Developing Flexible Economic Thresholds for Pest Management Using Dynamic Programming

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Abstract

The rice stink bug is a major pest of rice in Texas, causing quality related damage. The previous thresholds used for assisting in rice stink bug spray decisions lacked flexibility in economic and production decision variables and neglected the dynamics of the pest population. Using stochastic dynamic programming, flexible economic thresholds for the rice stink bug were generated. The new thresholds offer several advantages over the old, static thresholds, including increased net returns, incorporation of pest dynamics, user flexibility, ease of implementation, and a systematic process for updating.

Key Words: economic thresholds, dynamic programming, pest management, rice

The need for flexibility in management strategies for dynamic agricultural processes has been emphasized in many studies (Antle 1983 a,b; Mjelde, Dixon, and Sonka). One area in which this need has long been acknowledged is pest management (Stone and Pedigo). The development of economic threshold concepts and of integrated pest management techniques are direct results of the search for more systematic approaches to pest control (Stern *et al.*; Frisbie and Adkisson).

Headley's work marked the beginning of the integration of economic concepts with entomological research regarding pest damage. He redefined the concept of economic thresholds to be the pest population density that produces marginal damage equal to the marginal cost of preventing that damage. Work by Hall and Norgaard; Chatterjee; and Hueth and Regev further refined the concept of economic thresholds. Early economic thresholds were developed using benefit-cost analysis, expertise, and/or educated guesses. Pest management specialists encouraged the use of pest scouting techniques and these predetermined threshold values for making pesticide application decisions. The easy-to-use nature of these early thresholds encouraged their use because they provided producers with better information on which to base pest management decisions than had previously been available. However, entomologists and economists alike lacked confidence in these early thresholds because of their inflexible nature. In general, these thresholds disregarded the dynamic nature of insect populations, product markets, and insecticide costs and efficacy.

Research in the late 1970s and early 1980s sought to include the dynamic aspects of pest management into economic thresholds development (for examples in insect management, see Hall and

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Moffitt; Talpaz and Frisbie; for nematodes, see Moffitt, Hall, and Osteen; Zacharias, Liebman, and Noel; and for weeds, see Marra and Carlson; Marra, Gould, and Porter). Although these studies incorporated additional facets of pest management into economic thresholds, few fully accounted for the dynamic and stochastic aspects of the problem. These elements are necessary in developing a framework which will provide flexible economic thresholds for use by agricultural producers and crop consultants.

The objective of this study is to develop a framework for flexible economic thresholds implementable at the field level. The thresholds need to account for changing economic and production conditions, and the dynamic and stochastic nature of pest populations. To accomplish this objective, economic thresholds for management of the rice stink bug, *Oebalus pugnax* (Fabricius), in Texas rice production are developed using stochastic dynamic programming.

Rice Stink Bug Damage and Management

The rice stink bug (RSB), a major pest of ripening rice in the U.S., causes substantial economic losses because of decreased rice quality. Based on data from 1981-1984, it was estimated that RSB damage costs Texas rice producers between $5.91 and $29.34/A annually (Brorsen, Grant, and Rister). RSB damage occurs for an approximately four-week period during later-stage rice development. This period extends from heading to harvest (Swanson and Newsom). Adult RSB migrate into rice fields from earlier season hosts such as grain sorghum and grass. RSB are not a multiple generation type of pest in rice, so field infestation is a function of migration and level of management. RSB damage is attributed to the extraction of fluids from the developing rice kernel and the introduction of micro-organisms which cause a condition called "pecky" rice. This quality reduction manifests itself in two ways. First, kernels which are structurally weakened by RSB feeding activities may break during milling, lowering the percentage of whole grains (head yield). Second, probed kernels that do not break during the milling process develop discolorations (peck damage), leading to a reduction in the quality grade assigned. Several recent studies have quantified the price discounts associated with RSB related quality damage (Grant, Rister, and Brorsen; Fryar *et al.*; Traylor, Denison, and Conger).

Controlled cage experiments conducted in the 1960s and expert opinion formed the basis for development of early static treatment thresholds for RSB management. These thresholds were developed irrespective of rice value, treatment cost, and other variables of production. The Texas Agricultural Extension Service, at the suggestion of experiment station researchers, established the following thresholds in 1981: 5 RSB (adult and nymphs) collected per 10 sweeps of a sweep net for the first two weeks after 75 percent panicle emergence and 10 RSB thereafter (McIlveen, Bowling, and Drees). Changing economic and production environments, however, necessitated the development of dynamic flexible thresholds better suited to the complex rice production environment of the 1990s.

