A BIOECONOMIC SIMULATION APPROACH TO MULTI-SPECIES INSECT MANAGEMENT

William G. Boggess, Dino J. Cardelli, and C. S. Barfield

Abstract

Classical approaches to the economics of pest management have focused almost exclusively on single-species models. This study develops and implements a methodology with which to evaluate multi-species, non-stochastic, managerial decisions subject to stochastic elements of the plant-insect system. Multi-species insect management strategies (combinations of scouting interval, threshold value, and choice of pesticide) are analyzed using a physiological mechanistic soybean plant growth model coupled to three insect population dynamics models. Preliminary results indicate that net returns are maximized and variance is reduced with lower thresholds and more frequent scouting than current recommendations.

Key words: pest management, multi-species, simulation, stochastic dominance.

Classical approaches to economics have not focused adequately on development of tools (e.g., models) for agricultural decisionmaking under multiple insect species conditions. Far more emphasis has been placed on development of management strategies for single insect species (Watt; Carlson; Hall and Norgaard; Hueth and Regev; Marsolan and Rudd; Talpaz et al.). However, in many production systems, multiple insect pests are prevalent. In these cases, management may be much more complex than single species management since: (1) the pests may occur together or at different times in the season, (2) the pests may attack the plant in different ways (e.g., defoliators vs. pod feeders), and (3) the pests may exhibit different levels of susceptibility to controls.

This study represents a first step in multi-species insect management. The objective is to develop and implement a methodology with which to evaluate multi-species, non-stochastic, managerial decision variables subject to stochastic elements of weather and the plant-insect system. To accomplish this task, the Florida Soybean Integrated Crop Management (SICM) Model was used (Wilkerson et al., 1983b). This model was designed to integrate the effects of various soybean insect pests at the field level under varying weather, cultural, and soil conditions.

PREVIOUS PEST MANAGEMENT MODELING RESEARCH

Biological simulation models of insects and crops are relatively recent developments. Early modeling efforts begun in the mid-1970's focused on controlling boll weevils in cotton. Brown et al. provide an excellent overview of the development of the Mississippi cotton growth and insect dynamic models. Gutierrez et al. were the first to publish an analysis of cotton pest management based on a detailed biological simulation model. Talpaz et al. followed closely behind with an economic optimization model which incorporated a detailed plant-pest interactive system with a pesticide control scheme. The model used a temperature dependent boll weevil model combined with a mechanistic fruit drying and cotton fruiting model.

Marsolan and Rudd developed one of the earliest soybean insect dynamics models. They used a distributed-parameter population dynamics model of the southern green stinkbug [*Nezara viridula* (L)] to evaluate optimal control strategies. The model described the mortality, fecundity, and movement as an age dependent function and assumed instantaneous control by methyl-parathion.

William G. Boggess is an Associate Professor of Food and Resource Economics, University of Florida; Dino J. Cardelli is a Corporate Economist, Tropicana Inc., Bradenton, Florida; and C. S. Barfield is an Associate Professor of Entomology, University of Florida.

Florida Agricultural Experiment Station Journal Series No. 6439. This work was supported by the Institute of Food and Agricultural Sciences, University of Florida and by EPA Grant No. CR-806277-02-0.

Reichelderfer and Bender were the first to use biological simulation in the evaluation of pest control in soybeans. Predator-pest relationships of the Mexican bean beetle were incorporated into a microanalytic model to generate output response surfaces of alternative biological and chemical control strategies. The response surfaces were combined with cost data to construct benefit-cost ratios for intraseasonal control options.

In the 1980s, several articles advanced the development of dynamic management-oriented models. Zavaleta and Reusink examined potential gains derived from biological means of control, as well as the introduction of host plant resistance in their model. Shoemaker developed a stochastic dynamic programming model to analyze the integrated control of alfalfa weevils in central New York. The management alternatives considered included biological control by the parasitoid *Bathyplectes curculionis,* cultural control by harvesting, and chemical control by insecticides. Wilkerson et al. (1983a) developed a time-dependent dynamic model for evaluating within-season management decisions for velvetbean caterpillars in soybeans.

MODEL AND PROCEDURES

The present study uses a multi-species bioeconomic simulation model (Wilkerson et al., 1983b) to build on the previous single-species models presented in the literature. This modeling approach avoids two of the major limitations of the neoclassical theory of the firm as it relates to the problem of evaluating multiple-species management strategies. First, the plant-insect ecosystem is a complex, dynamic system in which timing is a critical element. The SICM simulation model is essentially a computer model of the elementary processes that define the soybean production system. In this approach, the simulation model replaces the classical production function and is used to empirically derive the relationships between the various insect management strategies, yields, and pesticide applications. These empirical relationships are used to determine the profit maximizing strategies, the demand for pest control, and the marginal cost of pest control under various influx and price conditions.

The second limitation of the classical approach is that it ignores risk. Given the stochastic nature of weather and insect influxes, the risk associated with alternative control strategies can be a critical factor in the evaluation and choice of strategies. The simulation model facilitates evaluation of alternative strategies under stochastic conditions, allowing empirical derivation of probability distribution functions for each of the strategies. The various probability distribution functions can then be compared using stochastic dominance procedures in order to determine risk efficient strategies. No distributional assumptions are required in order to apply stochastic dominance rules.

