Economic Analysis of Insect Control Strategies Using an Integrated Crop Ecosystem Management Model

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ABSTRACT

The Integrated Crop Ecosystem Management Model (ICEMM) (stochastic simulation model) was used to predict cotton lint yields for five insect management strategies under various states of nature (i.e., weather and insect densities) using historical weather data, insecticide rates, bollworm/tobacco budworm densities, and economic inputs. The economic outcomes of these bollworm/tobacco budworm management strategies under various states of nature are presented. Based on the economic comparison of different strategies, production of transgenic cotton (*B.t.* cotton) expressing an insecticidal protein from a bacterium, *Bacillus thuringiensis (B.t.*) resulted in the highest net returns. Moreover the *B.t.* cotton resulted in the best net returns for all years together compared to other more conventional insect management strategies using probabilities for different states of nature. This paper presents and discusses methods for use in the analysis and prediction of optimum insect management strategies for cotton with a stochastic system simulation model, ICEMM, of insect-plant interactions and Bayesian probability analysis.

Keywords: Cotton, water stress, yield, insect pest management, economic analysis.

Y. Lan, J. Benedict, D. Ring and W. Hoffmann. “Economic Analysis of Insect Control Strategies Using an Integrated Crop Ecosystem Management Model”. Agricultural Engineering International: the CIGR Ejournal. Manuscript IT 06 001. Vol. VIII. September, 2006.

1. INTRODUCTION

Cotton is grown on an estimated 13.5 million acres in the United States. Pests reduced overall yields by 4.18% in 2004. The bollworm/budworm complex retained the top ranking as the number one cotton pest by reducing yields by 1.23%. Almost 82% of the US crop was infested with the complex of which 94% were bollworms. Total cost of management and loss to insects to the 2004 crop was $1.118 billion or $81.58 per acre. Of those costs approximately $54 are direct insect management costs (Williams, 2005).

Scientists and engineers have been developing simulation models of various crops. Although there are considerable differences in the mathematical structures and the levels of detail and mechanism in each model, there are also some major similarities. Most models are deterministic, operate on daily time steps and require similar input data for soil, weather and management conditions. The crop model software, COTMAN which was developed by the University of Arkansas Division of Agriculture with major financial support from Cotton Incorporated, uses cotton crop monitoring techniques to summarize crop developmental status, detect stress, and assist with in-season and end-of-season management decisions (COTMAN, 2006). Cros et al. (2003) proposed a conceptualized structure and behavior of management related aspects of an agricultural production system. They outlined the specific modeling needs when the decision-making behavior and work process play a central role in the intended study.

Applying crop protection chemicals by aircraft is a complex combination of application equipment, operational conditions, meteorological factors, and human judgment, which come together to influence on- and off-target deposition and the overall effectiveness of an agrochemical application (Kirk et al., 1991; Salyani and Cromwell, 1992). Computer models for predicting spray deposition and dispersal have been developed and successfully applied to the complex task of aerial application (Teske et al., 2000; Hoffmann, 2006). AgDISP is a near-wake model that “solves a Lagrangian system of equations for the position and position variance of spray material released from each nozzle on an aircraft” (Teske and Thistle, 1999) and is the most commonly-used and accepted spray deposition and transport model.

An Integrated Crop Ecosystem Management Model, ICEMM, was developed for use in making management decisions for cotton (Benedict et al. 1991; Eddleman et al. 1991; and Landivar et al., 1991). Systems simulators such as ICEMM are an integration of a series of mathematical equations derived from basic research data describing physical, biological, or economic processes for soils, plants or insects. Simulation modeling is one way of putting the pieces of information about a system back together to analyze how it functions as a whole (Duncan, 1967). The development of ICEMM capitalizes on the existence of models for cotton, soil, and insects such as the cotton model, GOSSYM (Baker et al., 1983), the soil process model, RHIZOS

(Whisler et al., 1982), and the insect pest model, TEXCIM (Sterling et al., 1989). The details of ICEMM may be found in Benedict et al. (1991), Landivar et al. (1991), and Eddleman et al. (1991).

