Soil Productivity and Farmers' Erosion Control Incentives—A Dynamic Modeling Approach

B. Colby Saliba

Important linkages between farm management variables, soil loss, crop yields, and incentives to practice soil conservation have often been omitted from previous empirical studies, due to regional data limitations and incomplete knowledge of soil loss/crop yield relationships. An optimal control model is developed with explicit attention to interactions between management choices, soil loss, and long-term farmland productivity. Analysis of the optimality conditions generates a number of hypotheses related to farmers' productivity-linked conservation incentives, which can be tested empirically without precise knowledge of specific erosion-productivity relationships.

Soil erosion represents an important policy issue in terms of water quality impacts—soil sediment is the most pervasive of U.S. water pollutants [Clark *et al.*]—and long-term threats to agricultural productivity. Some researchers believe current soil loss rates in the Corn Belt could lead to a 30 percent reduction in grain yields over the next 50 years (U.S.D.A.). While media coverage of soil erosion has typically focused on the Midwestern Corn Belt, western agriculture is also confronted by a number of soil productivity issues. The 1980 RCA Appraisal (U.S.D.A) estimated that the percentage of cropland losing more than five tons per acre of soil each year (due to sheet and rill erosion) ranges from seven to nineteen percent among the western states.[1] Intense seasonal rains contribute to sheet and rill erosion, sometimes extending to gully formation. Eroded soil clogs irrigation systems, and soil salinity buildup is an issue of increasing concern for western agriculture. Satisfactory resolution of these problems, in the context of voluntary erosion control, demands increased attention to farmers' soil management incentives and decision processes.

Knowledge regarding relationships between agricultural activity, soil erosion, and crop yields is central to formulation of sound conservation policy. Research on the technical and agronomic aspects of erosion and soil productivity has expanded in recent years. However, few economists have complemented these efforts by conceptually and empirically exploring the linkages between farmers' incentives to control erosion, erosion-induced productivity changes, and future farmland productivity. A better understanding of these relationships is essential to soil conservation planners and policy makers, as individual farmers remain the central decision makers with respect to erosion control on U.S. farmlands.

While economists have taken a number of approaches in their soil conservation research, only a handful of farm-level studies have given attention to the dynamic

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The author is Assistant Professor in the Department of Agricultural Economics at the University of Arizona.

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[1] These percentages would be even higher if wind-induced soil loss was included.

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relationships between farm management practices, soil erosion, and crop yields. Theoretical models focused on these relationships are essential to erosion research for a number of reasons. A model illuminates linkages between economic, physical and biological systems, and farmers' values and objectives. The interrelationships in a theoretical model and associated optimality conditions suggest questions worth exploring in more depth and provide structure and direction to empirical research.

This article provides a more complete theoretical model to guide empirical research on the economics of erosion control. This research develops an optimal control model of linkages between farm management, soil erosion, and land productivity, and uses the model to generate hypotheses which suggest specific directions for future farm-level research. The study concludes that further attention needs to be given to the relationship between erosion control and farmland values, to tradeoffs between soil and other crop production inputs, and to the impact of farmland's erosion vulnerability on farmers' incentives to practice erosion control.

A Review of Dynamic Farm-Level Models

Soil loss generally occurs in small increments and it is the cumulative effects on soil quality and crop yields which are important. Therefore, models which examine the relationship between erosion processes, crop yields, and economic variables must employ dynamic mathematical techniques. Conservation decisions should also be modeled in a dynamic framework to accommodate farmers' changing management strategies in response to accumulating impacts of soil loss on crop yields and farm income. The four studies discussed below illustrate how economists have incorporated erosion-productivity processes into previous dynamic economic models. Some simplifications have been made in the models discussed in order to focus on the details most relevant to this research.