Two stochastic dominance rules, first degree and second degree are applied in this study. First Degree Stochastic Dominance (FSD) states, ***Any alternative B is preferred to any alternative A if $F_B(x) \leq F_A(x)$ for all values of x, i.e., if the cumulative probability of B lies to the right of A.*** The only assumption required to use FSD is that the decisionmaker prefers more to less (Anderson et al.). Second Degree Stochastic Dominance (SSD) states, ***Alternative B is preferred to Alternative A for all risk averters if the cumulative difference between $F_A(x)$ and $F_B(x)$ is non-negative over the domain of X.*** Mathematically, SSD requires that:

$$(1) \quad \int_a^x [F_A(x) - F_B(x)]\, dx > 0$$

for all values of x. The SSD rule assumes that the decisionmaker prefers more to less and is risk averse (Anderson et al.).

Strategies were constructed to illustrate how the model may be used to evaluate the sensitivity of profit to various combinations of population threshold levels, scouting frequencies, and pesticide types and rates. Forty strategies were developed to account for five threshold levels of total worms (0, 5, 10, 15, and 20 per 3 row feet), four scouting frequencies (3, 5, 7, and 10 days) and two chemical combinations. These combinations were designed to bracket the current recommendation of 12 worms and a 7-day scouting interval (Johnson et al.). "Total worms" is defined as the sum of medium and large velvetbean caterpillar larvae plus large corn earworm larvae. The southern green stinkbug treatment threshold was set at 1 adult per 3 row feet which is the current extension recommendation (Johnson et al.).

For each strategy, both an early season and a late season pesticide type were chosen. The early (pre-bloom) pesticide is used to control foliage feeders while the late (post-bloom) pesticide is primarily used to control pod feeding insects. Two pesticide combinations were chosen to examine the effects of pesticide types. Methomyl was the early pesticide used in both pesticide combinations. Methyl-parathion and acephate are both recommended by the Extension Service for late season stinkbug and corn earworm control (Johnson et al.). Acephate is more expensive than methyl-parathion but has a longer residual effect on both the pest and predator populations.

The primary stochastic variables affecting the plant-insect ecosystem are related to weather. The strategies were evaluated over 10 years (1954-1963) of actual daily radiation, precipitation, and maximum and minimum temperatures.

The influx timing and intensity of insect pests are also important stochastic variables. However, there are insufficient data to statistically estimate probability distributions. In order to provide sensitivity analyses, independent, uniform distributions were assumed for both influx intensity and initial influx timing. Three levels of velvetbean caterpillar influx intensity (small, average, and heavy) were specified. The specific values were determined from light trap data under actual conditions (Wilkerson et al., 1983b). In addition, three levels of initial influx timing of velvetbean caterpillar (early, on-time, and late) were specified. Julian dates of the influxes are 179 (June 29), 202 (July 22) and 219 (August 10) (Wilkerson et al., 1983b).

Current components of the SICM model include crop growth, insect, tactics (pesticides and irrigation), and economics. An overview of each of these components follows with the reader being referred to the appropriate literature for specific details.

Soybean Crop Growth Model (SOYGRO)

SOYGRO is a process oriented growth and yield model which comprises the core of the SICM model. Physiological processes of photosynthesis, respiration, tissue synthesis, nitrogen remobilization, and senescence are modeled. These processes are coupled to weather, soil, pest and crop conditions, and are linked mathematically by a series of differential equations that depend on the phenological phase of crop development. Because of the length and complexity of the state equations describing this system, readers interested in a more detailed explanation are referred to Wilkerson et al. (1983c).

The usefulness of the SICM model is obviously dependent upon the accuracy of the crop growth simulation model results. Validation of the crop growth model was performed by comparing simulated yields with observed experimental yields over a 3-year period. A correlation between the simulated and observed yields of 0.98 was obtained.

Insect Models

Three insect[1] models are linked to the crop growth model. These models simulate insect population dynamics (fecundity, development, and mortality) and link the insects to the crop via consumption of leaves and pods.

Insect Development

Velvetbean caterpillar populations (VBC) are divided into six developmental stages: eggs, small larvae (instars 1-2), medium larvae (instars 3-4), large larvae (instars 5-6), pupae, and adults. Within each growth stage, an age structure is maintained. Insects move from age block to age block within a given growth stage until they have accumulated a sufficient number of physiological days to advance to the next developmental state (Wilkerson et al., 1985).

The corn earworm (CEW) population model developed by Stinner et al. uses a variation in development time for a given temperature to simulate the change of generations and prevent discrete overlapping. The model accumulates proportions of insects that entered a given stage on previous dates developing to the next stage on a specific later date. In the simulation, insect densities are calculated daily, starting with the first date of influx.

Rudd modeled the emergence of stinkbug individuals from a stage by an emergence function, which is the fraction or percentage of those individuals that have progressed to the next stage by time t. The derivative of

[1]Insect components include velvetbean caterpillars, *Anticarsia genmatalis* [Hubner]; corn earworm, *Heliothis zea* [Boddie]; and southern green stinkbug, *Nezara viridula* [L].

this function with respect to time is an age-dependent probability distribution that describes the progression of the individuals through stages; i.e., the probability of an individual emerging from a stage at time t. The probability distribution for the southern green stinkbug was obtained from development data by Kiritani et al. and Herzog et al.

Mortality

At present, mortalities inflicted by predators, pesticide applications (also *Bacillus thuringiensis* Berliner), and food shortage are incorporated into the model. Functionally, mortality is represented as:

$$(2)\quad \mu_i = (1-s_{iB})(1-s_{iF})(1-s_{iP})(1-s_{iT}),$$

where μ_i is the proportion of insects in development stage i which die, and the s_i's represent the proportion of the population in stage i which survive the particular mortality factors (background (B), food (F), predators (P), and pesticides (T), respectively).

