FARM LEVEL DYNAMIC ANALYSIS OF SOIL CONSERVATION: AN APPLICATION TO THE PIEDMONT AREA OF VIRGINIA

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Abstract

A conceptual optimal control theory model which considers farm level decision making with respect to soil management is developed. A simplified version of the theoretical model is applied to the Piedmont area of Virginia. The model includes the productivity impacts of both soil erosion and technological progress. Both the theoretical model and its empirical application are improvements over previous efforts. Results suggest that farmers in the study area can achieve substantial reductions in soil erosion by adopting alternative farming practices.

Key words: optimal control theory, soil conservation, dynamic anlysis, productivity.

Most contemporary analyses of the economics of soil conservation have recognized the complex dynamic nature of soil management decisions. Among the noteworthy theoretical and applied works on the overall economics of soil conservation—which incorporate methods of analysis such as optimal control theory, dynamic programming, econometrics, and simulation—are those of McConnell; Saliba; Burt (1972, 1981); and Bhide et al. While the theoretical works of McConnell and Saliba addressed important factors that should be considered in a farm level soil conservation model, they did not consider explicitly state variables relating to investments in soil conservation capital and productive properties of the soil. In the empirical works of Burt (1981) and Bhide et al., optimal decision rules of soil use were derived to maximize the net present value of returns; however, these studies did not consider policy implications of their findings relating to soil conservation issues. In addition, the decision rules in these studies were not clear cut with respect to their implications for farm management practices.

The model presented in this article is an improvement in both the theoretical and empirical application of control theory to soil erosion analysis. The theoretical model is more comprehensive than previous efforts, especially with respect to its treatment of investment in soil conservation capital and soil productivity. The empirical model's results can be applied directly at the farm level.

The specific objectives of this research were: first, to formulate a general farm level dynamic model of soil conservation that would narrow the linkages among variables which affect soil use; second, to empirically apply a version of that model to the Piedmont Area of Virginia; and third, to draw soil conservation policy implications from the empirical application. Because of the scope of this research, the detrimental non-point source pollution effects of soil erosion, as well as the benefits of soil conservation in terms of reduced levels of non-point source pollution, were not considered.

A DYNAMIC DECISION MAKING MODEL OF SOIL CONSERVATION

In this section a dynamic formulation of the soil management problem faced by an economic agent who maximizes the net present value of returns with perfect information is presented. The perfect information assumption is made in order to achieve a better understanding of how soil erosion and the soil productivity impacts of soil erosion affect the economic

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agent's decision making process. For simplicity in the presentation, it will be assumed that the economic agent produces a single crop rotation whose production function is:[1]

$$(1)\ Y_t = f_t(X_{1t}, X_{2t}, ..., X_{nt}, SD_t, SL_t, SP_t, CK_t, W_t, T_t),$$

where Y_t is the yield of the single crop rotation in time t; $X_{1t}, X_{2t},..., X_{nt}$ are the variable inputs of production in time t; SD_t is the topsoil depth in time t; SL_t is the soil loss in time t; SP_t is an index of the stock of "productive properties" (indicator of soil quality) of the soil in time t; CK_t is an index of the stock of conservation capital in time t; W_t is an environmental index in time t; and T_t is a technological index in time t. It is assumed that the first partial derivative of Y_t with respect to any one of the arguments is positive, and the W_t and T_t are exogenously given.

Change of the topsoil depth over time is given by the following equation of motion:

$$(2)\ SD_{t+1} = SD_t + SF_t - SL_t,$$

where SF_t is soil formation in time t, and the other variables are as previously defined.[2] Since soil loss and soil formation could be expected to be a function of the crop being produced, they could be hypothesized to take the following forms:[3]

$$(3)\ SL_t = g_t(X_{1t}, X_{2t}, ... , X_{nt}, SD_t, SL_t, SP_t, CK_t, W_t, T_t), \text{ and}$$

$$(4)\ SF_t = \ell_t(X_{1t}, X_{2t}, ... , X_{nt}, SD_t, SL_t, SP_t, CK_t, W_t, T_t).$$

The index of the stock of soil conservation capital is assumed to change over time according to the following equation of motion:

$$(5)\ CK_{t+1} = CK_t(1 - \delta) + CI_t,$$

where δ is the depreciation rate, which is assumed to be constant, and CI_t is an index of the investment in soil conservation capital at time t. Also, the equation of motion that describes the change over time of the index of the stock of the productive properties of soil is:

$$(6)\ SP_{t+1} = SP_t + PI_t - PL_t,$$

where PI_t is the index of investment in the stock of productive properties[4] and PL_t represents the index of the productive properties lost due to production. Thus, PL_t can be written as:

$$(7)\ PL_t = h_t(X_{1t}, X_{2t}, ... , X_{nt}, SD_t, SL_t, SP_t, CK_t, W_t, T_t).$$

Given equations (1) through (7), the dynamic model formulated below includes three state variables: topsoil depth, stock of soil conservation capital, and stock of the productive properties of the soil.

The behavior of the economic agent toward soil use is determined by the soil's impacts on net revenue, where net revenue, NR_t, is defined as:

$$(8)\ NR_t = P_{Yt}Y_t - \sum_{i=1}^{n} Px_{it}X_{it} - P_{Pt}PI_t - P_{ct}CI_t,$$

where P_{Yt} is the price of the crop in time t; Px_{it} is the price of the i^{th} variable input in time t; P_{pt} is the price per unit of investment in productive properties of the soil in time t; P_{ct} is the price per unit of investment in soil conservation capital in time t; and other terms are as previously defined. The objective of the economic agent, maximization of the net present value of returns, can be represented as:

$$(9)\ \text{Max} \left\{ \sum_{t=0}^{\infty} NR_t(1 + r)^{-t} \right\},$$

where r is the discount rate. It can be argued that infinity is too long for a reasonable planning horizon. The decision maker can separate expression (9) into two components: (1) the net

[1]In the empirical application which follows, the model is extended to include several crop rotations.

