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A BIOECONOMIC DECISION MODEL FOR WEED MANAGEMENT IN WINTER WHEAT

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I. Introduction

Sustainable development and environment becomes one of the critical issues in all countries. The UN Conference on Environment and Development(Rio de Janeiro, 3-14 June 1992) has placed multiple demands for action to environmentally sound and sustainable development at international, regional and national levels on governments, intergovernmental organizations. FAO decided that integrated sustainability criteria should be adopted in all its programs and activities. We have less experiences in this issue although it is a serious problem. It is time to pay our interest on environmentally sustainable agriculture in Korea.

A significant portion of U.S. Pacific Northwest farm income comes from small grains grown on highly erodible land. The Conservation Compliance provision of the 1985 Food Security Act required farmers with highly erodible cropland to file conservation plans by 1990 and fully implement them by 1995 in order to maintain eligibility for USDA farm program benefits. To meet these requirements, a change in crop rotation, a change in tillage system, and the addition of conservation practices is often required. Reduced tillage, using a chisel rather than a plow, and no-tillage can reduce erosion, but often have more problems with weeds than conventional tillage. Increased chemical control of weeds has been identified as a possible economical measure to sustain yields.

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Most U.S. bioeconomic weed management studies involve corn (King et al.; Lybecker et al.; Swinton and King), and soybeans(Marra and Carlson; Wilkerson, Modena, and Coble). Similar work in wheat has been centered outside the U.S.(Cousens et al.; Doyle et al.; Pannell). No works have been done in Korea. Most economic weed management studies have focused on a single weed species in a single crop. A few studies involving multiple weed species in a single crop have been appeared since the late 1980s(King et al.; Lybecker et al.; Swinton and King; Wilkerson, Modena, and Coble). No management models for multiple weed species in various crop rotation systems were found in the literature.

The purpose of this paper is to develop bioeconomic weed management decision models for winter wheat grown under different crop rotations and tillage systems. The field trials providing the data were conducted in the dryland Palouse region of the Inland Pacific Northwest which receives 18-22 inches of annual rainfall.

Relationships between weed management and weed survival, weed survival and crop yields, and crop yields and profitability will be described using statistically estimated equations. Optimal herbicide rates will be determined under specified environmental and field conditions observed at the decision period.

Ⅱ. Data

The USDA-ARS IPM project in the Washington-Idaho Palouse region was developed to assess the appropriate level of chemical weed control for conservation and conventional tillage systems in the area. Two crop rotations were examined, one containing two years of winter wheat (WW1 and WW2) and one year of spring wheat (SW), and the other one year each of winter wheat(WW), spring barley(SB), and spring peas(SP). Each crop in each rotational sequence was grown every year of the experiment. Three levels of chemical weed management were chosen to correspond roughly to 90%, 70%, and 50% of the recommended label rates of utilized herbicides. Actual rates and combinations of herbicides were determined annually by the projects weed scientists. The project attempted to reflect current farm production methods, to use full-size farm machinery, and to utilize larger plots than is normal in research situations. The research site was located three miles northwest of Pullman, Washington and had been farmed nine years previously in no-till small grains.

The IPM experiment compared 12 complete farming systems: (2 rotations) x (2 tillage levels) x (3 weed management levels). The conservation systems used no-till on the leading winter wheat crop in each rotation followed by chiseling of the following two crops. Under conventional tillage, all crops were plowed except for winter wheat following spring peas which was disked. The experiment was a randomized complete block, split-plot design with four replications. It was repeated for six years over 1985/86 through 1990/91 yielding 432 observations for winter wheat.

The weed management decision model permits the user to insert any level of crop prices, herbicide prices, and other costs that prevail. In the results section, the model will be illustrated with specified "benchmark" prices and state variables for the study region.

III. Bioeconomic Modeling

A bioeconomic model links biological relationships to an optimizing economic model. In this study, the bioeconomic model will be developed in three steps. First, a system of weed survival functions will be specified to determine weed density levels after herbicide applications. Second, a yield response function will be specified to describe the relationship between crop yield and aggregated surviving weed density and other important variables. Finally, the estimated results will be incorporated into a profit function to determine profit maximizing herbicide rates. Optimal herbicide rates are conditional upon the state variables included in the biological and economic relationships. These state variables include such factors as spring weed densities, soil moisture, tillage type, preceding crop, herbicide prices, and expected crop prices. If the decision model is to be operational, all state variables must be known or have formulated expectations at the time the weed control decision is made.

