Evaluation of Bollworm-Tobacco Budworm Control Strategies with ICEMM

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ABSTRACT

Economic comparisons of insect pest management strategies were made for the heliothine pests, bollworm, *Helicoverpa zea* (Boddie), and tobacco budworm, *Heliothis virescens* (F.); under 18 different combinations of in-season rainfall, pest densities, insecticide use, insect resistant cotton, and densities of beneficials insects. Comparisons were made using a mechanistic simulation model of insect-plant interactions. The model, referred to as the Integrated Crop Ecosystem Management Model (ICEMM), combined modified versions of the insect model, TEXCIM 5.0, and the cotton plant model, GOSSYM. Economic returns were calculated for each management strategy under each combination of in-season rainfall condition and heliothine density. In-season rainfall conditions were categorized as dry, average, optimum, and wet. Tobacco budworm densities were none, low, medium, and high. Management strategies were: no insect management when heliothines were absent; no insect management when heliothines were present; no insect management when heliothines were present with a light or heavy density of beneficial insects; one insecticide application at a low or high rate when heliothines were present; one insecticide application at a low or high rate when heliothines were present with a light or heavy density of beneficials; transgenic cotton expressing a C*ry1A* gene encoding an insecticidal delta-endotoxin from *Bacillus thuringiensis* var. *kurstaki*, (*Bt* cotton), with no pest management; *Bt* cotton with a light or heavy density of beneficials; and *Bt* cotton with one application of insecticide at a low or high rate. The greatest net returns were obtained when heliothines were absent and insect management was not employed. When heliothines were present, the management strategy with doing nothing plus heavy beneficials resulted in the highest net returns. Optimum rain fall also improved net returns compared to other in-season rainfall rates.

1. INTRODUCTION[1]

Several factors have an impact on net returns of cotton, *Gossypium hirsutum* L., injured by bollworm, *Helicoverpa zea* (Boddie), and tobacco budworm, *Heliothis virescens* (F.) (Lepidoptera: Noctuidae). The choice of a management strategy for these insects (subsequently referred to as heliothines) may differ depending on the impact of other factors on net returns. Two factors that strongly influence net returns are in-season rainfall conditions and density of insect pests.

One method of comparing management strategies when utilized under different in-season rainfall conditions and heliothine densities is the use of a simulation model. The Integrated Crop Ecosystem Management Model (ICEMM) is well suited to make such comparisons. Components included in ICEMM are models for soils, cotton plants, and insects (Benedict et al. 1991, Eddleman et al. 1991, Landivar et al. 1991). Also components from GOSSYM (Baker et al. 1983), RHIZOS (Whistler et al. 1982), and TEXCIM (Sterling et al. 1989) are included in ICEMM.

There is a wide array of management strategies that may be used to control heliothines. These include no management when heliothines are absent, no management when heliothines are present, and the application of insecticides at a low or high rate. Dramatically different combinations of strategies become available with the development of cotton genetically engineered to express a C*ry1A* gene encoding a delta-endotoxin from *Bacillus thuringiensis* var. *kurstaki* (*Bt* cotton). These toxins are lethal to heliothines. Moreover, conventional insecticides and beneficial insects may be used in conjunction with *Bt* cotton to suppress insect pest injury.

We report on the comparison of economic returns from heliothine management strategies utilized in dry, average, optimum, and wet in-season rainfall conditions and with different heliothine egg densities. Expected net returns are reported from multiplying economic returns by the joint probability of in-season rainfall conditions and heliothine densities. These expected net returns are what a farmer might expect to receive (net returns) over time modified by the joint probabilities of occurrence of the various states of in-season rainfall and pest densities. This is an economic method to help identify the most likely conditions (states) of nature (i.e., insect pest density and weather). Moreover, it helps identify the insect management strategy(s) that works best to control pest injury and optimize economic (dollar) returns under this condition(s).

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.

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2. MATERIALS AND METHODS

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 mechanisms 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.

2.1 ICEMM

An Integrated Crop Ecosystem Management Model, ICEMM for Windows, was developed and may be used in making management decisions for cotton. 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 pieces of information about a system back together to analyze how it functions as a whole (Lan et al. 2006). 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 (Whistler et al. 1982), and the insect pest model, TEXCIM (Sterling et al. 1989). ICEMM runs under Windows in a PC-DOS environment. ICEMM is developed as the development and linkage of the modified version of GOSSYM and TEXCIM. TEXCIM has mechanistic routines for insect population growth and plant injury for bollworm, tobacco budworm, cotton fleahopper, and boll weevil. These insect models were uncoupled from SIMPLECOT, the cotton fruiting model in TEXCIM and linked to the plant model in ICEMM. A menu was developed that allows alteration of default insect pest reproduction, growth, survival, and behavior parameters so that host plant resistant cotton genotypes, that alter insect pest behavior, growth and/or survival, can be modeled.