[2]In some special cases soil formation could be regarded as zero.

[3]Notice that soil loss in time t, SL_t, in equation (2) and in the left hand side of equation (3) will become a summation of soil losses across crop rotations once the model is expanded to include more than one crop rotation.

[4]PI_t could include factors such as investments made in drainage systems, and certain variable inputs such as fertilizers, lime, etc. could be accounted for in this equation of motion.

present value of returns during the planning horizon, from t=0 to t=T; and (2) the net present value of the land at the end of the planning horizon, which would be represented by the resale value of the land. As McConnell pointed out, breaking up the expression in this manner is equivalent to maximizing the present value of the consumption stream, if the decision maker has access to smoothly working capital markets. Thus, expression (9) can be written as:

$$(10)\ \text{Max}\left\{\sum_{t=0}^{T} NR_t(1+r)^{-1} + \sum_{s=T+1}^{\infty} NR_s(1+r)^{-s}\right\}.$$

The right hand part of expression (10) represents the resale value of the land (RV), which is a function of the state variables at T + 1.[5] That is, the present value of the land at T + 1 is a function of the topsoil depth, the index of the stock of conservation capital, and the index of the stock of productive properties of the soil at T + 1. The right hand part of expression (10) can therefore be represented as the following function of topsoil depth, soil conservation capital, and productive properties of the soil:

$$(11)\ RV(SD_{T+1}, CK_{T+1}, SP_{T+1})(1+r)^{-(T+1)}.$$

By substituting expression (11) into (10), the optimization problem can be written as:

$$(12)\ \text{Max}\left\{\sum_{t=0}^{T} NR_t(1+r)^{-t} + RV(SD_{T+1}, SP_{T+1}, CK_{T+1})(1+r)^{-(T+1)}\right\},$$

subject to:

$$(13)\qquad SD_{t+1} = SD_t + SF_t - SL_t,$$

$$(14)\qquad CK_{t+1} = CK_t(1-\delta) + CI_t,$$

$$(15)\qquad SP_{t+1} = SP_t + PI_t - PL_t,$$

$$(16)\qquad SD(0) = SD_0,$$

$$(17)\qquad SP(0) = SP_0,\ \text{and}$$

$$(18)\qquad CK(0) = CK_0$$

for all:

$$0 \le t \le T,$$

where $X_{1t}, X_{2t}, \dots, X_{nt} \ge 0$; $SD_t \ge 0$; $SF_t \ge 0$; $SL_t \ge 0$; $CK_t \ge 0$; $CI_t \ge 0$; $SP_t \ge 0$; $PI_t \ge 0$; $PL_t \ge 0$; and for $t \ge T + 1$; $SD_{T+1} \ge 0$; $SP_{T+1} \ge 0$; and $CK_{T+1} \ge 0$. The present value Hamiltonian of this problem can be written as:

$$(19)\ H = NR_t + \mu_{t+1}[SF_t - SL_t] + \beta_{t+1}[-\delta CK_t + CI_t] + \Gamma_{t+1}[PI_t - PL_t],$$

where μ_{t+1}, β_{t+1}, are user costs of soil depth, stock of soil conservation capital, and stock of productive properties of the soil, respectively. The other variables are as previously defined.

The necessary conditions for the solution of this control problem are obtained in terms of the derivatives of the present-value Hamiltonian with respect to the control, state, and co-state variables plus transversality conditions associated with the state variables of the problem. Thus, taking the partial derivatives of (19) with respect to the control variables results in:[6]

$$(20)\ \frac{\partial H}{\partial X_{it}} \rightarrow P_{Y_t}\left(\frac{\partial f_t}{\partial X_{it}}\right) = P_{X_{it}} + \mu_{t+1}\left(\frac{\partial g_t}{\partial X_{it}}\right) - \mu_{t+1}\left(\frac{\partial \ell_t}{\partial X_{it}}\right) + \Gamma_{t+1}\left(\frac{\partial h_t}{\partial X_{it}}\right) \text{ for } i = 1, \dots, n,$$

$$(21)\ \frac{\partial H}{\partial SL_t} \rightarrow P_{Y_t}\left(\frac{\partial f_t}{\partial SL_t}\right) = \mu_{t+1}\left(\frac{\partial g_t}{\partial SL_t}\right) - \mu_{t+1}\left(\frac{\partial \ell_t}{\partial SL_t}\right) + \Gamma_{t+1}\left(\frac{\partial h_t}{\partial SL_t}\right),$$

$$(22)\ \frac{\partial H}{\partial CI_t} \rightarrow P_{ct} = \beta_{t+1},\ \text{and}$$

$$(23)\ \frac{\partial H}{\partial PI_t} \rightarrow P_{pt} = \Gamma_{t+1}.$$

Condition (20) requires that the value of the

[5]The theoretical justification for this result is discussed by Dorfman, and by Sheti and Thompson.

[6]Notice that there will be additional control variables if more crop rotations are introduced into the model.

marginal product of the i^{th} variable input be equal to the value of the input cost plus the marginal user cost of using the soil, minus the marginal user cost due to the formation of new soil, plus the marginal user cost incurred by using the productive properties of the soil. If it is assumed that soil formation due to production is zero, that is, $(\partial \ell / \partial X_{it}) = 0$, then condition (20) indicates that production will be at a "lower" level than it would be if soil properties and soil loss had not been taken into account in the production process because of the "penalties" (marginal user costs) implied by soil use in production. Condition (21) implies that soil loss is tolerated until the marginal unit value of soil loss equals the foregone profits from having the soil on the farm which is represented by $\Gamma_{t+1}(\partial h_t / \partial SL_t) + \mu_{t+1}(\partial g_t / \partial SL_t - \partial \ell_t / \partial SL_t)$.

Condition (22), for the investment in soil conservation capital, requires that a unit of soil conservation capital should be added to the stock up to the point at which its cost equals the marginal user cost of the capital for conservation. In contrast, condition (23), for the investment in productive properties of the soil, requires that the stock of productive properties should be increased up to the point at which its price equals the marginal user cost of the properties of the soil.

