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ABSTRACT

WEED CONTROL STRATEGIES UNDER UNCERTAINTY

By

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Continuous corn weed control strategies under uncertainty are analyzed. The analytical model considers both flexible and fixed strategies and intertemperal relationships. At current prices annual herbicide use is optimal. At higher herbicide prices alternate year herbicide use is optimal. The framework is applicable to a wide range of pest problems.

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Introduction

Weeds are an important pest problem in the production of corn. In general they are controlled with a combination of tillage, cultivation, and herbicide application. With both fuel and labor costs rising rapidly in recent years, however, producers have increased their dependence on herbicides for weed control. As this trend continues, an important question that must be considered is how frequent and intense herbicide applications need to be to maintain weed population levels at or below an economically acceptable level. This question is being asked not only by producers but also by non-agriculturalists concerned with the impact of herbicide residues on the environment.

In this paper we present the results of an economic analysis of data collected during a five-year experiment designed to identify weed control strategies for continuous corn production which maximize net returns to producers while keeping herbicide use to a minimum. Two important features of the analysis should be noted. First, the intertemporal nature of weed control decisions is explicitly recognized. Weed control practices in one year have an impact on the potential for weed infestation in the following year, and this fact must be considered in the selection of an overall control strategy. Second, the fact that choice of weed control measures must be made in an uncertain environment is also recognized. The need for and

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the efficacy of pre-plant and pre-emergence herbicides, for example, cannot be known with certainty at the time when application must be made. In such situations risk preferences and the availability of forecasts of future weed population levels have an impact on weed management strategies. These factors are considered explicitly in this analysis.

In the sections which follow the bioeconomic system for which weed control strategies are developed is first described. The formulation of potential control strategies and the procedure by which optimal strategies are identified are then discussed. Finally, the results of the analysis are presented, and the implications of this study for future pest management research are discussed.

Though weed management strategies are the focus of this paper, it draws upon and integrates conceptual insights from several previous pest management studies concerned with insect control (Reichelderfer and Bender; Feder; and Talpaz, et al.). The general analytical approach presented here is applicable, then, to a much wider range of pest management problems.

The Bioeconomic System

The cropping system analyzed is continuous corn under irrigation in eastern Colorado. The analysis is based upon a herbicide experiment started in 1975 and continued for five years. The herbicide treatments are: (1) pre-emergence alachlor (2 lbs./A.) plus atrazine (1.5 lbs./A.) lightly harrowed, followed with 2,4-D LV ester (0.5 lbs./A.) when the crop is 6-10 inches tall and (2) pre-emergence atrazine (2 lbs./A.) lightly harrowed. Fertilizer rates, seeding rates and variety, irrigation applications and insect control measures were the same for all of the plots. After three years, all herbicide treatments were discontinued on half of the plots to provide information regarding the dynamics of weed and weed seed populations without herbicide treatment.

The analysis which follows considers strategies which allow only one of two possible pest control actions in any given year: (1) pre-emergence atrazine followed by 2,4-D and (2) no herbicide application. In a forthcoming study more complex strategies permitting a wider range of control actions will be analyzed. It should also be noted that only five years of data were available for the system being modeled. Additional information would have permitted a more accurate specification of the system parameters. Finally, weed species are aggregated in this analysis, and no consideration is given to differences in the impact of specific species.

A simple mathematical model of the system was constructed to represent the impact of weed seed levels and weed control actions on weed population, the effect of weed population on yields, and the effect of all these factors on overall performance of the system as measured by annualized net returns. The model is dynamic, with weed seed levels and weed control strategies from previous years having an impact on current weed seed and weed population levels. It is also stochastic, with weed populations, yields, and weed seed counts being affected by exogenous random factors.

