

where

$$\begin{aligned} &J_S^{(T-1)}(\underline{X}_{T-1},\underline{y}_{T-2},\mu,\underline{S}_{T-2}) = \\ &\max_{y_{T-1}} E_{S_{T-1}|\underline{X}_{T-1},\mu;y_{T-2}} V_*^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu\underline{S}_{T-1}) \end{aligned} \tag{18}$$

and

$$\begin{aligned} &J_{NS}^{(T-1)}(\underline{X}_{T-2},\underline{y}_{T-2},\mu,\underline{S}_{T-2}) = \\ &\max_{y_{T-1}} E_{S_{T-1}|\underline{X}_{T-2},\mu;\underline{y}_{T-2}} V_*^{(T)}(\underline{X}_{T-1},\underline{y}_{T-1},\mu,\underline{S}_{T-1}). \end{aligned} \tag{19}$$

The backward recursion process continues on back to the first period where the scouting and spraying decisions in that period are selected with the view towards how these decisions influence the choice of future scouting and spraying decisions for the maximization of expected utility.

The Value of Scouting

The scouting information collected regarding the extent of the pest infestation in the field is typically imperfect, but it may play a role in improving the operator's decision. The expected value of scouting information (EVSI) is defined as the difference between the expected values of the options of scouting and not scouting, respectively, when the scouting cost is zero. If this value exceeds the actual cost of scouting, then, all other things being equal, the field should be scouted.

Where there are several future scouting decisions to be made, the problem of evaluating scouting information and making optimal decisions at each stage is more complex. Consider, for example, the decision regarding whether to scout in the first period. The operator must consider expanding his information set by scouting. The decision is made by directly comparing the two data bases. The value of scouting in the t th period depends on the current information as well as the information the operator anticipates receiving. This value is

$$G^*(e_t=1) = E_{\mu|\underline{X}_{t-1};\underline{y}_{t-1}} E_{\underline{S}_{t-1}|\underline{X}_{t-1},\mu;\underline{y}_{t-1}} \cdot E_{X_t|\underline{X}_{t-1},\mu;\underline{y}_{t-1}} J_S^{(t)}(\underline{X}_t,\underline{y}_{t-1},\mu,\underline{S}_{t-1}). \tag{20}$$

If scouting is not performed

$$G^*(e_t=0) = E_{\mu|\underline{X}_{t-1};\underline{y}_{t-1}} E_{S_{t-1}|\underline{X}_{t-1},\mu;\underline{y}_{t-1}} \cdot J_{NS}^{(t)}(\underline{X}_{t-1},\underline{y}_{t-1},\mu,\underline{S}_{t-1}). \tag{21}$$

The expected value of the optimal adaptive control sequence is not worse than the expected value of the optimal open loop control sequence. The latter is not worse than the expected value of the optimal control sequence when no information is collected in the first period (Bertsekas, 1976).

One can distinguish between two types of EVSI; an addition to the information set (i.e., whether to scout once more) and the development of an entire information set (i.e., whether to scout or not during the season). Large operators tend to coordinate their own scouting activities and, therefore, may be interested in the former type of EVSI. Most operators can only contract for these services on a seasonal basis and, therefore, the latter version of EVSI is appropriate.

III. Application to the Cotton-Lygus Bug System

The theory developed in the previous section is applied to the cotton-lygus bug (*lygus hesperus* (Knight)) system in the San Joaquin Valley of California. Cotton is attacked by a variety of insect and mite pests which are continuing problems to operators and may require some method of control or suppression each year. Along with the pink bollworm, *pectinophora gossypiella* (Saunders), the lygus bug is one of the more important insect pests attacking cotton in California. The development of the cotton plant proceeds from the emergence of the cotton buds (or squares) which bloom and eventually mature to yield cotton lint and seed. The lygus disrupts this process by feeding on the squares, reducing the number of bolls that are formed and thus reducing the yield. Empirical work reported elsewhere (Mangel, Stefanou and Wilen, 1985) suggests that lygus significantly injure cotton yields during two disjoint periods. The first period is during the early squaring stage of the plant when square formation is increasing at an intrinsic rate of approximately 100 percent a week. The second period of vulnerability is when the number of squares per acre has peaked. Although the plant growth and development depends upon heat accumulation (a time scale commonly typically measured in degree days), the phenology of the plant can be used to identify the stages when lygus may adversely impact cotton yields.

