A Computable Economic Threshold Model for Weeds in Field Crops with Multiple Pests, Quality Effects and an Uncertain Spraying Period Length

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A model is developed to determine the minimum weed population where a decision to apply a postemergence herbicide would be profitable. The economic threshold model accounts for changing economic conditions, the effect of weeds on crop quality, the effect of multiple weed species on yield and quality, and uncertainty about spraying period length. The model is uncomplicated enough for microcomputer or programmable calculator applications. An example of weed threshold calculations for round white potatoes is given.

Introduction and Review of Current Literature

With the current focus on the conflict between agricultural production decisions and environmental quality, any farm management tool that may be able to improve farm profitability without contributing to environmental damage or to improve environmental quality while maintaining farm profitability will be viewed favorably by both sides of the debate. The concept of economic threshold pest densities is just such an unique tool. When used as a guide for pest control decisions, it may result in higher profit for farmers and/or less pressure on the environment from insecticides and herbicides. Development of economic threshold models, therefore, has become an important research topic in a number of disciplines.

Some of the first work in the area of economic thresholds was by applied entomologists. V. M. Stern (1966, p. 42) first defined the economic threshold as "the density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level." Much of the work since has been devoted to a more precise definition of the optimal decision criterion. (See, for example, Headley, Ferris, *et al.* and Posten, Pedigo and Welch.) A recent review of the conceptual work accomplished so far can be found in Pedigo, Hutchins and Higley.

Others, mostly agricultural economists, have concentrated on the development of the theoretical threshold model by examining various real-world aspects of the pesticide decision problem. Hall and Norgard considered the optimal timing of pesticide applications throughout a season for a single pest. A theoretical model that determines both the threshold pest density and the optimal dosage (the M-threshold) for a single nematode pest in corn was developed recently by Moffit, Hall and Osteen. Marra and Carlson considered the effect of spraying period uncertainty on the threshold value for four single weed species in soybeans. Another recent contribution was made by Wetzstein, Szmedra, Musser and Chou where they examined the problem in a dynamic setting with two, possibly interacting, pests.

With the exceptions of Moffit, *et al.* and Marra and Carlson, few have attempted to apply their theoretical work to real-world pesticide decisions. Model complexity, data requirements and data availability have been limiting factors. Also, the economic influence of pests on the quality of the crop has received relatively little attention in theory or in practical application, thus far. The reason may be that much of the past threshold research has focused on food and feed grains where pest impacts on quality may be a relatively unimportant determinant of total revenue compared to the yield ef-

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fects of pests (Marra and Carlson). The question of how pests affect quality becomes more relevant, however, when calculating economic thresholds for fruit and vegetable crops where there may be a significant price difference between higher and lower quality grades and/or where the grading standards are more exacting for the retail market.

This paper first presents a theoretical model for an economic threshold for weed pests in field crops where crop quality effects as well as multiple pest species are considered. Next, the possibility of spraying period uncertainty is introduced. The theoretical model is then applied to the postemergence herbicide application decision for potatoes using current prices and weed-potato competition data from test plot experiments in Maine. Finally, the results of sensitivity analysis performed with respect to some of the important variables in the model are presented, followed by conclusions and suggestions for further research.

The Theoretical Threshold Model

The objective function (1) is one-period, per acre profit maximization (π) from the application of post emergence herbicides. The total benefit (g(W)) and total cost (f(W)) functions are assumed to be, respectively, concave and quasi-convex functions of weed numbers per unit length of row (W).

$$(1) \qquad \text{Max } \pi = \text{Max } [g(W) - f(W)]$$

The cost of scouting (or counting weed numbers for a number of random areas in the field) is assumed to be negligible for this problem and the marginal per acre costs of herbicide treatment are assumed not to vary with weed numbers. For many crops, scouting occurs for other purposes than to count weeds, and the scouts could be used for weed sampling along with their other duties. Thus, the relevant costs to be considered from the standpoint of the decisionmaker are the per acre cost of the recommended dosage of herbicide (or recommended tank mixes) (C_h) and the per acre application cost (C_a), which is composed of variable labor and machinery cost. The model with spraying period uncertainty, presented later, takes account of the possibility of higher herbicide costs due to delays during the spraying period. The marginal benefit (L) is composed of the physical loss per weed derived from the relationship between crop loss and weed density (L_w) times the value of that loss, or expected crop price (P), multiplied by the expected efficacy (percent control) of the recommended dosage of herbicide (E). With these costs and benefits specified separately, the optimal weed density (W*) at or above which spraying should occur is given by:

