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Conservation Tillage and Pesticide Use in the Cornbelt

Keith O. Fuglie

ABSTRACT

Adoption of conservation tillage can lead to substantial environmental benefits from reduced soil erosion. But benefits may be partially offset if adoption increases reliance on agricultural chemicals. Using area study data from the Cornbelt, this study examines factors affecting adoption of no-till and other conservation tillage systems and their effect on chemical use and corn yield. The results find no evidence that herbicide or fertilizer application rates are higher on fields with conservation tillage systems compared with conventional tillage. However, insecticide use may increase somewhat and yield may be lower. Current demographic trends in U.S. agriculture favor continued diffusion of conservation tillage.

Key Words: conservation tillage, multinomial logit model, pesticides, technology adoption

The gradual increase in adoption of conservation tillage[1] since the 1960s has attracted considerable attention from within and outside agriculture due to its implications for agricultural productivity and environmental quality (Crosson; Gebhardt et al.). Less intensive tillage significantly reduces soil erosion and saves labor, fuel, and machinery costs. However, it may also lower crop yields and increase use of agrichemicals as farmers compensate for less tillage. Environmental gains from reduced soil erosion may be offset by increased reliance on chemical fertilizers and pesticides (Crosson; Heimlich and Ogg; Setia and Piper).

While studies of conservation tillage have clearly demonstrated significant environmental benefits from reduced soil erosion, much less is known about environmental costs from changes in chemical use. Heimlich and Ogg used a linear programming model to assess soil conservation and pesticide use tradeoffs in North Carolina corn production. They assumed that more pesticides are used with no-till than conventional tillage and evaluated total pesticide exposure from alternative chemical strategies. They demonstrated that the negative effects of increased pesticide use

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[1] The Natural Resource Conservation Service defines *conservation tillage* as a system that maintains at least 30% crop residue cover after planting. No till and ridge till are well-defined tillage systems that meet this criterion. Other types of tillage practices that achieve at least 30% soil cover are called *mulch tillage systems.* By 1993, one-third of U.S. cropland was cultivated with some type of conservation tillage (USDA). "Minimum tillage" or "reduced tillage" include tillage systems that break up but do not invert the soil (i.e. the non-use of a moldboard plow). Reduced and minimum tillage systems often do not leave sufficient crop residue to meet the conservation tillage criterion (Crosson).

in no-till systems could be minimized by selecting chemicals with more favorable environmental characteristics. Setia and Piper used a simulation model to assess the consequences of alternative tillage and chemical systems in the Cornbelt. They also assumed that conservation tillage involves higher pesticide use, and determined that the expansion of corn and soybean acreage under conservation tillage would increase the amount of pesticides leached to ground water. One of the few studies to assess the actual (versus simulated or assumed) relationship between tillage choice and pesticide application is Bull et al., which compared herbicide application rates among different tillage systems for corn and soybeans in the Midwest. Using a simple means test applied to three years of farm survey data, they found no consistent increase in herbicide use in conservation tillage systems. They surmised that weather, soil types, cropping patterns, operator experience, and inherent weed problems were more important factors than tillage in explaining the variation in herbicide use among farms. They did, however, find significant differences in the type of herbicides applied among tillage system. No-till farmers were more likely to use more than one kind of herbicide compound than were farmers using conventional tillage.

This paper provides further evidence on the relationship between tillage and agrichemical use. Using recently available data that link cropping practices to farm resource characteristics, a recursive system of equations is estimated to determine how agricultural chemical use and crop yield are affected by the adoption of conservation tillage systems. The first equation examines the choice of tillage system using a multinomial logit model. A second set of equations explores the effect of tillage and other variables on the quantity and quality of chemicals applied and on crop yield. The model is estimated with area study data from a sample of farms in the Cornbelt.

Model

To empirically examine the adoption of new tillage systems and the effects of adoption on chemical use and crop yield, a recursive model is developed and estimated. The first equation specifies the optimal choice of mechanical tillage. Since adopting a new tillage system may involve significant learning costs, affect crop rotations, and require new machinery, it is likely to be made over a multiyear time horizon. In the model, the selection of the tillage system j is assumed to be a discrete choice among J + 1 alternatives (i.e., $j = 0, 1, 2, \ldots, J$) and is indicated by a dummy variable, $T_j = 1$. Farmers are assumed to select the tillage system that maximizes expected utility over the planning horizon, where the expected utility of choice j can be written in the form $U_j(\mathbf{Z}) = \beta_j'\mathbf{Z} + \epsilon_j$. The first term $\beta_j'\mathbf{Z}$ is nonstochastic and reflects the "representative" preferences of farmers with attributes **Z**. The error term ϵ_j is stochastic and reflects the effects of idiosyncrasies in preferences, unobserved variations in attributes, and measurement error. Vector **Z** contains observed factors that determine tillage choice such as the relative prices of inputs, farm operator characteristics, farm resource endowments, policy, and institutional variables.

McFadden showed that if ϵ_j has a Weibull distribution, then the probability P_j that a farmer with characteristics **Z** chooses j is given by

$$(1) \quad P_j = \text{Prob}(T_j = 1) = \frac{\exp(\beta_j'\mathbf{Z})}{1 + \sum_{j=1}^{J} \exp(\beta_j'\mathbf{Z})},$$

$$j = 1, 2, \ldots, J$$

where β is a vector of parameters which satisfy $\log(P_i/P_j) = (\beta_i - \beta_j)'\mathbf{Z}$. This is the multinomial logit model. Note that the model has been normalized on T_0 (i.e., once probabilities for T_1 through T_J are known, T_0 is given since the probabilities sum to one). Estimation of the parameters in equation (1) provides information on the influence of resource characteristics, farm size, human capital, policies, and other variables on the pattern of technology adoption and can help identify constraints to further adoption.