Although large operators coordinate their own scouting and spraying activities, most cotton operators' scale of production is such that they contract for scouting services on a seasonal basis. These scouting services involve monitoring plant development and a variety of pest populations during the season. The typical charge for such services is $5.00 per acre per season in 1982, which implies a cost of 25 cents per acre per week for a five month scouting contract.

The maximization of expected profit is the focus of this analysis in order to obtain a measure, in cents per acre, of the value of scouting for lygus.* Since the results may depend upon a large number of parameters, a base case is used.. † The effectiveness of a spray is assumed to be 90 percent killed. The ranges for the lygus population are Low: [0, 4], Medium: [5, 8], and High: greater than 9 lygus per 50 sweeps. The immigration into the field in between periods plus the increase in the lygus population because its predators are killed by spraying in the first period is treated as a parameter. Low immigration assumes that 3 lygus per 50 sweeps immigrate to the field, and high immigration assumes that 8 lygus per 50 sweeps immigrate to the field. If significant stands of alfalfa, safflower or native growth are present in neighbouring fields then a high immigration of lygus is assigned. The results of the measurement of lygus injury to cotton yields indicate that lygus does not significantly injure cotton yields for above average first period plant performance (Mangel, Stefanou and Wilen, 1985).

The probability distribution for the mean, μ, of the underlying distribution of the true lygus population is given by partitioning the gamma distribution in the following manner:

$$\Pr\{\mu = \text{Low} \int_{O}^{L} y(x,a,ß)dx \tag{23}$$

$$\Pr\{\mu = \text{Medium}\} = \int_{L}^{M} y(x;a,ß)dx$$

$$\Pr\{\mu = \text{High}\} = 1 - \Pr\{\mu = \text{Low}\} - \Pr\{\mu = \text{Medium}\}.$$

where L and M denote the upper bounds of the low and medium lygus population ranges, respectively. The operator's prior belief and the coefficient

* The money equivalent of the increment in expected utility must be smaller than the increment in expected profit for risk averters. Thus, expected profit provides an upper bound estimate of the value of information.

† The base case for this analysis has the price of cotton lint as \$ .70 per pounds, the cost of spraying at \$8.00 per acre and the fraction of lygus killed by a spray at .9. Source: University of California Cooperative Extension Budget Generator for cotton production in Kern County in 1982.

‡ An operational procedure to elicit the parameters α and β is to elicit the operator's prior belief regarding the mean lygus population level and the confidence he has in that belief. This can be done by asking the operator what he believes the expected value of the mean to be, say $\hat{\mu}$, and a confidence level for that value. $\Pr\{a<\hat{\mu}<b\} = k$, where $0<k<1$ and a and b are the lower and upper limits of the confidence statement. Therefore, the problem is to determine the values of α and β that satisfy $\mu=\alpha/\beta$ and

$$(\beta^{\alpha}(\alpha-1)!) \int_{a}^{b} x^{\alpha-1} \operatorname{expr}(-\beta x)dx = k$$

This identification can be simplified to choose ß such that

$$(\beta^{\beta\hat{\mu}}/(ß\hat{\mu}-1)!) \int_{a}^{b} x^{(\beta\hat{\mu}-1)}\exp(-ßx)dx = k.$$

of variation (CV) of that belief are used to identify the parameters α and β. The values of 4, 8 and 15 lygus per 50 sweeps are assigned to the categories low, medium and high, respectively. In the analysis that follows the CV of the operator's belief is assumed to be 50 percent. Since the CV is a dimensionless measure, all of the scenarios that characterise the operator's prior belief regarding the lygus population level are equivalent in a variational sense.‡

The only scouting options that are considered in the following analysis are the no scouting option or a particular scouting procedure which implies a fixed intensity of scouting effort as measured by the accuracy of information parameter. In practice an operator may have a number of scouting procedures available, based upon varying degrees of scouting intensity. If relatively high lygus populations are observed early in the season, the operator may choose to scout more intensively in the subsequent scouting. That is, the intensity of scouting may depend upon the results of previous scoutings. Incorporating such a range of scouting procedures might add realism to the model but unfortunately makes the problem analytically and computationally unwieldy.