Study Area and Data

This analysis is based on field data collected at two Texas Agricultural Experiment Station research sites in the Texas Rice Belt (upper Texas Gulf Coast area): Beaumont on the eastern side and Eagle Lake on the western side. Data collected from large plot studies from 1984 to 1987 were used to develop RSB damage functions (Harper, *et al.*). In turn, these functions were used in the development of the flexible economic thresholds for RSB management.

RSB Dynamic Programming Model

A single acre, intraseasonal dynamic programming (DP) model is developed for RSB management (see Burt or Kennedy for a general discussion of the use of DP models). Within the model, five stages that represent identifiable reference points for pest sampling are defined (figure 1). These stages correspond to the following maturation stages of the rice plant: heading (stage 5), milk (stage 4), soft dough (stage 3), hard dough (stage 2), and maturity (stage 1). Overall, the five stages comprise the approximately four week period during which RSB migrations and damage occur.

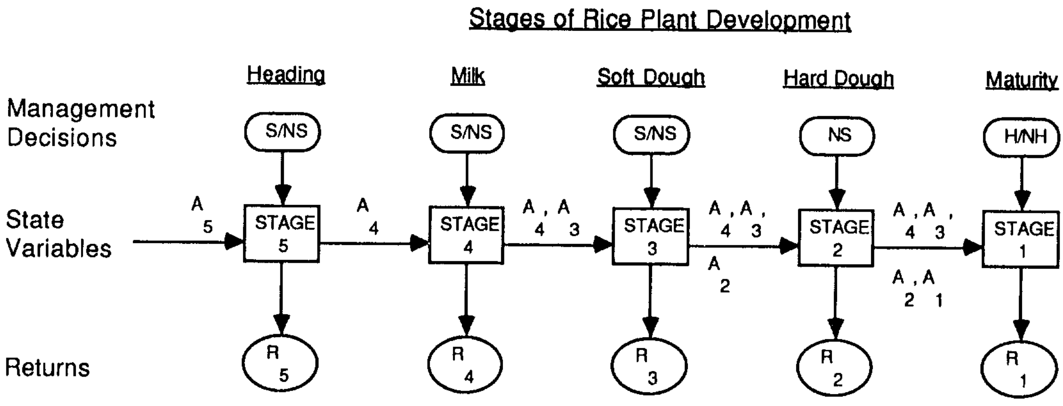
For stages 5 to 3, corresponding to heading, milk, and soft dough, two decisions are possible: spray (*S*) to control the RSB or do not spray (*NS*). Only one insecticide spray using EPA registered insecticides at labeled rates can be made in each stage. This reflects the typical lag of one week between scouting, spraying, and the next scouting period. The spray decision affects the number of adult RSB present in subsequent stages. At hard dough, only the *NS* decision is possible, because of EPA regulations concerning permissible levels of insecticide residues on food grains (U.S. Environmental Protection Agency). The hard dough stage was included to account for differences in the quantity and types of damage during the entire period when rice is vulnerable to RSB. Finally, the decision at maturity is to harvest or not to harvest the field.

State Variables and Transition Equations

Specification of the dynamic programming (DP) model for RSB management requires six state variables. Five of the state variables represent the number of adult RSB observed at the beginning of the various stages (A_1 through A_5 in figure 1). The sixth state variable functions as a possible constraint on the total number of insecticide applications. The model uses the number of RSB observed at each stage, instead of using an accumulated damage state variable (Burt and Stauber). An accumulated damage function state variable would decrease the dimensionality of the RSB model from six to two state variables. Methods that decrease dimensionality have been discussed extensively in the literature (Burt), but in this model decreasing the dimensionality would lead to increased difficulty in applying the thresholds at the field level. In order to use a DP model employing an accumulated damage function state variable, producers would be required to keep track of accumulated damage (which would have to be calculated) rather than RSB numbers (which are observed directly by virtue of the sampling process).

As illustrated in figure 1, the number of state variables relevant to the RSB decision process varies by stage. The state variable for adult RSB at heading (A_5), for example, was used only to describe the state of the system at heading. Because the damage relationships utilized do not include RSB numbers at heading, this state variable does not help in describing the system in later stages. The number of adult RSB and the spray decision at heading, however, affects the state of the system by influencing the number of adult RSB present in later stages. The remaining four RSB state variables (A_1 - A_4) were used in conjunction with estimated relationships to assess the damage associated with a given level of infestation. The use of RSB levels to determine damage is further discussed in the Damage and Yield Relationships section.