The model is comprised of four basic equations. Parameter values for the first three equations, which were estimated statistically using ordinary least squares regression, are given in Table 1. The first equation determines weed population per acre in year t, POP_t.

$$POP_t = b_{10} + b_{11}SEED_{t-1} + b_{12}HERB_t + b_{13}HR_t + u_{1t} \qquad (1)$$

where $SEED_{t-1}$ is the seed count prior to planting, $HERB_t$ is a binary variable equal to 1 if herbicide is applied in year t and 0 if it is not, and HR_t is a binary variable equal to 1 if herbicide is applied in year t or was applied in year t-1 and 0 otherwise. The effects of exogenous factors not considered in the model are included in the random disturbance term, u_{1t}.

Table 1. Parameter Estimates for Bioeconomic Model

Equation	b_0	b_1	b_2	b_3	σ_u	R^2
1	55250 (1459)[a]	3.0175 (15.3)	-5623.6 (2777)	-47271 (3516)	6688	.92
2	4.804 (.027)	-.0000093 (.000001)	--	--	.179	.50
3	9.4604 (35.4)	.00107 (.003)	.1392 (.240)	.3536 (.111)	50.2	.64

[a]Figures in parentheses are standard errors.

The second equation describes the impact of weed population levels on yield per acre in year t, Y_t.

$$Y_t = e^{(b_{20} + b_{21}POP_t + u_{2t})} \tag{2}$$

where u_{2t} is a random disturbance term and other variables are as defined above. A semi-log form was chosen for this equation because it provided a good fit and because it ensured that yields would be positive.

The third equation determines the number of weed seeds in the soil at the end of year t, $SEED_t$, measured in millions per acre.

$$SEED_t = b_{30} + b_{31}POP_t + b_{32}SEED_{t-1} + b_{33}SEED_{t-2} + u_{3t} \tag{3}$$

Again, u_{3t} is a random disturbance term which accounts for the effects of factors not included in the equation.

Finally, the fourth equation calculates net return for year t, R_t.

$$R_t = [(P - HC)Y_t - CH \cdot HERB_t - AC]ACRES \qquad (4)$$

where P is the price of corn, HC is the cost of harvesting and drying each bushel of corn, CH is the cost of herbicide per acre, AC is the cost of other variable inputs per acre, and ACRES is the number of acres cultivated.[1]

Because the herbicide treatment considered in this study has carryover effects, the performance of the system under alternative weed control strategies cannot be adequately evaluated on the basis of net returns for a single year. Therefore, system performance was simulated over a 20-year period for each of the control strategies considered. Overall performance was measured by annualized net returns, ANR, which is defined by the following expression:

$$ANR = [D/(1 - (1+ D)^{-20}] [\sum_{t=1}^{20} R_t(1 + D)^{-t}] \qquad (5)$$

where D is a discount factor set equal to .12 in this study.

The Identification of Preferred Weed Management Strategies

The identification of an optimal weed management strategy in an uncertain environment can be viewed as a stochastic optimal control problem in which the sequence of control actions which maximizes the decision maker's expected utility over the planning horizon is sought. It has been shown that the optimal solutions to such problems tend to take the form of flexible strategies which make forthcoming actions contingent upon information which

[1] In this study P = \$2.25, HC = \$0.15, AC = \$69.52, and ACRES = 100. The cost of herbicide, CH, was varied in this analysis. Values considered were \$8.00, \$10.00, and \$12.00.

becomes available as time passes (Dreyfus). In accordance with this, the weed control strategies considered in this study take the form of a feedback control rule:

$$\begin{aligned} HERB_t &= 1 \text{ if } SEED_{t-1} \geq ET_t \\ &= 0 \text{ otherwise.} \end{aligned} \tag{6}$$

ET_t is an economic threshold for the weed seed count. It is defined by the following expression:

$$ET_t = V_1 + V_2 HERB_{t-1} \tag{7}$$

where V_1 and V_2 are choice variables. Note that the effect of the second term of equation 7 is to raise the economic threshold when herbicide was applied in the previous year. Herbicide carryover effects make this justifiable. It should also be noted that the control rule is a flexible one, since it uses information about the current state of the environment, $SEED_{t-1}$, to determine control actions. There is no assurance that this is a truly optimal form for the feedback control rule. It is intuitively appealing, however, and easy to explain to growers.