Pesticide Applications

The first period optimal pesticide application decision depends upon a number of factors that include plant performance, the operator's prior belief regarding the lygus population level, the price of cotton, the cost of spraying, the accuracy of scouting, and the scouting strategy. Table 2 summarises the optimal scouting and spraying procedure assuming a low immigration level. Of initial interest is the result that scouting does not alter the spraying strategy under certain scenarios. For the base case, the optimisation results indicate that the operator should spray when field development is in poor condition initially (150 squares per .001 acre in the first period), regardless of the scouting strategy, the operator's prior belief of the true lygus population level, or the immigration level. To understand this result, it appears that in this scenario the crop is performing so poorly at the rapid square formation period that even a relatively low lygus population level can significantly injure cotton yields. Thus, scouting for lygus is not informative for a poorly performing field. For the case of a high immigration level the results are identical except for 2 out of the 36 cases.

Table 2. Conditions Under Which First Period Spraying is Recommended with Low Immigration

		Scouting Strategies			
Prior	*Initial Square Load*	*Scout in Both*	*Scout in 1 Only*	*Scout in 2 Only*	*Don't Scout*
	(per .001 acre)	*(entries indicate first period scouting results)*			
L = Low	150	ALL	ALL	ALL	ALL
	200	M,H	H	ALL	ALL
	250	H	NO	NO	NO
M = Medium	150	ALL	ALL	ALL	ALL
	200	ALL	ALL	ALL	ALL
	250	M,H	H	ALL	ALL
H = High	150	ALL	ALL	ALL	ALL
	200	ALL	ALL	ALL	ALL
	250	ALL	ALL	ALL	ALL

The second period spray decision is influenced by the between period immigration, the operator's prior belief regarding the lygus population, the first period plant performance, the first period scouting and spraying results, and the second period scouting results. Although lygus pressure in the second period can induce square shed, the damage in this period was estimated to be less than half the damage the lygus can inflict on the plant in the first period. A second period spray test is recommended for only eight out of a possible 576 scenarios tested. All of these cases require a high between period immigration and a poor first period square load.

Scouting Decision

Given first period scouting has taken place, the net value of cotton production is not improved when the operator scouts in the second period. Therefore, when the cost of scouting is positive the optimal scouting decision will be chosen between the strategies of either scouting in the first period only or not scouting at all. Operationally, the only realistic scouting choices available to the operator are the cases of always scouting or never scouting. Even the large operators who coordinate their own scouting employ a pest control advisor and supporting staff.

Since the accuracy of information is difficult to identify, it is modelled as a parameter σ (Table 1). To see how σ affects the EVSI (equations (21) and (22)), consider the case of only two possible scouting strategies: always scouting and never scouting. Table 3 presents the EVSI for scouting accuracy ranging from no information ($\sigma = 1/3$) to perfect information ($\sigma = 1$) for low and high immigration respectively, under varying conditions. For the cases of poor to below average plant performance and low immigration, the EVSI is positive with scouting accuracy of .7 and better. In the case of low immigration, scouting is most valuable for below average plant performance. Scouting is not highly valued when the plant performance is poor or average. In the former case, the cotton crop is performing so poorly that even a relatively low lygus population level can significantly reduce the yield. Consequently, scouting does not alter the operator's strategy to spray for lygus. In the latter case, the cotton crop is performing well enough to endure even a moderate lygus population without a significant reduction in yields. Consequently, scouting will not alter the operator's strategy to not spray for lygus.

Table 3. The Value of Always Scouting Vs. the Value of Never Scouting for Varying Levels in the Accuracy of Scouting (Cents/Acre).

Accuracy of Information	*Prior Q:*	*Low*			*Medium*			*High*		
		150	*200*	*250*	*150*	*200*	*250*	*150*	*200*	*250*
.33		0[a] (0)[b]	0 (0)	(0) (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
.50		0 (0)	18 (15)	0 (6)	1 (0)	1 (4)	0 (7)	0 (0)	0 (1)	0 (2)
.70		2 (0)	35 (48)	0 (31)	2 (0)	10 (12)	1 (35)	1 (0)	2 (2)	0 (12)
.80		3 (0)	52 (64)	3 (45)	5 (0)	15 (16)	4 (49)	1 (0)	3 (3)	2 (17)
.90		5 (0)	70 (80)	11 (58)	5 (0)	20 (21)	14 (64)	2 (0)	4 (3)	5 (22)
1.00		7 (3)	91 (105)	27 (76)	9 (1)	32 (35)	25 (81)	5 (0)	9 (8)	9 (32)

Notes: [a]Accuracy of Scouting with High Immigration

[b]Accuracy of Scouting with Low Immigration

Q = First Period Square Load, Price of Lint = \$.70/Pound, Cost of Spray = \$8.00/Acre, Effectiveness of Spray = .9.