ICEMM integrates multiple insect pests (cotton fleahopper, boll weevil, bollworm, and tobacco budworm) with GOSSYM, a detailed plant physiology model. Plant stresses due to insects and the environment can be simulated with this model to help the producer and crop consultant in making crop management decisions based on biological and economic outcomes. Densities of insect pests and natural enemies, plant development, soil moisture, soil fertility, weather and economics information can be entered in the model.

One of the major limitations of other models for cotton management is that they usually consist of a single insect or plant model so that there is no way of forecasting the impact and interactions of single or multiple pests and their natural enemies with a plant growing under changing (daily) environmental conditions. These models tend to focus on insect numbers or injury with no interdependence or interaction with the plant, or with other crop management strategies. These models generally lack user friendly features which allow easy entry of data on field counts of insects, weather, soil, economics, and pest control. Also graphic features for easy analysis of costs and benefits of crop management practices are usually absent. ICEMM attempts to overcome these limitations.

The primary objective of this research was to develop biological outcomes, economic returns, and economic analysis for a range of insect management strategies and states of nature using ICEMM, and historical weather and soil data for South Texas. A secondary objective was to briefly present the methods and reasoning used in this analysis.

2. MATERIALS AND METHODS

2.1 Cotton Varieties Simulated

Cotton is grown primarily as a fiber crop, but the seed can be used to provide vegetable oil and a protein-rich animal food. Over 1000 herbivorous species of insects have been recorded inhabiting cotton (Hargreaves, 1948). However, only a few of these normally reach pest status in a particular cotton-growing area, and then usually only over a part of the season. The most critical period of crop development takes place during a period about 10 weeks after plant emergence. During this period of rapid plant growth there are an increasing number of flower buds and then bolls which are attacked by several different insect pests, including the bollworm and tobacco budworm.

The development of *B.t.* cotton varieties represents a major technological change in cotton production. The *B.t.* plant has been genetically engineered to include a gene from a common soil bacterium, *Bacillus thuringiensis* var. *kurstaki*, that produces an insecticidal protein which is toxic to specific caterpillar-type pests (e.g., bollworm, leafworm, tobacco budworm, pink bollworm) but not humans, mammals, or most beneficial insects. Eddleman (1994) used an agricultural simulation model that totals the consumer/producer economic surplus, imports and exports, government costs under the farm commodity program from increased output and substitutions in production for competing commodities, and other factors such as yield and production costs associated with pesticide use versus *B.t.* cotton use. He predicted that the benefit of *B.t.* cotton to the United States would be $337 million annually (yields constant, chemical treatment costs reduced) and $236 million annually (yields increase, chemical treatment constant costs).

2.2 Procedures

ICEMM for Windows was used to estimate the yield related to weather conditions, insecticide rates, insect density, and economic inputs. The procedures used were as follows.

The first step was to establish bollworm/tobacco budworm control strategies and states of nature. Beneficial insects that attack and kill bollworm/tobacco budworm were considered absent from these conditions and strategies, and thus had no effect on yield loss or economic outcomes.

A. The strategies were:
   - I. Do nothing when bollworm/tobacco budworms were absent on conventional cotton (no insecticides used);
   - II. Do nothing when bollworm/tobacco budworms were present on conventional cotton (no insecticides used) (cost is lint lost);
   - III. Use conventional insecticide at a low rate when bollworm/tobacco budworms were present on conventional cotton;
   - IV. Use conventional insecticide at a high rate when bollworm/tobacco budworms were present on conventional cotton; and
   - V. Use transgenic *B.t.* cotton variety when bollworm/tobacco budworms were present (no insecticides used).