Figure 1. Schematic of the Rice Stink Bug Dynamic Programming Model



where:

A_n is the number of adult rice stink bugs present in stage n,
R_n is the return based on the decision made in stage n, and
S, NS, H, and NH represent the spray, don't spray, harvest, and don't harvest decision alternatives

Transitions for the RSB state variables are both deterministic and stochastic depending on the stage. At the milk stage, for example, the relevant state variable is A_4, the number of adult RSB observed at the beginning of this stage. The spray decision depends on A_4, as well as expected future RSB numbers, the value of the rice crop, and the cost of control. The transition for observed RSB at milk (A_4) from the milk to soft dough is deterministic, because the producer cannot affect RSB numbers already observed. At the milk stage, however, the transition for the number of RSB at soft dough (A_3) is stochastic, depending on the decision to spray or not to spray and the number of RSB present at the milk stage. Similar deterministic and stochastic relationships exist between the other RSB state variables.

Each RSB state variable takes on 16 possible values, ranging from zero to 15 RSB in increments of one adult insect. Values represent the average number of adult RSB observed when using a 15-inch diameter sweep net in the recommended sampling method (Texas Agricultural Extension Service).

Estimated state variable transition equations for the stages when the RSB are stochastic are (Harper):

$$A_1 = \underset{(3.01)}{2.0870} + \underset{(6.70)}{0.8070}\,A_2 + \epsilon_1 \tag{1}$$

$$\bar{R}^2 = .35 \qquad F = 44.9,$$

$$A_2 = \underset{(4.16)}{2.1014} + \underset{(5.47)}{0.5343}\,A_3 + \epsilon_2 \tag{2}$$

$$\bar{R}^2 = .24 \qquad F = 29.9,$$

$$A_3 = \underset{(5.65)}{2.4157} + \underset{(4.18)}{0.2048}\,A_4 + \epsilon_3 \tag{3}$$

$$\bar{R}^2 = .14 \qquad F = 17.5, \textit{ and}$$

$$A_4 = \underset{(2.40)}{3.9579} + \underset{(2.48)}{0.9885}\,A_5 + \epsilon_4 \tag{4}$$

$$\bar{R}^2 = .10 \qquad F = 6.1,$$

where A_n is the number of adult RSB at stage n, ϵ_n represent error terms, and *t*-ratios are in parentheses below the estimated coefficients. All the coefficients associated with lagged RSB numbers are statistically significant (α=0.05), indicating that a strong Markov relationship exists in the estimated equations. Of the functional forms examined (linear, quadratic, and square root), the linear form provided the best statistical fit.

Stochastic transitions for RSB numbers were developed by fitting cumulative distribution functions (CDF) for the error terms associated with equations (1)-(4). The approach, which utilizes a hyperbolic tangent function to estimate the CDF, allows for conditional probabilities to be generated (Taylor 1984, 1986). Transitions are conditional on the level of previous RSB numbers. The estimated CDF were assumed to be independent of each other. Maximum likelihood estimates of the CDF are:

$$F(\epsilon_1) = 0.5 + 0.5 \tanh\,(\underset{(1.09)}{0.1013} + \underset{(10.74)}{2.2545}\,\epsilon_1) \tag{5}$$

$$F(\epsilon_2) = 0.5 + 0.5 \tanh\,(\underset{(-0.65)}{-0.0515} + \underset{(10.15)}{5.7779}\,\epsilon \tag{6}$$

$$F(\epsilon_3) = 0.5 + 0.5 \tanh\,(\underset{(3.31)}{0.3055} + \underset{(11.57)}{3.6135}\,\epsilon_3 - \underset{(-6.35)}{3.8088}\epsilon_3^2 + \underset{(4.07)}{1.5441}\,\epsilon_3^3) \tag{7}$$

$$F(\epsilon_4) = 0.5 + 0.5 \tanh (\underset{(1.82)}{0.2404} + \underset{(7.79)}{1.5105}\ \epsilon_4 - \underset{(3.38)}{0.6255}\ \epsilon_4^2 + \underset{(2.00)}{0.1174}\ \epsilon_4^3) \qquad (8)$$

where *t*-ratios are in parentheses below the estimated coefficients. Polynomial terms included in the CDF's are based on maximizing the Schwarz criterion. The CDF's of the error terms represent the effect that exogenous factors such as migration and weather have on RSB infestation levels.