$$(2) \qquad W^* = \frac{C_h + C_a}{L_w PE}.$$

Consider, first, the possibility that weeds have a significant effect on the quality of the crop as well as the total yield. In this case, the value of the loss per weed avoided would be a function of the opportunity value of the lost yield per weed and the value of the loss per weed in the quality of the remaining yield. For example, assume the maximum yield that could be achieved without weed pressure (Y_{max}) is some proportion, V, of top quality product sold at the higher price (P_h) and the remaining proportion, (1 − V), is the amount of product expected to be of lower quality sold at a lower price (P_l). The value of the total loss in yield (Y_l) is:

$$(3) \qquad Y_l = (Y_{max} - Y)(VP_h + (1 - V)P_l) = h(W)$$

where Y is the observed yield with weed pressure. The additional loss due to the change in quality of the remaining, observed yield with weed pressure can be thought of as a change in the proportion of top quality product to, say, Z(V > Z). The total change in value of the remaining yield (Q_l) is given by:

$$(4) \qquad Q_l = Y(V - Z)(P_h - P_l) = i(W).$$

The opportunity losses in yield and quality are functions of weed numbers, and the loss per weed in each case (Y_{lw} and Q_{lw}) will replace the value of the yield loss per weed (L_wP) and enter the model additively as in (5).

$$(5) \qquad W^* = \frac{C_h + C_a}{(Y_{lw} + Q_{lw})E}$$

The loss of yield and quality is a function of not only total weed numbers but of the different weed specific marginal effects. Some weed species may not be as competitive with a particular crop as others. Since it is unlikely that fields sampled would contain only one type of weed, the threshold model should allow for the effects of multiple weed species.

Estimation of damage functions with multiple pests raises the possibility of interaction effects between pest species. Pest interaction can be beneficial to the crop as where two weed species compete with each other as well as with the crop for water and nutrients. There are also some cases where pest interaction is detrimental to the crop as in the case where a weed species provides an ideal habitat for an insect pest. In inter-specific weed interaction, the former case probably would dominate, if it is present at all. Since, at weed densities around expected threshold levels, interaction effects should be quite small or zero and, since ignoring competitive interaction between weed species errs on the side of conservatism in the threshold calculations, weed interaction effects are assumed to be zero in what follows.

Assume three weed species (or categories of weed species), W1, W2, W3, are observed in the field. If there is no interaction between species, then the yield and quality losses per weed will be the sum of the marginal effects of each species weighted by the proportion of each species in the total weed count. For example, if the marginal effect on yield of each weed species is denoted by W_{yi}, i = 1,2,3 and the proportion of species i in the total weed count is a_i ($\Sigma a_i = 1$), then the value of the marginal effect of the observed weeds on yield will be:

$$(6) \quad Y_{1w} = [a_1W_{y1} + a_2W_{y2} + (1 - a_1 - a_2)W_{y3}](VP_h + (1 - V)P_1).$$

The same type of weighted marginal effect will also be true for the loss in quality of the remaining yield per weed. If the marginal quality effect per weed of each species is denoted by W_{qi}, then the value of the marginal effect of the observed weeds on the quality of the remaining yield will be:

$$(7) \quad Q_{1w} = [a_1W_{q1} + a_2W_{q2} + (1 - a_1 - a_2)W_{q3}](P_h - P_1).$$

Note that only weeds that affect losses significantly and that can be controlled with a postemergence treatment should be weighted in each expression (6 and 7) above. These new expressions for the the value of yield and quality losses will replace those for the effects of the single weed in the model. Threshold pest densities have been shown to be very sensitive to choice of functional form for the damage function in some cases (Marra and Carlson). The first derivatives of the functional form for the estimated damage functions with the best statistical fit in the neighborhood of expected threshold weed numbers are the appropriate ones to use in the model.

Uncertainty about the length of the spraying period introduces another dimension into the model. If, for example, the decisionmaker were uncertain about whether all weeds could be sprayed before they grow to the point that 1) a higher dosage of herbicide would be required and/or 2) the efficacy of the herbicide is affected by weed growth then the cost and benefits to spraying would change. A decision theoretic approach can be taken to modify the threshold model to account for this uncertainty (Mumford and Norton, Marra and Carlson).