Consumption

The insect models are tied to the crop model through leaf and pod consumption. Consumption of pods directly reduces crop yield; whereas, leaf consumption (defoliation) reduces yields via reduced photosynthesis. Consumption rates are 0.06, 3.0, and 48.0 cm^2/day for small, medium, and large larvae, respectively. These values were obtained by converting fresh leaf weight consumption from Moscardi to dry weight, and then to area using relationships developed by Boote.

Tactics Model

Various tactics can be used to control pest populations and reduce crop stress. In particular, pesticides can be used to manage insect populations and irrigation can be used to control water stress. Pesticides affect pest insect mortality directly (μ_{iT}) and also indirectly by decreasing predator populations. Mortality of target insects due to pesticide spraying is calculated as:

$$(3)\qquad \mu_{iT}(t) = 1.0 - \prod_{k=1}^{1} s_{iT_k}(t - t_k),$$

where 1 is the number of pesticide applications which have been made to date, and s_{iT_k} $(t - t_k)$ is the proportion of the population, stage i, present $t - t_k$ days after spraying, which survive the effect of pesticide T_k (applied at time t_k). The s_{iT_k} $(t - t_k)$ represents input data for each pesticide type and insect stage.

Predator populations are affected in a similar manner. First the model computes the factor S_{pT_k} by which predator populations are reduced below those of an untreated field $(t - t_k)$ days after pesticide T_k was applied. Thus, the number of predators present in the field at time t is calculated as:

$$(4)\quad PR = PR_{max}(t) \bullet \prod_{k=1}^{1} s_{pT_k}(t - t_k),$$

where $PR_{max}(t)$ is the number of predators which will be present in the field at time t, if the field was not sprayed.

Economics Model

The economics model integrates the effects of a particular management strategy on crop yield and input use with prices to determine net returns. This value is calculated by subtracting the total variable costs incurred during the season from the gross return. The costs are broken down in the model into: (1) variable production costs other than insect control, (2) scouting costs, and (3) variable pest management costs.

Variable production costs per acre excluding insect control costs are calculated as:

$$(5)\quad Cm = 111.50 + [2.98\ Pg + 9.20\ Pd]\ 1.15,$$

where Cm = variable production costs ($/acre) excluding insect control costs, Pg = price of gasoline per gallon and Pd = price of diesel fuel per gallon. Equation (5) is derived from a North Florida soybean cost of production budget prepared by Hewitt.

Scouting costs are based on the commercial rate of $5 per acre per year for a once-a-week scouting program. The number of trips was divided into the $5 per acre per year costs to yield a marginal cost of $0.45 per trip per acre. Total scouting costs are given by:

$$(6)\quad Cs = \$0.45 \bullet \text{number trips made.}$$

Variable costs of pest control (pesticide and application costs) are calculated as:

$$(7)\ Cpm = (Pm \cdot N) + (Pap \cdot N),$$

where Cpm = total seasonal variable costs of pest control ($/acre), Pm = cost of chemicals applied per acre per spray application, Pap = application cost per acre, and N = number of spray applications per acre.

RESULTS

Initially, each of the forty strategies was simulated over all nine insect influx conditions and all 10 weather years. A strategy consisting of a 3-day scouting interval, 5 worms per 3 row feet threshold, and a methomyl, methyl-parathion pesticide combination maximizes expected net returns for all strategies evaluated, Table 1. There is considerable variation in mean net returns over the 40 strategies, ranging from a low of $-15.82 per acre to a maximum of $83.92 per acre.

The top eight strategies had expected net returns within 10 percent of the optimal strategy and the top 18 strategies had expected net returns within 20 percent of the optimal strategy, Table 1. Of the top 10 strategies, eight had a threshold of five worms.

Note that the yield obtained with treatment at a five-worm threshold (Strategy 1) is greater than the yields obtained with calendar treatments (strategies 33-40). This is an example of the so called "pesticide treadmill." Early and heavy pesticide treatments deplete the predator complex. This allows more rapid resurgence of the pest insects as well as secondary breakouts of normally minor pests. Since the pesticides do not kill all of the target insects, there continues to be damage. The net effect of the more rapid resurgence and secondary outbreaks is a reduction in yield. The reduction in yield is greater the longer the scouting interval (interval between calendar sprays).

Results demonstrate a systematic relationship between net returns and scouting interval and between net returns and threshold level. As the threshold level is increased from 5 worms (holding scouting interval and pesticide type constant), mean net return declines and the standard deviation of net returns increases. These results can be seen by comparing strategies 1, 7, 13, and 21. As the threshold is increased from 5 to 10 to 15 to 20 worms, net returns steadily decrease from $83.92 to $58.45 and the standard deviation of net returns increase from $88.95 to $94.96, Table 1. In a similar fashion, as the scouting interval is increased (holding threshold constant at 10 worms and using methyl-parathion), mean net return decreases and the standard deviation of net returns increases. As the scouting interval increases from 3 to 5 to 7 to 10 days, mean net return decreases from $78.35 to $72.44 to $71.88 to $69.11, respectively, and the standard deviation of per acre net returns increases from $92.06 to $95.02 (strategies 7, 9, 11, and 29, Table 1). Similar relationships exist between the mean and standard deviation of yields and scouting interval and between the mean and standard deviation of yields and threshold level.