Because the data set used to estimate the transition functions did not include the effect of spraying on RSB populations, other research findings were used. Based on findings reported by Way, Bowling, and Wallace, the average effectiveness of chemicals labeled to control RSB in rice is approximately 85 percent. To account for spraying, the slope coefficients were reduced to 15 percent of their estimated values. Transitions in the model, therefore, use equations (1)-(4) as presented for the case when no spraying occurs. If spraying occurs, the transitions are based on equations (1)-(4) with reduced slope coefficients. The estimated cumulative density functions for the error terms remain the same regardless of spraying.

As noted earlier, the sixth state variable constrains the number of stages in which insecticide applications can occur. Such a state variable can represent several constraints placed on the system. One possibility is a constraint on total insecticide expenditures. Another might be future governmental regulations limiting the number of insecticide applications for RSB control. The transition for the constraint state variable is deterministic depending on the decision to spray or not to spray.

The number of values for the constraint state variable varies by stage. At the start of the management process (heading) there are three stages where spraying potentially can occur (heading, milk, and soft dough). The constraint state variable at this stage assumes one of four possible values: 0, 1, 2, or 3. Each value represents the number of possible times during the process that spraying can occur. A "2", for example, indicates that of the three stages when insecticide can be applied, spraying can occur during only two of the stages. The model determines which two stages, if at all, spraying occurs. At milk, the constraint state variable represents 0, 1, or 2 possible insecticide applications. Finally, at soft dough the constraint state variable indicates a simple spray/no spray possibility.

Recursive Equation

The objective of the model is to maximize expected net returns associated with RSB management. This leads to the general recursive equation:

$$V_n(A_1, A_2, A_3, A_4, A_5, F) = \max_{S,\ NS} \{R_n + E\ V_{n-1}(A_1, A_2, A_3, A_4, A_5, F)\} \qquad (9)$$

where V_n is the expected net returns at stage n given the state and the optimal decision rule are followed to the end of the planning horizon, A_n represents the five RSB state variables, F represents the constraint state variable, R_n is the immediate net returns at stage n, S and NS represent the spray/no spray decision, and E is the mathematical expectation operator over RSB numbers. Subscripts on the state variables denoting the stages have been suppressed for simplicity. As discussed earlier, the relevant state variables vary by stage. If a state variable is not relevant at a particular stage, it can only take on one value in the model, effectively making it irrelevant to the decision process at that stage.

Components within the immediate return function, R_n, vary by stage. For the stages heading through soft dough, the immediate return function represents the cost of spraying. If spraying occurs, R_n is the cost of insecticide application. If no spraying occurs, R_n is zero for this stage.

At harvest the immediate returns function determines the per acre returns, π, associated with RSB management; that is,

$$\pi = \{(P - HC) \bullet Q\}, \tag{10}$$

where P is the price received, HC is harvest costs, and Q is rice yield. Harvest cost is an exogenous parameter charged at $0.90/cwt (Dismukes).

The price received by producers for their rice depends on prevailing supply and demand conditions and the total amount of peck, head yield damage, and other quality losses incurred over the course of the growing season. To develop more realistic RSB decision rules, two separate price relationships were incorporated to represent a range of potential supply/demand situations in the DP model. These supply and demand conditions are characterized by 1) rice moving into the U.S. government loan program (excess supply) or 2) rice moving directly into the market (high demand). Rice price, therefore, is a function of:

$$P = f(PECK, HY, SD, X) \tag{11}$$

where $PECK$ is RSB peck damage (percent), HY is head yield (percent), SD is the supply/demand situation, and X represents all other rice quality factors that are exogenous to the RSB management decisions. As noted earlier, increases in RSB numbers increase percent peck and decrease head yield. The number of RSB, therefore, influences the price which producers receive.

For rice moving into the loan program, the price received was determined by taking into account the percentage of whole kernels (head yield), broken kernels (mill yield minus head yield), and the level of peck. Government loan values are used for head yield and brokens, and a discount structure was used for damaged kernels (including peck- and smut-damaged kernels) and red rice (an undesirable variety of rice which is regarded as a weed). The price received under the loan (P_L) is:

$$P_L = (HY/100 * WKLV) + (BROKENS/100 * BKLV) - DISC \tag{12}$$

where $WKLV$ is the whole kernel loan value ($/cwt), $BKLV$ is the broken kernel loan value ($/cwt), and $DISC$ is the discount ($/cwt) associated with damaged kernels (peck and smut) and red rice (USDA).