McConnell introduces soil depth and soil loss into a model of crop production in order to analyze the optimal private rate of soil loss over time. Crop yields are modeled as a function of soil depth (the state variable), soil loss, and input use. The author does not specify a functional form for the production function, but does assume that it is concave—that crop yields increase with soil loss, soil depth and input use, with diminishing returns in crop production associated with each of these three variables. In McConnell's model the change in soil depth equals natural regeneration minus soil loss. Input use does not directly influence soil depth or loss in this model. Farmers are assumed to maximize the present value of the stream of net profits plus the market value of their farm at the end of the planning horizon by choosing appropriate levels of the two control variables—input use and soil loss.

Clark and Furtan conduct their economic analysis of soil fertility in the setting of Saskatchewan dryland agriculture. They use soil moisture to represent the Ricardian fixed allocation component of land, and total nitrogen content to represent the capital component—nitrogen flows being influenced through crop rotations (with particular attention to legumes and fallow) and fertilizer applications. A profit maximizing producer is shown to equate marginal revenue of fertilizer to its dynamic marginal cost, to utilize nitrogen-fixing crops to the point where marginal cost equals the marginal revenue of their price plus the discounted value of the nitrogen they make available for future periods, and to manage fallow so that any current profits foregone are offset by increased future profits. Simulation experiments with this model for the dark brown Saskatchewan soil zone demonstrate the importance of interest rates, changing fallow techniques, and precipitation patterns in farmers' soil management decisions.

Burt develops an optimal control model of soil conservation economics for the wheat-pea area of the Palouse in eastern Washington and western Idaho. Two state variables serve as measures of overall productivity—topsoil depth and percentage of organic matter in the top six inches of soil. He uses a single decision variable, crop rotation, measured as percentage of land planted to wheat. Farmers select their rotation to maximize the present value of net returns over an infinite time horizon, taking into account the influence of the two state variables on crop yields. Each year's net returns are a function of current soil depth, percent organic matter, and crop rotation. Burt uses data collected in the 1950s to estimate the functions in his model. Due to insufficient data, topsoil does not affect loss of organic matter in this model. This may be appropriate for the deep soils of the Palouse region, but, as Burt points out, it would be an unacceptable assumption in areas with a shallow soil mantle. The model indicates that at higher wheat prices, 87.5 percent of the rotation would be in wheat for almost the entire domain of the two state variables. When a lower wheat price is assumed, percent of land in wheat decreases as percentage of organic matter decreases.

Walker develops a damage function to portray the economic consequences to a farmer of employing conventional tillage instead of conservation tillage. This model indicates the optimal time in the farmer's planning horizon to switch tillage practices. A damage function compares the present value of net revenues from the alternative tillage choices a farmer faces each year. Walker uses data on wheat yields and soil depth along with information on the costs and returns associated with several different tillage systems. The resulting series of damage functions shows that farmers would profit from immediate adoption of conservation tillage on shallower eroded topsoils and would benefit from delaying adoption on deeper soils. The economic incentives to conserve soil increase as soil loss accumulates.

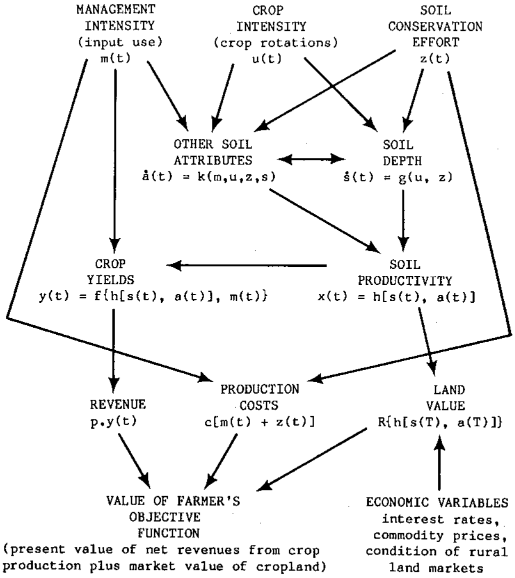

Figure 1. Variables and Functions in the Farm-Level-Conservation Model.