B. The states of nature used were:
   1. Bollworm/budworm egg densities were categorized as none, low, medium, and high. The densities of bollworm/tobacco budworms for each level were shown in Table 1.
   2. Weather conditions were considered a state of nature and classified as dry, average, optimum, and extra wet on the basis of how it affected root growth and yield of cotton plants.

The second step was to create a pay-off matrix (yield in lbs. of lint/ac) for each strategy. Each strategy had an average level of insect control and certain costs associated with it which was used in calculating the net returns.

The third step was to create a joint probability matrix for the expected occurrence of the states of weather and bollworm/tobacco budworm egg density. This was done for each bollworm/tobacco budworm egg density by averaging expert opinions of two cotton insect research scientists, two cotton insect extension agents, and one commercial cotton consultant from the Lower Gulf Coast. The probabilities for the occurrence of different states of bollworm/tobacco budworm density as related to weather conditions were given in Table 2. The probabilities for the amount of in-season rainfall were determined as follows using the method of Eddleman et al. (1991). ICEMM simulations were run using weather conditions recorded during 1980-1993 at Corpus Christi. Years were classified in four groups based on number of drought days (DDY) occurring during the growing season: 10 DDY was considered wet, 20 DDY was optimum, 30 DDY was average, and >30 DDY was dry. A drought day is a unit used to measure the effects of weather on plant growth during the growing season. It is defined here as a day during the growing season when the plant is unable to obtain sufficient moisture from the soil for growth. Numerically, a DDY occurs when the water stress index in ICEMM is equal to or less than 0.50. The probabilities associated with 10, 20, 30, and greater than 30 drought days were 1/7, 1/7, 1/7, and 4/7 based on historical weather data for Corpus Christi, Texas. The joint probabilities of both a given rainfall pattern and a given level of bollworm/tobacco budworm egg density were found by multiplying the two probabilities to form a joint probability and are presented in Table 3.

The fourth step was to calculate the cost/benefit for each strategy and state of nature to determine which strategy was most economically beneficial under each state of nature. The data necessary for this economic analysis include lint yield, price of lint and seed as well as insecticide treatment costs, seed costs, and costs related to yield, such as harvesting, hauling, ginning, bagging and ties, and transportation. Total variable production costs were ignored (considered constant) because we were only interested in the comparisons of economic changes resulting from use of different strategies. Estimated prices and costs used in this study are shown in Table 4. They represent values from dryland cotton production in the Lower Gulf Coast (Texas Agricultural Extension Service, 1994). These values were used to estimate the market value and the economic net returns per acre for various cotton production scenarios. The equation used to calculate the net returns per acre was given as follows:

Net returns= (Lint yield x Lint price) + (Seed weight x Cottonseed price) - (Costs of seed, scouting, insecticide, ginning, hauling, transportation, and harvesting).

3. RESULTS AND DISCUSSION

The net returns per acre of different strategies under different weather conditions and bollworm/budworm egg densities are shown in Table 5. The greatest net returns were obtained by Strategy I, where bollworm/tobacco budworms were never present, but this rarely occurs in commercial cotton production in South Texas. When bollworm/tobacco budworms were present the best net returns for all years together were observed using transgenic *B.t.* cotton variety to manage these pests compared to other management strategies using a conventional cotton variety. Since the price of *B.t.* seed is not currently known, its price was estimated to be $0.80/lb. This price includes a price premium of approximately 45 percent more than conventional non-*B.t.* seed.

Use of transgenic *B.t.* cotton resulted in the highest net returns with a low bollworm/tobacco budworm density during dry years ($124.8/acre) and wet years ($259.9/acre). Strategy II, no management when bollworm/tobacco budworms were present, resulted in the highest net return with a low bollworm/tobacco budworm density during average years ($233.7/acre) and optimum years ($384.7/acre). All strategies resulted in similar net returns when low bollworm/tobacco budworm densities were present. However, when medium or high densities of bollworm/tobacco budworm were present the best strategy was V under all states of weather. Strategy V (use a *B.t.* cotton variety to control bollworm/tobacco budworm injury) resulted in the highest net returns with a medium bollworm/tobacco budworm density during dry years ($123.0/acre), average years ($214.7/acre), optimum years ($375.7/acre), and wet years ($257.7/acre).