Taking the partial derivatives of the Hamiltonian in (19) with respect to the state variables, and simplifying, results in the following three equations. For SD_t, the topsoil depth in time t, the corresponding optimal path of its associated user cost is:

$$(24)\quad \mu_{t+1} - \mu_t = r\mu_t - \left[P_{Y_t}\left(\frac{\partial f_t}{\partial SD_t}\right) + \mu_{t+1}\left(\frac{\partial \ell_t}{\partial SD_t} - \frac{\partial g_t}{\partial SD_t}\right) - \Gamma_{t+1}\left(\frac{\partial h_t}{\partial SD_t}\right) \right].$$

Equation (24) indicates that the implicit cost of soil depth, $\mu_{t+1} - \mu_t$, must grow at the rate of discount, r, minus the contribution of soil depth to current profits and the net effect on one-period-ahead soil depth, plus its one-period-ahead effect on productive properties of the soil.

For SP_t, the stock of productive properties of the soil in time t, the corresponding optimal path of its associated user cost is:

$$(25)\quad \Gamma_{t+1} - \Gamma_t = r\Gamma_t - \left[P_{Y_t}\left(\frac{\partial f_t}{\partial SP_t}\right) + \mu_{t+1}\left(\frac{\partial \ell_t}{\partial SP_t} - \frac{\partial g_t}{\partial SP_t}\right) - \Gamma_{t+1}\left(\frac{\partial h_t}{\partial SP_t}\right) \right].$$

This equation indicates that the implicit cost of productive properties of the soil, $\Gamma_{t+1} - \Gamma_t$, must grow at the rate of discount r minus the contribution of the productive properties to current profits and their net effect on one-period-ahead soil depth, plus its one-period-ahead effect on productive properties of the soil. For CK_t, the stock of conservation capital in time t, the corresponding optimal path of its associated user cost is:

$$(26)\quad \beta_{t+1} - \beta_t = r\beta_t - \left[P_{Y_t}\left(\frac{\partial f_t}{\partial CK_t}\right) + \mu_{t+1}\left(\frac{\partial \ell_t}{\partial CK_t} - \frac{\partial g_t}{\partial CK_t}\right) - \Gamma_{t+1}\left(\frac{\partial h_t}{\partial CK_t}\right) \right] - \beta_{t+1}(-\delta).$$

Equation (26) indicates that the implicit cost of soil conservation capital, $\beta_{t+1} - \beta_t$, must grow at the rate of discount, r, minus the contribution of soil conservation capital to current profits and its net effect on one-period-ahead soil depth, plus its one-period-ahead effect on beneficial soil properties, and the one-period-ahead proportional marginal user cost of soil conservation capital. This last term in condition (26), $\beta_{t+1}(-\delta)$, updates the soil conservation capital user cost, since soil conservation capital at t depreciates by δ before the time period t+1.

The conditions with respect to how the stocks of soil depth, soil properties, and soil conservation capital change through time, depending on new additions, if any, to the stocks, are given by:

$$(27)\quad SD_{t+1} - SD_t = SF_t - SL_t,$$

$$(28)\quad SP_{t+1} - SP_t = PI_t - PL_t, \text{ and}$$

$$(29)\quad CK_{t+1} - CK_t = CI_t - \delta CK_t.$$

Finally, the conditions for the stocks in period T+1, that is, the transversality conditions associated with this control problem, are:

$$(30)\quad \frac{\partial RV}{\partial SD_{T+1}} = \mu_{T+1},$$

$$(31) \qquad \frac{\partial RV}{\partial SP_{T+1}} = \Gamma_{T+1}, \text{ and}$$

$$(32) \qquad \frac{\partial RV}{\partial CK_{T+1}} = \beta_{T+1}.$$

As pointed out by McConnell, and indirectly by others such as Aoki and Kamien and Schwartz, conditions (30), (31), and (32) make it uneconomical for the decision maker to deplete the value of the land near the end of the planning horizon. These conditions would hold if economic agents were fully aware of the contribution of a soil to both current production and the resale value of the land.

It is appropriate to point out some general results of the soil management model formulated above. Assuming that the marginal product of soil is positive, in general, it would be expected that decreased variable factor prices, increased product prices, and technological changes that increase the value of holding the topsoil depth in future time periods will provide incentives to economic agents to conserve the soil resource for the future. Also, the lower the discount rate used in the analysis, the greater the incentives will be to conserve soil for the future.

One of the attractive characteristics of the model formulated above is that control of soil erosion through time can be accomplished not only by choosing the crop rotations to be grown but also by investing in soil conservation capital. Two instruments are therefore available to achieve desired levels of soil erosion. Another important characteristic of the model is that it takes into account the loss of productive properties of the soil as erosion occurs. Also, the model is more flexible than previous models because it is easier to modify in terms of introducing soil conservation policies such as cost-sharing and variable cost-sharing. For example, these policies could be introduced directly in the objective function when the model is analyzed for a given conservation practice such as terraces or stripcropping. These characteristics will become clearer later when an application of the above model is presented. Furthermore, as will be seen later, the model will provide straightforward recommendations with respect to what, when, and in which amounts crop rotations should be employed so that the soil resource is used optimally.[7]

THE STUDY AREA

The Soil Conservation Service of the United States Department of Agriculture has determined that the soils of the fourteen-county Piedmont Bright Leaf Area of south-central Virginia are among the most severely eroded in the nation (SCS, 1983). Average annual topsoil loss on cropland is 18 tons per acre. This rate is over twice the state average, and three and one-half times greater than the tolerance value ("T" value) of the soils in the area.[8] Soil conservation in this region has therefore become an important policy issue, not only because of erosion impacts on long-term agricultural productivity, but also because of the degradation of water quality in the streams of the region. While this latter consideration is very important, it was beyond the scope of this study.

