REGIONAL DIFFERENCES IN THE RELATIONSHIP BETWEEN EROSION AND CROP YIELDS: SOME IMPLICATIONS FOR SOIL CONSERVATION POLICY

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Abstract

Differences in the relationship between topsoil depth and crop yields are explored for typical soils in the northwestern and southeastern United States using agronomic and economic models. Important distinctions in the slopes of the yield/topsoil depth functions were found. These differences have significant implications for the economics of soil conservation and also indicate a need for more heterogeneous soil conservation policies.

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Introduction

The adverse effects of soil erosion on cropland productivity and environmental quality in the United States are well recognized. Since the 1930's the U.S. government has devoted substantial resources to the study and prevention of soil erosion. In the past decade, the awareness of the effects of soil erosion on water quality has stimulated additional efforts to manage and control soil erosion. This awareness has been increased by the data collected in the National Resources Inventory (NRI) and the analysis of soil erosion undertaken as part of the Soil and Water Resources Conservation Act (RCA) (Soil Conservation Service).

Government involvement in soil conservation programs is based on some presumed differences in the private and public interests in soil conservation. Acting in the public interest, the federal government has assumed a responsibility to maintain the long term productivity of the nation's soil resources and the quality of streams and rivers. The formulation of adequate soil conservation policies requires clear and comprehensive analyses of the microeconomic effects of soil erosion on crop yields. Such analyses also recognize both the interregional and intraregional differences in the erosion processes. Theodore Schultz recently observed that:

> Soil erosion is location specific. It's technical and economic attributes vary widely both within and between locations. For the purpose at hand, the unit of land on which it occurs is a farm and the decision entity is the farmer. This being the case, a nationally administered soil conservation program that is politically designed to provide funds and services to all parts of agriculture, is bound to be a model of inefficiency (Schultz).

This paper explores the critical influence of the relationship assumed between soil erosion and crop yields in formulating policy to control soil erosion. It presents evidence of the existence of a sigmoid or "S" shaped functional relationship between yields and soil depth for certain soils in contrast to the continuously decreasing curvilinear relationship generally assumed. The paper analyzes data on the relationship between soil loss and soybean yields on Cecil soils in Georgia, and makes some comparisons with a regional study which investigated soil loss/yield relationships on Palouse soils in the State of Washington. The economic consequences of the shape of the yield-soil depth function are explored and some implications for alternative soil conservation policies are presented.

Procedure

A model was developed to estimate the value to the farmer of soil lost through erosion. This model considers the given stock of soil a capital good for use in crop production, and soil erosion represents a depreciation or a decline in value of this capital good. Thus, the cost of erosion can be defined as the depreciation of the soil resource. If soil losses occur at relatively small increments per year, the value of the soil lost will be the discounted value of the decline in crop yield associated with the loss of topsoil.

Many factors influence the expected yield from a given acre, including soil type, depth of topsoil, weather, fertilizer applications, and pesticide use. Soil scientists have developed yield functions relating yields to soil types, soil depth, and other characteristics. We applied the following generalized model, which uses a yield soil depth function for a given crop, soil type and geographical location to estimate the cost of soil loss. In this model, the value of soil lost varies inversely with the discount rate and varies positively with the value of the crop, the rate of yield growth due to technology, the length of the planning horizon, and the change in yield.

$$V_{SL} = \left(\sum_{t=1}^{n} \frac{P_t}{(1 + r)^t} \right) . \Delta Y (1 + k)^n$$

where

V_{SL} = The present value over the planning period of the loss of one ton per acre of topsoil

$\Delta Y = Y_t - Y_{t+1}$ = yield change associated with loss of one ton of topsoil

$Y_t = f(D_t)$ = yield in year t

D_t = depth of soil in year t

$D_{t+1} = D_t - .007 L_t$

L_t = soil loss in ton/acre in year t

.007" = assumed depth of one ton of soil spread over an acre

P_t = price of output in year t

n = years in farmers' planning horizon

r = farmers' real discount rate

k = the proportional rate of yield growth due to technology for next n years

Yield-Topsoil Relationships

The critical factor influencing the yield component of the model is the slope of the yield function, which varies with soil depth in all nonlinear yield-topsoil depth functions. The assumptions of the shape of the yield-topsoil function have important implications for data interpretation and subsequent formulation of soil conservation policies. In the following discussion, two distinct functional forms will be discussed and the economic implications of each analyzed.