Conservation effort was not an explicit choice variable in any of the four models reviewed. The studies treat the link between farm management decisions and soil erosion in a number of ways. McConnell uses soil loss as a decision variable though farmers do not actually choose a level of soil loss. Farmers choose tillage practices and crop rotations and these, along with other management decisions and the topography and soils of their land, influence their rate of soil loss. Two farmers could make identical management decisions yet have different rates of erosion because one farmer has more erosion-prone slopes and soils than the other. On the other hand, two farmers could have identical rates of soil loss yet be making widely differing conservation decisions, the farmer on steep slopes using terraces and contour strips to keep soil loss to the level his valley neighbor obtains with no conservation practices. Soil loss is not a realistic choice variable for a farm-level model. The Saskatchewan study [Clark and Furtan] focuses on several decision variables—fertilizer application, legumes, and fallow. Burt used crop rotation as the decision variable and assumed that farmers would use a fixed amount of fertilizer and other inputs associated with each rotation choice. Walker used timing of conservation tillage adoption as his decision variable. The variable input decisions were subsumed into the cost function.

None of the four models directly addresses the relationship between soil erosion and soil productivity. Clark and Furtan include nitrogen content and soil moisture in their yield functions and do not explore the role of soil depth. Burt includes both soil depth and percentage of organic matter in his analysis but does not address overall soil productivity.

These models do not adequately address tradeoffs between production inputs, soil conservation, and intensity of crop rotations. Farmers may substitute (to a limited extent) commercial fertilizer, better plant varieties, irrigation water, and other inputs for declining soil productivity in order to maintain crop yields; or they could employ conservation practices which maintain or enhance soil productivity itself. A farmer could also shift to less erosive crop rotations as a supplement to explicit conservation measures such as terraces or contour strips. McConnell included input use as a decision variable but does not relate inputs or cropping decisions to the rate of soil loss or to future crop yields. Clark and Furtan do examine the tradeoffs between fertilizer, legumes, and fallow as alternative means of achieving desired crop yields, but their research focused on nitrogen content and soil moisture rather than on overall soil productivity. Burt included crop rotation as a choice variable but assumed that fertilizer and cultural practices were fixed at specific levels in his analysis. Walker's model can accommodate substitution between inputs and soil productivity in maintaining crop yields, but he limited his discussion to tillage practices and did not address the more general issue of tradeoffs between conservation effort, crop rotations, and production inputs.

Soil Productivity and Conservation Incentives—A Farm-Level Model

A comprehensive farm-level soil conservation model should include the following variables and functions:

a. Functional relationships which capture the impact of farm management choices (the control variables) on soil attributes (the state variables). These are the state equations in an optimal control framework.
b. State variables which reflect changes in soil depth and other productivity-related soil characteristics.
c. Erosion-productivity linkages which relate changes in soil charcteristics to crop yields.
d. Crop yield functions which incorporate both soil productivity and management variables so that substitution possibilities between soil and other inputs are explicitly included in the model.

The studies reviewed incorporate some of these elements but none incorporates all of them in an explicit manner. In the theoretical model developed here, conservation effort is used as an explicit decision variable. The concept of soil productivity is incorporated through relationships between soil depth, other soil attributes, and soil productivity. The tradeoffs between soil conservation, input levels, and crop rotations are highlighted by including all three as decision variables. Figure 1 summarizes the relationships within the model.

The following notation is used to denote variables in the discussion that follows.

$x(t) \equiv$ soil productivity,
$s(t) \equiv$ soil depth,
$a(t) \equiv$ other soil attributes,
$u(t) \equiv$ crop rotation,
$m(t) \equiv$ management intensity,
$z(t) \equiv$ soil conservation,
$r \equiv$ discount rate,
$T \equiv$ terminal year in planning horizon,
$c \equiv$ per unit cost of inputs,
$p \equiv$ price received for farm output,
$y \equiv$ crop output, and
$R[s(T)] \equiv$ market value of land at end of planning horizon.