SPECIFICATION OF THE DYNAMIC REPRESENTATIVE FARM MODEL FOR THE PIEDMONT AREA OF VIRGINIA

Using data from the 1982 Census of Agriculture (U.S. Department of Commerce), a representative farm for the Piedmont Bright Leaf Area with 174 acres of cropland was developed. Four basic farming practices were included in the empirical modeling. They were up-and-down-the-slope cultivation, contouring, stripcropping, and terracing.

Twenty-eight crop rotations were considered in the models as the decision variables. The crops which form part of the rotations are defined as: tobacco (TB); barley (BA); wheat (WH); corn (CT); no-till corn (CNO); soybeans (S); no-till soybeans (SNO); no-till wheat-soybean double-cropped (DWS); no-till barley-soybean double-cropped (DBS); sorghum (SG); no-till sorghum (SGNO); no-till

[7]From a social point of view, the degree of efficiency and/or optimality of use of the soil resource as determined by the necessary conditions of the above model will depend on the information generated by both the economic agent and the market. Assuming the absence of externalities, by satisfying the above necessary conditions an optimal management of the soil resource will be achieved. In the presence of externalities, however, the solution provided by the model could lead to under-conserving or over-conserving the soil resource, which could lead to a social loss.

[8]"T" value of a soil is defined as the maximum amount of soil loss per acre per year that will permit a high level of productivity to be sustained economically and indefinitely (Stamley and Smith).

corn silage (CS); no-till rye silage (RS); alfalfa (AL); and fescue (FE). All crops were cultivated with a conventional tillage system unless otherwise indicated.[9]

Optimally, "state variables in a dynamic system must encompass sufficient information on the decision process so that when the variables are at a given level at a point in time, the history of the decision process is almost completely subsumed for purposes of optimal decisions in the future" (Burt 1981, p. 84). Thus, in empirical applications of control models which seek to optimize the use of the soil resource, variables associated with plant nutrients and chemistry of the soils should be considered. Information with respect to the relationship of these variables to crop yields is either not very precise or unavailable. A simplification must therefore be made, and a focus must be placed on variables which are affected directly by erosion and which in turn affect crop yields. In the empirical models considered below, only one state variable, topsoil depth, was taken into account explicitly. Another state variable, soil conservation capital, was also indirectly considered in the models since they were formulated for four different farming practices. The decision variables are specified in terms of the percentage of one acre of the representative farm's land in a particular crop rotation. That is, the models have been scaled down to one acre of the representative farm, and their results can be generalized to the 174 acres of the representative farm. The specification of the dynamic system considered in this study is:

$$(33)\ \text{Max}\left\{\sum_{i=1}^{28}\sum_{t=0}^{50} U_{it}(NR_{it})[(1+\upsilon)/(1+r)]^t\right\},$$

subject to:

$$(34)\ X_{t+1} = X_t - \sum_{i=1}^{28} U_{it}(NSL_i) \text{ for } t = 0,1,\dots,50,$$

$$(35)\ \sum_{i=1}^{28} U_{it} \leq 1 \text{ for } t = 0,1,\dots,50,$$

$$(36)\ U_{1t} + \left(\frac{1}{2}\right)(U_{11t} + U_{12t} + U_{15t} + U_{16t}) + \left(\frac{1}{3}\right)(U_{13t} + U_{14t}) \leq 0.1035$$

$$\text{for } t=0,1,\dots,50, \text{ and}$$

$$(37)\ X_0 = 6.4973,$$

where U_{it} is the percentage of one acre of land in crop rotation i in time t; NR_{it} is a per-acre net return function for the i^{th} crop rotation in time t; υ is a technological change factor; r is the discount rate; X_t is the topsoil depth in inches in time t; and NSL_i is the net soil loss per acre per year caused by the i^{th} rotation. The technological change factor, υ, used in this paper is defined as the proportion by which the net revenue function shifts over time due to technical progress. The net soil loss figure used is equal to the gross soil loss obtained for each rotation, as computed by using the Universal Soil Loss Equation, minus the equivalent in inches of the "T" value for the soils common in the area, which is 0.0315 inches, or 5 tons per acre per year (Wischmeier and Smith). Notice that a fifty-one year planning horizon was employed in the analysis (year 0, plus 50 years). A planning horizon of this length was used because it is hard to believe that a decision maker would plan more than two generations ahead. Also, in the limit, the marginal increment to the objective function value due to an increase in the planning horizon will almost be zero, thus, the solution to the fifty-one year analysis can be regarded as a stable solution.

Equation (35) is a land constraint. Equation (36) is a constraint on the percentage of land devoted to the production of tobacco. This constraint was introduced due to the existence of tobacco production quotas. A tobacco allotment of 37,800 pounds was assumed for the 174-acre representative farm.[10] Finally, condi-

[9]In particular, the rotations considered, with the number in parentheses representing the number of years in the rotation, were: R1 = TB (1); R2 = CT (1); R3 = WH (1); R4 = BA (1); R5 = S (1); R6 = SG (1); R7 = AL (1); R8 = CS (1); R9 = RS (1); R10 = FE (1); R11 = TB WH (2); R12 = TB BA (2); R13 = TB DWS FE (3); R14 = TB DBS FE (3); R15 = TB TB DWS FE (4); R16 = TB TB DBS FE (4); R17 = CT DWS (2); R18 = CT DBS (2); R19 = CT DWS SG (3); R20 = CT CT DWS (3); R21 = CNO DWS (2); R22 = CNO DWS SGNO (3); R23 = CNO CNO DWS (3); R24 = SG DWS (2); R25 = SGNO DWS (2); R26 = SG SG DWS (3); R27 = SGNO SGNO DWS (3); and R28 = CS RS AL (10). For example, R20 = CT CT DWS (3) means a three-year rotation with two years of conventional-tillage corn followed by one year of double-cropped wheat-soybeans. An analogous procedure could be applied to interpret the rest of the rotations with the exception of R28. R28 is a ten-year rotation in which there will be one year of corn silage followed by five years of rye silage followed by five years of alfalfa.