The price received (and discounts for RSB damage) for rice moving directly into the market are driven by supply and demand conditions, rather than being calculated from the government loan program formula. To simulate the effects of selling in the rice market, a hedonic price model estimated by Brorsen, Grant, and Rister for the 1981/82 marketing year was used. The 1981/82 marketing year was selected because it had the most prices above the government loan value of the three marketing years for which hedonic price relationships were fitted (1981/82, 1982/83, and 1983/84).

In the hedonic equation, rice price is a function of mill price, head yield, broken kernels, weed seeds, red rice, peck, smut damage, chalky kernels, heat-damaged kernels, and test weight (Brorsen, Grant, and Rister). For purposes of developing economic thresholds for RSB management, all quality factors except percent head yield, percent peck, and test weight were set equal to average values calculated from data found in Grant, Rister, and Brorsen. Percent head yield and percent peck were calculated from the damage functions discussed in the next section. Test weight was found using an estimated equation relating peck to test weight (Grant, Rister and Brorsen). Finally, in this analysis, mill price was varied.

Damage and Yield Relationships

RSB affect both head yield and peck associated with rice. Functions relating head yield and peck to the number of adult RSB at each stage were used to determine the values used in the price equations. Various theories of damage and functional forms were tested by Harper *et al.* Linear functions of adult RSB were found to provide the best fit for these quality variables. No significance was found between RSB numbers and crop yield, so rice yield is simply a function of a variety binary variable and planting date. The estimated damage functions are (Harper *et al.*):

$$\begin{aligned} PECK = {} & \underset{(5.80)}{1.0381} - \underset{(-3.74)}{.0051\, PD} + \underset{(3.37)}{.0206\, A_1} + \underset{(3.45)}{.0334\, A_2} \\ & + \underset{(2.19)}{.0209\, A_3} + \underset{(4.16)}{.0190\, A_4} \\ & \bar{R}^2 = .59,\ F = 35.2 \end{aligned} \tag{13}$$

$$\begin{aligned} HY = {} & \underset{(6.04)}{36.811} + \underset{(3.11)}{.00104\, YIELD} + \underset{(4.30)}{.1832\, PD} - \underset{(-0.97)}{.3346\, A_2} \\ & - \underset{(-3.37)}{1.0763\, A_3} - \underset{(-2.78)}{.5318\, A_4} \\ & \bar{R}^2 = .45,\ F = 13.6 \end{aligned} \tag{14}$$

where *PECK* is the percentage of rice grains exhibiting peck damage, *HY* is head yield (percentage of whole grains), *PD* is planting date (Julian day), and A_n is the number of adult RSB at stage n.

Previous thresholds were based on nymphs plus adult RSB, but Harper *et al.* found that adult population densities alone accounted for as much of the variation in damage as nymphal and adult populations. This finding greatly simplifies field sampling because adult RSB are much easier to identify than nymphs.

Results

Several types of results are presented. First, unconstrained decision rules for RSB management are discussed. Second, the impact on the decision rules from limiting the number of insecticide applications (constrained decision rules) is discussed. Finally, the DP decision rule is compared to alternative decision criteria.

Unconstrained Decision Rule

The unconstrained economic thresholds for the RSB are found in table 1. The values in the table indicate the threshold (or minimum) number of adult RSB per 10 sweeps at which the decision to spray is economically warranted. Eighty-one combinations of supply/demand conditions, insecticide cost, planting date, and yield are presented. The DP model can be tailored to specific situations by altering assumed levels of these exogenous variables, along with the values for the non-RSB related quality factors. Regardless of the stage, the threshold levels generally increase as spray costs increase and decrease as planting date increases, expected yield increases, and when rice enters the market instead of being placed in the government loan program.

The thresholds for heading are presented in part A of table 1. Thresholds for this period are the lowest of the three sampling periods. Because the number of adult RSB at heading influences the number of insects present in the remaining stages, reducing RSB infestations at heading decreases the probability of high numbers of RSB in later periods. The thresholds for rice moving into the loan program are generally higher than for rice directly entering the market. This was expected because rice directly entering the market has a higher value than rice entering the government loan program. At heading, the threshold levels vary the most between the loan and mill price situations for rice planted on April 1. Thresholds for later-planted rice vary little between the loan and mill price situations. For the two mill prices considered, the thresholds are nearly identical for all spray cost, planting date, and yield combinations. The thresholds vary from 3 to 9 adult RSB per 10 sweeps depending on economic and production factors.