Soil depth and soil productivity are two different concepts. Soil productivity has been defined as the soil's capacity to produce a specified set of plants or plant sequences under a physically defined set of management practices [Larson *et al.*]. Productivity is a relationship between inputs and outputs. Changes in soil depth and other characteristics affect productivity differently on various soils. In this model soil productivity is a function of soil depth and other soil attributes, $x(t) = h[s(t), a(t)]$, where $x(t)$ is soil productivity, $s(t)$ is soil depth ($\partial h/\partial s \geq 0$), and $a(t)$ represents other relevant attributes—organic matter, nitrogen content, and others as appropriate for specific regions. Inclusion of this relationship in the model gives it flexibility because the form of the function, $h[s(t), a(t)]$, can be varied depending on the type of soils under consideration. On deep, naturally fertile soils $\partial h/\partial s$ could be very close to zero, indicating that decreases in soil depth do not diminish the productive potential of the soil. On shallow soils $\partial h/\partial s$ would be larger, indicating that productivity declines associated with soil loss are large. This soil depth-productivity function also provides a link between what can actually be measured in the field, soil depth, and the more difficult to measure concept of soil productivity.

The three decision variables are soil conservation effort—$z(t)$; an index of management intensity—$m(t)$ [the larger $m(t)$ is, the more production inputs are applied]; and crop intensity—$u(t)$, representing the percentage of the rotation in row crops as opposed to forage crops. Production costs are determined by soil conservation effort and the management intensity applied to each crop. Crop yields depend on management intensity and soil productivity (and thus on soil depth and other attributes). The production function can be written $f\{h[s(t), a(t)], m(t)\}$, where $\partial f/\partial h(s, a)$ and $\partial f/\partial m$ are both positive, implying that crop yields increase as either soil productivity or management intensity rise. Changes in soil depth over time, denoted $\partial s(t)/\partial t$, depend on crop intensity and on soil conservation effort, $\dot{s}(t) = g[u(t), z(t)]$, where $\partial g/\partial u \leq 0$—more erosive rotations decrease soil depth, and $\partial g/\partial z \geq 0$—more erosion control conserves soil depth. Changes in other productivity-linked attributes over time, $\dot{a}(t)$, may depend on all three control variables, as well as on soil depth. This relationship will vary depending on the attributes of interest for a particular region. For example, nitrogen content would be related to cropping patterns, soil depth, and input use. Organic matter can be linked to tillage practices and soil depth. As in the models previously discussed, crop prices, input prices, and interest rates are exogenous. The farmer chooses $u(t)$, $m(t)$ and $z(t)$ at each point in time to maximize the present value of the stream of net revenues from his farm plus the market value of the land at the end point in his planning horizon, $R\{h[s(T), a(T)]\}$. The optimal control framework enables management variables to continually respond to accumulating effects of past management decisions on soil quality and crop yields.

A few simplifying assumptions facilitate development of optimality conditions. First, the analysis will focus only on soil depth, $s(t)$, as a determinant of soil productivity—the role of other attributes, $a(t)$, would be analogous. Next, assume the farmer's cropping pattern is divided between a row crop (more erosive) with a yield function $f_1[h(s), m_1]$ and a forage crop (less erosive) with a yield function $f_2[h(s), m_2]$. The values of $m_1(t)$ and $m_2(t)$ indicate the levels of management intensity applied to each type of crop. The row crop sells at a per unit price of p_1, the forage crop at a per unit price of p_2, and the crop intensity variable, $u(t)$, designates the proportion of the farmer's rotation which is in row crops. Let c denote the per-unit cost of management intensity, $m(t)$ and w denote the per-unit cost of conservation effort, $z(t)$. The objective function can then be written as follows:

$$\begin{aligned}\underset{u,z,m}{\text{Max}} \int_0^T & e^{-rt}\{up_1f_1[h(s), m_1] \\ & + (1 - u)p_2f_2[h(s), m_2] \\ & - c[um_1 + (1 - u)m_2] - wz\} \, dt \\ & + e^{-rT}R\{h[s(T)]\}\end{aligned}$$