Strategy V resulted in the highest net returns with a high bollworm/tobacco budworm density during dry years ($117.3/acre), average years ($214.1/acre), optimum years ($373.2/acre), and wet years ($248.3/acre). The net returns for other strategies were much lower than *B.t.* cotton, Strategy V, when bollworm/tobacco budworm density was high. The maximum increase in net returns with *B.t.* cotton compared to conventional cotton was about 232% for dry years, 128% for average years, 154% for optimum years, and 186% for wet years.

The net returns using different management strategies under weather risk are shown in Figure 1. The net return under risk (called expected net return by economists) is determined by multiplying the probability of that risk occurring (See Methods) in this case the state of weather times the net return for the particular states of nature (Table 5). *B.t.* cotton except Strategy I resulted in the highest average net returns during all years (i.e., dry, $125.9/acre; average, $220.9/acre; optimum, $374.2/acre; and wet, $262.3/acre).

The net returns using different management strategies under bollworm/tobacco budworm risk were shown in Figure 2. Strategy V with a *B.t.* cotton variety resulted in the highest average net returns with medium ($242.7/acre) and high ($238.2) densities of bollworm/tobacco budworm. Strategy III, conventional insecticide at a low rate, resulted in the highest net returns ($243.4/acre) with low bollworm/tobacco budworm densities. All strategies except Strategy I resulted in similar net returns, i.e., Strategy II ($242.78/acre), Strategy III ($243.4/acre), Strategy IV ($239.0/acre), and Strategy V ($240.4/acre).

The expected net returns of different strategies under risk were determined by multiplying the net returns by the joint probabilities (Table 6). Under risk, the maximum expected net returns were not obtained using Strategy I but rather when using Strategy V, *B.t.* cotton, to control the pest insects (Figure 3). *B.t.* cotton had the greatest expected net returns compared to all other strategies (Figure 3). *B.t.* cotton appears to be the most desirable management strategy when bollworm/tobacco budworms are present.