Of the three periods, thresholds are the highest during the milk stage (table 1, part B). The threshold values are generally between two and three times higher at milk than at heading. The thresholds at milk vary from a low of 6 to a high of more than 15 adult RSB. For the situation of high spray cost combined with low yield, the threshold was in excess of 15 adult RSB. Fifteen was the upper bound associated with observed RSB in this analysis, because of the limited number of observations of adult RSB levels above 15 in the data set (Harper). A threshold in excess of 15 adult RSB is denoted by 15+ in table 1. The higher thresholds at milk are because estimated peck damage associated with RSB this stage has the smallest of the coefficients associated with RSB numbers, while the estimated coefficient for determining percent head yield has the second smallest coefficient (equation 14). Further, the coefficient associated with RSB numbers in the transition equation for this state has the smallest value (equation 3).

The thresholds for soft dough (table 1, part C) are similar to those for the milk stage. The thresholds under the loan are represented as a range of possible values with the exact value contingent on the number of adult RSB observed at milk. This is caused by the fixed nature of the discount structure under the government loan program. In contrast, the market situation was characterized by the hedonic price models where the quality discounts are continuous. Using the first entry in part C of table 1 as an example, the thresholds at soft dough for an expected yield of 4500 lb., $5.20/acre spray cost, and April 1 planting date are 9-13 RSB. The thresholds which depend on the number of RSB observed at milk are: 1) 13 adult RSB if less than 3 adult RSB were observed at

Table 1. Flexible Economic Thresholds for the Adult Rice Stink Bug (RSB) for Alternative Yield, Planting Date, Spray Cost, and Price Assumptions[1]

(A) ADULT RSB THRESHOLDS AT HEADING

Spray cost ($/A)	Plant date	Yield								
		4500 lbs/A Rice price			6000 lbs/A Rice price			7500 lbs/A Rice price		
		Loan[2]	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt
5.20	4/1	5	4	4	4	3	3	3	3	3
	5/1	4	4	4	3	3	3	3	3	3
	6/1	4	4	4	3	3	3	3	3	3
8.35	4/1	7	6	5	6	4	4	5	4	4
	5/1	6	5	5	5	4	4	4	4	4
	6/1	6	5	5	5	4	4	4	4	4
11.50	4/1	9	7	7	7	6	6	6	5	5
	5/1	8	7	7	6	6	6	5	5	5
	6/1	8	7	7	6	6	6	5	5	5

(B) ADULT RSB THRESHOLDS AT MILK

Spray cost ($/A)	Plant date	Yield								
		4500 lbs/A Rice price			6000 lbs/A Rice price			7500 lbs/A Rice price		
		Loan	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt
5.20	4/1	12	9	9	10	7	7	8	6	6
	5/1	12	9	9	8	7	7	6	6	6
	6/1	11	9	9	9	7	7	7	6	6
8.35	4/1	15+	14	13	14	11	11	12	9	9
	5/1	15+	13	13	14	11	11	12	9	9
	6/1	15+	13	13	12	11	11	10	9	9
11.50	4/1	15+	15+	15+	15+	14	14	15	12	12
	5/1	15+	15+	15+	15+	14	14	15+	12	12
	6/1	15+	15+	15+	15	14	14	15	11	12

able 1 (continued). Flexible Economic Thresholds for the Adult Rice Stink Bug (RSB) for Alternative Yield, Planting Date, Spray Cost, and rice Assumptions[1]

(C) ADULT RSB THRESHOLDS AT SOFT DOUGH

		Yield								
		4500 lbs/A Rice price			6000 lbs/A Rice price			7500 lbs/A Rice price		
Spray cost ($/A)	Plant date	Loan	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt	Loan	$9/cwt	$11/cwt
	4/1	9-13	10	10	8-12	8	8	8-11	7	7
5.20	5/1	11-15+	10	10	10-12	8	8	7-11	7	7
	6/1	9-15+	10	10	8-12	8	8	7-11	7	7
	4/1	11-15	14	14	10-14	11	11	9-13	10	10
8.35	5/1	13-15+	14	14	12-15+	11	11	11-15	10	10
	6/1	9-15+	14	14	10-15+	11	11	9-15	10	9
	4/1	15+	15+	15+	11-15+	14	14	10-14	12	12
11.50	5/1	15+	15+	15+	13-15+	14	14	12-15+	12	12
	6/1	15+	15+	15+	15+	14	14	11-15+	12	12

The numbers in the table indicate the average level of adult RSB per 10-sweep sample at which treatment is economically warranted. A value of 5+ indicates the threshold exceeds 15 adult RSB.