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 ICEMM Editor includes pests, plant, management, and weather. These data can be changed according to the users' problem. Pest input includes densities of fleahopper, cotton bollworm, tobacco budworm, boll weevil, pink bollworm, white fly, and aphids. Plant input includes cultivar, soils, plant map, and cultural practices. Management input includes insecticides, pest economic threshold, plant resistance, predators, parasites, and agronomic actions. Weather input includes current weather, normal weather, generate normal weather, and a weather file converter. The ICEMM model focused on dryland cotton only.

The integrated crop ecosystem management model was used to estimate yields of cotton grown under different heliothine management strategies. The insect management strategies were: (1) do nothing to control insect pests; (2) do nothing except using beneficials (light) to control insect pests; (3) do nothing except using beneficials (heavy) to control insect pests; (4) use insecticide at a low rate; (5) use insecticide at a low with a light density of beneficials; (6) use insecticide at a low rate with a heavy density of beneficials; (7) use insecticide at a high rate; (8) use insecticide at a high rate of with a light density of beneficials; (9) use insecticide at a high rate with a heavy density of beneficials; (10) use transgenic *Bt* cotton to control insect pests; (11) use transgenic *Bt* cotton and beneficial (light) insects to control insect pests; (12) use transgenic *Bt* cotton and beneficial (heavy) insects to control insect pests; (13) use transgenic *Bt* cotton and insecticide at a low rate; (14) use transgenic *Bt* cotton, beneficials (light), and insecticide at a low rate; (15) use transgenic *Bt* cotton, beneficials (heavy), and insecticide at a low rate; (16) use transgenic *Bt* cotton and insecticide at a high rate; (17) use transgenic *Bt* cotton, beneficials (light), and insecticide at a high rate; and (18) use transgenic *Bt* cotton, beneficials (heavy), and insecticide at a high rate. Simulations also were run without heliothines present as a control. Heliothine densities in eggs/plant were classified as none, low, medium, and high (see Table 1 for egg densities used). Simulations were run using actual weather data from Corpus Christi, Texas during 1980-1993. In-season rainfall was classified as dry, $\geq$ 30 drought days (DD); average, $\geq$ 20 to $<$ 30 DD; optimum, $\geq$ 10 to $<$ 20 DD; and wet $<$ 10 DD. A drought day was defined as a day during the growing season when the cotton plant was unable to obtain moisture from the soil. The number of drought days for each year was calculated as the number of days during the growing season that the water stress index was $\geq$ 0.5 from ICEMM simulations made without heliothines present.

A joint probability matrix was constructed for the expected occurrence of in-season rainfall conditions and expected heliothine densities. The probabilities of in-season rainfall were calculated using the method of Eddleman et al. (1991) and were 4/7 (dry), 1/7 (average), 1/7 (optimum), and 1/7 (wet). Expected heliothine densities were estimated using the averaged opinions of two cotton insect researchers, two cotton insect extension specialists, and one cotton insect consultant from the Lower Gulf Coast of Texas. Each person estimated the probability that heliothine densities would be none, low, medium, and high in response to dry, average, optimum, and wet in-season rainfall years. Averages of the opinions for the combination of each heliothine density and in-season rainfall condition were calculated (Table 2). The joint probabilities of in-season rainfall conditions and heliothine densities were determined by multiplying the values in Table 2 by the probabilities of in-season rainfall reported above (Table 3). This provides a measure of the effect of risk on net returns over time and helps identify the optimum insect management strategy(s) (See above comments). Economists speak of the expected net returns as being the net returns under risk of different states of nature.

Table 1. The densities of bollworm-tobacco budworm eggs used in simulations.

	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

* Number of eggs/plant.