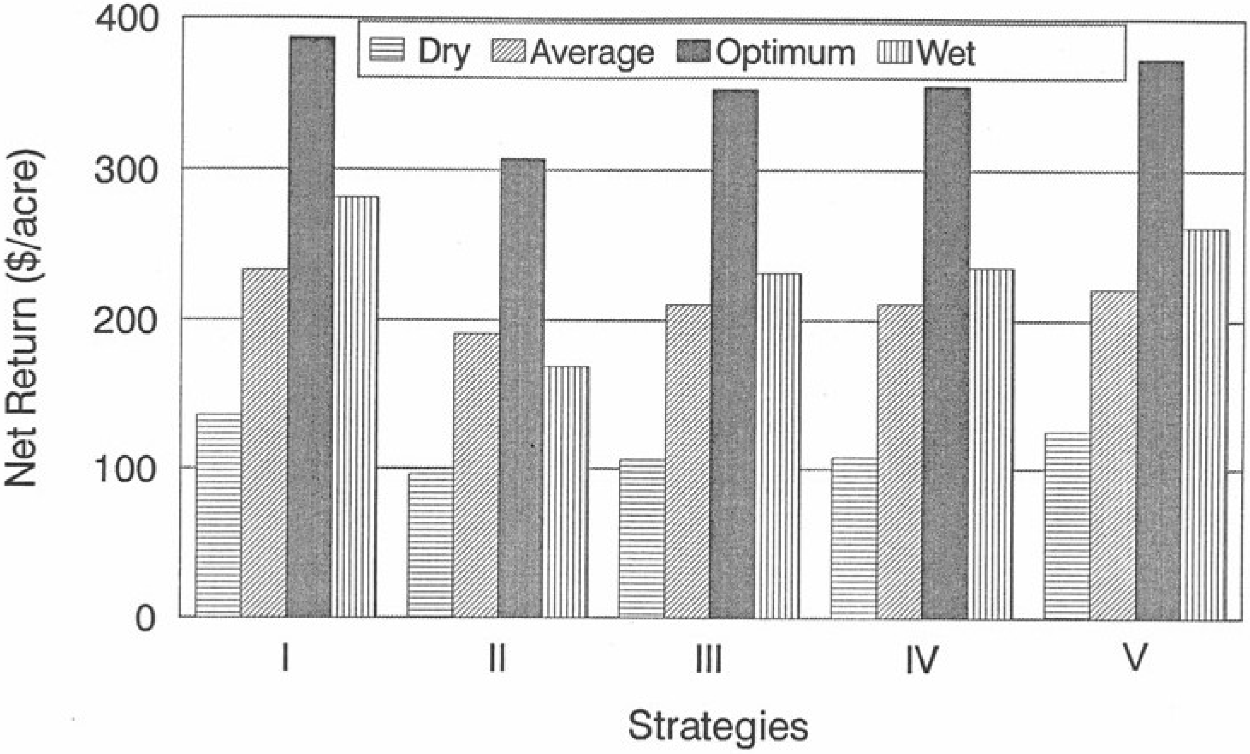

Figure 1. Average net returns for different management strategies under weather risk. Strategies were: I=do nothing, no pest insects present; II=do nothing, insect pest present; III=use insecticide @ low rate; IV=use insecticide @ high rate; V=use transgenic *B.t.* cotton only.