One limitation of the multinomial logit model is that it assumes the independence of irrelevant alternatives, or the IIA property (Hausman and McFadden). This property implies that if a new choice is added to or removed from the set of alternatives, the probability ratios between the existing alternatives are not affected. In other words, adopters of the new choice should come from users of the existing alternatives in equal proportions so that the odds ratios P_i/P_j are unchanged. This is a strong behavioral assumption but one that can be easily tested. The Hausman-McFadden specification test for the IIA assumption is based on the notion that if a subset of the choice set is irrelevant, then omitting it from the model altogether will not change the remaining parameter estimates significantly. However, if the odds ratios are not independent of an omitted alternative, then the parameter estimates obtained when a choice is omitted will be inconsistent with the set of estimates using the full data set. The specification test statistic is

$$(2) \qquad \chi^2 = (\beta_s - \beta_f)' [\mathbf{V}_s - \mathbf{V}_f]^{-1} (\beta_s - \beta_f)$$

where β_s is a K × 1 vector of estimates from the restricted set of choices, β_f is the corresponding set of estimates from the full set of choices, and $\mathbf{V}_s$ and $\mathbf{V}_f$ are the estimates of the covariance matrices. Under the null hypothesis that $\beta_s = \beta_f$, the statistic has a χ^2 distribution with K degrees of freedom.

While the decision to adopt technology is assumed to be made over a multiyear time horizon, farmers make seasonal or annual decisions on variable inputs used in production. Let crop yield Y be a function of variable inputs X, tillage choice T_j (a fixed factor in the short-run), and resource endowments R. Farmers are assumed to make decisions on variable input use primarily on the consideration of short-run per acre profits (π), given by

$$\pi = P_y\, Y(X, T_j, R) - P_X\, X$$

where P_y and P_x are output and input prices, respectively. Under the standard assumptions of a quasi-concave production function, price-taking behavior and profit maximization, optimal input use is a function of prices and fixed factors:

$$(3) \qquad X^* = X(P_y, P_x, T_j, R)$$

where X^* is the choice of X that maximizes profits.

A difficulty in estimating equation (3) with cross-sectional survey data is that there may be little variation in prices among observations in the sample. Price variation among observations in the sample is likely to be correlated with geographic location or other farm characteristics such as farm size. For example, larger farms may pay lower prices for inputs due to quantity discounts or preferential credit terms. Using a cross-sectional sample of observations, optimal per acre variable input use is modeled as:

$$(4) \qquad X^* = \gamma_{11}G + \gamma_{12}S + \gamma_{13}R + \sum_{j=1}^{J} \alpha_{1j}T_j + \nu_1$$

where G is a set of dummy variables for geographic locales, S is farm size, R is a set of farm resource endowments and cropping practices that may affect the marginal productivity of variable input use, and T_j is the tillage system. The error term ν_1 is assumed to be independently and identically distributed, and γ_{1j} and α_{1j} are parameters to be estimated. The per-acre crop production (yield) function is estimated directly as:

$$(5) \qquad Y = \gamma_{21}G + \gamma_{22}S + \gamma_{23}R + \sum_{k=1}^{K} \gamma_{24k}X_k^* + \sum_{j=1}^{J} \alpha_{2j}T_j + \nu_2$$

where k = 1, . . . , K is the number of variable inputs X.

The system of equations (1), (4), and (5) is a recursive model of technology adoption. Estimates of the parameters of equation (1) provide information about the factors that determine the adoption of new resource-conserving technology. Estimates of α_{1j} and α_{2j} in equations (4) and (5) show the effect of technology adoption on input use and crop yield. For example, if $\alpha_{1j} > 0$, then adoption of tillage system j (i.e., $T_j = 1$) resulted in an increase in input use per acre. Equations (4) and (5) are

Table 1. Tillage Systems and Herbicide Use in the Study Area

Tillage System	Observations n	Corn area (%)	Herbicide application Pre-emergence	Herbicide application Post-emergence
Conventional tillage with moldboard plow	180	11.5	1.45	3.32
Other conventional tillage systems	288	17.2	1.14	2.83
No till	195	14.1	1.83	3.07
Ridge till	85	5.6	1.57	2.80
Mulch tillage systems	677	51.5	1.52	2.98
All	1,425	100.0	1.52	3.02

Herbicide application rate is total lbs/acre of active ingredient based on fields where at least some herbicide was applied.

estimated by two-stage least squares (2SLS) using the estimated probabilities of tillage choice from equation (1) as instruments for T_j. The model was estimated using Limdep Version 6 by Greene.

Data

Data are from the Area Studies Survey conducted by the United States Department of Agriculture (USDA). This survey was a collaborative effort by the USDA's Natural Resource Conservation Service, National Agricultural Statistics Service, and Economic Research Service, and the U.S. Department of Interior's Geological Survey to investigate relationships between agricultural practices and water quality. The survey links resource data from the National Resource Inventory and the SOILS-5 database with information about farm characteristics and production practices. In each of twelve survey areas, an area-frame sample of points was selected and data were collected for the field in which a sample point fell (limited to one observation per farm). Farm operators were interviewed about crops grown, yield, production practices, and chemicals applied in the sample field, in addition to general information about the farm. For the present study, fields planted to corn in the Midwestern survey areas were selected.[2] In these four areas, 4,883 agricultural fields (or farms) were sampled and 3,864 personal interviews with the farm operators were completed during 1991 and 1992. Of these, 1,425 farmers grew some corn in the sample fields during the survey year. In the statistical analysis, each observation is weighted by the size of the field divided by the probability that the field was selected to give a spatially representative sample.

The most common tillage system employed by the sample was mulch till, covering 47.5% of the observations and 51.5% of the area in corn (Table 1). Conventional tillage with a moldboard plow was used on 11.5% of the corn area and other conventional tillage systems (mainly chisel plow) were used on another 17.2%. No till covered 14.1%, and ridge till the remaining 5.6% of corn acreage. Table 1 also shows average application rates for pre- and post-emergence herbicides by tillage system on fields where at least some herbicide was applied. All tillage systems relied upon post-emergence herbicides to a greater degree than pre-emergence herbicides, although conservation tillage systems applied a slightly larger proportion of herbicides after crop emergence than conventional systems. The differences in mean application rates among tillage systems are not statistically significant, however.

Table 2 defines the variables used in the model. Tillage systems were grouped into (i) conventional tillage with or without a moldboard plow, (ii) no till, and (iii) other types of conservation tillage (mulch till or ridge till).