[10]Thirty-seven thousand eight hundred pounds of tobacco is equivalent to 18 acres of land in tobacco production, and 18/174 ≅ 0.1035.

tion (37) is an initial condition on topsoil depth in the area.[11] Thus, the objective of this model is to maximize the sum of the discounted value of net returns to land, overhead, risk, and management for one acre of land of a representative farm in the Piedmont Bright Leaf Area from t=0 to t=50, equation (33), subject to state equation (34), constraints (35) and (36), and an initial condition (37).

ESTIMATION OF PER ACRE NET RETURN FUNCTIONS

Following Soil Conservation Service Guidelines (SCS, 1977), budgets for each of the crops considered were developed. Five-year (1980–84) average prices of crops and operating costs were used. This procedure was followed to minimize the risk of overestimating or underestimating the prices and costs due to weather or other cyclical variations. Given the five-year average price of crops and their corresponding per-acre yields, a total gross revenue figure per crop was obtained. Then the associated per-crop operating costs were adjusted for the four different farming practices considered and a net return per unit of yield per farming practice was calculated.

There are two ways in which relationships between crop yields and topsoil depth can be obtained. The first is by actual measurement of topsoil depths and crop yields across several fields or plots. Then, estimates of the relationship between crop yield and topsoil depth can be found by performing regression analysis on those data points. The second method is subjective elicitation of the relationships between topsoil depth and crop yields through a survey of knowledgeable individuals. With careful survey design, a particular functional form can be imposed.

The regression analysis procedure may be regarded as superior, since parameter estimates can be subjected to hypothesis testing. Such a procedure, however, could become both time consuming and costly if it had to be performed for very many crops, which would have been the case in this study. Therefore, the second procedure discussed above was chosen. The method used to subjectively elicit estimates of the relationship between topsoil depth and crop yields is known as the Percentile-Based Beta Distribution Procedure (Young). The functional form imposed in the survey was the Mitscherlich-Spillman, which has been found to be appropriate for this type of analysis.[12] For a detailed description of the survey and results, see Segarra. Segarra has also demonstrated that the elicitation procedure produced similar results to the plot-regression analysis approach for soybeans.

Having obtained net return per unit of production per farming practice figures and a per acre yield function for each of the crops in the rotations, a net revenue function per rotation per farming practice was constructed according to the number of crops and number of years in that rotation. The net revenue function per rotation for a particular farming practice took the form:

$$(38)\quad NR_t = P_i[R_i(Y_{it})] + P_k[R_k(Y_{kt})] + \cdots + P_n[R_n(Y_{nt})],$$

where NR_t is the per acre net return at time t of rotation j; $P_i \ldots P_n$ is the proportion of years of crop i in the rotation to the total number of years in rotation j, for crop i to crop n; $R_i \ldots R_n$ is the net return per unit of production of crop i to crop n; and $Y_{it} \ldots Y_{nt}$ is per acre yield of crop i to crop n in time t.

The highly non-linear nature of the per acre net return functions per rotation formularized in (38) could have led to stability problems in the dynamic optimization model. Net returns were therefore simulated through time in order to reduce the nonlinearity of the system, using the following procedure. With an initial topsoil depth of 6.4973 inches (Segarra), and given the net topsoil losses associated with the rotations as predicted by the Universal Soil Loss Equation (Wischmeier and Smith), a series of net returns for each farming practice per acre per rotation was generated. Also, the topsoil depths corresponding to these net returns were obtained. Then, a quadratic function of the following form was fitted to these data points for each of the rotations and farming practices by using Ordinary Least Squares:

[11] A topsoil depth of 6.4973 inches was the mean value of topsoil depth obtained from a survey conducted in the Piedmont Bright Leaf Area (Segarra).

[12] The Mitscherlich-Spillman function used to model per acre crop yields took the form $Y_t = a + b(1 - R^{X_t})$, where Y_t is per acre crop yield in time t; a is per acre crop yield when topsoil depth is zero; a + b is the asymptotic value of crop yield when $\lim X_t \to \infty$; R is a constant ratio of the marginal product of the X_{t+1}th topsoil depth to the marginal product of the X_tth topsoil depth; and X_t is topsoil depth in time t.

(39) $NR_t = \alpha + \beta_1 X_t + \beta_2 X_t^2 + \epsilon_t$,

where X_t is topsoil depth in year t, and ϵ_t is an error term. Goodness of fit of equation (39) was excellent (see Segarra for more details). The parameters α, β_1, and β_2 of (39) were used in the objective function of the optimization problem, equation (33).

RESULTS OF THE REPRESENTATIVE FARM MODEL

The representative farm models were solved[13] for a range of discount rates, but results reported here are only those obtained for 8.5 percent. Also, three technological change scenarios were considered in the analysis. They were: pessimistic at zero percent, moderate at 1.5 percent, and optimistic at 3 percent increase per time period.

After solving the representative farm models for the three technological change scenarios and the four farming practices, a maximum of four crop rotations out of the twenty-eight appeared in the optimal solutions. These crop rotations were TB, TB TB DWS FE, CNO DWS, and CNO CNO DWS. Tables 1 to 4 present the levels and trajectory of the decision variables corresponding to the optimal solutions.

Up-and-Down-the-Slope Cultivation

As indicated by the trajectory and levels of the decision variables in the optimal solutions of this model, presented in Table 1, technological progress has little impact on the optimal decision rule. Looking at the optimal decision rule across technical change scenarios, the only difference is that with the 1.5 and 3.0 percent technical change scenarios, 79.30 percent of the land is planted in the CNO CNO DWS rotation rather than the CNO DWS rotation, with zero technical change, in the last year of the planning horizon.

The reason for that result is that given the topsoil depth at T−1, the net revenue function associated with the CNO CNO DWS rotation dominates that of the CNO DWS rotation, and as a result, the switch occurs. In fact, what triggers a change in the optimal decision rule to follow, indicated by the switching of rotations, is the overlapping of the quadratic net revenue functions of the rotations at a particular topsoil depth and point in time. That is, there are ranges of topsoil depth over which a certain rotation dominates another, but as erosion occurs over time, there may be topsoil depths at which it becomes dominated by the other crop rotation.