Loan values based on the 1989 government commodity program.

milk, 2) 12 if 3 to 6 were observed, 3) 11 if 7 to 9 were observed, 4) 10 if 10 to 13 were observed, and 5) 9 if more than 14 were observed. This general trend of decreasing thresholds at soft dough as RSB numbers at milk increases holds for the different scenarios under the loan model. The thresholds at soft dough vary from a low of 7 to a high of more than 15 adult RSB. Again, if spray costs are high and yield expectations low, the thresholds exceed 15 adult RSB per 10 sweeps regardless of marketing conditions.

Constrained Decision Rule

Constraining the number of insecticide applications had little effect on the thresholds. For the majority of the scenarios presented in table 1, if at a given stage an insecticide application was possible, the constrained decision rules for that stage are identical to the unconstrained decision rule. For those situations in which the constrained and unconstrained rules differed, the change had one basic pattern; the threshold level of RSB increased by one insect when the constraint indicated that only one opportunity for spraying remained, but more than one stage was left in which spraying could occur under the unconstrained model.

Comparison of Decision Rules

To determine the value of the unconstrained flexible decision rule, the values of these rules are compared to four alternative decision criteria. These are: 1) insurance applications (always spraying at the three stages irrespective of RSB numbers), 2) never spraying, 3) using the previously established (traditional) thresholds, and 4) using a modified set of traditional thresholds. As noted earlier, the traditional thresholds indicated that spraying was recommended if 5 RSB were observed at heading and if 10 RSB were observed at milk and soft dough (the "5-10" rule). The sampling unit for previously established thresholds includes both adults and nymphs, but the sampling unit for the flexible thresholds developed in this study was based solely on adult RSB. To account for this change, an alternative decision criteria of 4 adults at heading, 9 adults at milk, and 8 adults at soft dough was developed (the "4-9" rule). These numbers are based on the 5-10 rule with the average number of nymphs observed at each stage removed (Harper).

Expected increases in net returns for flexible thresholds over alternative decision criteria are presented in table 2 for selected economic and production scenarios. Employing the flexible thresholds instead of always spraying increases

Table 2. Examples of Expected Increases in Net Returns for Flexible RSB Thresholds Over Alternative Decision Criteria ($/A)

	Alternative Decision Criteria			
	Always[1]	Never[2]	5-10[3]	4-9[4]
Example 1: 6000 lb/A yield, 5/1 Planting Date, $8.35/Application Spray Cost				
Market Situation:				
Loan Prices	18.73	0.68	0.20	0.55
$9 Mill Price	17.92	1.39	0.01	0.17
$11 Mill Price	17.88	1.44	0.02	0.16
Example 2: 6000 lb/A yield, 5/1 Planting Date, Loan Prices				
Spray Cost/A:				
$5.20	10.34	1.81	0.28	0.08
$8.35	18.73	0.68	0.20	0.55
$11.50	27.83	0.25	0.82	1.71
Example 3: 5/1 Planting Date, $8.35/Application Spray Cost, Loan Prices				
Yield/A:				
4500 lb.	20.06	0.21	0.54	1.16
6000 lb.	18.73	0.68	0.20	0.55
7500 lb.	17.75	1.50	0.19	0.26

[1] Always Spray: producer applies insurance applications of insecticide at each grain maturation stage.

[2] Never Spray: producer uses no insecticide to manage RSB populations.

[3] 5-10: producer uses previous static thresholds based on the total number of RSB adults and nymphs.

[4] 4-9: producer uses previous static thresholds modified to account for only adult RSB.

expected net returns by approximately $10/acre to $28/acre for the scenarios considered. In the case of RSB management, insurance applications of insecticides are not economically justified when profit maximization is the objective. Experience with the 5-10 thresholds indicates that some producers and consultants adjust the thresholds downward slightly, reflecting a certain degree of risk aversion by those users. Consideration of the impact of differences in risk preferences on RSB management decisions, however, was beyond the scope of this study.

The value of the new thresholds over the three remaining decision criteria (never, 5-10, 4-9) was positive, as expected, because the flexible thresholds encompass these criteria. The magnitude of expected increases in net returns in these situations was much smaller than in the case of always spraying, ranging from $0.01/acre to $1.81/acre for the scenarios considered.

Although the flexible thresholds increase expected per acre net returns only slightly over the three alternative decision criteria, the increase in expected value of the thresholds for a given growing season depends highly on the initial RSB infestation level. The value of employing the thresholds in a particular growing season over the alternative decision criteria is better gauged by examining results for selected numbers of adult RSB observed at heading. In table 3, one combination of economic and production factors is used to illustrate this point. The value of the flexible thresholds decrease relative to always spraying as the initial infestation of RSB increases.