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[2] The four survey areas include the following National Water-Quality Assessment Program (NAWQA) watersheds: the White River Basin in Indiana and the Central Nebraska Basins surveyed in 1991, and the Eastern Iowa Basins and the Lower Illinois River Basin surveyed in 1992.

Table 2. Variables in the Model

Variable	Description	Mean	Std. dev.
Herbicide expenditure	\$/acre for all herbicides applied to corn	16.830	10.533
Insecticide expenditure	\$/acre for all insecticides applied to corn	3.927	7.518
Fertilizer expenditure	\$/acre for nitrogen, phosphate, and potassium	37.140	21.486
PLP index	Pesticide leaching potential index	1.318	1.333
PE index	Potential exposure index for acute toxicity (health hazard)	0.539	1.137
Atrazine application	lb/acre of atrazine herbicide applied to corn	0.718	0.694
Corn Yield	bu/acre	140.14	40.59
Conservation compliance	1 if subject to conservation compliance	0.151	0.358
Technical assistance	1 if have developed a conservation plan	0.537	0.499
College	1 if have some post-secondary formal education	0.439	0.496
Ln(Experience)	log (years of farming experience)	3.015	0.680
Ln(Farm size)	log (acres operated)	6.561	0.858
Owner	1 if own sample field	0.390	0.488
Off-farm work	time worked off the farm (days per year/365)	0.108	0.229
Irrigation	1 if sample field is irrigated	0.169	0.375
Rotation	1 if rotate crops in sample field	0.690	0.463
Soil quality index	Pierce index of soil quality (value from 0.00 to 1.00)	0.928	0.134
SLP-low	1 if low soil leaching potential ($SLP < 100$)	0.477	0.499
SLP-moderate	1 if moderate soil leaching potential ($100 \leq SLP < 146$)	0.435	0.496
SLP-high	1 if high soil leaching potential ($SLP \geq 146$)	0.088	0.284
EROSION-low	1 if low potential soil erosion (≤ 0.4 cm/year)	0.627	0.484
EROSION-moderate	1 if moderate potential soil erosion (0.4 to 0.8 cm/year)	0.435	0.496
EROSION-high	1 if high potential soil erosion (≥ 0.8 cm/year)	0.167	0.373
Ln(Season)	log (average annual frost-free days)	5.108	0.089
Ln(Rain)	log (average annual rainfall)	6.658	0.196
Iowa	1 if sample field is in Iowa or Minnesota	0.339	0.465
Illinois	1 if sample field is in Illinois	0.319	0.466
Indiana	1 if sample field is in Indiana	0.100	0.300
Nebraska	1 if sample field is in Nebraska	0.242	0.428

Conventional tillage is defined as the numeraire tillage system ($j = 0$). Socioeconomic characteristics of the farm hypothesized to affect tillage adoption include farm size, land tenure, farmer education, and farm management experience. Lee and Stewart found that larger, owner-operated farms were more likely to adopt conservation tillage, although their finding concerning tenure was disputed by Heimlich. Rahm and Huffman observed a positive association between human capital and adoption of conservation tillage. Cropping system characteristics that may constrain the choice of tillage system include the use of irrigation and crop rotation.

The model also includes two conservation policy variables. Both technical assistance programs and economic incentives have been used to encourage adoption of soil conservation practices such as conservation tillage. Farmers may voluntarily seek technical help from the Natural Resource Conservation Service to develop a conservation plan, but are generally not required to follow the plan's provisions. However, if a farmer receives agricultural program benefits and farms highly erodible land, then he or she is subject to conservation compliance, in which a soil conservation plan must be implemented or the farmer risks losing program benefits. Whether a farmer received technical assistance in developing a conservation plan or was subject to conservation compliance are treated as dummy variables in the adoption model to represent the two policy approaches. Note however that since nearly all sample farms that were subject to conservation compliance also had a conservation plan, the compliance variable essentially combines economic incentives with technical assistance.

Three indicators of resource characteristics that may affect tillage choice are included in the model: inherent soil quality, soil erosion potential, and soil leaching potential. Soil quality is measured by the ability of a soil to hold and deliver nutrients and water to plant roots for optimal plant growth according to the model developed by Pierce et al. Thus, inherent soil quality is independent of nutrient or water availability, which may be supplied through fertilizers and irrigation. Soil erosion potential is measured by the physical parameters of the Universal Soil Loss Equation (Wischmeier and Smith) and Wind Erosion Equation (Woodruff and Siddoway) and divided into high, moderate, and low categories according to Bills and Heimlich. Soil leaching potential (SLP), which is related to soil drainage, is measured by an index developed by Weber and Warren and divided into low, moderate, and highly leachable categories. Because sampled fields in the Area Studies Survey are linked to the National Resource Inventory and the SOILS-5 database, values for these indices are derived uniquely for each sample field based on its specific physical characteristics (see the Appendix for more detail on these soil and resource indices).

Climate variables included in the model are the average length of the growing season and average annual rainfall and are based on 30 years of county-level data. Previous research has found that conservation tillage, especially no till, may not perform well in areas with poorly drained soils, short growing season, and high rainfall (Crosson).

Chemical input use is measured as the per-acre expenditure for herbicide, insecticide, and fertilizer, respectively. Using prices to weight the quantities of different chemical compounds applied captures some of the quality attributes of the chemicals, such as potency, but may not take into account other quality attributes, such as the risk a chemical poses to the environment or human health (Beach and Carlson). Regressions using the total quantity of chemicals applied (pounds of active ingredients per acre) gave similar results as expenditures, however, since pesticide expenditures and quantities applied are highly correlated in the sample.