Assume that three states may occur if spraying is delayed by lost field days due to weather (primarily rainfall). The first state would be where no delays occur, and spraying can proceed in a timely manner causing no loss of efficacy at the lower recommended herbicide dosage. The second state would be if there is moderate delay and a higher dosage of herbicide could still achieve the maximum control. A third state can occur if there is significant delay so that the higher dosage would achieve a level of control lower than the maximum. A fourth state, where delay is so long that most or all of the crop is lost, is assumed to be so unlikely that it is not considered. The producer is assumed to choose the machinery complement to avoid the fourth state. The probability of each state occurring during any spraying period is a function of the probability of lost field days during the period and how much time it takes to spray all of the acreage, given the producer's machinery complement. The probability (P) of X field days lost out of the total number of days in the spraying period, N, is assumed to follow a binomial probability distribution with parameter θ. That is:

$$(8) \quad P_x = \binom{N}{X}\theta^x(1 - \theta)^{n-x}.$$

The parameter θ (the probability that any one day will be lost during the spraying period) will vary depending on historical rainfall probabilities and soil characteristics as well as the type of crop in some cases. The threshold model with spraying period uncertainty is given by:

$$(9) \quad W^* = \phi_1\frac{C_1}{(Y_{1w} + Q_{qw})E_1} + \phi_2\frac{C_2}{(Y_{1w} + Q_{1w})E_1} + \phi_3\frac{C_2}{(Y_{1w} + Q_{1w})E_2}$$

where: $C_{1,2}$ are the marginal costs with the lower and higher herbicide dosages described in states one and two,

$E_{1,2}$ are the expected maximum and reduced control percentages of the herbicides described in states two and three,

$\phi_1 = [\sum_{i=0}^{T}(T - i)A_dP_i]/A_t,$

$\phi_2 = [\sum_{j=0}^{M}(M - j)A_dP_j]/A_t,$

$$\phi_3 = [\sum_{k=0}^{D} (D - k)A_dP_k]/A_t, \text{ and}$$

T is the number of total days in state one, given weed growth rates and herbicide recommendations,

M is the number of total days in state two,

D is the remainder of the total days in the spraying period (the time it takes to spray all of the acreage in the decision area),

i, j, k are the number of field days lost during each state,

P_i, P_j, P_k are the binomial probabilities of i, j, k field days lost during each state,

A_d = the number of acres able to be sprayed in one day, given the producer's machinery complement and labor availability, and

A_t = the total number of acres in the decision area.

The model defined in (9) is a probability-weighted threshold model conceptually similar to approaching the problem in a decision theoretic manner by use of a payoff matrix or a decision tree.[2] For a more detailed discussion of the uncertainty aspects of the model, see Marra and Carlson.

An Example Application to Postemergence Herbicide Decisions in Round White Tablestock Potatoes

Currently, post emergence herbicide treatment options for annual broadleafs and grasses for Maine potatoes are relatively limited. The general practice is to use a pre-emergence herbicide treatment and then treat weed escapes with metribuzin. Recommended postemergence dosage rates for metribuzin range from 1/2 to 1 pt./ac. (a.i.) for Lexone 4L or Sencor 4 or 1/3 to 2/3 pt./ac. (a.i.) for Lexone DF or Sencor DF (Plissey, *et al.*) Until this year there has been no effective postemergence herbicide labeled for rhizomatous grasses, such as quackgrass. Beginning with the 1988 crop season Poast was registered for postemergence use in potatoes and will give producers more flexibility to choose postemergence "treat as necessary" options in the future.

For this example, assume there is a short (4 day) period when the weeds and crop are small (emergence to 2" tall) that spraying can be undertaken without significant crop injury, and a postemergence treatment of 1/2 pt./ac. of Sencor 4 will achieve 80% control. After the weeds grow taller than 2", a 1 pt./ac. treatment is assumed to achieve 80% control for the rest of the spraying period. For this application of the model, therefore, only two states are relevant.

Table 1. Initial Model Parameters

Herbicide and Dosage	Sencor 4 @ 1 pt./ac.
C_a	$3.05/ac.
C_h	$12.50/ac.
E	.90
P_h	$8.00/cwt.
P_l	$0.55/cwt.
a_1, a_2, a_3	1/3
V	.80
W* (Weeds per 10 ft. of Row)	5.74

Table 1 contains the initial model parameters, based on 1987 Maine averages, used to calculate the simple threshold weed density with the effects of three weeds, barnyardgrass (W1), lambsquarters (W2) and mustard (W3), with the assumption that all weeds can be sprayed in the initial spraying period (state 1).