Risk Considerations

The relative magnitude of the standard deviations of net returns indicates that the stochastic nature of weather, pest levels, and timing greatly influence net returns (i.e., the coefficients of variability are greater than 1.0 for the majority of the strategies). This suggests that risk considerations may play an important role in selecting strategies. For example, it may be desirable to switch strategies once the timing and magnitude to the insect influx is known. In order to examine this possibility, cumulative probability functions of the various strategies were derived from various velvetbean caterpillar influx conditions. In approximately half of the influx conditions, the overall "optimum" strategy (5 worms, 3 days, methyl-parathion) dominated the other strategies by second degree stochastic dominance. An example is the case of a small, late influx, Figure 1. However, under other influx conditions, alternative strategies outperformed the 5-worm, 3 days, methyl-parathion strategy. In the case of a heavy, on-time influx, the 5-worm, 7 days, methyl-parathion strategy dominated by first degree stochastic dominance, Figure 2.

The latter case illustrates the potential value of information about uncertain events (e.g. insect influxes). If you know the influx is heavy and on-time, a 7 day scouting interval matches up very well with the influx and development of VBC. The crop is scouted at just the right time to catch the pest at damaging levels. This allows very effective control with an average of one less pesticide application than would be applied under a

TABLE 1. MEANS AND STANDARD DEVIATIONS OF YIELD, NET RETURNS, AND PESTICIDE COSTS FOR 40 SIMULATED INSECT MANAGEMENT STRATEGIES, SOYBEANS, FLORIDA[a]

Strategy	Pesticide[b]	Threshold[c]	Scouting interval[d]	Mean yield	Mean net returns	Mean pesticide costs	Std. dev. yield	St. dev. net returns
				bu./ac.	\$ per ac.	\$ per ac.	bu./ac.	\$ per ac.
33	Mp	0	3	34.62	−15.82	129.49	11.86	82.27
34	Or	0	3	34.62	−15.82	129.49	11.86	82.27
35	Mp	0	5	31.73	10.93	82.50	9.97	69.50
36	Or	0	5	31.73	10.93	82.50	9.97	69.50
39	Mp	0	10	27.74	12.21	53.33	7.54	52.36
40	Or	0	10	27.74	12.21	53.33	7.54	52.36
37	Mp	0	7	29.88	22.91	57.59	8.87	61.89
38	Or	0	7	29.88	22.91	57.59	8.87	61.89
27	Mp	20	10	26.65	41.12	16.79	13.92	95.53
28	Or	20	10	28.00	45.88	21.46	12.60	87.94
25	Mp	20	7	28.12	50.44	17.74	13.79	95.17
26	Or	20	7	29.19	52.99	22.70	12.66	88.81
31	Mp	15	10	28.57	53.16	18.16	13.72	94.41
24	Or	20	5	29.62	53.72	24.95	12.37	87.26
23	Mp	20	5	29.11	54.21	20.91	13.67	94.27
32	Or	15	10	29.68	55.94	23.15	12.84	88.82
21	Mp	20	3	30.29	58.45	24.94	13.83	94.96
16	Or	15	5	31.07	61.93	26.90	12.74	89.23
17	Mp	15	7	30.24	63.61	19.43	13.64	93.94
18	Or	15	7	30.94	63.73	24.17	12.69	88.89
30	Or	10	10	31.32	65.00	25.54	12.93	89.66
22	Or	20	3	32.02	65.07	30.43	13.16	89.96
15	Mp	15	5	31.06	66.08	22.66	13.88	95.60
10	Or	10	5	32.20	67.98	28.76	12.42	87.15
29	Mp	10	10	31.25	69.11	20.97	13.73	95.02
12	Or	10	7	32.15	70.08	26.30	12.36	86.83
13	Mp	15	3	32.39	71.10	26.93	13.60	93.80
14	Or	15	3	33.15	71.45	31.95	13.19	89.88
11	Mp	10	7	31.72	71.88	21.52	14.00	96.47
9	Mp	10	5	32.23	72.44	24.53	13.56	93.62
4	Or	5	5	33.65	74.49	32.37	12.17	85.02
6	Or	5	7	33.48	76.14	29.56	12.25	85.85
20	Or	5	10	33.63	76.78	29.96	12.80	87.15
8	Or	10	3	34.20	77.44	33.31	12.59	86.38
7	Mp	10	3	33.66	78.35	28.63	13.35	92.06
5	Mp	5	7	33.20	79.39	24.33	13.71	94.57
2	Or	5	3	35.09	80.34	36.61	12.05	83.47
3	Mp	5	5	34.15	81.77	28.62	13.23	91.10
19	Mp	5	10	33.70	82.62	24.63	13.20	90.10
1	Mp	5	3	35.04	83.92	32.66	12.92	88.95

[a]Statistics are calculated over nine influx conditions, 10 years of weather data (1954-63), and a growth model validated using actual yields for years 1970-1980.
[b]Combination of pesticides used for a given strategy with MP = (Methomyl Methyl-parathion) and Or = (Methomyl, Acephate).
[c]Threshold of large and medium VBC and large CEW per 3 row feet.
[d]The number of days between sampling observations.