As previously noted, adopting conservation tillage systems may involve switching to new types of chemical compounds which may have different environmental and health-risk attributes that are not reflected in comparisons of quantities applied or expenditures. For example, for a given soil type, certain chemicals pose a larger risk to ground water because they are more likely to leach through the soil. Chemicals with a longer half-life (i.e. they persist longer in the environment) may have higher environmental and health risks than chemicals that degrade quickly into inert compounds. Some chemicals present larger risks to human health in either the short-term (acute toxicity) or long-term (chronic toxicity, or cancer risk). To examine these issues, regressions were run using various measures of the risks to ground water and human health of the chemicals applied in a field. To construct these measures, the amount of each herbicide and insecticide compound applied was weighted by specific environmental and health-risk attributes and aggregated together (see the Appendix for details on how the indices for pesticide leaching potential, acute toxicity, and chronic toxicity were constructed). These measures of environmental and health risk have limitations, however. For example, they do not account for possible synergistic effects from applying several chemicals together. Moreover, they only measure potential, rather than actual, exposure or risk. Nevertheless, the indices do indicate whether the types of chemicals applied with conservation tillage systems have relatively undesirable environmental and health attributes compared to chemicals used with conventional tillage.

Table 3. Multinomial Logit Model of Tillage Adoption

Variable	No Till Partial Effect	No Till t-ratio	Other Conservation Tillage Partial Effect	Other Conservation Tillage t-ratio
Constant	−23.033	−2.997**	8.6369	1.531
Conservation compliance	0.7105	1.829**	0.0022	0.008
Technical assistance	0.7688	3.904**	0.3409	2.560**
College	0.3000	1.525	0.3592	2.607**
Ln(Experience)	0.1373	0.935	0.1868	1.823*
Ln(Farm size)	0.4480	3.475**	0.2955	3.333**
Owner	−0.1376	−0.690	−0.2254	−1.642*
Off-farm work	0.8497	2.009**	−0.1705	−0.533
Irrigation	−1.6830	−3.242**	−0.6850	−2.575**
Rotation	0.3582	1.512	−0.0096	−0.061
Soil quality index	−0.9179	−0.934	0.2807	0.510
SLP-moderate	0.4565	2.114**	0.2791	1.736*
SLP-high	−0.4351	−0.800	0.3476	1.185
EROSION-moderate	1.0159	3.889**	0.5516	3.015**
EROSION-high	0.2841	0.698	0.5664	2.018**
Ln(Season)	7.4292	3.464**	4.6756	3.135**
Ln(Rain)	−2.9033	−1.883**	−5.2242	−4.379**
Illinois	0.9822	3.354**	0.9171	4.088**
Indiana	−0.4132	−0.980	−0.0264	−0.087
Nebraska	−1.2732	−2.528**	−1.8050	−4.765**

Coefficients for conventional tillage have been normalized to 1.0.
** Significant at 5% level; * significant at 10% level.
Goodness of fit measures:
$\chi^2(38)$ of regression = 304.6.
Veall and Zimmermann's pseudo R^2 = 0.27

Frequencies of actual and predicted outcomes:

Actual	Predicted 0	Predicted 1	Predicted 2	All
0—conventional tillage	180	6	282	468
1—no till	34	19	142	195
2—other conservation tillage	127	14	621	762
All	341	39	1,045	1,425

Results

Tests for the IIA assumption were carried out by first estimating the model with all three choices, and then dropping one choice and re-estimating the model with the smaller data set. The Hausman-McFadden test statistic was estimated using the appropriate pair of parameter vectors from the regressions according to equation (2). Under the null hypothesis that the parameters from the pairs of regressions are equal, the estimated χ^2 statistics are 1.74, 1.45, and 0.38, far below the critical value for the χ^2 test (38.6, at the 5% level of significance). Thus, the IIA hypothesis cannot be rejected, implying that farmers consider choices among these three classes of tillage systems independently, rather than, say, as a decision-tree. However, the IIA property may not hold if finer distinctions are made among tillage systems.

The estimates from the multinomial model of tillage choice are presented in Table 3, along with several measures of goodness-of-fit for the model. The frequency of predicted to actual outcomes is 820 out of 1,425 cases,

Table 4. Partial Effects of Variables on Tillage Adoption

Variable	Conventional Tillage Partial Effect	Conventional Tillage t-ratio	No Till Partial Effect	No Till t-ratio	Other Conservation Tillage Partial Effect	Other Conservation Tillage t-ratio
Conservation compliance	−0.0266	−0.397	0.0860	2.165**	−0.0594	−0.839
Technical assistance	−0.0806	−3.055**	0.0527	2.688**	0.0279	0.966
College	−0.0683	−2.556**	0.0049	0.277	0.0634	2.260**
Ln(Experience)	−0.0353	−1.783*	0.0007	0.056	0.0346	1.621*
Ln(Farm size)	−0.0630	−3.564**	0.0243	1.845*	0.0387	2.077**
Owner	0.0422	1.570	0.0018	0.018	−0.0440	−1.541
Off-farm work	−0.0103	0.040	0.1286	2.686**	−0.1184	−1.526
Irrigation	0.1749	3.096**	−0.0919	−2.186**	−0.0830	−0.718
Rotation	−0.0088	−0.308	0.0347	1.750*	−0.0260	−0.837
Soil quality index	−0.0191	−0.178	−0.1105	−1.232	0.1296	1.069
SLP-moderate	−0.0599	−1.941**	0.0265	1.371	0.0334	1.054
SLP-high	−0.0477	−0.774	−0.0554	−1.364	0.1031	1.749*
EROSION-moderate	−0.1136	−3.371**	0.0707	2.408**	0.0428	1.579
EROSION-high	−0.0951	−1.883*	−0.0126	−0.298	0.1031	1.970**
Ln(Season)	−1.0070	−3.408**	0.4189	1.908*	0.5881	1.875*
Ln(Rain)	0.9601	4.402**	0.0729	0.452	−1.0330	−4.181**
Illinois	−0.1679	−4.152**	0.0327	1.146	0.1352	3.267**
Indiana	−0.0158	−0.295	−0.0350	−1.051	0.0192	0.352
Nebraska	0.3788	4.448**	−0.0201	−0.033	−0.3587	−4.148**

Partial effect is the change in the probability of adopting tillage system j given a one-unit change in Z_k. For continuous variables, the partial effect is given by $\partial P_{jk}/\partial Z_k = P_{jk}(B_{jk} - \Sigma_{j=0}^{J} P_{jk}B_{jk})$. For dummy variables, the partial effect is found by calculating $\text{Prob}(Z_k = 1) - \text{Prob}(Z_k = 0)$, holding other variables constant at their mean values. Estimation of the standard errors of the partial effects is described in Greene. The constant term has been omitted from the table.