Palouse Soils. Hoag and Young investigated yield-topsoil relationships for wheat on the Palouse soils in the state of Washington by fitting a nonlinear function to cross section data of winter wheat yield and soil depth (Hoag and Young). They stated that the requirements of a proper theoretical model to represent yield topsoil response function should (1) display nonnegative marginal returns to topsoil throughout, (2) allow a nonzero intercept, (3) have diminishing marginal returns to topsoil, and (4) have some maximum level of attainable yields (Hoag and Young).

The functional form used by Hoag and Young to describe yield-topsoil response, which they labeled a Mitscherlich-Spillman (M-S) function, is:

$$Y = A + B\,(1.0 - R^{\text{Topsoil depth}})$$

where

Y = winter wheat yield

A = intercept term or yield at zero topsoil

B = maximum yield increment from topsoil

R = constant ratio between consecutive terms of declining geometric yield increment series. R is always between 0 and 1.

This functional form, developed by E. A. Mitscherlich in the nineteenth century, was shown to apply to yield-topsoil relationships by Spillman and Lang (Stewart: Spillman). This function, which we refer to as the single factor Mitscherlich-Spillman function, is shown graphically in Figure 1.

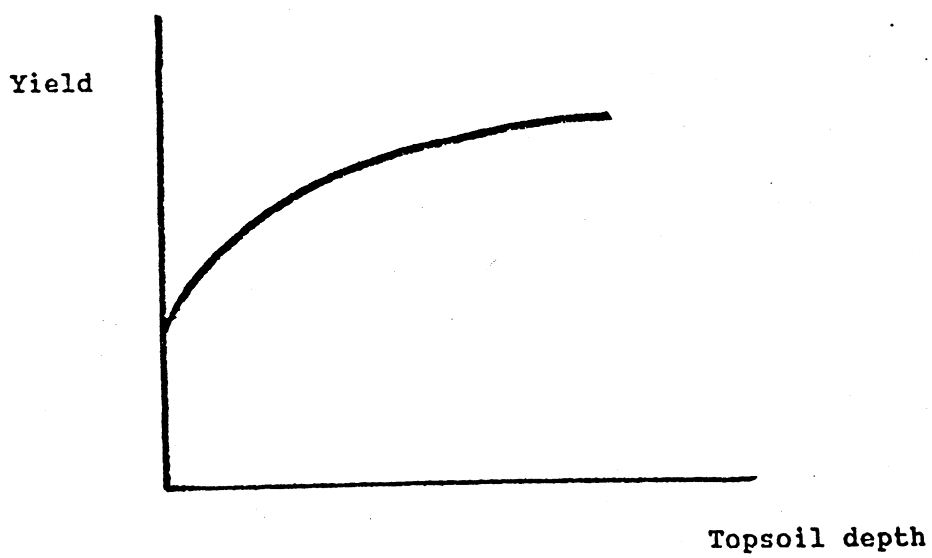

Figure 1: Shape of functional relationship between yield and topsoil depth, single factor Mitscherlich-Spillman function.

Hoag and Young's empirical investigation showed that the fit to their data of the M-S function was superior to the fit of a linear function. This function relates yield to a single homogeneous factor, topsoil depth. In the Palouse case, the M-S function is concave to the horizontal axis and therefore exhibits increasing slope and yield loss as the topsoil depth decreases as a result of erosion.