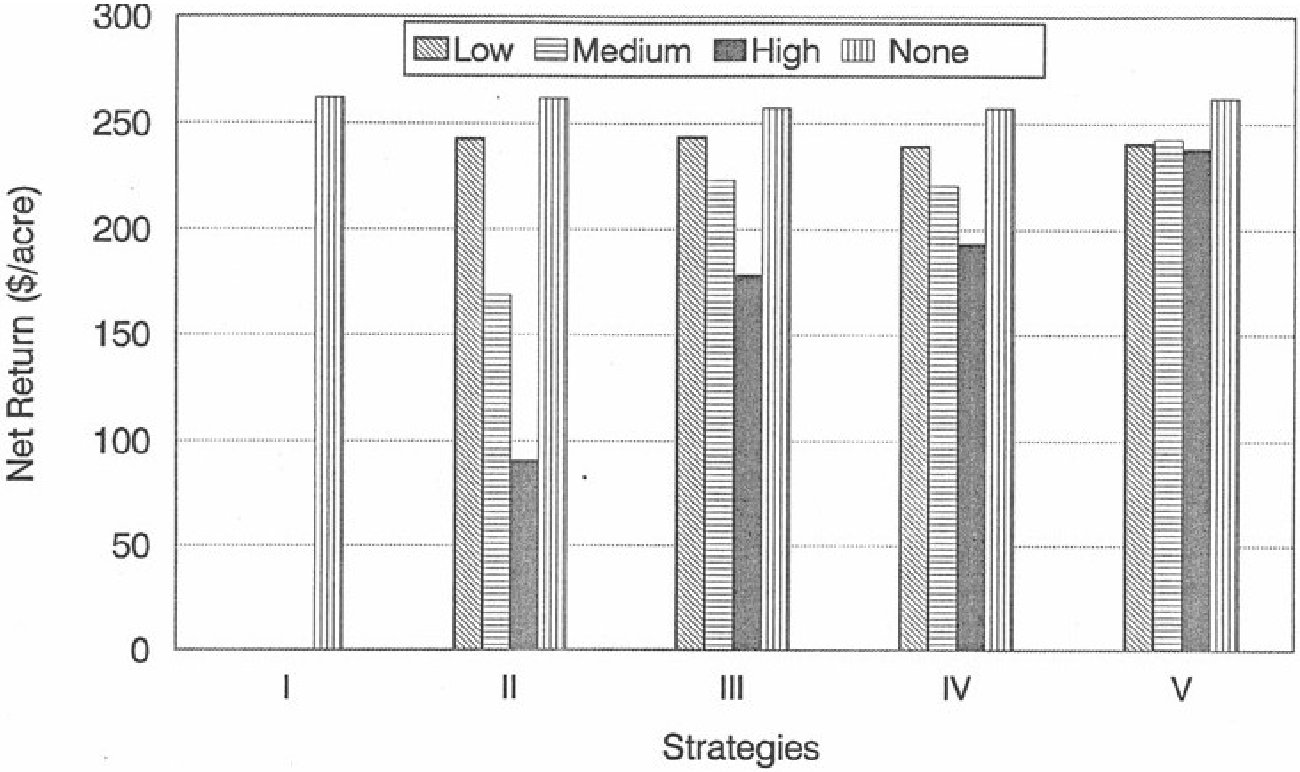

Figure 2. Average net returns for different management strategies under bollworm/tobacco budworm egg density risk. Strategies were: I=do nothing, no pest insects present; II=do nothing, insect pest present; III=use insecticide @ low rate; IV=use insecticide @ high rate; V=use transgenic *B.t.* cotton only.