Maximization is constrained by the farmland's vulnerability to erosion (reflected in the following soil loss equation) and initial soil depth. In addition, there is a limit on the values $u(t)$ can take because it is a proportion and there is a technological upper limit, m_{max}, on the level of management intensity. These constraints can be written:

$\dot{s}(t) = g[u(t), z(t)]$	Soil loss equation
$s(t = 0) = s_0$	Initial soil depth
$0 \leq u(t) \leq 1.0$	Bounds on crop intensity
$0 \leq m(t) \leq m_{max}$	Bounds on management intensity

The maximum principle approach provides a framework in which to analyze this problem [Kamien and Schwartz]. The costate variable, denoted as $\lambda(t)$, is the marginal value to the farmer of one more unit of soil depth at time t. It precedes the soil loss equation in the Hamiltonian function. The current value Hamiltonian is written as follows:

$$\begin{aligned}H(m, u, z, s, \lambda) = {} & up_1f_1[h(s), m_1] \\ & + (1 - u)p_2f_2[h(s), m_2] \\ & - c[um_1 + (1 - u)m_2] \\ & - wz + \lambda g[u, z]\end{aligned}$$

There are five types of necessary conditions for this optimal control problem.

(1) The maximum principle requires that the derivative of the Hamiltonian with respect to each control variable be equal to zero.

a. For z(t): $\partial H/\partial z = 0 \rightarrow \lambda \, \partial g/\partial z = w$

$$\begin{array}{r}\text{value of the}\\\text{marginal soil}\\\text{conserved}\end{array} = \begin{array}{l}\text{marginal cost}\\\text{of conservation}\\\text{effort}\end{array}$$

b. For u(t): $\partial H/\partial u = 0 \rightarrow [p_1f_1 - cm_1] - [p_2f_2 - cm_2] = -\lambda \, \partial g/\partial u$

$$\begin{array}{r}\text{the ``benefits'' of}\\\text{more row crops}\\\text{in terms of}\\\text{net revenues}\end{array} = \begin{array}{l}\text{the ``costs'' of more}\\\text{row crops in terms of}\\\text{the marginal value of}\\\text{soil erosion caused}\end{array}$$

c. For m(t): $\partial H/\partial m_1 = 0 \rightarrow p_1\partial f_1/\partial m_1 = c_1$

$\partial H/\partial m_2 = 0 \rightarrow p_2\partial f_2/\partial m_2 = c_2$

$$\begin{array}{r}\text{value of the}\\\text{marginal product}\\\text{of management}\\\text{intensity in}\\\text{crop production}\end{array} = \begin{array}{l}\text{marginal cost}\\\text{of management}\\\text{intensity}\end{array}$$

(2) The costate equation introduces the rate of change of the costate variable—the marginal value of soil depth, $\lambda(t)$.

$$\begin{aligned} & r\lambda - \partial H/\partial s = \dot{\lambda} \rightarrow \\ & \dot{\lambda} = r\lambda - [up_1\partial f_1/\partial h(s)\partial h(s)/\partial s \\ & \qquad + (1 - u)p_2\partial f_2/\partial h(s)\partial h(s)/\partial s]\end{aligned}$$

This implies that changes in the marginal value of soil depth, $\dot{\lambda}$, depend on the discount rate—r, the current value of the costate variable—$\lambda(t)$, crop prices—p_1 and p_2, the crop intensity variable—$u(t)$, the influence of soil productivity on crop yields $[\partial f/\partial h(s)]$, and the influence of soil depth on soil productivity—$[\partial h(s)/\partial s]$.