Cecil Soils. The relationship of yield and soil depth was investigated for soybeans on a major Georgia soil, Cecil Sandy loam. A function was developed from 1982 experimental data developed by scientists at the USDA's Southern Piedmont Conservation Research Center, Watkinsville, Georgia (White and others). These data came from twenty-three conventionally tilled sites, each with slightly, moderately, and severely eroded areas. Statistical analysis of these data gives evidence of a sigmoid or "S" shaped.

A Mitscherlich-Spillman function can be sigmoid or "S" shaped when the factor in question, in this case topsoil depth, is not homogeneous but contains increasing proportions of the limiting factor. This limiting factor is that component of topsoil that is not present in sufficient proportion to provide for maximum yield.

This sigmoid function is shown in figure 2. This function, called a varying proportion M-S function, is:

$$Y = A + B\,(1 - R^{f(\text{Topsoil depth})})$$

where

f (Topsoil depth) = an increasing function of the limiting factor to topsoil depth

Y = yield for the crop in question

A = an intercept term

B = the maximum yield increment from topsoil

R = constant ratio between consecutive terms of the declining geometric yield increment series

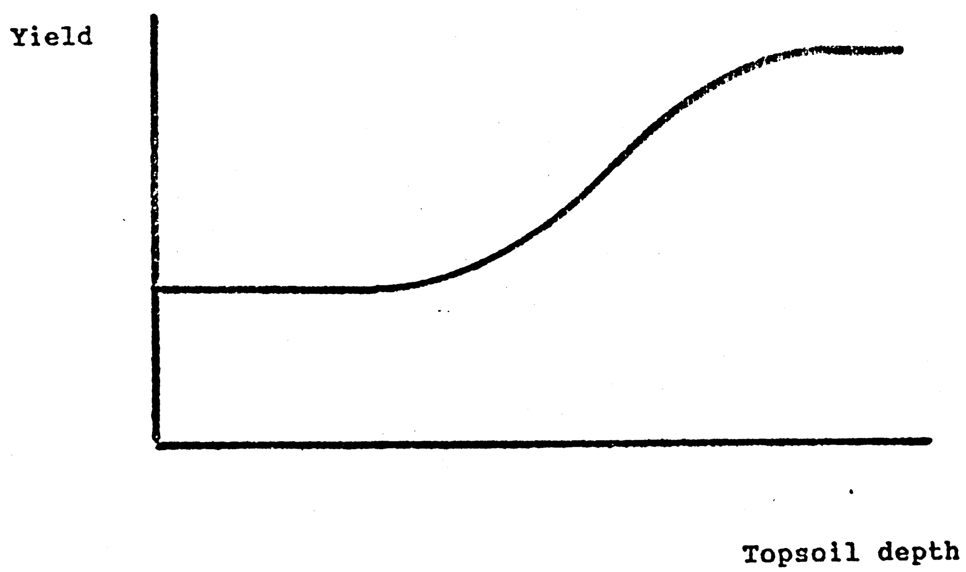

Figure 2. Shape of functional relationship between yield and topsoil depth, varying proportion Mitscherlich-Spillman function.

Physical evidence of increasing proportion of the limiting factor in Georgia Cecil soil is indicated by the varying proportion of the major soil components over the topsoil range. For example, clay content varies from 50 percent for severely eroded topsoil 3-6 inches deep to approximately 15 percent for slightly eroded soil 7-11 inches deep. The varying clay content can be explained by the fact that for these shallow Cecil topsoils the clay subsoil is mixed in by repeated plowing. As erosion occurs, the proportion of clay increases due to this mixing process. Therefore there are decreasing proportions of the nonclay components, sand and silt over the topsoil range which could result in "S" shaped Mitscherlich-Spillman yield-topsoil depth function for the Cecil soils. This analysis gives support to the assumption that for Cecil soils the yield-topsoil function is sigmoid or "S" shaped.