** Significant at 5% level; * significant at 10% level.

or 57.5% correct predictions, although the prediction for no-till adoption is poor (only 19 out of 195 cases). One limitation of this measure of goodness-of-fit is that it gives all the weight to the alternative receiving the highest predicted probability and ignores possible predictive error in the model. For example, suppose the predicted probabilities for conventional tillage, no till, and other conservation tillage systems are arranged in order, P_0, P_1, and P_2. If the model estimates predicted probabilities of adoption for two farms as (0.34, 0.33, 0.33) and (0.90, 0.05, 0.05), respectively, it would "predict" the first alternative, conventional tillage, for each, giving no account to the higher likelihood of predictive error in the first case. In a comparison of several alternative goodness-of-fit measures for a logit model, Windmeijer found that the Veall-Zimmermann psuedo-R^2 was close to a "true" R^2, while the predicted probability (percent of correct predictions) performed the poorest among the alternatives examined. For this model, the Veall-Zimmermann psuedo-R^2 is 0.27.

The coefficients of the multinomial model themselves are difficult to interpret, so partial effects are reported in Table 4. The partial effect is the change in the probability of adopting a tillage system resulting from a one unit change in the value of the explanatory variable. For dummy variables, the partial effect with respect to variable Z_k is found by taking the difference in the predicted probabilities calculated at $Z_k = 1$ and $Z_k = 0$, holding other variables constant at their mean values. Note that the partial effects sum to one, so that an increase in the probability of adopting one tillage system implies a decrease in the probability of adopting another system.

The results in Table 4 show that farmers who used conventional tillage tended to be those without college education, below-average experience, farming a relatively small area, without a conservation plan (technical assistance), and using irrigation. There was a strong correlation between conservation tillage adoption and farm size, which may be due to economies of scale or greater demand for labor-saving technologies. College-educated farmers were more likely to adopt conservation tillage systems like mulch till or ridge till (other conservation practices), while farmers with off-farm jobs were more likely to adopt no till. College may serve to enhance farmers' ability to learn and adapt new technology to their farming situation, thereby reducing adoption costs (Rahm and Huffman). The relationship between no till, college, and off-farm work is also consistent with the hypothesis that conservation tillage is more likely to be adopted by farmers who have a higher opportunity cost of labor due to off-farm employment options.

Land ownership had no significant effect on the choice of tillage system, which supports earlier empirical findings by Heimlich. While theory predicts that tenant farmers would invest less in soil conservation than owner-operators (McConnell), empirical evidence does not appear to bear this out, at least with respect to adoption of conservation tillage. In some cases adoption may be motivated by short-run cost savings rather than long-run considerations of soil erosion. Another possible explanation is that the interests of land owners and tenant farms may converge if tenancy contacts are long-term, based on crop shares instead of cash rents, and between family members (Dillman and Carlson).

In fact, for many farms the choice of tillage system was significantly influenced by potential soil erosion. Conventional tillage was least likely to be used on moderately or highly erodible soils. There was a higher likelihood of no till adoption on moderately erodible soils while other conservation tillage systems were chosen more often for highly erodible soils. Conservation policies (compliance and technical assistance) were more instrumental in influencing the adoption of no till than other conservation tillage systems. Other resource characteristics in the model were relatively unimportant in explaining tillage choice: soil quality had no measurable effect on the selection of tillage type and there was no consistent relationship between tillage choice and increased soil leaching potential.

Two-stage least squares estimates of the effects of tillage choice and other variables on chemical use and corn yield are shown in Table 5. Soil leaching potential is included in the chemical use equations to see whether ground water concerns may influence producer behavior. Neither the leaching nor erosion variables are assumed to have much impact on yield in the short run, so these variables are excluded from the corn yield production function. A missing variable from the chemical use equations is a direct measure of pest populations. While climate and cropping systems variables may partly account for recurring pest problems, seasonal weather patterns, and other factors also influence pest populations. This may partly explain the relatively low explanatory power (R-squares) of the chemical use equations.

The results in Table 5 reveal that tillage is just one of several factors that influence agrichemical use in corn production. The adoption of conservation tillage had mixed implications for chemical use and a negative effect on yield. Adoption of no till appears to have reduced expenditures on herbicide and fertilizers, but left insecticide use unchanged. Other conservation tillage systems (mulch till and ridge till) used higher levels of insecticides, but herbicide and fertilizer use were unaffected. The finding that a reduction in mechanical tillage did not increase reliance on chemical tillage challenges some basic assumptions about conservation tillage but is consistent with other survey research (Bull et al.). One possible explanation is that reliance on chemical tillage may lessen once no till has been practiced in field for several years (Sandretto). Unfortunately, data limitations prevent us from examining whether chemical use differed between long-time users and recent adopters of no till.

Other factors influencing agrichemical use

Table 5. Factors Affecting Agricultural Chemical Use and Corn Yield (2SLS estimates)