(3) The state equation:

$$\partial H/\partial \lambda = \dot{s} \rightarrow \dot{s} = g(u, z)$$

(4) The endpoint conditions:

a. Initial condition: $s(t = 0) = s_o$

b. Transversality condition: $\lambda(T) = \partial R\{h[s(T)]\}/\partial s(T)$

In the final period, T, the marginal value of soil depth will correspond to the influence that soil depth has on the market value of the land.

(5) Constraints on the control variables [Kamien and Schwartz, p. 170] assure that the variable u(t) cannot lie outside the bounds between 0 and 1.0; that management intensity is nonnegative and does not exceed the technological maximum, m_{max}; and that soil conservation effort is nonnegative.

The Model's Implications for Farm-Level Research

The optimality conditions suggest that a number of factors, often overlooked in previous empirical studies, may significantly affect incentives to practice erosion control. These factors are outlined along with a summary of relevant empirical findings.

Erosion-productivity relationships have an important influence on all three farm management variables. Soil productivity and the vulnerability of farmland to erosion-induced productivity losses ($\partial h/\partial s$) affect the optimality conditions for all decision variables. The magnitude of the derivative $\partial h/\partial s$ will depend on the soil types, topsoil depth, and cropland slopes. This model implies that soil and topographical characteristics of farmland play an important role in crop rotation and erosion control decisions. For example, farmers with deep topsoils or minimal productivity differentials between topsoil and subsoil would have small $\partial h/\partial s$, would lose little productive potential by permitting topsoil runoff, and therefore have less incentive to adopt erosion control measures.[2]

Empirical research in Wisconsin [Saliba 1985] found a significant relationship between farmland erosion vulnerability and use of conservation practices. Farmland characteristics such as slope and erodibility of farm soil types were more significant in explaining conservation behavior than variables typically included in farm-level studies—such as income, debt-to-asset ratios, and type of farm operation.[3] Ervin and Ervin, in Missouri, also found significant relationships between farmland erosion vulnerability and use of conservation practices but, overall, few empirical studies have looked at farmland characteristics.

The susceptibility of farmland to soil loss must be distinguished from the productivity deterioration that may accompany that soil loss. The quantity of soil runoff may be a key issue from a water quality point of view, but farmers' private conservation incentives are based on the crop yield reductions (or more accurately—their perceptions of crop yield reductions) that can result from varying rates

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[2] In the costate equation the effect of soil depth on soil productivity, $\partial h(s)/\partial s$, influences the rate of growth of the marginal value of soil depth, $\dot{\lambda}$. If soil depth does not affect soil productivity (this could occur on land for which subsoil productivity does not differ noticeably from that of the topsoil), $\partial h(s)/\partial s$ will equal zero, and then $\dot{\lambda}/\lambda = r$—the percentage change in $\lambda(t)$ equals the interest rate and is not affected by soil depth. Farm soil management practices will be influenced by economic factors such as interest rates, rather than by concern regarding future farmland productivity and crop yields.

[3] This study used detailed data from U.S.D.A. 1983 Wisconsin Family Farm Survey based on a random sample of over 500 farmers. Soil type, slopes, and land characteristics of each farm studied were obtained from Soil Conservation Service County Soil Surveys. Slope and erodibility of farmland were significant at the five percent level in regression equations linking various explanatory variables to use of terraces, strip crops, contour plowing, minimum tillage, and conservation-oriented crop rotations. Income, debt-to-asset ratio, type of farm operation and farm operator attitudes regarding the impact of erosion on crop yields were also significant at the five or ten percent level. A logit transformation was used to accommodate the limited range of the dependent variables. R^2 ranged from 28 percent to 58 percent among the equations estimated. These percentages are high for logit models in particular [Pindyck and Rubinfeld, p. 255] and for cross-sectional research on conservation behavior in general.

of soil loss. As Benbrook notes, this distinction is often overlooked in both conceptual and empirical work. Swanson and Harshbarger are a notable exception. They found—for specific soil types, cropping patterns, and management practices—that income losses due to erosion-induced yield declines were smaller than the costs of implementing recommended conservation practices. They used Illinois data and models to estimate yield declines. However, as Walker (p. 691) points out, there is little data available on productivity declines associated with erosion, what exists is highly site-specific, and many yield-response models are based on naive assumptions. The Erosion–Productivity Impact Calculator (EPIC) is a recently developed and sophisticated approach. It consists of eight submodels for simulating erosion, plant growth, and related processes. The model was been tested for various sites and has indicated crop yield reductions of up to 40 percent under conditions of high soil loss and unproductive subsoils (Williams *et al.*).