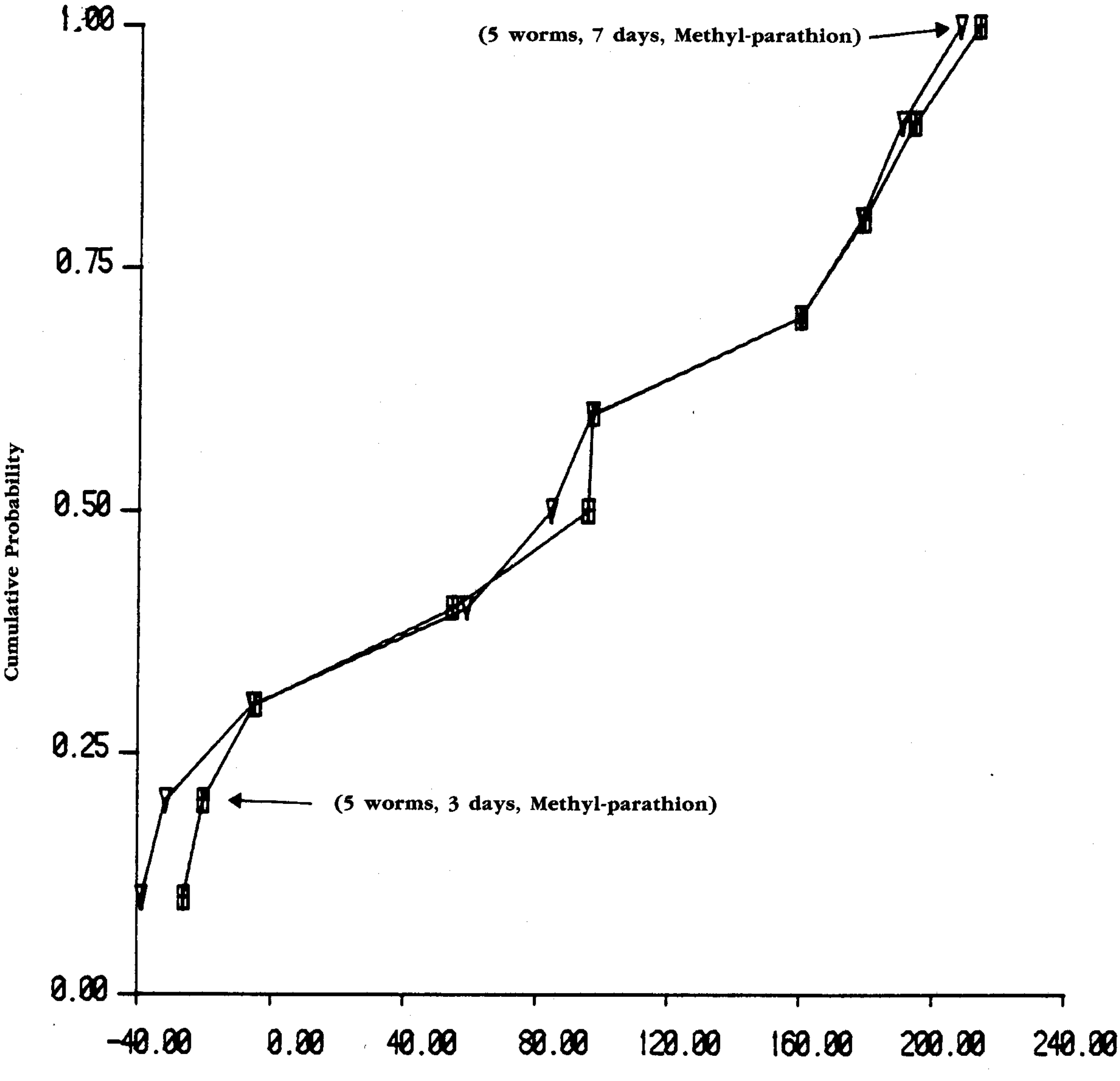

Figure 1. Cumulative Probability Functions of Net Returns for a Small Late Influx of Velvetbean Caterpillars in Soybeans, Florida.

three day scouting interval with an additional savings of \$6.30 in scouting costs.

Pest Control Demand and Marginal Cost Curves

Due to the dynamic nature of the soybean production process, there is no single derived demand or marginal cost curve for pest control. Rather, pest control is the cumulative effect of scouting, treatment threshold, and control tactic applied on pest populations. Various combinations of these parameters will result in varying degrees of pest controls (e.g. different levels of pest populations over time). If any two of these three strategy variables are held constant, conditional marginal value product and marginal cost curves can be derived.

For example, the maximum net return is generated from scouting on a 3 day interval,