The estimated weed survival functions are specified as follows:

$$WD_i = b_0 + b_1 SWD_i + b_2 SM + b_3 OM + b_4 TIL_1 + b_5 TIL_2 + \sum_{j=1}^{6} d_j H_j \qquad (1)$$

with i=1.... 4.

where WD_i is weed density of i-th subgroup in July, SWD_i is spring weed seedling counts of i-th subgroup, SM is soil moisture, OM is organic matter, TIL's are discrete variables for tillage system, H_j's are application rate of j-th type of herbicide, and b's and d's are estimated coefficients. Over 50 weed species were recorded in the IPM experiment over six years. These were classified into four subgroups: spring grasses, winter grasses, spring broadleaves, and winter broadleaves.

Each weed subgroup competes not only with the crop but with the other weed subgroups. All the weed subgroups are also affected by the same weather and other external influences within a given year. This means that disturbances(error terms) in the different weed survival functions for a crop are correlated with each other within the same time period, while they are uncorrelated in different time periods. To accommodate the dependency in the error structure, the Seemingly Unrelated Regression(SUR) technique was used to estimate survival functions. The greater the correlation of the disturbances, the greater the efficiency gain of SUR over Ordinary Least Squares(OLS) regression (Judge et al.).

Two "damage functions" have been frequently used to represent the effect of weed density on crop yield: logistic and hyperbolic functions. Cousens compared these models in winter wheat with a single weed species, but not with multiple weed species. In this study, a modified Mitscherlich-Baule production function was combined with both logistic and rectangular hyperbolic damage functions. The yield function with logistic damage was specified as:

$$Y = b_1(1 - e^{-b_2SM})(1 - e^{-b_3OM})\left[1 - \frac{m}{1+e^{-(i+jTWD)}}\right] + a_1TIL_1 + a_2TIL_2 \qquad (2)$$
$$+ c_1CR_1 + c_2CR_2.$$

Variables shared with the survival functions in equation (1) are as defined above. b_1 is maximum potential crop yield with nonlimiting soil moisture, nonlimiting organic matter, and no weeds. The parameter m is maximum proportionate yield damage at infinite weed density and j is a weed competition coefficient. Parameters i, b_2, b_3, a_1, a_2, c_1, and c_2 are estimated regression coefficients. The parameter m was found in this study by a search over different values rather than by direct estimation. The total weed competition index, TWD, is calculated from weighted predicted weed survival levels over subgroups: $TWD = 0.92(WD_1) + 1.00(WD_2) + 0.19(WD_3) + 0.74(WD_4)$ in winter wheat, where the competitive index weights are based on July frequency and dry weight of weeds in each subgroup. The $\hat{WD}_i$ for each weed group are predicted from equation (1).

The general specification of the yield response function with rectangular hyperbolic weed damage was:

$$Y = b_1(1 - e^{-b_2 SM})(1 - e^{-b_3 OM})\left[1 - \frac{iTWD}{100(1 + iTWD/j)}\right] + a_1 TIL_1 + a_2 TIL_2 + c_1 CR_1 + c_2 CR_2. \tag{3}$$

where common variables with (2) are defined as above, j is the maximum percentage yield loss as weed survival approaches infinity, and i is the proportionate yield loss as weed survival approaches zero, b_1, b_2, b_3, c_1, and c_2 are estimated regression coefficients.

SAS/ETS SYSNLIN nonlinear least squares(NLS) was used to estimate the yield response functions. Two measures of goodness of fit were used to select final yield response functions for each functional form: adjusted R^2(Adj-R^2) and root mean-squared error(Root MSE). Higher R^2's and lower Root MSE's indicate better fit. These values cannot be used to select a specification from several alternative nonnested models. Consequently, a P-test developed by Davidson and MacKinnon was used to test the two alternative yield model specifications.