	Herbicide ($/acre)		Insecticide ($/acre)		Fertilizer ($/acre)		Corn Yield (bu/acre)	
Variable	Coeff.	t-ratio	Coeff.	t-ratio	Coeff.	t-ratio	Coeff.	t-ratio
Ln(farm size)	1.061	2.637**	0.120	0.377	1.344	1.624	7.712	5.568**
Irrigation	−0.960	−1.219	2.446	2.538**	5.298	2.112**	44.769	10.601**
Rotation	2.038	3.192**	−3.182	−6.307**	0.420	0.320	7.664	3.256**
Soil quality index	2.512	1.077	7.670	4.161**	2.432	0.507	21.183	2.883**
SLP-moderate	0.336	0.525	0.731	1.445	−0.315	−0.240	—	—
SLP-high	−1.455	−1.154	0.857	0.861	−1.702	−0.657	—	—
Ln(Season)	7.036	1.032	5.558	1.031	3.625	0.258	110.160	4.577**
Ln (Rain)	−9.203	−1.440	−5.717	−1.132	−15.651	−1.191	−66.637	−3.023**
Constant	36.254	1.208	3.447	0.145	119.900	1.893**	−30.639	−0.292
Illinois	−0.951	−1.088	−1.579	−2.285**	10.939	6.083**	2.945	0.919
Indiana	−3.912	−3.147**	1.361	1.385	20.372	7.968**	−49.387	−10.999**
Nebraska	−13.329	−6.542**	0.007	0.005	−23.034	−5.496**	−67.957	−10.181**
Prob(no till)	−7.767	−2.023**	4.198	1.383	−19.188	−2.430**	−42.225	−3.291**
Prob(other conserv. till)	0.670	0.154	6.045	3.573**	−5.770	−0.620	−29.059	−1.932*
Herbicide	—	—	—	—	—	—	0.222	1.996**
Insecticide	—	—	—	—	—	—	0.144	1.082
Fertilizer	—	—	—	—	—	—	0.194	3.968**
Std. dev. of residuals	9.552		7.550		19.684		34.429	
F-statistic	23.33**		18.63**		21.15**		39.14**	
R-squared	17.7%		12.7%		16.3%		28.0%	

** Significant at 5% level; * significant at 10% level.

Table 6. Factors Affecting Environment and Health Effects of Agricultural Chemical Use (2SLS estimates)

	Ground water leaching (PLP index)		Acute Toxicity (PE index)		Chronic Toxicity (lb/acre of Atrazine)	
Variable	Coeff.	t-ratio	Coeff.	t-ratio	Coeff.	t-ratio
Ln(farm size)	0.039	0.604	0.023	0.399	0.056	1.931**
Irrigation	0.108	0.556	0.254	1.452	0.077	0.866
Rotation	0.132	1.304	−0.242	−2.647**	−0.050	−1.070
Soil quality index	0.305	0.824	0.780	2.335**	−0.172	−1.014
SLP-moderate	−0.026	−0.260	0.145	1.578	0.039	0.845
SLP-high	−0.292	0.200	−0.098	−0.545	−0.004	−0.041
Ln(Season)	−0.424	−0.392	0.355	0.363	2.319	4.676**
Ln(Rain)	−0.151	−0.148	−0.225	−0.246	−0.841	−1.809*
Constant	3.403	0.714	−0.128	−0.262	−5.392	−2.470**
Illinois	0.163	1.174	−0.223	−1.784*	0.090	1.412
Indiana	0.060	0.306	0.485	2.726**	0.335	3.706**
Nebraska	−0.594	−1.834*	0.263	0.901	−0.361	−2.442**
Prob(no till)	−1.088	−1.784*	0.092	0.168	−0.211	−0.758
Prob(other conserv. till)	1.273	1.773*	0.873	1.350	−0.513	−1.561
Std. dev. of residuals	1.517		1.368		0.694	
F-statistic	8.668**		7.801**		11.73**	
R-squared	6.3%		5.7%		11.7%	

** Significant at 5% level; * significant at 10% level.

were the regional dummy variables, crop rotations, irrigation, soil quality, and farm size. Rotation increased herbicide costs (perhaps to control for volunteer plants from previous crops in the rotation) but reduced insecticide costs, most likely due to the positive effects of rotation on controlling insect pest populations such as corn root worm. Irrigated fields received increased insecticide and fertilizer application and recorded higher crop yield. Fields with better soil quality received larger doses of insecticides and achieved higher yield even though fertilizer use was not significantly affected. Finally, there was a positive correlation between farm size, herbicide use, and crop yield. Soil leaching potential appeared to have had no significant effect on farmer's decisions to apply chemicals. However, even if a farmer is concerned about the effects of chemical leaching on the quality of ground water, if ground water is an open-access resource there may be little individual incentive to limit chemical use in response to such concerns.

To further explore potential environmental and health risks associated with changes in agrichemical use, Table 6 examines how pesticide quality may be affected by tillage and other factors. The results indicate that the type of chemical pesticides applied to other conservation tillage systems (mulch till and ridge till) may have a somewhat greater potential to leach to ground water compared with conventional tillage systems. However, this risk was lower for no till, probably because of the substantial reduction in herbicide use indicated in Table 5. Acute toxicity (primarily a property of insecticides) was lower when crops were grown in rotation and greater on better quality soils—both factors associated with higher insecticide use. Even though other conservation tillage systems also had higher insecticide expenditures, there was no significant increase in the acute toxicity index. This could be due to differences in the types of insecticides applied with these tillage systems. Chronic toxicity (measured by the amount of the herbicide at-

Table 7. Elasticities of Selected Factor Effects

Variable	No Till	Other Conserv. Tillage	Herbicide	Insecticide	Fertilizer	Corn Yield
Conservation compliance	0.092**	−0.017				
Technical assistance	0.200**	0.028				
College	0.015	0.052**				
Ln(experience)	0.005	0.065*				
Owner	0.005	−0.032				
Off-farm work	0.098**	−0.024				
Ln(farm land)	0.172*	0.072**	0.063**	0.031	0.036	0.055**
Irrigation	−0.110**	−0.026	−0.010	0.106**	0.024**	0.054**
Rotation	0.169*	−0.034	0.084**	−0.559**	0.008	0.038**
Prob(no till)			−0.066*	0.154	−0.074**	−0.043**
Prob(other conserv. till)			−0.022	0.867**	−0.087	−0.117*
Herbicide						0.027**
Insecticide						0.004
Fertilizer						0.051**

** Regression coefficient significant at 5% level; * significant at 10% level. Constant term, natural resource, climate, and state dummy variables have been omitted from the table.

razine applied[3]) was not significantly affected by tillage but was higher for larger farms, which also had higher herbicide expenditures.

The coefficient estimates from the regressions are translated into elasticities (calculated at the means of the variables) in Table 7. The elasticities provide a convenient way to quantify the effects of changes in the attributes of a "representative" farm on the dependent variables in the model. For example, increasing the likelihood by 1% that the representative farm is subject to conservation compliance increases the probability of no till adoption by 0.092%. The increase in no till adoption would change average herbicide use by (0.092) × (−0.066) = −0.006% and fertilizer use by (0.092) × (−0.074) = −0.007%. Average corn yield would be reduced by the direct yield penalty of no till and by the reduction in input use, which sum to a 0.004% decline in average yield.