Cost/benefit analysis was performed on each management strategy under the 16 possible combinations of in-season rainfall and bollworm-tobacco budworm density. The cost values were based on the market prices in 1995. The market value used was $0.70/lb for lint and $0.0575/lb for seed. Costs were estimated at $0.80/lb for non-transgenic planting seed, $2.30/lb for transgenic *Bt* planting seed, and $4.75/ac for scouting (insect pest consulting). Insecticide costs were $8.50/ac (low rate) and $12.50/ac (high rate) including insecticide and application costs. These market values and costs were representative of values from dry land cotton production in the Lower Gulf Coast of Texas (Texas Agricultural Extension Service 1994), Table 4. The price of transgenic *Bt* planting seed is unknown and was estimated by cotton experts. Net returns for each management strategy were calculated using the formula: net return = (yield of lint * lint price) + (cottonseed weight * cottonseed price) – (costs of planting seed, scouting, insecticide, ginning, and harvesting). Expected net returns under risk were calculated by multiplying net returns by the joint probabilities of in-season rainfall conditions and expected heliothine densities.

The payoff matrix for yields in lbs/acre using different management strategies under combinations of in-season rainfall conditions and heliothine densities is presented in Table 5. The probability of occurrence of each in-season rainfall condition and heliothine density was assumed to be one in the payoff matrix. The payoff matrix for net returns in $/acre using

Table 2. The probability of a given level of bollworm-tobacco egg density based on expert opinions.

In-season rainfall condition	Bollworm-tobacco budworm egg density			
	None	Low	Medium	High
Dry	0.500	0.283	0.133	0.084
Average	0.167	0.400	0.333	0.100
Optimum	0.117	0.383	0.367	0.133
Extra wet	0.100	0.183	0.583	0.134

Table 3. The joint probability for the occurrence of different combinations of in-season rainfall conditions and bollworm-tobacco budworm egg density.

In-season rainfall condition	Bollworm-tobacco budworm egg density			
	None	Low	Medium	High
Dry	0.286	0.162	0.076	0.048
Average	0.024	0.057	0.048	0.014
Optimum	0.017	0.054	0.053	0.019
Extra wet	0.014	0.026	0.083	0.019

Table 4. Assumed price and production costs of cotton, Texas Coastal Bend Region, 1995.

Variable	$ Value/Cost
Lint price ($/lb)	0.70
Cotton seed ($/lb)	0.0575
Deficiency pmt. cotton	26.00
Seed price (*Bt* $/lb)	2.30
Seed price (non-*Bt* $/lb)	0.80

Cost per treatment for insect (low rate of insecticide)	8.50
Control, including cost of insecticide and applications ($/ac) (high rate of insecticide)	12.50
Ginning = 0.075 * lint	
Pick and Module 0.09	0.09
Fertilizer 17.74 (3-4)=21.00	21.00
Herbicide PRE-EM	9.62
Caparol	7.80
Scouting	4.75
Fuel and Lube-Machinery	11.24
Repairs-Machinery	3.48
Labor-Machinery	10.67
Defoliants and application	10.38
Machinery and Equipment	42.72
Land	39.40

Table 5. Yields (lbs/acre) (pay-off matrix) using different management strategies under combinations of in-season rainfall conditions and bollworm-tobacco budworm egg densities.

		Bollworm-tobacco budworm egg density			
Strategy	Rainfall condition	None	Low	Medium	High
1. Do nothing	Dry	415.09	360.94	266.20	122.55
No beneficials	Average	677.86	660.76	571.93	281.11
	Optimum	1095.66	1070.55	866.48	425.95
	Wet	779.39	649.50	505.90	262.32
2. Do nothing	Dry	415.09	393.84	377.26	347.55
+ benficials (light)	Average	677.86	348.28	633.62	626.80
	Optimum	1095.66	1042.06	1030.72	1032.51
	Wet	779.39	777.87	776.80	771.33