TABLE 1. LEVELS OF DECISION VARIABLES IN THE OPTIMAL SOLUTION OF THE REPRESENTATIVE FARM MODEL UNDER THREE SCENARIOS OF TECHNOLOGICAL CHANGE AND AN 8.5 PERCENT DISCOUNT RATE FOR UP-AND-DOWN-THE-SLOPE CULTIVATION[a]

	Percentage of An Acre of Land 0.0% Tech. Change			
Year	TB (18.17)	TB TB DWS FE (9.35)	CNO DWS (1.62)	CNO CNO DWS (4.94)[b]
0	10.35	00.00	89.65	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	10.35	00.00	89.65	00.00
31	00.00	20.70	79.30	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
50	00.00	20.70	79.30	00.00

	Percentage of An Acre of Land 1.5% and 3% Tech. Change[c]			
Year	TB	TB TB DWS FE	CNO DWS	CNO CNO DWS
0	10.35	00.00	89.65	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	10.35	00.00	89.65	00.00
31	00.00	20.70	79.30	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
49	00.00	20.70	79.30	00.00
50	00.00	20.70	00.00	79.30

[a]Results are reported only when the levels of the decision variables change.

[b]Numbers in parentheses represent the soil loss per rotation in tons per acre per year.

[c]Results were the same with 1.5 percent technological change as with 3.0 percent technological change.

[13]Solution of the dynamic system (33) through (37) was obtained by using a computer package referred to as the Modular In-core Nonlinear Optimization System (MINOS). The algorithms used by MINOS to solve the model are a reduced-gradient algorithm (Wolfe) in conjunction with a Quasi-Newton algorithm (Davidson). The implementation of these algorithms follows that described by Murtagh and Saunders. Separate models were solved for each of the four management options due to computer limitations. In addition to computer limitations, there is an additional reason that all four different management practices were not incorporated into an overall model. Such an overall model would be problem specific to a particular farm, for example with respect to how many acres can be in terraces, since all fields on a farm may not be steep enough to need terraces. Because the model was formulated to give solutions in terms of the proportion of one acre of land in a particular rotation under a given cultivation practice, the resulting solutions can be applied in a per field fashion to a farm.

Contouring

As illustrated by the optimal solutions to this modeling, presented in Table 2, technological progress has no influence on the optimal decision rule. Notice that the contouring optimal decision rules are very similar to those of up and down the slope. However, note that the topsoil losses caused by contouring are much lower than those for up and down the slope. Since the costs associated with contouring are not much different than those associated with up and down the slope and topsoil losses associated with contouring are much lower than those associated with up and down the slope, crop yields, and thus optimal net present values of contouring, will be higher than those of up and down the slope across technological change scenarios.

TABLE 2. LEVELS OF DECISION VARIABLES IN THE OPTIMAL SOLUTION OF THE REPRESENTATIVE FARM MODEL UNDER THREE SCENARIOS OF TECHNOLOGICAL CHANGE AND AN 8.5 PERCENT DISCOUNT RATE FOR CONTOURING[a]

	Percentage of An Acre of Land 0.0, 1.5, 3% Tech. Change[b]			
Year	TB (6.59)	TB TB DWS FE (2.17)	CNO DWS (−1.68)	CNO CNO DWS (−0.03)[c]
0	10.35	00.00	89.65	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	10.35	00.00	89.65	00.00
31	00.00	20.70	79.30	00.00
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
50	00.00	20.70	79.30	00.00

[a]Results are reported only when the levels of the decision variables change.

[b]Results were the same for 0, 1.5, and 3 percent technological change.

[c]Numbers in parentheses represent the soil loss per rotation in tons per acre per year. Negative numbers indicate net soil gain.

Stripcropping

As depicted by the levels of the decision variables and their trajectory in the optimal solution of this model, presented in Table 3: (1) the continuous tobacco rotation, TB, is always kept at its upper limit, 10.35 percent across technological change scenarios, and (2) the higher the rate of technological change, the sooner the switch from the CNO DWS to the CNO CNO DWS rotation occurs. Overall, with stripcropping the optimal decision rules tend to be more sensitive to technological progress than with up and down the slope and contouring. Also notice that when comparing the optimal decision rules for stripcropping with respect to tobacco production, as contrasted with the two previous farming practices, the TB rotation stays in the stripcropping solution and no switch occurs to the TB TB DWS FE rotation as was the case with up and down the slope and contouring. The reason for this is the lower soil loss, and thus yield as well as revenue maintenance, with TB production under stripcropping, as compared to the other two practices.

TABLE 3. LEVELS OF DECISION VARIABLES IN THE OPTIMAL SOLUTION OF THE REPRESENTATIVE FARM MODEL UNDER THREE SCENARIOS OF TECHNOLOGICAL CHANGE AND AN 8.5 PERCENT DISCOUNT RATE FOR STRIPCROPPING[a]

	Percentage of An Acre of Land 0.0% Tech. Change		
Year	TB (3.99)	CNO DWS (−2.48)	CNO CNO DWS (−1.22)[b]
0	10.35	89.65	00.00
.	.	.	.
.	.	.	.
.	.	.	.
46	10.35	89.65	00.00
47	10.35	00.00	89.65
.	.	.	.
.	.	.	.
.	.	.	.
50	10.35	00.00	89.65
	Percentage of An Acre of Land 1.5% Tech. Change		
Year	TB	CNO DWS	CNO CNO DWS
0	10.35	89.65	00.00
.	.	.	.
.	.	.	.
.	.	.	.
44	10.35	89.65	00.00
45	10.35	00.00	89.65
.	.	.	.
.	.	.	.
.	.	.	.
50	10.35	00.00	89.65
	Percentage of An Acre of Land 3.0% Tech. Change		
Year	TB	CNO DWS	CNO CNO DWS
0	10.35	89.65	00.00
.	.	.	.
.	.	.	.
.	.	.	.
42	10.35	89.65	00.00
43	10.35	00.00	89.65
.	.	.	.
.	.	.	.
.	.	.	.
50	10.35	00.00	89.65

[a]Results are reported only when the levels of the decision variables change.