The marginal effect of each weed is taken from weed competition test plot data collected in 1986 and 1987 at the Maine Agricultural Experiment Station farm in Presque Isle, Maine (Porter, *et al.*). Results from regressions of yield loss and the loss of quality of the remaining yield on weed numbers are presented in Table 2. A quadratic (with nested linear) and a log linear form for each was estimated. In both cases the log linear form was a poorer statistical fit than the functional form reported in Table 2. The effect of only one weed, mustard, was found in the yield loss regression with both the linear and quadratic terms significant at the 5% level. The quality loss of the remaining yield was found to be influenced by lambsquarters through a linear effect and by two linear interaction effects: between barnyardgrass and lambsquarters and between lambsquarters and mustard. It is obvious that more weed competition data should be collected and evaluated before the model becomes useful for actual recommendations to farmers. These regression results will allow illustration of model calculations, however, and will be used for that purpose.

Table 3 contains example weed thresholds calculated with various changes in the initial model parameters. These sensitivity results illustrate the model's flexibility and that it conforms to expected directions of change derived from economic the-

[2] We thank Jim Leiby, especially, for his contributions to the conceptualization of the uncertainty aspects of the model.

Table 2. Regression Results from 1986 and 1987 Experimental Weed-Potato Competition Data

Independent Variable[a]	Dependent Variable: Quality Adjusted Yield Loss	Dependent Variable: Quality Loss of Remaining Yield
	Parameter Estimate (Standard Error)	Parameter Estimate (Standard Error)
W2		4.2621 (1.5471)
W3	7.5643 (0.9197)	
W3*W3	−0.0672 (0.0182)	
W1*W2		−0.2527 (0.1073)
W2*W3		−0.1367 (0.0562)
Intercept Dummy for Year (1987 = 1)	46.5913 (16.6854)	−13.9658 (4.4618)
Adjusted R^2	0.7118	0.4627

[a]All other parameter estimates not significant at the 5% level. N = 80.

Table 3. Economic Weed Thresholds with Selected Changes in Model Parameters

Parameter Change (% Change)	Expected Direction of Change in Threshold Value	W* (Per 10 Row Ft.) (% Change)
1. Original Parameter Values	0	5.74
2. P_h = \$9.00/cwt. (+12.5)	−	5.11 (−11.0)
3. C_h = \$13.50/ac. (+8.0)	+	5.82 (+1.4)
4. V = .90 (+12.5)	−	4.98 (−13.2)
5. Θ = .045[a] (−50.0)	+	6.02 (+7.7)
6. A_d = 40 (−20.0)	−	4.59 (−17.9)

[a]Changes 5 and 6 pertain to the uncertainty model with two relevant states and the following initial assumptions: $A_d = 50$, $A_t = 400$, $T = 4$, $M = 4$, $C_1 = \$9.50$ (½ pt./ac.), $C_2 = \$15.55$; $E_1 = .8$, $E_2 = .8$, $\Theta = .09$, $W^* = 5.59$.

ory. The threshold weed density is more sensitive to the expected price for the higher quality product (P_h), the proportion of total yield expected to be of the higher quality (V) and to the choice of machinery complement (the acreage able to be sprayed in one day, A_d) than it is to the cost of herbicide materials (C_h) or the probability that any one field day is lost during the spraying period (θ).

Conclusions and Suggestions for Further Work

The theoretical model presented allows for many of the real world complexities of the post emergence herbicide decision process. It allows for the possibilities that weeds affect quality as well as yield and that it may not be possible to spray all weeds before a higher cost control is needed. It is still simple enough, however, for use with a small, programmable calculator or for a microcomputer application. Perhaps the most significant weakness is the lack of weed competition data. More interdisciplinary research is needed to gather these competition data from experiments limited to assessment of losses with weed numbers around expected threshold densities.

The dynamic aspects of the herbicide decision are not considered in this model. Carryover effects of herbicides and weed numbers to different crops or years can be an important cost to be considered and are an area for future work. The effects of certain types of weeds, such as quackgrass, on harvest costs are also an important factor in the decision to treat and should be considered as information becomes available.

This model provides another step toward practical application of the appealing notion of economic threshold pest densities. More work is needed before general acceptance by farmers can be expected. Interdisciplinary effort is called for to move toward usable models.

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