3. Do nothing	Dry	415.09	408.17	401.29	404.67
+ beneficials (heavy)	Average	677.86	668.41	643.32	658.16
	Optimum	1095.66	1073.75	1036.76	1076.39
	Wet	779.39	777.87	776.80	771.33
4. Use insecticide	Dry	415.09	395.35	334.30	243.77
@low rate	Average	677.86	648.48	625.64	566.27
No beneficials	Optimum	1095.66	1074.69	1054.54	847.65
	Wet	779.39	764.05	649.71	520.05
5. Use insecticide	Dry	415.09	397.18	384.94	366.45
@low rate	Average	677.86	661.86	636.82	639.93
+ beneficials (light)	Optimum	1095.66	1036.28	1031.97	1029.31
	Wet	779.39	770.42	465.92	687.55
6. Use insecticide	Dry	415.09	421.72	407.84	395.04
@low rate	Average	677.86	648.48	664.21	645.33
+ beneficials (heavy)	Optimum	1095.66	1070.97	1057.36	1079.41
	Wet	779.39	775.30	773.33	771.84
7. Use insecticide	Dry	415.09	396.92	348.79	274.99
@high rate	Average	677.86	646.41	631.85	597.42
No beneficials	Optimum	1095.66	1061.98	1035.69	932.19
	Wet	779.39	768.06	659.79	577.49
8. Use insecticide	Dry	415.09	399.64	390.67	376.59
@high rate	Average	677.86	655.76	642.57	634.81
+ beneficials (light)	Optimum	1095.66	1042.61	1042.51	1024.28
	Wet	779.39	764.79	767.97	758.18
9. Use insecticide	Dry	415.09	421.99	415.26	403.21
@high rate	Average	677.86	673.81	650.54	642.97
+ beneficials (heavy)	Optimum	1095.66	1064.11	1060.73	1039.57
	Wet	779.39	778.92	777.83	773.96
10. Use *Bt* cotton	Dry	415.09	408.00	403.05	387.48
No beneficials	Average	677.86	663.67	643.65	650.18
	Optimum	1095.66	1041.93	1088.51	1081.81
	Wet	779.39	772.58	768.53	742.98
11. Use *Bt cotton*	Dry	415.09	405.38	398.57	387.51
+ beneficials (light)	Average	677.86	665.31	646.06	637.52
	Optimum	1095.66	1039.76	1040.65	1087.03
	Wet	779.39	781.16	772.42	766.85
12. Use *Bt* cotton	Dry	415.09	413.14	410.54	410.25
+ beneficials (heavy)	Average	677.86	678.48	680.52	647.69
	Optimum	1095.66	1041.93	1088.51	1081.84
	Wet	779.39	779.46	777.14	777.83
13. Use *Bt* cotton	Dry	415.09	404.88	400.24	387.08
+ insecticide	Average	677.86	649.06	604.20	607.01
@ low rate	Optimum	1095.66	1038.43	1087.04	1088.06

	Wet	779.39	776.80	777.27	765.15
14. Use *Bt* cotton	Dry	415.09	405.34	400.56	393.00
+ beneficials	Average	677.86	669.13	654.81	645.66
+ insecticide	Optimum	1095.66	1040.06	1039.56	1040.41
@low rate (light)	Wet	779.39	777.31	771.29	765.55
15. Use *Bt* cotton	Dry	415.09	411.36	412.00	403.27
+ beneficials	Average	677.86	674.50	657.10	640.94
+ insecticide	Optimum	1095.66	1040.93	1040.10	1040.50
@low rate (heavy)	Wet	779.39	778.91	777.34	771.07
16. Use *Bt* cotton	Dry	415.09	405.24	405.37	386.77
+ insecticide	Average	677.86	649.64	660.91	645.75
@high rate	Optimum	1095.66	1039.76	1040.65	1087.03
	Wet	779.39	777.71	771.18	769.64
17. Use *Bt* cotton	Dry	415.09	408.17	402.39	402.11
+ beneficials	Average	677.86	675.28	648.86	640.29
+ insecticide	Optimum	1095.66	1042.09	1040.37	1038.06
@high rate (light)	Wet	779.39	777.68	776.52	769.86
18. Use *Bt* cotton	Dry	415.09	407.51	411.41	410.03
+ beneficials	Average	677.86	679.30	680.80	674.89
+ insecticide	Optimum	1095.66	1035.55	1035.87	1041.28
@high rate (heavy)	Wet	779.39	779.50	779.18	778.92

different management strategies under combinations of in-season rainfall conditions and heliothine densities is presented in Table 6.

Simple numerical comparisons were made among management strategies to determine the strategy that tended to provide the greatest net return under different in-season rainfall conditions and heliothine densities (i.e., states of nature).

3. RESULTS AND DISCUSSION

As expected the greatest net returns in the absence of heliothines were realized by employing no management strategy under all in-season rainfall conditions (Table 6). The lowest net returns in the absence of heliothines were realized by employing *Bt* cotton under the dry weather conditions. The cost for the strategy of insecticide application in the absence of heliothines, was only the cost of scouting because insecticides were not applied. For non-*Bt* cotton, the strategy resulting in the greatest net returns in the presence of heliothines was cotton plus heavy beneficials under dry, average, optimum, and wet rainfall conditions and low and high heliothine densities. For *Bt* cotton, the strategy resulting in the greatest net returns in the presence of heliothines was *Bt* cotton plus heavy beneficials under dry, average, optimum, and wet rainfall conditions and low, medium, or heavy heliothine densities.