Two profit functions for this problem can be written as:

$$\pi = P\hat{Y}(\vec{H}) - \vec{P}_h\vec{H} - AC(\vec{H}) - OC \tag{4}$$

where π is net returns over total costs (\$/ac), $\hat{Y}(\vec{H})$ is the estimated yield response function, H is the vector of herbicide applications, P is crop price, $\vec{P}_h$ is herbicide prices, $AC(\vec{H})$ is herbicide application cost which is function of the herbicides applied, and OC is other costs. One objective of this study is to find profit maximizing herbicide rates under constrains on WD_i's, TWD, and H_j. The problem can be expressed algebraically as:

$$\underset{H_i's}{\text{Max}}\ \pi = PY - \Sigma P_{hi}H_i - \Sigma AC_i(I(H_i)) - OC \tag{5}$$

Subject to

$$SUR_i \geq s(SWD_i, \vec{H}, T_1, T_2, CRP_1, CRP_2),\ i=1,.., 4$$
$$TSUR = \sum_{1}^{4} CI_i \times \hat{SUR}_i$$
$$SUR_i \geq 0,\ i=1,.., 4$$
$$H_j \geq 0,\ j=1,.., m$$

where CI_i is the biomass-based competitive index of the i-th weed subgroup.

Theoretically the optimal herbicide rates are represented by derived ordinary short-run herbicide demand functions. The optimal herbicide rates are determined by the expected crop price, herbicide prices, herbicide application costs, initial weed seedling counts, tillage, and all other field-specific state variables. The factor demand functions, h*'s, show precisely those levels of herbicides that the grower should apply on a field to equate the value of the marginal products of each herbicide to its price. They are described implicitly as:

$$H^* = h^*(P, \vec{P}_h, AC, CF, \vec{SUR}_o, \vec{T}, SM, \vec{C}, \vec{W}, OM) \tag{6}$$

where H^* is optimal levels of herbicide use, and all other variables are defined as before as many of these functions for each crop as there are aggregated types of herbicides for that crop. The optimal herbicide rate varies for each combination of expected crop price (P), herbicide prices ($\vec{P}_h$), herbicide application costs (AC), soil moisture(SM), organic matter (OM), tillage ($\vec{T}$), previous crop ($\vec{C}$), weed seedling counts ($\vec{SUR}_o$), and dominant weed species ($\vec{W}$). Not all state variables will be relevant, statistically significant, and included for all crops. Optimal herbicide rates($\vec{H}^*$) can be derived using the mathematical first-order and second-order conditions for a maximum. The first-order conditions are known as the Kuhn-Tucker conditions for a maximum subject to inequality conditions. Nonlinear programming was used to solve this problem involving maximization of a nonlinear profit function subject to inequality constraints. The MINOS nonlinear programming algorithm within the GAMS software package was used(Brooke, Kendrick, and Meeraus).

IV. Results

Table 1 presents the four estimated weed survival functions. Unreported OLS results were generally similar to the SUR results in Table 1. All spring weed density(SWD_i) coefficients have expected positive signs and are statistically significant at the 1% level. Clearly, spring weed seedling counts appear to be a good indicator, other factors equal, of mid-summer weed competition from spring annual grasses(SAG), winter annual grasses(WAG), spring annual broadleaves(SAB), and winter annual broadleaves(WAB) for winter wheat in this region. Nonselective herbicides(H_1) were not significant at the 5% level in predicting survival of summer annual grasses, but their negative sign was consistent with expectations. H_1 significantly suppressed both broadleaf weed groups, but not winter annual grasses. Postemergence broadleaf herbicides(H_5) significantly reduced the winter annual broadleaf weed population, but not summer annual broadleaves and

TABLE 1. Estimated Linear Weed Survival Functions in Winter Wheat

Variable	Weed Type			
	SAG	WAG	SAB	WAB
Constant	8.725 (4.375)	4.067 (3.757)	0.719 (0.601)	2.053 (0.940)
SWD_i	0.642 (0.045)	0.231 (0.017)	0.054 (0.005)	0.048 (0.005)
H_1	-12.672 (8.155)		-4.739 (1.808)	-3.613 (1.189)
H_5				-2.168 (0.828)
H_6	-11.369 (4.976)	-5.145 (4.286)		
TIL_1	14.717 (5.287)	7.785 (4.161)	3.506 (1.172)	3.336 (0.773)
TIL_2	20.196 (5.194)	17.749 (4.466)		