While erosion-productivity research is extremely relevant to economists investigating farmers' conservation incentives, it is not state-of-the-art models that influence actual conservation decisions. Farmers' **perceptions** of crop yield declines associated with soil loss on their land determine whether erosion control appears worthwhile to them. Ervin and Ervin found that perception of erosion as a problem affects adoption of minimum tillage. Saliba [1986] found that farmers who believe most strongly that erosion reduces long-term crop yields are more likely to use terraces, strip crops, and contour plowing. Interestingly, Walker and Young have found that farmers' expectations regarding progress in yield-enhancing technologies can accelerate the adoption of profitable conservation tillage practices. Research to date supports the hypotheses generated by the theoretical model. Farmers consider both the erosion vulnerability of their land and expected crop yield declines when they make conservation decisions.

Soil characteristics also influence management decisions through the soil loss function, $\dot{s} = g(u, z)$. The model indicates that two relationships will particularly influence the methods a farmer uses to maintain soil productivity. These are the erosiveness of alternative crop rotations ($\partial s/\partial u$) and the effectiveness of conservation practices in preventing soil loss ($\partial s/\partial z$). While the erosiveness of various crop rotations is a matter for agronomists and soil scientists, economists could contribute substantially to understanding the economic tradeoffs between less erosive (and perhaps less valuable) crops and adoption of other erosion control alternatives. A few studies have explored farmers' perceptions about the effectiveness of different conservation practices. Carlson *et al.* found a definite relationship between use of a practice and its perceived effectiveness. They also found that farmers were aware of the relative erosiveness of common Palouse-area crop rotations. Saliba [1983] found that Wisconsin crop producers ranked "preventing soil-runoff" as a very important consideration (along with profitability and need for dairy forage) in determining crop rotations. Miranowski emphasizes the role of perceived riskiness in farmers' considerations of reduced tillage practices. Farmers' pessimistic expectations about yields under conservation tillage can affect their management decisions. Much more attention needs to be given to on-farm tradeoffs between crop rotations versus specific erosion control practices as alternative strategies for reducing soil loss.

The effects of soil productivity and other inputs on crop yields are reflected in the yield function, $f[h(s), m]$. The maximum principle indicates that the optimal level of management intensity depends on its marginal productivity in crop production, $\partial f/\partial m$, and is influenced by soil productivity through the yield function.[4] This model highlights the importance of the marginal contributions of soil productivity and nonsoil inputs to crop yields ($\partial f/\partial h$ and $\partial f/\partial m$), and of the relative marginal costs of controlling soil loss versus substituting other inputs as means of maintaining yields.

According to this model a profit-maximizing farmer evaluates the relative contributions and costs of soil and other inputs in crop production when making decisions regarding conservation practices and input use. In fact, recent empirical studies indicate that farmers' perceptions of these tradeoffs and substitution possibilities do influence their management decisions. Saliba [1983], in a study of Wisconsin farmers, found that over 85 percent of the farm operators studied believed that crop yields in their region are affected by continued erosion and that soil erosion requires farmers to use more fertilizer and other inputs to prevent decreases in crop yields. Statistical analyses indicated that the farmers who most strongly believe erosion has negative productivity consequences use significantly more effective erosion-control practices than other farmers in the group studied. Walker notes that the cost of additional inputs used to compensate for declines in soil productivity is a significant component of the damage function he develops, though he was unable to include these costs in his empirical work. Swanson recommends explicit consideration of fertilizer–topsoil tradeoffs but notes that experimental data on the degree to which fertilizer can compensate for eroded soil is sparse.