Table 6. Net returns ($/acre) (pay-off matrix) using different management strategies under combinations of in-season rainfall conditions and bollworm-tobacco budworm egg densities.

		Bollworm-tobacco budworm egg density			
Strategy	Rainfall condition	None	Low	Medium	High
1. Do nothing	Dry	103.17	68.91	8.95	-81.97
No beneficial	Average	269.49	258.67	202.44	18.39
	Optimum	533.92	518.03	388.87	110.05
	Wet	333.75	251.54	160.65	6.49
2. Do nothing	Dry	103.17	89.73	79.24	60.43
+ benficials (light)	Average	269.49	250.77	241.48	237.18
	Optimum	533.92	500.00	492.82	493.95
	Wet	333.75	326.55	313.28	244.50
3. Do nothing	Dry	103.17	98.88	94.45	96.59
+ beneficials (heavy)	Average	269.49	263.51	247.63	257.02
	Optimum	533.92	520.05	496.64	521.72
	Wet	333.75	332.66	332.11	328.65
4. Use insecticide	Dry	103.17	82.19	43.55	-13.75
@ low rate	Average	269.49	242.40	227.94	190.37
No beneficials	Optimum	533.92	512.15	499.39	368.45
	Wet	333.75	315.54	243.17	161.11
5. Use insecticide	Dry	103.17	83.86	75.60	63.90
@ low rate	Average	269.49	250.86	235.02	236.99
+ beneficials (light)	Optimum	533.92	487.84	485.11	483.43
	Wet	333.75	319.57	316.72	267.12
6. Use insecticide	Dry	103.17	98.87	90.10	81.99
@ low rate	Average	269.49	242.40	253.35	240.40
+ beneficials (heavy)	Optimum	533.92	509.79	501.18	513.13
	Wet	333.75	322.66	321.41	320.47
7. Use insecticide	Dry	103.97	79.58	49.12	2.41
@ high rate	Average	269.49	237.48	228.27	204.58
No beneficial	Optimum	533.92	500.50	483.86	418.36
	Wet	333.75	314.48	245.96	193.87
8. Use insecticide	Dry	103.17	81.30	75.63	66.72
@ high rate	Average	269.49	243.40	235.05	230.14
+ beneficials (light)	Optimum	533.92	488.24	488.18	476.64
	Wet	333.75	312.41	314.42	308.32
9. Use insecticide	Dry	103.17	95.45	91.19	83.57
@ high rate	Average	269.49	254.83	240.10	235.31
+ beneficials (heavy)	Optimum	533.92	501.85	499.71	486.32
	Wet	333.75	321.35	320.66	318.21
10. Use *Bt* cotton	Dry	73.17	68.69	65.56	55.71
No beneficials	Average	239.49	230.51	217.84	221.97
	Optimum	503.92	469.91	499.39	495.17

	Wet	303.75	299.44	296.87	280.71
11. Use *Bt* cotton	Dry	73.17	67.04	62.73	55.73
+ beneficial (light)	Average	239.49	231.55	219.36	213.96
	Optimum	503.92	469.15	464.92	464.84
	Wet	303.75	304.87	299.34	295.81
12. Use *Bt* cotton	Dry	73.17	71.95	70.31	70.12
+ beneficials (heavy)	Average	239.49	239.91	241.18	237.48
	Optimum	503.92	469.91	499.39	495.17
	Wet	303.75	303.79	302.32	302.44
13. Use *Bt* cotton	Dry	73.17	58.22	55.28	46.95
+ insecticide	Average	239.49	212.76	184.37	186.15
@ low rate	Optimum	503.92	459.20	489.96	490.61
	Wet	303.75	293.61	293.91	286.24
14. Use *Bt* cotton	Dry	73.17	58.51	55.49	50.70
+ beneficials	Average	239.49	225.46	216.40	210.61
+ insecticide (light)	Optimum	503.92	460.21	459.91	460.45
@ low rate	Wet	303.75	293.93	289.96	286.48
15. Use *Bt* cotton	Dry	73.17	62.32	62.73	57.20
+ beneficials	Average	239.49	228.87	217.85	207.62
+ insecticide	Optimum	503.92	460.78	460.25	460.50
@ low rate (heavy)	Wet	303.75	294.95	293.95	289.98
16. Use *Bt* cotton	Dry	73.17	54.85	54.93	43.16
+ insecticide	Average	239.49	209.53	219.66	207.07
@ high rate	Optimum	503.92	456.44	457.00	486.36
	Wet	303.75	290.58	286.45	285.48
17. Use *Bt* cotton	Dry	73.17	56.70	53.05	52.86
+ beneficials	Average	239.49	225.76	209.04	203.61
+ insecticide	Optimum	503.92	457.91	456.83	455.36
@ high rate (light)	Wet	303.75	290.57	289.83	285.62
18. Use *Bt* cotton	Dry	73.17	56.29	58.75	57.88
+ beneficials	Average	239.49	228.30	229.25	225.51
+ insecticide	Optimum	503.92	453.77	453.98	457.40
@ high rate (heavy)	Wet	303.75	291.72	291.51	291.35