Table 3. Example of Expected Increases in Net Returns for Flexible RSB Thresholds Over Alternative Decision Criteria at Different Initial RSB Infestation Levels ($/A)[1]

Observed RSB Infestation Level at Heading	Alternative Decision Criteria			
	Always[2]	Never[3]	5-10[4]	4-9[5]
0	22.40	0.09	0.17	0.42
1	20.71	0.11	0.19	0.48
2	18.77	0.12	0.20	0.54
3	16.64	0.14	0.24	0.63
4	14.34	0.16	0.27	1.04
5	13.70	1.93	0.18	0.46
6	13.64	4.31	0.18	0.47
7	13.57	6.66	0.18	0.47
8	13.51	8.93	0.18	0.48
9	13.45	11.07	0.19	0.50
10	13.39	13.03	0.20	0.51
11	13.32	14.79	0.19	0.51
12	13.26	16.33	0.20	0.52
13	13.19	17.64	0.20	0.53
14	13.13	18.70	0.20	0.54
15	13.06	19.51	0.21	0.56

[1] Scenario assumed is rice yield of 6000 lb/A, May 1 Planting Date, $8.35/Application Spray Cost, and Government Loan Program Assumption.

[2] Always Spray: producer applies insurance applications of insecticide at each stage.

[3] Never Spray: producer uses no insecticide to manage RSB populations.

[4] 5-10: producer uses previous static thresholds based on total RSB population (adults and nymphs).

[5] 4-9: producer uses previous static thresholds modified to account for only adult RSB.

An opposite pattern occurs when the alternative criteria compared is never spraying. Both of these patterns were expected, because an increase in initial infestation levels leads to spraying at heading under the flexible rule.

For the 5-10 and 4-9 criteria, the pattern is to increase, then decrease, and finally increase in value again as initial RSB infestation levels increase. The flexible threshold at heading for this scenario (table 1) is 5 RSB which is approximately the same as the two alternative decision criteria; therefore, the expected value of the flexible over the alternative manifests itself in the milk and soft dough stages. For the scenario in table 3, the 5-10 rule is closer to the flexible threshold than the 4-9 rule. Similar patterns, but different magnitudes, were observed for different combinations of the economic and production factors.

Discussion and Conclusions

The results show the superiority of the flexible thresholds under a profit maximizing framework. The flexible thresholds increase the expected net returns to RSB management relative to the four alternative decision criteria considered. This is as expected, because the flexible criteria encompass the other criteria. For several of the alternative criteria and combinations of economic and production factors, this increase in expected value is small. The flexible decision rule increases in expected value over the 5-10 and 4-9 decision criteria as the returns to spraying decrease. When compared to the never spray rule, an opposite pattern is observed. Evidence suggests that the new flexible thresholds have been widely adopted by producers (Domangue 1990 and 1991), consultants (Crane; Bradshaw), and extension personnel (Texas Agricultural Extension Service).

Based on economic conditions as they currently relate to the rice industry, the flexible thresholds appear to offer only relatively minor gains when compared to the old 5-10 thresholds. Several advantages, however, are apparent for the new thresholds over the old. First, the old 5-10 thresholds were based on little more than expert opinion. Because new thresholds are based on a combination of data, economic modeling, and expert opinion, a higher degree of confidence is associated with the new thresholds. Second, the flexible thresholds have the ability to adapt to changing economic conditions. Third, the new thresholds are no more difficult to implement than the previous thresholds. The sampling procedure, by far the most time consuming step in the pest management process, is simplified by the elimination of the need to account for RSB nymphs as the previous thresholds required. Although a single, easily remembered rule no longer suffices, the flexible thresholds are summarized in a single table which is disseminated through various extension channels. Finally, the flexible thresholds provide a framework for the incorporation of additional data on pest dynamics or changing economic conditions. The static 5-10 thresholds had no systematic process for incorporating changes of these types.

Constraining the number of possible insecticide applications has little effect on the thresholds. This occurs even though the model has differing damages associated with RSB infestation levels at the various stages. The most plausible explanation for this observation is that the lowest threshold level occurs in the initial stage. On average, spraying earlier tends to suppress later population pressure and makes subsequent sprays less cost-effective.

This study is only one example of how dynamic programming could be applied to pest management decisionmaking problems. Economic thresholds for other pests could be developed in a similar fashion. The flexibility of the dynamic programming framework allows for the development of thresholds which encompass a wide range of theoretical and applied considerations. This research is an working example of how enhanced production information can be realized through multidisciplinary research and extension efforts.

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