System weighted MSE = 0.9990 with 1708 d.f.
System weighted R^2 = 0.3083

Note: Standard errors are in parentheses. Variables are defined in the text.

grass weeds. Postemergence grass herbicides(H_6) helped control both winter and summer annual grass populations, but the coefficient was statistically insignificant at the 5% level for WAG. As expected, no-till (TIL_1) and chisel plowing(TIL_2) increased(relative to conventional tillage) midsummer weed competition from all weed groups in winter wheat.

Table 2 compares NLS estimates of logistic and rectangular hyperbolic yield response functions as specified in (2) and (3). The Root MSE was lowest for m equal to 0.30 in the logistic damage-yield response function. This value for m was selected from the results of a search ranging over 0.2 to 0.6 in increments of 0.025. The logistic damage-yield response model was not rejected at the 5 percent level by the Davidson-MacKinnon P-test, while the rectangular hyperbolic model was rejected at the 5 percent level. Consequently, the logistic model as reported in Table 2 will be used in the subsequent analyses. All estimates of the logistic function have expected signs and are statistically significant at the 1 percent level. Maximum predicted

TABLE 2. Estimated Yield Response Functions in Winter Wheat

Parameter	Logistic Model (m=0.3)			Rectangular Hyperbolic Model		
	Estimate	Std. Err.	t-ratio	Estimate	Std. Err.	t-ratio
b_1	90.885	5.073	17.91	91.482	4.965	18.42
b_2	0.165	0.015	11.33	0.152	0.013	11.65
b_3	0.845	0.183	4.62	0.922	0.216	4.26
i	-8.143	3.441	-2.37	0.236	0.086	2.76
j	0.189	0.080	2.34	223.098	279.430	0.80
a_1	14.243	2.209	6.45	13.981	2.328	6.01
a_2	7.740	2.424	3.19	3.364	2.986	1.29
c_1	8.051	2.352	3.42	8.932	2.340	3.72
c_2	23.787	2.263	10.51	23.835	2.346	10.16
Root MSE	16.792			17.013		
Adj-R^2	0.515			0.493		
Total obs.	432			432		

Note: Parameters are defined in equations (2) and (3).

TABLE 3. Comparison of Dollars Estimated Marginal Value Product (MVP) and Marginal Factor Cost (MFC) of an Additional Label Rate of Herbicide Use, Evaluated at the Means of Herbicide Use and Other Variables in the IPM Experiment

MVP/MFC	H_1	H_5	H_6
MVP[a]	19.59	2.06	20.07
MVP[b]	16.35	1.72	16.74
MFC[c]	16.16	13.73	26.76
Minimum Required Wheat Price($/bu) for Add. Herb.[d]	3.28	26.48	5.31

[a] Expected effective (market plus net program returns) wheat price of $3.98/bu was used.

[b] Expected market wheat price of $3.32/bu was used.

[c] MFC is the weighted average local price of herbicide and application costs per acre in herbicide group H_i in 1991.

[d] Minimum wheat price required to make an additional 1.0 label rate beyond IPM average of herbicide application profitable.

yield with this model at nonlimiting soil moisture, organic matter, and weed-free conditions is 90.9 bu/ac with conventional tillage for winter wheat after winter wheat. This potential yield exceeds by 19 bu/ac the average yield over six years of conventional tillage winter wheat after winter wheat in the IPM experiment. Chisel plow and notill winter wheat had predicted maximum yields that were 7.7 bu/ac and 14.2 bu/ac higher than that for conventional tillage.

Estimated marginal value products(MVP) of herbicides at average IPM rates and constant herbicide and application costs(or marginal factor cost(MFC)) are shown in Table 3. The MVP of nonselective herbicides(H_1) is higher than its price, but those of postemergence herbicides are lower. The results indicate increasing nonselective herbicide rates above those used in the IPM experiment would boost profit assuming current costs, specified crop prices, and weed densities and other state variables at their means. Winter wheat price would have to increase to $5.31 per bushel to justify the average rate of H_6 applied in the IPM experiment. Postemergence broadleaf herbicides appear to have been used at economically excessive rates in the IPM experiment.