The use of transgenic *Bt* cotton resulted in the highest net returns with a low heliothine density during dry years ($71.95/acre), average years ($239.91/acre), optimum year ($469.91/acre), and wet years ($303.79/acre); with a medium heliothine density during dry years ($70.31/acre), average years ($241.18/acre), optimum year ($499.39/acre), and wet years ($302.32/acre); with a high heliothine density during dry years ($70.12/acre), average years ($237.48/acre), optimum year ($495.17/acre), and wet years ($302.44/acre).

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 7). The highest average net returns during all years occurred under the strategy of no insecticide applications with heavy beneficials. The lowest net returns were obtained from the strategy of no management when heliothine densities were present.

Similar results were obtained when comparing management strategies under different heliothine densities over all in-season rainfall conditions. No insecticide applications with heavy beneficials resulted in the highest average net returns during all years. The lowest net returns were obtained from the strategy of no management when heliothine densities were present.

Table 7. Expected net returns using different management strategies under combinations of in-season rainfall conditions and bollworm-tobacco budworm egg densities.

	Rainfall	Bollworm-tobacco budworm egg density			
Strategy	condition	None	Low	Medium	High
1. Do nothing	Dry	29.51	11.16	0.68	-3.93
No beneficials	Average	6.47	14.74	9.72	0.26
	Optimum	9.08	27.97	20.61	2.09
	Wet	4.67	6.54	13.33	0.012
2. Do nothing	Dry	29.51	14.54	6.02	2.90
+ beneficials (light)	Average	6.47	14.29	11.59	3.32
	Optimum	9.08	27.00	26.12	9.39
	Wet	4.67	8.49	26.00	4.65
3. Do nothing	Dry	29.51	16.01	7.18	4.64
+ beneficials (heavy)	Average	6.47	15.02	11.89	3.60
	Optimum	9.08	28.08	26.32	9.91
	Wet	4.67	8.65	27.57	6.24
4. Use insecticide	Dry	29.51	13.31	3.31	-0.66
@ low rate	Average	6.47	13.82	10.94	2.67
No beneficials	Optimum	9.08	27.66	26.47	7.00
	Wet	4.67	8.20	20.18	3.06
5. Use insecticide	Dry	29.51	13.50	5.75	3.07
@ low rate	Average	6.47	14.30	11.28	3.32
+ beneficials	Optimum	9.08	26.34	25.71	9.19
	Wet	4.67	8.31	26.29	5.08
6. Use insecticide	Dry	29.51	16.02	6.85	3.94
@ low rate	Average	6.47	13.82	12.11	3.37
+ beneficials	Optimum	9.08	27.53	26.56	9.79
	Wet	4.67	8.39	26.68	6.09
7. Use insecticide	Dry	29.51	12.89	3.73	0.12
@ high rate	Average	6.47	13.54	10.96	2.86
No beneficials	Optimum	9.08	27.03	25.64	7.95
	Wet	4.67	8.18	20.41	3.68
8. Use insecticide	Dry	29.51	13.17	5.75	3.20