Application of the Model

The economic model was applied using yield functions for Palouse soils and for Cecil soils to demonstrate the important influence of the slope of the yield/topsoil depth function on estimating the value of soil lost, and subsequent policy implications.

The wheat yield function for the Palouse soils is a single factor M-S function developed by Walker (Walker). The function, based on a linear transformation regression analysis of five years of data, is:

$$Y_w = 36.44 + 47.01\,(1 - e^{-.09864X})$$

where

Y_w = wheat yield

X = topsoil depth

The value of a ton of soil lost at different soil depths was estimated assuming wheat prices of $3.00 per bushel, a 50-year planning horizon, an 8 percent discount rate, and a 1 percent annual yield increase due to

Table 1. Estimated relationship between topsoil depth, wheat yield, and value of soil lost, Palouse soils

	Topsoil depth in inches					
	0	5	10	20	30	40
Wheat yield (bushels)	36	58	67	78	81	83
Value of topsoil lost (V_{SL}) (dollars/ton)	1.86	1.15	.68	.24	.08	.03

technology. Results are presented in Table 1 and shown graphically in Figures 3a and 3b.

The soybean yield function for Georgia Cecil soils estimated from our data by a linear transformation regression is.

$$Y = 13 + 31\ (1 - e^{-7(NCC\ -\ .5)\ x/12})$$

where

Y_s = soybean yield in bushels

NCC = nonclay content of topsoil

X = topsoil depth

In addition NCC varies from .95 to .50 as topsoil depth goes from uneroded to severely or completely eroded. In this example uneroded topsoil depth will be assumed to be 10 inches and the topsoil is assumed to be completely eroded at 5.5 inches.

The value of a ton of soil lost at different soil depths was estimated assuming soybean prices of $6.00 per bushel, a 50-year planning horizon, an 8 percent discount rate, and a 1 percent annual yield increase due to technology. Results are presented in Table 2 and shown graphically in Figures 4a and 4b.

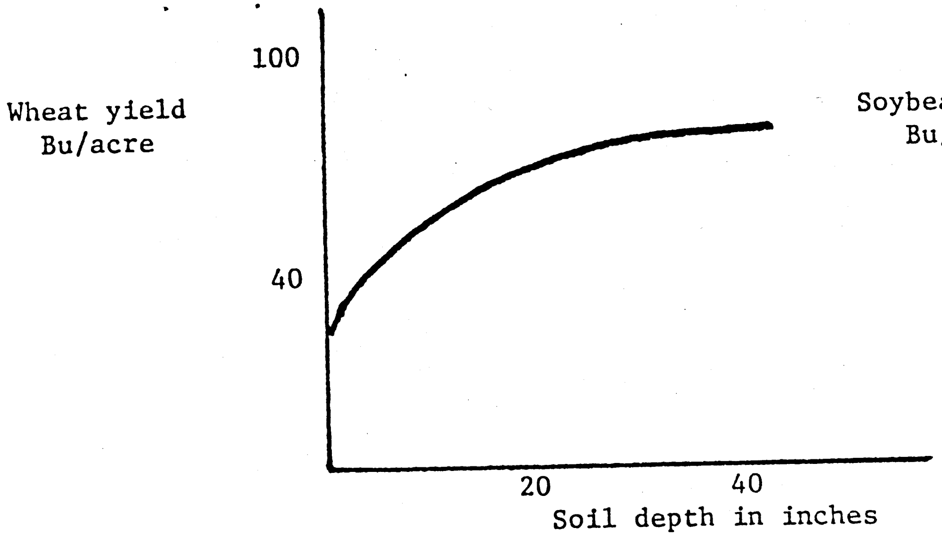

Figure 3a. Wheat yield, Palouse soils.