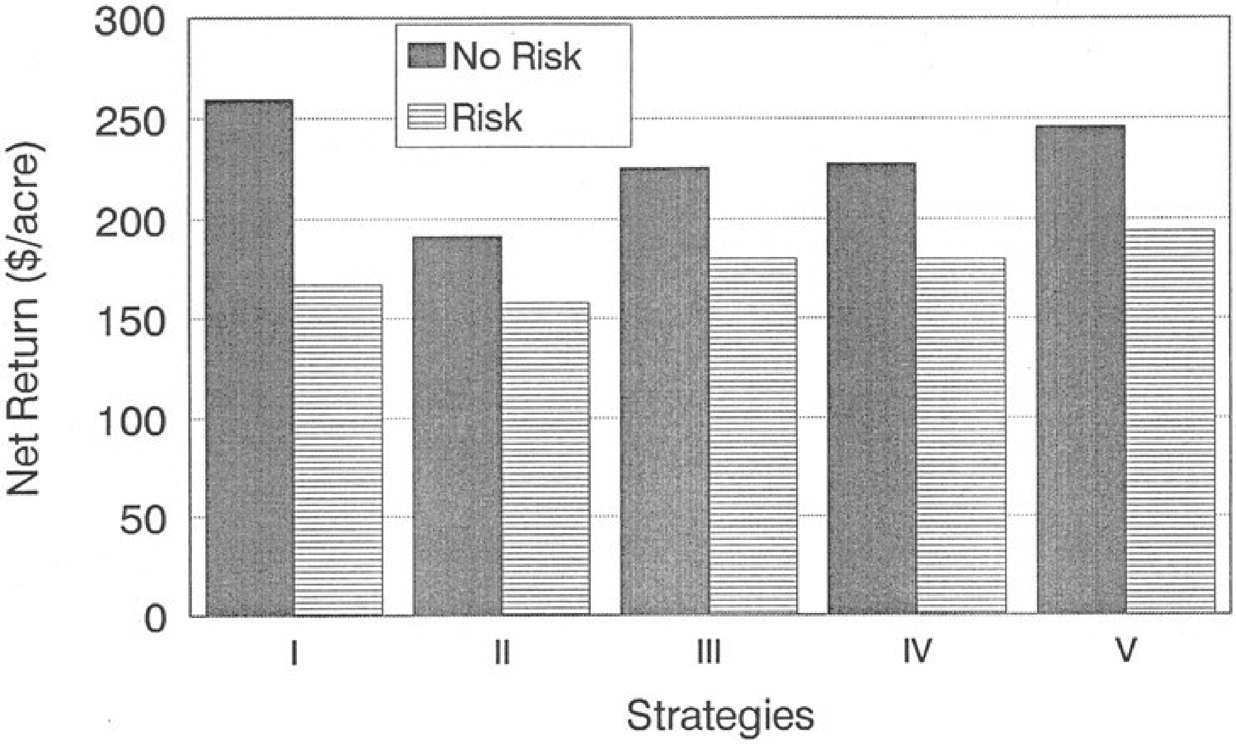

Figure 3. Comparisons of net returns using different management strategies under weather and bollworm/tobacco budworm egg density risk and no risk. Strategies were: I=do nothing, no pest insects present; II=do nothing, insect pest present; III=use insecticide @ low rate; IV=use insecticide @ high rate; V=use transgenic *B.t.* cotton only.

Table 1. The initial densities of bollworms/tobacco budworm eggs used in simulations as states of nature for these insects.*

	State of bollworm/tobacco budworm egg density			
Date	None	Low	Medium	High
5/10	0.00	0.14	0.35	0.70
5/11	0.00	0.21	0.53	1.05
5/12	0.00	0.28	0.70	1.40
5/13	0.00	0.42	1.05	2.10
5/14	0.00	0.56	1.40	2.80
5/15	0.00	0.70	1.75	3.50
5/16	0.00	0.84	2.10	4.20
5/17	0.00	0.70	1.75	3.50
5/18	0.00	0.56	1.40	2.80
5/19	0.00	0.42	1.05	2.10
5/20	0.00	0.28	0.70	1.40
5/21	0.00	0.21	0.53	1.05
5/22	0.00	0.14	0.35	0.70

* Unit: Initial number of eggs/plant.

Table 2. The probability of occurrence of a given bollworm/tobacco budworm egg density for different states of rainfall (weather) based on a poll of expert opinion.

State of in-season	State of bollworm/tobacco budworm egg density			
Rainfall	None	Low	Medium	High
Dry	0.378	0.375	0.175	0.072
Average	0.125	0.375	0.388	0.112
Optimum	0.088	0.343	0.425	0.144
Extra wet	0.075	0.150	0.575	0.200

Table 3. The joint probability for occurrence of different states of nature for rainfall and bollworm/tobacco budworm egg density.

State of in-season	State of bollworm/tobacco budworm egg density			
Rainfall	None	Low	Medium	High
Dry	0.219	0.217	0.102	0.041
Average	0.018	0.053	0.054	0.015
Optimum	0.012	0.048	0.060	0.020
Extra wet	0.011	0.021	0.081	0.028

Table 4. Assumed price and production costs of cotton, Texas Coastal Bend region.

Variable	$Value/cost
Lint price ($/lb)	0.58
Cotton seed ($/lb)	0.045
Seed price (*B.t.*, $/lb)	0.80
Seed price (Non-*B.t.*, $/lb)	0.55
Scouting cost ($/ac)	4.75
Cost per treatment for insect control, including cost of insecticide and applications ($/ac)	7.63 (low rate of insecticide)[1] 11.15 (high rate of insecticide)
Harvest cost ($/lb)	0.18
Ginning ($/lb)	0.088
Hauling ($/lb)	0.01
Transportation cost ($/lb)	0.01

[1] Bollworm/tobacco budworm density control level or mortality level.

Table 5. Net returns ($ per acre) using different management strategies under different states of nature for weather and bollworm/tobacco budworm egg densities.