A final avenue of research suggested by this model relates to the impact of past management choices on land values, and farmers' beliefs regarding this relationship. Soil depth appears in the transversality condition which specifies the marginal value of soil productivity at the end of the planning horizon. If soil productivity has (or if farmers believe it has) an impact on the market value of land, presumably this would provide an incentive to conserve productivity even near the end of farmers' planning horizons, as the years they will farm the land draw to a close.

Saliba [1986] notes that while 80 percent of farmers surveyed either agree or strongly agree that consistent use of erosion control practices has a positive effect on a farm's sale price, the strength of a farmer's opinion on this matter was not statistically related to his use of conservation practices. Bhide *et al.*'s model linking soil loss to farm net returns shows that if land markets were sensitive to soil depth, the profit-maximizing levels of soil loss would fall considerably. However, no research to date has indicated that land values are responsive to farmers' erosion-control practices. In a detailed study of farm sales and each farm's history of erosion control measures (particularly terracing, strip cropping, and contour plowing), Gardner found no statistically discernible influence of conservation practices on farmland prices.

Summary and Conclusions

Use of a generalized theoretical model can ensure that regionally-specific studies begin by considering a comprehensive set of relationships between farm management, soil productivity, crop yields, and

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[4] Suppose, for example, that the production function is concave in m(t), implying diminishing marginal returns to increased input use. Suppose further that yields are proportional to soil productivity, consistent with the usual definition of productivity. Under these assumptions, the yield function would be as follows:

$$y(t) = f[h(s), m] \equiv h[s(t)]m(t)^{\alpha}$$
$$0 \leq \alpha \leq 1$$

and the marginal product of management intensity would be:

$$\partial f/\partial m = \alpha h[s(t)]m(t)^{\alpha-1}$$

Soil productivity clearly affects optimal input levels.

other variables—which can then be adapted to specific research objectives and to data availability, typically the limiting factor in empirical work. The logic of research design suggests beginning with a conceptually complete model and then altering it to fit specific situations, rather than structuring models around data availability and other regional research limitations. The danger in the latter approach lies in not recognizing that some factors have been excluded and losing sight of important relationships and interactions which affect farm-level erosion control.

The model presented here treats soil conservation as an explicit decision variable. A relationship between crop intensity, soil conservation, and soil erosion is incorporated through the state equation and the model links productivity to soil depth and other soil characteristics. Tradeoffs between soil and nonsoil inputs are reflected in both the cost and yield functions, and the model allows soil loss to be reduced through less erosive crop rotations and/or increased soil conservation effort.

One purpose of the theoretical model is to provide structure and direction for empirical work by pinpointing relationships that deserve further attention and by generating testable hypotheses. The model suggests that private incentives to reduce soil loss depend strongly on both the erosion vulnerability of farm cropland and on farmers' perceptions of erosion's effects on farmland productivity and land values. Preliminary empirical evidence supports the notion that farmland erosion vulnerability and susceptibility to crop yield declines are important factors. Available evidence linking soil erosion to land prices is inconclusive.

U.S. soil conservation policy relies on voluntary farmer adoption of erosion control practices. Thus, even where a primary policy goal may be reduction of off-farm water quality impacts, policymakers must carefully consider farmers' perspectives and private incentives related to soil conservation. The question has often been raised: "Do cost-sharing and technical assistance programs provide effective inducements for erosion control?" The research reported here indicates that farmers consider the productivity consequences of their soil management decisions, and that farmers' incentives to adopt effective erosion-control practices can vary significantly depending on the characteristics of the land they farm. During the past five years there has been growing emphasis on the need to target conservation program resources to the nation's most erosive regions. In-depth knowledge of the strength and magnitude of erosion-control incentives highlighted in this research would be extremely useful to policymakers seeking to effectively allocate scarce conservation funds and personnel.

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