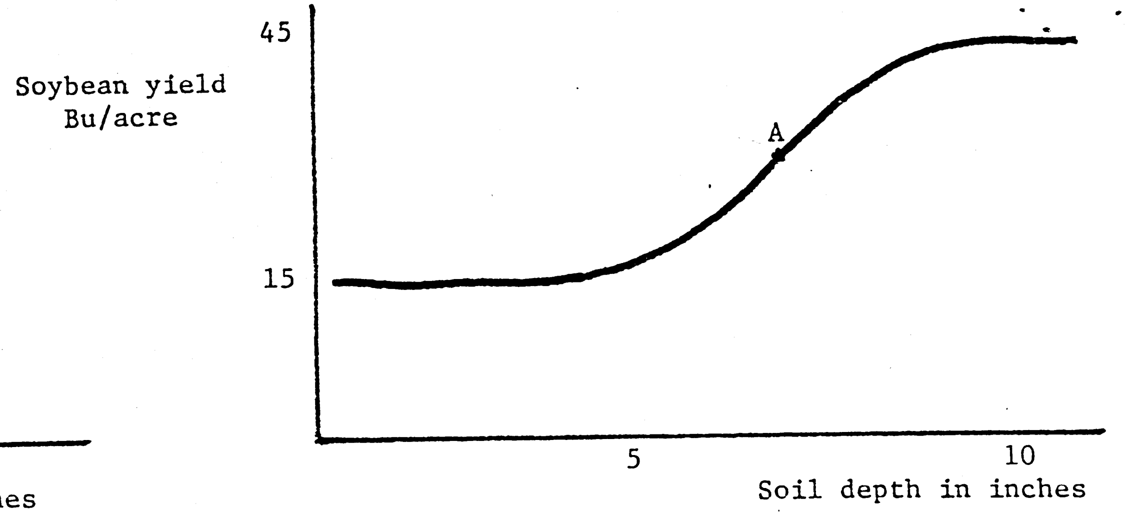

Figure 4a. Soybean yield, Cecil soils.