	State of	State of bollworm/tobacco budworm egg density			
Strategy	Weather	None	Low	Medium	High
1. No insects	Dry	138.6	—	—	—
	Average	275.5	—	—	—
	Optimum	389.5	—	—	—
	Wet	284.0	—	—	—
2. No management with insects	Dry	138.6	123.2	88.2	35.3
	Average	235.5	233.7	200.9	93.7
	Optimum	389.5	384.7	309.5	147.1
	Wet	284.0	229.5	76.6	86.8
3. Insecticide control low rate	Dry	133.9	123.5	100.9	67.6
	Average	230.8	216.8	208.3	186.5
	Optimum	384.8	373.9	366.4	290.2
	Wet	279.3	259.4	217.2	169.4
4. Insecticide control high rate	Dry	133.9	120.5	102.8	75.6
	Average	230.8	212.5	207.1	193.3
	Optimum	384.8	365.7	356.0	317.8
	Wet	279.3	257.3	217.4	187.1
5. *B.t.* cotton	Dry	138.6	124.8	123.0	117.3
	Average	235.5	219.1	214.7	214.1
	Optimum	389.5	358.5	375.7	373.2
	Wet	284.0	259.9	257.7	248.3

Table 6. Expected net returns ($ per acre) using different management strategies under weather and bollworm/tobacco budworm egg density risk in the Texas Coast Bend Region.

	State of	State of bollworm/tobacco budworm egg density			
Strategy	Weather	None	Low	Medium	High
1. No insects	Dry	30.4	—	—	—
	Average	4.2	—	—	—
	Optimum	4.7	—	—	—
	Wet	3.1	—	—	—
2. No management with insects	Dry	30.4	26.7	9.0	1.5
	Average	4.2	12.4	10.9	1.4
	Optimum	4.7	18.5	18.6	2.9
	Wet	3.1	4.8	6.2	2.4
3. Insecticide control low rate	Dry	29.3	26.8	10.3	2.8
	Average	4.2	11.50	11.3	2.8
	Optimum	4.6	18.0	22.0	5.8
	Wet	3.1	5.5	17.6	4.7
4. Insecticide control high rate	Dry	29.3	26.2	10.5	3.1
	Average	4.2	11.3	11.2	2.9
	Optimum	4.6	17.6	21.4	6.4
	Wet	3.1	5.4	17.6	5.2
5. *B.t.* cotton	Dry	30.4	27.1	12.6	4.9
	Average	4.2	11.6	11.6	3.2
	Optimum	4.7	17.2	22.5	7.5
	Wet	3.1	5.4	20.9	7.0

4. SUMMARY AND CONCLUSIONS

The data requirements for an economic analysis of bollworm/tobacco budworm control strategies using the Integrated Crop Ecosystem Management Model (ICEMM) were the yield projections from the cotton growth model for each alternate action being considered under different states of nature, quantities of the inputs used, product and input prices, application costs, insecticide treatment costs, seed costs, and costs related to harvest, such as picking, hauling, ginning, transportation, and the expert's subjective probabilities with respect to future of bollworm/tobacco budworm densities.

These analyses show that under all states of nature (i.e., weather and density of bollworms/tobacco budworms, no single strategy provides highest net returns. However, Strategy V, use of a *B.t.* cotton variety provides the best overall single strategy under all risk and states of nature, thus making it the optimum strategy for managing these insect pests.

The limitations of these and related mechanistic modeling approaches used to predict the outcomes of biological and/or economic events are: (1) the accuracy of the biological and economic models employed; and (2) the accuracy of the real world physical and biological data used to drive the models. In spite of these limitations, we believe the simulation results reported here are reasonably accurate in representing the relative outcomes among the range of pest management strategies compared. Moreover this study shows that computer simulation methods and economic analyses can be used to evaluate a range of insect management strategies for various states of nature for any pest and crop production system.

5. ACKNOWLEDGEMENTS

Many biological scientists, for example, Drs. B. Eddleman, J. Landivar, W. Sterling, programmers, and system engineers supplied their ideas, energies, and models to make ICEMM available. We give them our gratitude and appreciation.

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