@ high rate	Average	6.47	13.87	11.28	3.22
+ beneficials	Optimum	9.08	26.36	25.87	9.06
	Wet	4.67	8.12	26.10	5.86
9. Use insecticide	Dry	29.51	15.46	6.93	4.01
@ high rate	Average	6.47	14.53	11.52	3.29
+ beneficials	Optimum	9.08	27.10	26.48	9.24
	Wet	4.67	8.36	26.61	6.05
10. Use *Bt* cotton	Dry	20.93	11.13	4.98	2.67
No beneficials	Average	5.75	13.14	10.46	3.11
	Optimum	8.57	25.38	26.47	9.41
	Wet	4.25	7.79	24.64	5.33
11. Use *Bt* cotton	Dry	20.93	10.86	4.77	2.68
+ beneficials (light)	Average	5.75	13.20	10.53	3.00
	Optimum	8.57	25.33	24.64	8.83
	Wet	4.25	7.93	24.84	5.62
12. Use *Bt* cotton	Dry	20.93	11.66	5.34	3.37
+ beneficials	Average	5.75	13.67	11.77	3.32
(heavy)	Optimum	8.57	25.38	26.47	9.41
	Wet	4.25	7.90	25.09	5.75
13. Use *Bt* cotton	Dry	20.93	9.43	4.20	2.25
+ insecticide	Average	5.75	12.13	8.85	2.61
@ low rate	Optimum	8.57	24.80	25.97	9.32
	Wet	4.25	7.63	24.39	5.44
14. Use *Bt* cotton	Dry	20.93	9.48	4.22	2.43
+ beneficials	Average	5.75	12.85	10.39	2.95
+ insecticide	Optimum	8.57	24.85	24.38	8.75
@ low rate (light)	Wet	4.25	7.64	24.07	5.44
15. Use *Bt* cotton	Dry	20.93	10.10	4.77	2.75
+ beneficials	Average	5.75	13.05	10.46	2.91
+ insecticide	Optimum	8.57	24.88	24.39	8.75
@ low rate (heavy)	Wet	4.25	7.67	24.40	5.51
16. Use *Bt* cotton	Dry	20.93	8.89	4.17	2.07
+ insecticide	Average	5.75	11.94	10.54	2.90
@ high rate	Optimum	8.57	24.65	24.22	9.24
	Wet	4.25	7.56	23.78	5.42
17. Use *Bt* cotton	Dry	20.93	9.19	4.03	2.54
+ beneficials	Average	5.75	12.87	10.03	2.85
+ insecticide	Optimum	8.57	24.73	24.21	8.65
@ high rate (light)	Wet	4.25	7.55	24.06	5.43
18. Use *Bt* cotton	Dry	20.93	9.12	4.47	2.78
+ beneficials	Average	5.75	13.01	11.00	3.16
+ insecticide	Optimum	8.57	24.50	24.06	8.69
@ high rate (heavy)	Wet	4.25	7.59	24.20	5.54

Using the probabilities of occurrence of various states of nature to modify the net returns as expected net returns, helped to identify the best strategies under risk. The greatest expected net returns over all heliothine densities were obtained using non-*Bt* cotton plus heavy beneficials under dry, average, optimum, and wet in-season rainfall conditions (Table 8). The greatest expected net returns over all in-season rainfall conditions were obtained using non-*Bt* cotton plus heavy beneficials under low, medium, and high heliothine densities (Table 9).

Table 8. Expected net returns using different management strategies under in-season rainfall conditions over bollworm-tobacco budworm egg densities.

	In- season rainfall conditions			
Strategy	Dry	Average	Optimum	Wet
1. Do nothing No beneficials	37.42	31.19	59.75	24.66
2. Do nothing + beneficials (light)	52.97	35.67	71.59	43.81
3. Do nothing + beneficials (heavy)	57.34	36.98	73.39	47.13
4. Use insecticide @ low rate No beneficials	45.47	33.90	70.21	36.11
5. Use insecticide @ low rate + beneficials (light)	51.83	35.87	70.32	44.35
6. Use insecticide @ low rate + beneficials (heavy)	56.32	35.77	72.96	45.83
7. Use insecticide @ high rate No beneficials	46.25	33.83	69.70	36.94
8. Use insecticide @ high rate + beneficials (light)	51.63	34.84	70.37	44.75
9. Use insecticide @ high rate + beneficials (heavy)	55.91	35.81	71.90	45.69

10. Use *Bt* cotton No beneficials	39.71	32.46	69.83	42.01
11. Use *Bt* cotton + beneficials (light)	39.24	32.48	67.37	42.64
12. Use *Bt* cotton + beneficials (heavy)	41.30	34.51	69.83	42.99
13. Use *Bt* cotton + insecticide @ low rate	36.81	29.34	68.66	41.71
14. Use *Bt* cotton + beneficials (light) + insecticide @ low rate	37.06	31.94	66.55	41.40
15. Use *B.t* cotton + beneficials (heavy) + insecticide @ low rate	38.55	32.17	66.59	41.83
16. Use *Bt* cotton + insecticide @ high rate	36.06	31.13	66.68	41.01
17. Use *Bt* cotton + beneficials (light) + insecticide @ high rate	36.69	31.50	66.16	41.29
18. Use *Bt* cotton + beneficials (heavy) + insecticide @ high rate	20.62	32.92	65.82	41.58

Expected net returns equal net returns multiplied by the joint probabilities of in-season rainfall conditions and expected bollworm-tobacco budworm egg densities.