[b]Numbers in parentheses represent the soil loss per rotation in tons per acre per year. Negative numbers indicate net soil gain.

Terraces

Once again in the outcome of this analysis, presented in Table 4, as was the case with stripcropping, the continuous tobacco rotation, TB, is always kept at its upper limit, 10.35 percent across technological change scenarios. Unlike previous practices, the optimal decision rule starts with the CNO CNO DWS rotation in the early years, then switches to the CNO DWS rotation in year 11, and switches back to CNO CNO DWS in year 31. As with contouring, technological progress has no influence on the optimal decision rule.

Given the trajectory and levels of the decision variables depicted in Tables 1 to 4, two implications of the twelve alternative models can be deduced. First, tobacco production is always at its upper limit over the planning horizon across all models. With up and down the slope and contouring some switching occurs between the TB and TB TB DWS FE rotations, while with stripcropping and terracing the TB rotation is always present. This result should not be surprising since the high net returns of tobacco, relative to other crops, would be internalized in the decision making process, even though it has a high erosion rate and adverse productivity impact relative to other crops.

The other implication of these results is that given a particular farming practice, optimal decision rules tend to be somewhat stable across rates of technological progress. When comparing optimal decision rules across farming practices, however, some changes occur. For example, the up and down the slope and contouring optimal decision rules are not very different from each other, but if they are compared to terracing, significant differences are observed. This is an encouraging result of the analysis because, after taking the differences in cost of production implied by contouring and terraces and their differences in soil erosion rates into account, the model is able to re-rank crop rotations which should appear in the optimal decision rule. In other words, differences in decision rules, rather than indicating instability in the model formulation, reflect the underlying biological and economic factors influencing the decision making process.

A summary of the net present value of returns and soil loss implications corresponding to the solutions in Tables 1 to 4 is presented in Table 5.[14] As depicted in that table, given a particular farming practice, as technological

TABLE 4. LEVELS OF DECISION VARIABLES IN THE OPTIMAL SOLUTION OF THE REPRESENTATIVE FARM MODEL UNDER THREE SCENARIOS OF TECHNOLOGICAL CHANGE AND AN 8.5 PERCENT DISCOUNT RATE FOR TERRACING[a]

Year	Percentage of An Acre of Land 0, 1.5, 3% Tech. Change[b] TB (0.79)	CNO DWS (−3.33)	CNO CNO DWS (−2.50)[c]
0	10.35	00.00	89.65
.	.	.	.
.	.	.	.
.	.	.	.
10	10.35	00.00	89.65
11	10.35	89.65	00.00
.	.	.	.
.	.	.	.
.	.	.	.
30	10.35	89.65	00.00
31	10.35	00.00	89.65
.	.	.	.
.	.	.	.
.	.	.	.
50	10.35	00.00	89.65

[a]Results are reported only when the levels of the decision variables change.

[b]Results were the same for 0, 1.5, and 3 percent technological change.

[c]Numbers in parentheses represent the soil loss per rotation in tons per acre per year. Negative numbers indicate net soil gain.

TABLE 5. RESULTS OF THE REPRESENTATIVE FARM MODELS WITH AN 8.5 PERCENT DISCOUNT RATE UNDER FOUR DIFFERENT FARMING PRACTICES

Optimal Value ($/AC)[a]	Technological Change (Percent)	Farming Practice	Final Topsoil Depth (Inches)[b]	Average Gross Topsoil Loss (t/a/y)[c]	Average Net Topsoil Loss[d] (t/a/y)
3,560.49	0	Up and Down	5.44	8.29	3.29
4,189.93	1.5	Up and Down	5.42	8.34	3.34
5,037.18	3.0	Up and Down	5.42	8.34	3.34
3,675.77	0	Contouring	6.77	4.15	−0.85
4,329.32	1.5	Contouring	6.77	4.15	−0.85
5,209.09	3.0	Contouring	6.77	4.15	−0.85
3,379.58	0	Stripcropping	7.06	3.26	−1.74
3,980.95	1.5	Stripcropping	7.04	3.30	−1.69
4,790.50	3.0	Stripcropping	7.03	3.35	−1.65
3,520.71	0	Terracing	7.29	2.54	−2.46
4,148.67	1.5	Terracing	7.29	2.54	−2.46
4,994.91	3.0	Terracing	7.29	2.54	−2.46

[a]Net present value of returns to land, overhead, risk, and management per acre over fifty-one year planning horizon.

[b]Initial topsoil depth was 6.4973 inches.

[c]Tons per acre per year.

[d]Negative values indicate net topsoil gain.

[14]When the model was solved for other discount rates, it was found that as discount rates were increased the optimal values of the solutions were decreased. Furthermore, it was observed that the decision variables in the optimal solution were more sensitive to changes in the discount rates than to changes in technological progress.

change increases the optimal value of the solution increases. Also, notice the differences in the optimal value of the solutions across farming practices. These differences come about because each farming practice faces a different set of net revenues due to differences in the cost of production, soil erosion rates, and rotations in the solution.

An interesting interpretation of the optimal values of the solutions is that they should reflect the long-run price of an acre of cropland in the Piedmont Bright Leaf Area. Depending on several factors, the price of an acre of cropland in the Piedmont Area lies somewhere between $1,500 and $3,000 per acre. Deviations between the actual price of land and the implied long-run price of land could be due to: (1) overestimation of the long-term returns to land because of government intervention in the short-run in the markets of some agricultural commodities such as tobacco, (2) overestimation of future technological change, or (3) risk factors which were not introduced and which would tend to reduce the net present value of returns. Remembering that the optimal values obtained do not reflect ownership expenses, nor risk and management considerations, it can be stated that the solutions in Table 5, particularly the ones associated with low levels of technological progress, provide a good approximation of crop land price conditions in the Piedmont Area.