Stochastic optimal control problems are difficult if not impossible to solve analytically. A procedure developed by King, the generalized risk efficient Monte Carlo programming model, is well suited for the identification of nearly optimal solutions to such problems, however. This approach, which is described in detail elsewhere (King), combines random search, Monte Carlo simulation, and evaluation by stochastic dominance with respect to a function, a recently developed stochastic efficiency criterion (Meyer) which orders choices for classes of decision makers defined by upper and lower bound values on the absolute risk aversion function (Pratt).

In the problem under consideration here, 500 strategies defined by randomly generated values of V_1 and V_2 were evaluated. System performance under each strategy was simulated for 20 years under 20 randomly generated states of nature, with the disturbance terms in equations 1-3 of the model being the stochastic factors in the system for each state. In this way a 20-element distribution of annualized net returns was defined for each strategy. The distributions for all the strategies considered were ordered using the criterion of stochastic dominance with respect to a function for classes of decision makers having low, moderate, and high levels of absolute risk aversion.[1]

Results

Of the 500 strategies evaluated, only the five defined in Table 2 appeared in the efficient sets of the three decision maker classes considered here. When the cost of herbicide use per acre is at or below $8.00, as is currently the case, strategy 1 dominates all others for each decision maker class. It calls for herbicide use each year. When the cost of herbicide use reaches or exceeds $12.00 per acre, on the other hand, strategy 5 is preferred to all others by the decision makers in each class. It calls for herbicide use every other year. When the cost of herbicide use is $10.00 per acre, the efficient set of the low risk aversion decision maker class contains only strategy 5, that of the moderate risk aversion decision maker class contains strategies 2 and 5, and that of the high risk aversion class of decision makers contains strategies 2, 3, 4, and 5. The presence of

[1]Risk aversion intervals for the low, moderate, and high risk aversion decision maker classes were specified as (-.0001, .0001), (.0001, .0004), and (.0004, .0010) respectively.

Table 2. Average Herbicide Use, Corn Yields, and Income for Alternative Decision Strategies at Selected Herbicide Cost Levels.

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Decision Variable					
V_1 (Mil./ac)	0	0	0	0	0
V_2 (Mil./ac)	0	10	30	40	150
Average Herbicide Use (years in 20)	20 (0)[a]	15.40 (1.39)	13.75 (1.37)	13.25 (1.18)	10 (0)
Average Yield (bu/ac)	120.84 (21.23)	119.76 (21.16)	119.36 (21.20)	119.25 (21.23)	118.56 (21.26)
Average Annualized Net Return ($/100 acres)					
Herbicide Cost $8./ac Corn Price $2.25/bu	17499.08 (1141.23)	17468.85 (1121.78)	17444.82 (1117.53)	17446.74 (1132.25)	17406.01 (1127.75)
Herbicide Cost $10./ac Corn Price $2.25/bu	17299.08 (1141.23)	17306.90 (1121.14)	17298.88 (1117.93)	17306.40 (1133.67)	17311.67 (1127.75)
Herbicide Cost $12./ac Corn Price $2.25/bu	17099.08 (1141.23)	17144.96 (1120.65)	17152.93 (1118.49)	17166.07 (1135.20)	17217.33 (1127.75)

[a] Figures in parentheses are standard deviations.

more than one strategy in an efficient set means that a complete ordering was not possible given the available preference information.

It should be noted that strategies 1 and 5, though defined as flexible strategies, actually imply a fixed pattern of actions. The information presented in Table 3 compares system performance under these two strategies over the 20-year period defined by one state of nature. It should be apparent that, had V_2 been somewhere between 0 and 150 as is the case with strategies 2 through 4, the pattern of control actions would have been more complex. Under strategy 4, for example, herbicide is used in 13 of 20 years in this same state of nature.