Table 9. Expected net returns using different management strategies under bollworm-tobacco budworm egg densities over in-season rainfall conditions.

	Bollworm-tobacco budworm egg density			
Strategy	None	Low	Medium	High
1. Do nothing No beneficials	49.75	60.41	44.34	-1.46
2. Do nothing + beneficials (light)	49.75	64.32	69.73	20.26
3. Do nothing + beneficials (heavy)	49.75	67.76	72.96	24.39
4. Use insecticide @ low rate No beneficials	49.75	62.99	60.90	12.07
5. Use insecticide @ low rate + beneficials (light)	49.75	62.45	69.03	20.66
6. Use insecticide @ low rate + beneficials (heavy)	49.75	65.76	72.20	23.19
7. Use insecticide @ high rate No beneficials	49.75	61.64	60.74	14.61
8. Use insecticide @ high rate + beneficials (light)	49.95	61.52	69.00	21.34
9. Use insecticide @ high rate + beneficials (heavy)	49.95	65.45	71.54	22.59
10. Use *Bt* cotton No beneficials	39.50	57.50	66.55	20.52
11. Use *Bt* cotton + beneficials (light)	39.50	57.32	64.78	20.13
12. Use *Bt* cotton	39.50	58.61	68.67	21.85

+ beneficials (heavy)				
13. Use *Bt* cotton + insecticide @ low rate	39.50	53.99	63.41	19.62
14. Use *Bt* cotton + beneficials (light) + insecticide @ low rate	39.50	54.82	63.06	19.57
15. Use *Bt* cotton + beneficials (heavy) + insecticide @ low rate	39.50	55.70	64.02	19.92
16. Use *Bt* cotton + insecticide @ high rate	39.50	53.04	62.71	19.63
17. Use *Bt* cotton + beneficials (light) + insecticide @ high rate	39.50	54.34	62.33	19.47
18. Use *Bt* cotton + beneficials (heavy) + insecticide @ high rate	39.50	54.22	63.73	20.17

Expected net returns equal net returns multiplied by the joint probabilities of in-season rainfall conditions and expected bollworm-tobacco budworm egg densities.

The average expected net returns over all in-season rainfall conditions and heliothine densities for each strategy was: $153.02/acre (do nothing to control insects pests); $204.04/acre (do nothing expect using beneficials (light) to control insect pests); $214.84/acre [do nothing except using beneficials (heavy) to control insect pests]; $185.69/acre (use insecticide at a low rate); $202.37/acre (use insecticide at a high rate with a light density of beneficials); $210.88/acre (use insecticide at a low rate with a heavy density of beneficials); $186.72/acre (use insecticide at a high rate); $201.59/acre (use insecticide at a high rate with a light density of beneficials); $209.31/acre (use insecticide at a high rate with a heavy density of beneficials); $184.01/acre (use transgenic *Bt* cotton to control insect pests); $181.73/acre (use transgenic *Bt* cotton with a light density of beneficials to control insect pests); $188.63/acre (use transgenic *Bt* cotton with a heavy density of beneficials to control insect pests); $176.52/acre (use transgenic *Bt* cotton and insecticide at a low rate);$176.75/acre (use transgenic *Bt* cotton, with light dendity of beneficials

, and insecticide at a low rate); $179.14/acre (use transgenic *Bt* cotton, with a heavy density of beneficials, and insecticide at a low rate); $174.88/acre (use transgenic *Bt* cotton and insecticide at a high rate); $175.64/acre (use transgenic *Bt* cotton, with a light density of beneficials, and insecticide at a high rate); and $160.94/acre (use transgenic *Bt* cotton, with a heavy density of beneficial, and insecticide at a high rate). The management strategies that did not result in the greatest expected net returns when heliothines were present all used *Bt* cotton. However, should the price of *Bt* planting seed decrease this strategy would become more economically attractive.

4. SUMMARY AND CONCLUSIONS

The data requirements for an economic analysis of heliothine 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 cost, insecticide treatment costs, seed costs, and costs related to harvest, such as picking, ginning, and the expert's subjective probabilities with respect to future densities of heliothine densities.

In conclusion, these analyses show under all states of nature (i.e., weather) and density of the insect pests (i.e., heliothine) that no single strategy of insect control provides highest net returns. However, the use of non-*Bt* cotton with the heavy beneficial's and no insecticide applications provided the best strategy and net return under all risk and states of nature, thus making it the optimum strategy for managing these insect pests.

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