With respect to the average per acre topsoil losses implied by the activity levels of the optimal solutions depicted in Table 5, it can be seen that the gross topsoil losses for all the optimal solutions except for those of up and down the slope are below the "T" limit for the soils of the representative farm. Also, it can be noted that the net topsoil loss is minimal for up and down the slope and that, in net terms, topsoil will be created under the other three farming practices if production recommendations depicted in Tables 1 to 4 are followed.

One important policy implication which can be deduced from the results is that sizeable reductions in gross topsoil loss, which contributes to nonpoint source pollution, can be accomplished by switching from up and down the slope to another practice. In particular, switching from up and down the slope to contouring will increase the net present value of returns and decrease soil loss. Whereas, switching from up and down the slope to either stripcropping or contouring will reduce the value of the solution. This decrease, however, would be a minimal percentage in comparison to the percentage reduction of topsoil loss. For example, the solution for up and down the slope with 1.5 percent technological change is $4,189.93, with an associated average gross topsoil loss per acre per year of 8.3398 tons. Under the same technological change scenario, but with stripcropping, the optimal value would be decreased by $208.98, while average gross topsoil loss would be reduced from 8.3398 tons per acre per year to 3.3050 tons. That is, there would be a trade-off of a 5 percent decrease in net present value of returns for a 60 percent reduction in annual gross topsoil loss by switching from up and down the slope to stripcropping. Tables 1 and 3 present the changes that would have to be made to switch from up and down the slope to stripcropping in terms of the proportion of land in various rotations in those solutions. Notice that if terraces were employed, assuming the same scenario, net present value of returns would not be decreased by as much as with stripcropping and average annual gross topsoil loss would be decreased by more than with stripcropping.

These results can be used to establish subsidies or cost-sharing programs to promote soil conservation. In the particular case analyzed above, a potential policy would be, for example, to give a subsidy of $208.98 per acre to the farmers if and only if they follow the production recommendations obtained with stripcropping. The subsidy could be provided as either a lump-sum payment in the first year of the program or as an equivalent annuity of $16.63 over the planning horizon. Alternate policies could also be drawn. For example, since production recommendations implied by the models involve double cropping, and therefore no-tillage operations are required, a possible policy would be to provide half of the per acre subsidy in the first year, $104.49, and the rest as an annuity of $8.32 over the planning horizon so that farmers can make any needed adjustments in machinery without imposing a radical financial burden on their income in the short run.

These examples illustrate the kind of policies that could be drawn from the models. The empirical models formulated above are flexible enough so that changes in discount rates, technological progress, and planning horizon scenarios can easily be made to arrive at a more precise figure for a specific situation and/or to analyze a particular policy.

CONCLUSIONS

This research attempted to bring together both theoretical and empirical methods of economic analysis to address the crop productivity impacts of soil erosion as they affect the decision making behavior of private economic agents. The empirical models developed here are for a representative farm in a particular area. As deviations are made from that representative farm, changes would be expected in the value of the optimal solutions. It is felt, however, that the models developed here are flexible enough to accommodate additional characteristics and/or constraints that may be found in other regions where soil erosion represents a threat to both nonpoint source pollution and agricultural production.

The model formulated here has some distinctive features which are worth emphasizing. Previous empirical models of a similar nature (Bhide et al.; and Burt, 1981) were not very flexible, whereas the one formulated here permits easy introduction of additional constraints. Another improvement in the model is that the decision rule has a straightforward interpretation, whereas in previous empirical applications the number of decision variables was reduced to one or two, namely optimal soil loss per time period (Bhide et al.) or percentage of land in winter wheat (Burt, 1981).

A reduction in the number of decision variables to one or two is not by any means inadequate. In fact, the number of decision variables in the models treated in this paper could have been reduced to one (see Burt, 1972, and Burt and Cummings on how to reduce the number of decision variables). However, such a reduction may obscure and thus decrease the significance of the results because in some cases it can become quite difficult to explain and/or interpret the optimal decision rules which are obtained.

Analysis of the results of the representative farm models formulated in this research shows that sizeable reductions in topsoil loss can be accomplished by changing cultivation practices. Because of the change in farming practices, from up and down the slope to either stripcropping or terracing, reductions in the present value of net returns to land, overhead, risk, and management are expected, but this decrease in returns was found to be a minimal percentage when compared to percentage reductions in topsoil loss. This result has very important policy implications since conservation efforts could be accomplished by following production recommendations indicated by the solutions of the models. Policy mechanisms must be evaluated in terms of their effectiveness so that the correct set of incentives and/or circumstances are present in order to promote soil conservation. Thus, educational programs to make farmers aware of both erosion hazards and the minimal losses in income that result from adoption of soil conservation practices are imperative.

Production recommendations resulting from this research effort indicate that technical assistance programs designed to help farmers adopt no-tillage practices will probably be needed. Cost-sharing and/or subsidies are also likely to be necessary to make such a transition possible. What the most appropriate mix of cost-sharing and/or subsidies is and how the mix should be provided are questions that must be evaluated in terms of their effectiveness and cost to the government.

The modeling did have several limitations which future research efforts need to address. Two limitations which are somewhat related are the size of the model, which required the four farming practices to be evaluated separately, and the use of quadratic net revenue functions to reduce the non-linearity which consequently also reduced the size of the model. If computer capacity permitted, it would have been desirable to also analyze all four farming practices in the same model so that tradeoffs among the practices could be directly evaluated. Using the quadratic net revenue functions of equation (39), while they were very accurate in modeling the data, meant that some information contained in the functions they represented, equation (38), was lost. The model did not consider the influence of risk and commodity programs, other than the tobacco program, on farmer decision making. Finally, the analysis did not incorporate the off-site impacts of soil erosion.

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