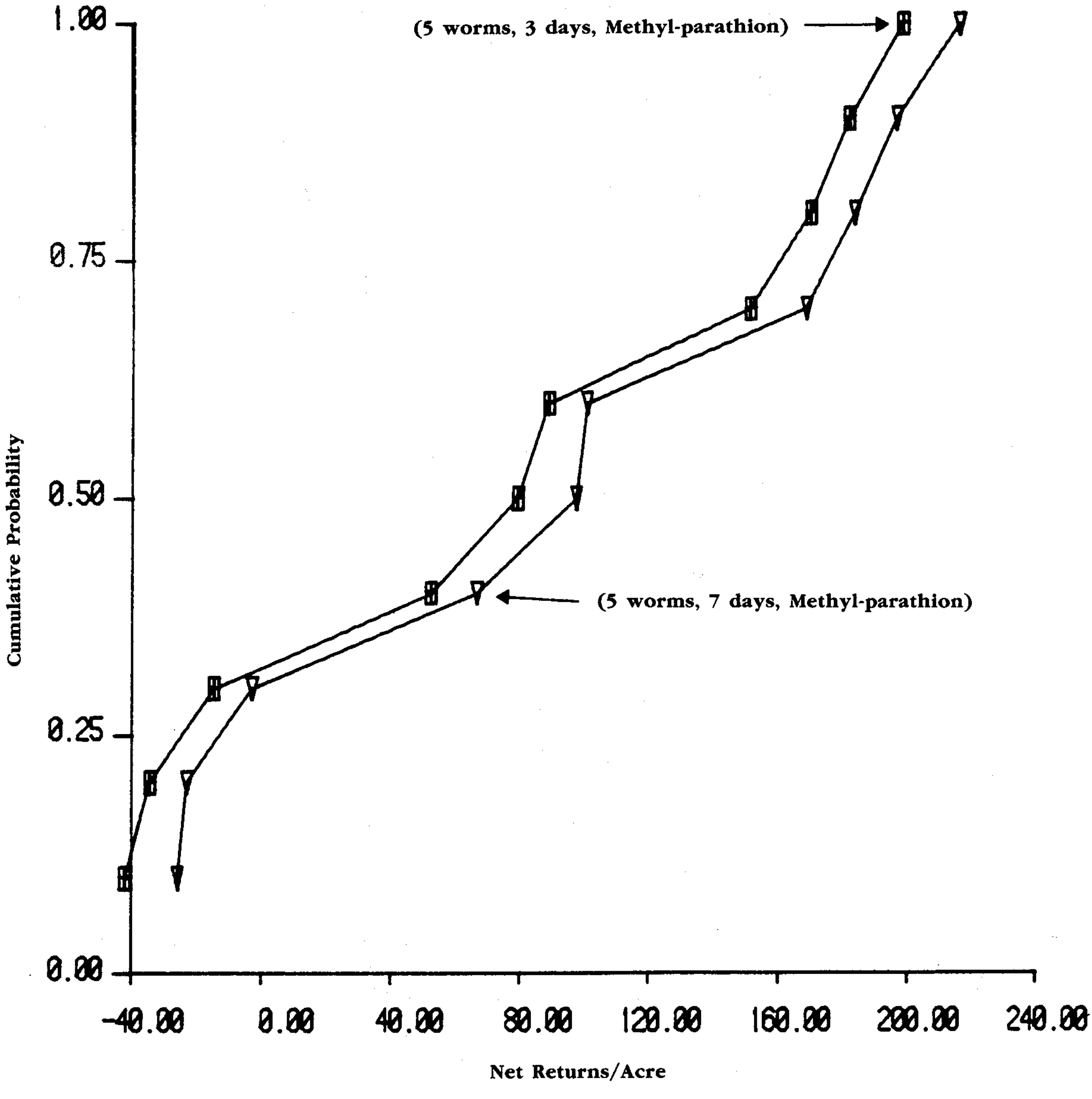

Figure 2. Cumulative Probability Functions of Net Returns for a Heavy, On-Time Influx of Velvetbean Caterpillars in Soybeans, Florida.

and treating at 5 worms per 3 row feet with methomyl and methyl-parathion. By holding the scouting interval and pesticide type constant, the conditional demand and marginal cost curves for treatment threshold are derived as a function of insect population. The curves are derived empirically from the simulation data using discrete interval calculations of the marginal product and marginal cost relationships, Table 2.

The base marginal cost curve (MC) and base marginal value product curve (MVP) are illustrated in Figure 3. The maximum net return threshold is approximately 7 worms per 3 row feet. This indicates that the maximum net return occurs between the 5 worms per 3 row feet and the 10 worms per 3 row feet points that were actually simulated. Use of the MVP and MC curves allows examination of the surface in a single dimension

TABLE 2. INTERVAL CALCULATIONS OF THE MARGINAL COST AND MARGINAL VALUE PRODUCT OF PEST CONTROL, MULTI-SPECIES INSECT MANAGEMENT MODEL FOR SOYBEANS, FLORIDA

Threshold[a]	Mean yield	Interval values: MP	Interval values: MVP-3[b]	Interval values: MVP-7[b]	Interval values: MVP-12[b]	Mean pesticide costs	Internal values: MC[c]	Internal values: MC-2[c]	Internal values: MC-5[c]
	bu./ac.	bu./ac.	$/ac.						
No control (50.0)	13.49					0			
		.56	1.68	3.92	40.32		.83	1.66	4.15
20.0	30.29					24.94			
		.43	1.29	3.01	5.16		.40	.80	2.00
15.0	32.38					26.93			
		.34	1.02	2.38	4.08		.34	.68	1.70
10.0	33.66					28.63			
		.27	.81	1.89	3.24		.80	1.60	4.00
5.0	35.04					32.66			
		.13	.39	.91	1.56		19.37	38.74	96.85
0.0	35.69					131.25			

[a]Number of large and medium VBC and large CEW per 3 row feet.
[b]Marginal value product with soybean prices at $3, $7, and $12 per bushel, respectively.
[c]Marginal cost of pest control averaged over 90 observations (MC), two times the average marginal cost (MC-2), and five times the average marginal cost (MC-5).