In other results not tabulated here, the optimal rates of H_5 and H_6, given assumed H_1 herbicide rates, and the specified prices, were computed using MINOS. Nonselective herbicides(H_1) were constrained at twice the average IPM rate in conservation tillage. Postemergence broadleaf herbicides were not recommended for winter wheat grown under conservation tillage. Instead, higher rates of nonselective and postemergence grass herbicides are recommended to maximize profit. Winter wheat after winter wheat required the highest rate of

TABLE 4. Sensitivity Tests of Bioeconomic Model for Winter Wheat after Winter Wheat under Conservation Tillage

Variable	Unit	Bench-mark	Sensitivity Test No. 1	2	3	4	5	6	7	8
SWD_1	weeds/m^2	19.4	50.0							
SWD_2	weeds/m^2	17.5		50.0						
SWD_3	weeds/m^2	35.0			100.0					
SWD_4	weeds/m^2	46.8				100.0				
P	$/bu	3.98					3.32			3.32
P_{h5}	$/l.r.	11.37								
P_{h6}	$/l.r.	23.86						11.93		
<u>Constraint</u>										
H_1	l.r.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
H_5	l.r.								1.0	1.0
<u>Solution</u>										
WD_1	weeds/m^2	14.6	21.1	9.1	14.1	13.2	15.5	11.9	15.7	16.7
WD_2	weeds/m^2	16.6	10.6	21.6	16.4	16.0	17.0	15.4	17.1	17.5
WD_3	weeds/m^2	0.2	0.2	0.2	3.7	0.2	0.2	0.2	0.2	0.2
WD_4	weeds/m^2	2.5	2.5	2.5	2.5	5.0	2.5	2.5	0.3	0.3
TWD	index/m^2	31.9	31.9	31.9	31.9	31.9	33.2	28.2	31.9	33.2
H_1	l.r.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
H_5	l.r.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
H_6	l.r.	1.8	3.0	2.3	1.8	1.92	1.7	2.0	1.7	1.6
Y	bu/ac	85.33	85.33	85.33	85.33	85.33	84.74	86.55	85.33	84.73
π	$/ac	58.14	27.15	45.28	57.00	54.90	2.00	80.89	47.12	-9.01

Notes: 1. Unspecified blanks are same as the benchmarks.
2. Abbreviations used: l.r. = label rate, others as previously specified.
3. OC = $222.99/ac, SM = 20.96%, and OM = 2.86%

postemergence herbicide under conservation tillage. With these herbicide rates, net revenues over total costs are projected to increase by 22 to 55 dollars per acre compared to those from using average IPM experiment rates. In unreported results for conventional tillage which did not include the H_1 constraint, the optimization results showed that no herbicides are recommended for winter wheat under conventional tillage, despite widespread farmer practices to the contrary.

The bioeconomic weed management models were tested by simulating how optimal herbicide rates responded to changes in spring weed seedling densities, crop prices, herbicide prices, and herbicide application constraints. Table 4 demonstrates the sensitivity results for winter wheat after winter wheat under conservation tillage. The specified benchmark values are the average of the IPM experiment over 6 years.

The sensitivity results generally show that the bioeconomic models behave as expected by economic and agronomic theory. For example, reducing wheat price from $3.98/bu to $3.32/bu in test 5 reduces herbicide use, yield, and profit. Increasing spring weed densities in tests 1 through 4 increases profit maximizing herbicide rates to sustain yield but profits fall.

V. Conclusions

On the whole, profit maximizing weed management recommendations from the bioeconomic models for winter wheat suggested more frugal and more targeted use of herbicides than is typical for grower practices in the region. This is good news for farmers and for the environment. Profits to growers could be boosted by eliminating excessive herbicides through greater use of weed counts and other information collected early in the season. The environment could benefit by a net reduction in annual chemical use. This model can be applied to growers' fields if weed seedling counts and other field conditions are measurable in early spring. Two years of field testing is planned to further refine the bioeconomic model.

Further studies are required to adopt the bioeconomic weed management model in Korean agriculture.

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