The EVSI in the second period is of no measurable value for three reasons. First, these second period squares do not significantly contribute to boll formation. Second, the lygus induced injury to the cotton plant is not as severe in the second period. Third, the immigration level, a key determinant of the lygus population level, is modelled as a known parameter. Consequently, lygus can inflict damage to cotton yields in this period but scouting information will not significantly influence the operator's actions.

Scouting has value to the extent it can alter the operator's decisons and improve his payoff. Depending on the initialising parameter values, the value of scouting information assessed before scouting is initiated can range from zero to \$1.05 per acre in the first period compared to an average cost of scouting of \$.25 per acre. The value of scouting assessed before scouting is initiated in the second period is negligible while the cost of scouting remains \$.25 per acre. In some cases, the value of scouting in the first period alone can exceed the cost of scouting by a factor of almost two.

An operator can use the computer programmes found in Stefanou (1983) to generate the management decisions processes generated in this section. The programs are written in BASIC and run on an APPLE II Plus microcomputer. The processing time for a given management scenario is less than five minutes.

IV. Summary

The Bayesian approach to incorporating pest information provides the operator with a specific framework for incorporating information into his decision process. For a given utility function, the model outlined in this paper requires three key operator inputs. First, the relationship of pest population pressure on crop yield is a crucial component of the decision model. The specification and estimation of the damage relationship and the effectiveness of controls on reducing crop yield tends to be the weakest link in pest damage models. Few specific plant/pest interaction models are available.

Second, the operator's subjective or prior belief of the distribution of the pest population (parameters α, β) must be elicited. These parameters can be developed from a variety of sources, such as from historical data or information obtained from other operators.

Third, the accuracy of the scouting information needs to be determined. The level of accuracy of this information depends upon the intensity and the method of sampling. Although research has been undertaken comparing various monitoring techniques, no specific work has been done to model and empirically measure the accuracy of varying degrees of scouting intensity, and the cost of scouting in terms of the accuracy of that information.

Since scouting information may reduce the uncertainty concerning the pest population pressure on crop yield, the operator may be able to improve his payoff with more effective pesticide applications.

References

Bertsekas, D. P. (1976). *Dynamic Programming and Stochastic Control.* New York: Academic Press.

Carlson, G. A. (1970). A Decision Theoretic Approach to Crop Disease Production and Control, *American Journal of Agricultural Economics*, **52**, 216-223.

Carlson, G. A. (1980). Economic and Biological Variables Affecting Demand for Publicly and Privately Provided Pest Information, *American Journal of Agricultural Economics*, **62**, 1001-1006.

Feder, G. (1979). Pesticides, Information, and Pest Management Under Uncertainty, *American Journal of Agricultural Economics*, **61**, 98-103.

Gilbert, R. J. and Richels, R. G. (1981). Reducing Uranium Resource Uncertainty, *Resources and Energy,* **3,** 13-37.

Mangel, M., Stefanou S. E. and Wilen, J. E. (1985). Modeling *Lygus hesperus* (Knight) Injury to Cotton Yields, *Journal of Economic Entomology,* **78,** 1009-1014.

Mumford, J. D. (1981). Pest Control Decision Making: Sugar Beet in England, *Journal of Agricultural Economics,* **32,** 31-41.

Pielou, E. C. (1976). *Mathematical Ecology*. New York: John Wiley and Sons.

Raiffa, H. and Schlaiffer, R. (1961). *Applied Statistical Desicion Theory*. Cambridge, Ma: Division of Research, Harvard Business School.

Stefanou, S. E. (1983). Impact of Scouting Information on Pesticide Application Decisions. Ph.D. Dissertation, Agricultural Economics, University of California, Davis.

Webster, J. P. G. (1977). The Analysis of Risky Farm Management Decisions: Advising Farmers About the Use of Pesticides, *Journal of Agricultural Economics,* **28,** 243-259.

Wetzstein, M. E. (1981). Pest Information and Integrated Pest Management, *Southern Journal of Agricultural Economics,* **13,** 79-83.

Wilson, L. T. and Room, P. M. (1983). Clumping Patterns of Fruit and Arthropods in Cotton with Implications for Binomial Sampling, *Environmental Entomology,* **12,** 50-54.

Zavaleta, L. R. and Dixon, B. L. (1982). Economic Benefits of Kalman Entering for Insect Pest Management, *Journal of Economic Entomology,* **75,** 982-988.