A corn price of $2.25 per bushel and harvest costs of $0.15 per bushel have been assumed throughout this analysis. At these levels, strategies that do not call for annual herbicide use begin to enter decision makers' efficient sets when the price of herbicide exceeds $8.00, or when the ratio of corn price less harvest costs to herbicide cost is approximately .26. A sensitivity analysis indicates that this ratio remains nearly constant over a wide range of price levels. When the price of corn less harvest costs is $2.75, for example, annual herbicide use is called for unless the cost of using herbicide exceeds $10.60. This implies that the results presented above are, for the production system under consideration, applicable under a wide range of economic conditions.

Finally, one of the objectives of the experiment upon which this analysis was based was to determine the feasibility of using weed seed counts to direct herbicide use by individual farmers. Such counts would not be needed under strategies 1 and 5, since they are, in effect, inflexible strategies. They are required for the implementation of strategies 2 through 4, but one must ask whether the added benefits for highly risk

Table 3. Herbicide Use, Weed Population, Corn Yield and Weed Seed Count Simulated for Twenty Years under Alternative Herbicide Weed Control Strategies.

Year	Herbicide Use Strategy 1	Herbicide Use Strategy 5	Weed Population (Plants/Ac) Strategy 1	Weed Population (Plants/Ac) Strategy 5	Yield (Bu/Ac) Strategy 1	Yield (Bu/Ac) Strategy 5	Seed Count (Mil/Ac) Strategy 1	Seed Count (Mil/Ac) Strategy 5
1	Yes	No	9,241	14,865	107.56	102.08	80.0	80.0
2	Yes	Yes	0	0	109.29	109.29	150.0	156.0
3	Yes	No	8,338	13,964	91.51	86.85	108.2	109.0
4	Yes	Yes	2,481	2,506	121.62	121.59	198.0	206.3
5	Yes	No	0	4,327	99.88	95.94	143.7	145.2
6	Yes	Yes	0	0	129.54	129.54	133.7	141.5
7	Yes	No	5,630	11,259	121.71	115.50	31.7	33.3
8	Yes	Yes	0	0	124.46	124.46	43.4	52.3
9	Yes	No	0	0	124.46	124.46	0.0	0.0
10	Yes	Yes	791	801	115.20	115.19	42.2	45.4
11	Yes	No	10,117	15,742	96.54	91.62	0.0	0.4
12	Yes	Yes	0	0	152.02	152.02	0.0	0.0
13	Yes	No	8,634	14,258	166.28	157.81	2.2	2.4
14	Yes	Yes	7,712	7,712	79.22	79.22	0.0	0.0
15	Yes	No	5,294	10,917	122.70	106.96	0.0	0.0
16	Yes	Yes	4,597	4,615	82.37	82.36	21.7	27.8
17	Yes	No	0	2,406	107.13	104.76	14.5	15.3
18	Yes	Yes	3,430	3,430	169.37	169.37	0.0	0.0
19	Yes	No	0	2,311	138.93	135.98	35.4	35.7
20	Yes	Yes	5,211	5,219	129.74	129.72	63.4	66.0
Average			3,574	5,562	113.25	110.52	53.4	55.8

averse decision makers under these strategies when herbicide costs are at an intermediate level exceed the cost of making weed seed counts. It is estimated that such counts would cost at least $50 per year for a 100-acre field. When the outcome distribution associated with strategies 2, 3, and 4 are adjusted for this cost, they disappear from the efficient set of even the most risk averse decision makers. This implies that, in this instance, the value of the information embodied in weed seed counts is exceeded by its cost.

Conclusions

In this paper optimal weed control strategies are identified using an analytical procedure that is applicable to a wide range of pest management decisions. Flexible action strategies and the effect of uncertainty are considered explicitly in an optimal control framework. This general approach could also be used to identify economic threshold levels for other pests and to evaluate alternative control strategies. It may also be useful in determining the value of information used to forecast future pest population levels.

The results indicate that the standard practice of applying herbicide annually in a continuous corn system is optimal under current economic conditions. Should the cost of herbicide rise appreciably relative to the price of corn, however, the results indicate that annual herbicide use is not optimal.

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