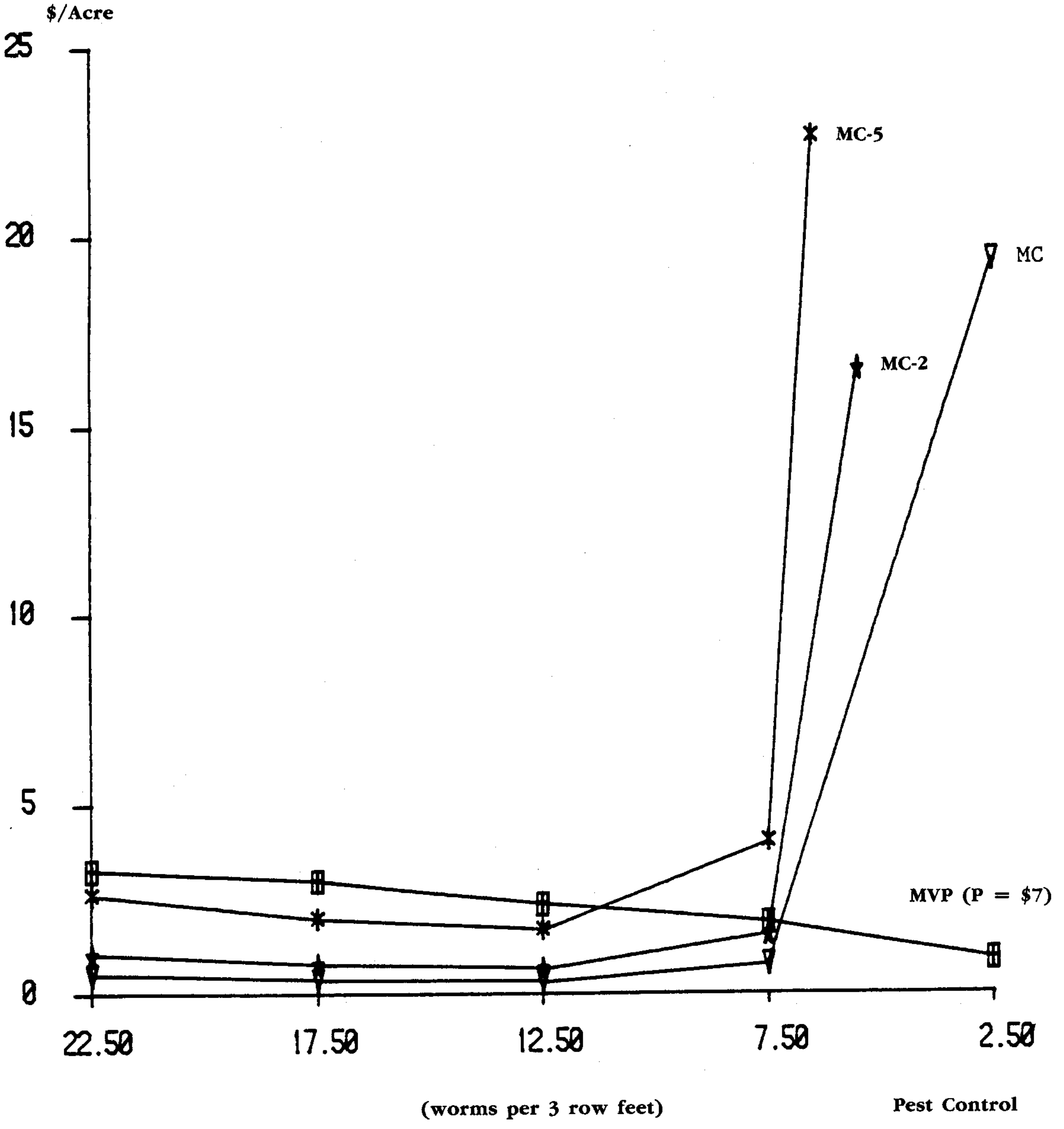

Figure 3. Marginal Value Product and Marginal Cost Curves for Pest Control Based on a 3-Day Scouting Interval and Methomyl, Methyl-Parathion Pesticide Combinations in Soybeans, Florida.

between the simulated reference points without the additional expense. If additional refinement of the surface is desired, interim points (e.g. 7 worms per 3 row feet) can be simulated.

Several factors can affect either the MVP or MC curves causing them to shift upward or downward. Factors which affect the marginal value product curve include: (1) changes in the basic processes which determine yield (e.g., insect population dynamics, scouting interval, or pesticide type) and (2) a change in the price of the output. The major factors affecting the position of the marginal cost curve are the price of inputs into the pest control process (e.g., chemicals, scouting, and application). An increase (decrease) in any one of these prices will shift the MC curve up (down).

Table 2 presents marginal value products calculated on the basis of soybean prices of $3, $7, and $12 per bushel. Note that all three marginal value product curves intersect the marginal cost curve in the interval between 10 and 5 worms, indicating that the maximum net return threshold is quite robust to changes in output price.

Table 2 also presents marginal cost values calculated on the basis of two- and five-fold increases in the prices of all pest control inputs. These curves are represented as MC-2 and MC-5 in Figure 3. As input prices increase, the optimal threshold increases. However, the optimal strategy is quite robust to a twofold increase in pest control costs. The threshold value increases only slightly compared to the original marginal cost curve. A fivefold increase in all pest control input prices is required before the optimal threshold increases significantly from approximately 7 worms to approximately 11 worms per 3 row feet.

CONCLUSIONS

Bioeconomic, process-level simulation models are effective tools for integrating multiple crop stresses and for evaluating management strategies. The approach explicitly recognizes the critical time dependencies of the biological system and facilitates evaluation of the profitability and risks of alternative management strategies.

The results of this particular application yield several preliminary conclusions and researchable hypotheses. Foremost, the maximum net return strategy of 7 worms and a 3-day scouting interval calls for more frequent scouting and treatment at a significantly lower threshold than the current Extension Service recommendations (Johnson et al.) of weekly scouting and a treatment threshold of 12 worms. The lower threshold results in a 19 percent increase in expected net returns and a 7 percent decrease in the standard deviation of net returns. However, the lower threshold and more frequent scouting result in approximately a 60 percent increase in pest control costs. This threshold is for two leaf feeding lepidoptera (or larval) insects and is defined in conjunction with a threshold of 1 adult per 3 row feet for the pod and stem feeding southern green stinkbug. Second, no one strategy is optimal for all VBC influx conditions. This suggests research that enables better prediction for VBC influx magnitudes and timings could yield sizable returns. Third, as the scouting interval decreased, holding threshold constant, the mean net returns increased and standard deviations of net returns decreased indicating that given current prices, the value of additional information (scouting) exceeds the cost and that additional information reduces risk. Finally, the economic optimal threshold is quite robust with respect to input and output price changes. The threshold varied less than one worm as soybean prices varied from $3 to $12 or as pest control costs doubled.