The elasticities can also be used to trace through the potential effects of some demographic changes occurring in U.S. agriculture. Over the next decade a significant proportion of farm operators are expected to retire since nearly half are 55 or older (Hoppe). The farmers who will replace them are likely to be better educated and farm larger areas, factors which are associated in the model with a higher likelihood of adoption of conservation tillage. The model predicts that further diffusion of conservation tillage would reduce herbicide and fertilizer use, increase insecticide application, and lower corn yield. But an increase in average farm size would also have a direct positive effect on herbicide use and corn yield. In fact, the direct effect on yield is likely to be much larger than the negative yield effect from conservation tillage, according to the model. For example, considering only the statistically significant effects, an increase of 1% in average farm size would increase the likelihood of no till adoption by 0.172% and other conservation tillage systems by 0.072%. Together, these changes in tillage systems (and the subsequent changes in input use) would reduce average corn yield by 0.015%. But the direct effect on yield of the increase in farm size is 0.057%, nearly four times the negative effect of conservation tillage. Thus, the net effect of larger farm size on both the diffusion of conservation tillage and corn yield is likely to be positive.

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[3] Atrazine is the most commonly used herbicide on corn and has been found to produce cancer in laboratory animals.

Conclusions

The diffusion of conservation tillage systems in the Cornbelt has contributed to a significant reduction of soil erosion. It has, however, raised concerns that if such systems are more dependent on agrichemicals some of the environment benefits from less erosion could be offset by the potential environmental and health risks posed by pesticides and fertilizers. This paper developed a recursive model to evaluate the effects of tillage choice on agrichemical use and corn yield using a sample of farms from several Cornbelt states. Statistical tests for the IIA property found that the multinomial logit model was an appropriate specification for the choice among three tillage systems: conventional tillage, no till, and other conservation tillage systems (mulch till and ridge till).

At the time of the survey, more than two-thirds of the sample were using one or another form of conservation tillage, and only 12.6% still used a moldboard plow for tillage. Policy provisions such as conservation compliance and the conservation extension services were significant factors explaining the adoption of conservation tillage systems, particularly no till. In addition, the level of potential soil erosion was positively correlated with the pattern of conservation tillage adoption. The results also found that larger farm size, college education, and having off-farm work were important factors explaining the adoption of conservation tillage. These variables are associated with a higher opportunity cost of farm labor, suggesting that reducing labor costs may be a primary motivation for many farmers to adopt less-intensive tillage systems. Larger farm size and better education may also reduce per-unit adoption costs (such as the per-acre costs of acquiring new equipment and learning new tillage management methods).

The empirical findings on the effects of conservation tillage adoption on agrichemical application rates challenge some basic conceptions on the potential tradeoffs between mechanical and chemical tillage. Herbicide and fertilizer expenditures appeared to have actually declined following the adoption of no till, and were not significantly affected by the adoption of other conservation tillage systems. The model did, however, find some evidence that insecticide expenditures increased following the adoption of other conservation tillage systems such as mulch till and ridge till. The adoption of conservation tillage systems also appeared to result in a crop yield penalty.

New tillage systems may also involve qualitative changes in the types of pesticides applied, which has implications for environmental and health risks associated with agrichemical use. The reduction in herbicide expenditure following the adoption of no till was found to significantly reduce the potential of pesticides to leach to ground water. However, chemicals applied to other conservation tillage systems appeared to pose a greater risk to ground water. Conservation tillage did not appear to have had any significant effect on the level of acute or chronic toxicity of applied pesticides. Fields planted with crop rotations reported significantly lower insecticide expenditures and lower acute toxicity levels than fields planted to continuous corn. However, the methodology for measuring the environmental and health risks of different combinations of chemical pesticides has serious limitations, and further exploration of this issue is needed.

The model predicts that the diffusion of conservation tillage will be positively affected by the current demographic shifts anticipated for U.S. agriculture, particularly continued consolidation of farms. It is likely that an expansion of conservation policies would also increase the use of conservation tillage. In particular, the expansion of no till would likely result in significant environmental benefits in the form of reduced soil erosion and carry little or no increased risk to ground water or health from changes in pesticide use. To the extent that demographic trends such as improvements in farmer education and growth in average farm size lead to further adoption of conservation tillage, potential yield penalties from conservation tillage are likely to be offset by the direct positive effect on yield associated with these demographic changes.

References

Alt, K.F. *An Economic Analysis of Field and Crop Production, Insecticide Use, and Soil Erosion in a Subbasin of the Iowa River.* PhD dissertation, Iowa State University, Ames, 1976.

Beach, E.D. and G.A. Carlson. "A Hedonic Analysis of Herbicides: Do User Safety and Water Quality Matter?"*Ameican Journal of Agricultural Economics* 75(August 1993):612–623.

Bills, N.L. and R.E. Heimlich. *Assessing Erosion on U.S. Cropland.* Agricultural Economics Report 513. Economic Research Service, U.S. Department of Agriculture, Washington DC, July 1984.

Bull, L., H. Delvo, C. Sandretto, and B. Lindamood. "Analysis of Pesticide Use by Tillage System in 1990, 1992, and 1992 Corn and Soybeans." Agricultural Resource Situation and Outlook Report 32. Economic Research Service, U.S. Department of Agriculture, Washington DC, October 1993.

Crop Protection and Chemicals Reference, eighth edition. New York: Chemical and Pharmaceutical Press, 1992.

Crosson, P. *Conservation Tillage and Conventional Tillage: A Comparative Assessment.* Akeny IA: Soil Conservation Society of America, 1981.

Dillman, D. and J. Carlson. "Influences of Absentee Landlords on Soil Erosion Control Practices." *Journal of Soil and Water Conservation* 37(Jan–Feb 1982):37–41.

Farm Chemicals Handbook. Willoughby, OH: Meister Publishing Company, 1993.