Research is on-going to refine and validate the insect model parameters and to further field test the results. Perhaps the most significant aspect of this study is that it demonstrates the ability of bioeconomic simulation models to integrate multiple crop stresses and to provide a vehicle for evaluating multi-species insect management strategies. Initial analyses such as those presented in this study are particularly useful in demonstrating the validity of the approach, generating research hypotheses for field testing, and for evaluating the sensitivity of the model to various parameters. This provides a framework for more effective use of the limited resources available for biological field research. Subsequent refinements in and validation of the model will provide additional confidence in the specific results.

The results presented in the study are specific to North Florida conditions. The basic model structure, however, is appropriate for other regions. Versions of the model have been released to Illinois, Mississippi, Georgia, Arkansas, Colorado, and Kentucky.

REFERENCES

Anderson, Jock R., John L. Dillion, and Brian Hardaker. *Agricultural Decision Analysis,* Iowa State University Press, Ames, Iowa, 1977.

Boote, K. J. Unpublished data, Agronomy Department, University of Florida.

Brown, L. G., R. W. McClendon, and J. W. Jones. "Cotton and Insect Management Simulation Model." Chapter 17 in *Cotton Insect Management with Special References to the Boll Weevil,* Edited by R. L. Ridgway, R. P. Lloyd and W. H. Corss, USDA, ARS, Agricultural Handbook 589, pp. 437-80, 1983.

Carlson, G. A. "A Decision Theoretic Approach to Crop Disease Prediction and Control." *Amer. J. Agr. Econ.,* 52(1970):216-23.

Gutierrez, A. P., T. F. Leigh, Y. Wang, and R. D. Cave. "An Analysis of Cotton Production in California: Lygus Hesperus Injury-An Evaluation." *Can. Entomol.,* 109(1977):1,375-86.

Hall, D. C. and R. B. Norgaard. "On the Timing and Application of Pesticides." *Amer. J. Agr. Econ.,* 55(1973):198-201.

Herzog, D. C., L. D. Newsom, and R. M. McPherson. Unpublished data, 1975.

Hewitt, Tim. "Budgets Generated for the Farm System Lab." Dept. of Food and Resource Econ., University of Florida, 1983.

Hueth, D. and U. Regev. "Optimal Agricultural Pest Management with Increasing Pest Resistance." *Amer. J. Agr. Econ.,* 56(1974):543-50.

Johnson, F. A., D. C. Herzog, and R. K. Sprenkel. "Soybean Insect Control." *Extension Entomology Report #58,* University of Florida, Gainesville, May, 1984.

Kiritani, K. N., N. Hokyo, and K. Kiroma. "Survival Rate and Reproductivity of Adult Southern Green Stinkbug, *Nezara viridula,* in the Cage." *Jap. J. Appl. Entomol.,* 7(1963):113-8.

Marsolan, N. F. and W. G. Rudd. "Modeling and Optimal Control of Insect Pest Populations." *Math Biosciences,* 30(1976):231-44.

Moscardi, F. *Effect of Soybean Crop Phenology on Development, Leaf Consumption, and Oviposition of Anticarsia gemmatalis Hubner,* Ph.D. dissertation, University of Florida, Gainesville, 1979.

Reichelderfer, K. H. and F. E. Bender. "Application of a Simulation Approach to Evaluating Methods for the Control of Agricultural Pests." *Amer. J. Agr. Econ.,* 61(1979):258-67.

Rudd, W. G. "Status of Systems Approach to Pest Management." *Ann. Rev. Entomol.,* 21(1976):27-44.

Shoemaker, C. A. "Optimization Analysis of the Integration of Biological, Cultural, and Chemical Control of Alfalfa Weevil (*Coleoptera curculionidae*)." *Env. Entomol.,* 21(1983):286-95.

Stinner, R. E., R. L. Rabb, and J. R. Bradley. "Population Dynamics of *Heliothis zea* (Boddie) and *H. virescens* (F.) in North Carolina: A Simulation Model." *Env. Entomol.;* 3, 1(1974):163-8.

Talpaz, H., G. L. Curry, P. J. Sharpe, D. W. DeMichele, and R. E. Frisbie."Optimal Pesticide Application for Controlling the Boll Weevil on Cotton." *Amer. J. Agr. Econ.,* 60(1978):469-75.

Watt, K. E. F. "The Use of Mathematics and Computers to Determine Optimal Strategy and Tactics for a Given Insect Pest Control Problem." *Can. Entomol.,* 96(1964):202-20.

Wilkerson, G. G., J. W. Mishoe, J. W. Jones, W. G. Boggess, and D. P. Swaney. "Within-Season Decisionmaking for Pest Control in Soybeans."Agr. Eng. Dep. Paper No. 83-4044, University of Florida, 1983a.

Wilkerson, G. G., J. W. Mishoe, J. W. Jones, J. L. Stimac, D. P. Swaney, and W. G. Boggess. "SICM Florida Soybean Integrated Crop Management Model: Model Description User's Guide." Agr. Eng. Dep. Rpt. AGE 83-1, University of Florida, November, 1983b.

Wilkerson, G. G., J. W. Jones, K. J. Boote, K. T. Ingram, and J. W. Mishoe."Modeling Soybean Growth for Crop Management." *Transac. ASAE;* 26, 2(1983c):562-8.
Wilkerson, G. G., J. W. Mishoe, and J. L. Stimac. "Modeling Velvetbean Caterpillar Populations for Crop Management." 1985 (In Review).
Zavaleta, Luis R. and William G. Ruesink. "Expected Benefits from Non-chemical Methods of Alfalfa Weevil Control." *Amer. J. Agr. Econ.,* 62(1980):801-5.