Gebhardt, M.R., T.C. Daniel, E.E. Schweizer, and R.R. Allmaras. "Conservation Tillage." *Science* 230(Nov 1985):625–630.

Hausman, J. and D. McFadden. "Specification Tests for the Multinomial Logit Model." *Econometrica* 52(Sep 1984):1219–1240.

Heimlich, R.E. "Landownership and the Adoption of Minimum Tillage: Comment." *American Journal of Agricultural Economics* 67(Aug 1985):679–681.

Heimlich, R. E. and C. W. Ogg. "Evaluation of Soil Erosion and Pesticide Control Strategies." *Journal of Environment Economics and Management* 9(1981):279–288.

Hoppe, R.A. *Who Are Retired Farm Operators?* Agricultural Economics Report 730, Economic Research Service, U.S. Department of Agriculture, Washington DC, April 1996.

Greene, W.H. *Limdep 6.* Bellport, NY: Econometric Software, Inc., 1991.

Lee, L.K. and W.H. Stewart. "Landownership and the Adoption of Minimum Tillage." *American Journal of Agricultural Economics* 65(May 1983):256–264.

McFadden, D. "The Measurement of Urban Travel Demand." *Journal of Public Economics* 3(1974):303–328.

Pierce, F.J., W.E. Larson, R.H. Dowdy, and W. Graham. "Productivity of Soils: Assessing Long-Term Changes Due to Soil Erosion." *Journal of Soil and Water Conservation* 38(January–February 1983):39–44.

Rahm, M. and W. Huffman. "The Adoption of Reduced Tillage: The Role of Human Capital and Other Variables." *American Journal of Agricultural Economics* 66(November 1984):405–413.

Sandretto, C. "Weed Control and Tillage." Agricultural Resources and Environmental Indicators, 1996–97. Agricultural Handbook 712, Economic Research Service, U.S. Department of Agriculture, Washington DC, July 1997, p. 168.

Setia, P. and S. Piper. "Effects of Soil and Agricultural Chemicals Management on Farm Returns and Ground Water Quality." *Review of Agricultural Economics* 14(January 1992):65–80.

U.S. Department of Agriculture. Agricultural Resources Situation & Outlook Report 30. Economic Research Service, U.S. Department of Agriculture, Washington DC, May 1993.

Weber, J.B. and R.L. Warren. "Herbicide Behavior in Soils: A Pesticide/Soil Ranking System for Minimizing Ground Water Contamination." *Proceedings of the NE Weed Science Society* 47(1993):144–157.

Windmeijer, F.A.G. "Goodness-of-Fit Measures in Binary Choice Models." *Econometric Reviews* 14(1995):101–116.

Wischmeier, W.H. and D.D. Smith. Predicting Rainfall Erosion Losses—A Guide to Conservation Planning. Agricultural Handbook 537. Soil Conservation Service, U.S. Department of Agriculture, Washington DC, 1978.

Woodruff, N.P. and F.H. Siddoway. "A Wind Erosion Equation." *Soil Science Society of America Proceedings* 29(1965):602–608.

Appendix: Natural Resource and Health-Risk Indices

The NRI and SOILS-5 databases, together with data on pesticide characteristics, are used to construct several measures of farmland quality, natural resource vulnerability, and health risk from farm pesticide use. Sources of data for the toxicity properties of agricultural pesticides are the *Crop Protection and Chemicals Reference* and the *Farm Chemicals Handbook.*

For soil quality, defined as the soil's ability to deliver nutrients and water to roots for plant growth, the index developed by Pierce et al. is used:

$$\Omega = \sum_{i=1}^{n} WF_i \cdot A_i \cdot B_i \cdot C_i$$

where WF_i is a weighting factor for soil horizon i based on its depth, A_i is the sufficiency of the available water holding capacity for horizon i, B_i is the sufficiency of bulk density, C_i is the sufficiency of pH, and n is the number of soil horizons or layers in the root zone. Potential crop yield is reduced if one of the soil properties falls below a threshold level. If all factors are at or above their threshold, then the value of Ω achieves is maximum of 1.00. The difference between 1.00 and the estimated value of Ω is the percent yield loss due to suboptimal soil conditions.

Potential soil erosion due to rainfall and wind is measured from the physical components of the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEQ). The inherent soil erodibility of a field due to rainfall (sheet and rill) is measured by a multiplicative relationship among rainfall (R), soil type (K), slope length (L), and steepness (S) (Wischmeier and Smith). WEQ determines the amount of soil erosion from wind as a function of a soil erodibility index, a soil ridge roughness factor, a climatic factor, field length, wind erosion direction, and vegetative cover (Woodruff and Siddoway).

Another natural resource characteristic is the potential of a soil to leach chemicals and pesticides into ground water. Weber and Warren developed an index of soil leaching potential (SLP) as a function of a soil texture rating pH value and percent organic matter. Each of these factors is given a weight and then summed to construct the SLP index for a particular soil type.

The amount of pesticide to actually reach ground water depends not only on the characteristics of the soil but also of the pesticides applied. For pesticide leaching potential, Weber and Warren developed another index that weights the amount of each chemical applied by the fraction of a chemical that reaches the soil, its persistence in the environment (half-life, or THALF), and its soil retention factor (Koc):

$$PLP = \sum_{k=1}^{n} \frac{THALF_k}{Koc_k} F_k X_x$$

where F_k is the fraction of the pesticide quantity X_k that reaches the soil, for $k = 1, \ldots, n$ herbicide and insecticide compounds. Thus, the risk that agrichemicals may leach to ground water depends upon the properties of the soil (SLP) and the chemical compounds (PLP).

Two measures of health risk from chemical application are acute and chronic toxicity. For acute toxicity, Alt developed a pesticide exposure index (PEI) in which the quantity of each chemical applied is weighted by its LD50 rating (which decreases as a chemical becomes more toxic to mammalian forms of life) and its persistence in the environment:

$$PEI = \sum_{k=1}^{n} \frac{THALF_k}{LD50_k} X_k.$$

For chronic toxicity we consider the application rate for atrazine, the most commonly used herbicide in U.S. corn production and which has been found to cause cancer in laboratory animals.