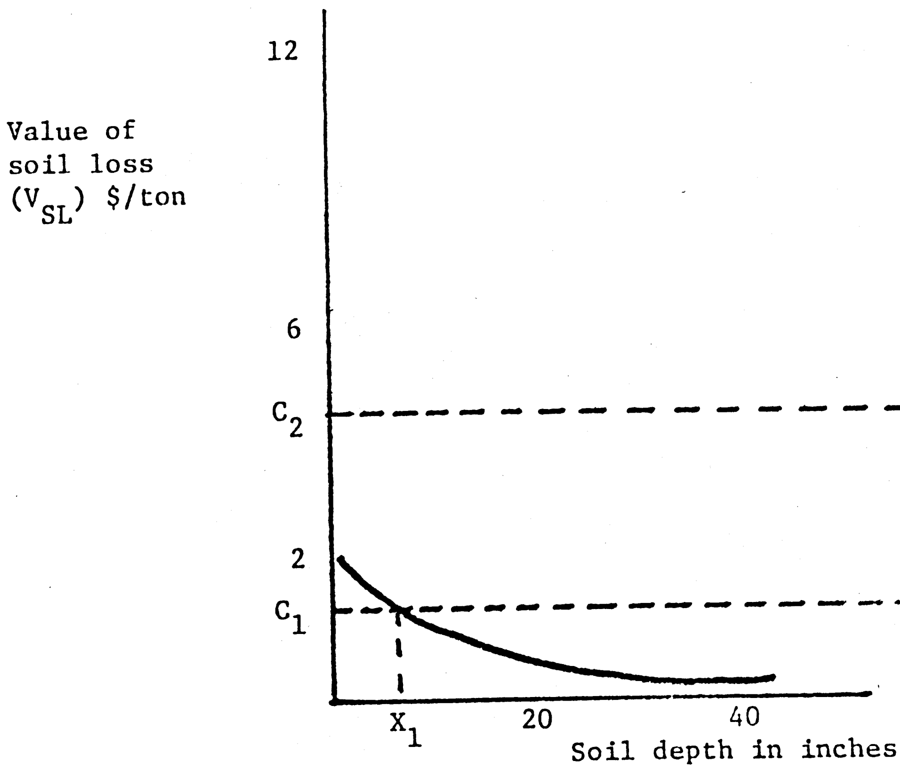

Figure 3b. Value of soil loss, Palouse soils

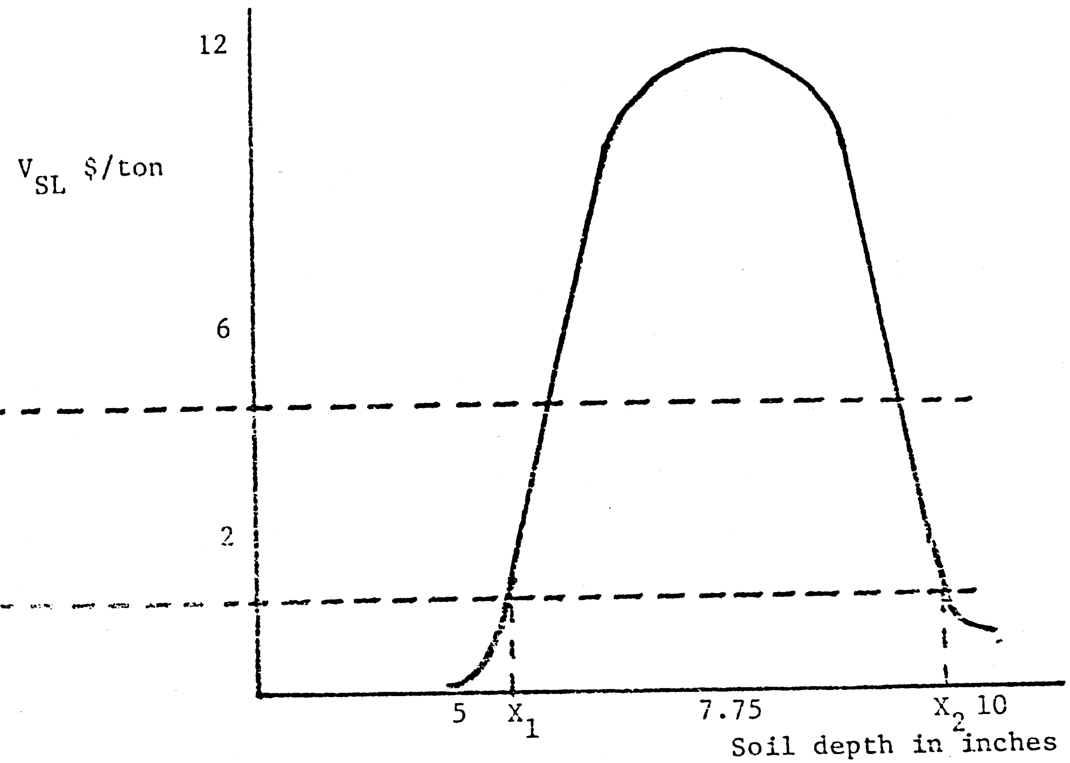

Figure 4b. Value of soil loss, Cecil soils.

Table 2. Estimated relationship between topsoil depth, soybean yield, and value of soil lost, Cecil soils

	Topsoil depth in inches				
	5.5	6.5	7.5	8.5	10.0
Soybean yield (bushels)	13	15.4	29.2	39.2	41.7
Value of soil lost (V_{SL}) (dollars/ton)	.17	4.82	12.46	3.70	.50

Implications

Both the shape and slope of yield-topsoil functions have important economic implications. For the single factor M-S function on Palouse soils, the present value of income loss due to erosion on deeper soils may be so low that conservation benefits are not worth additional control costs. However, yield damages, measured by present value of lost income, increase as topsoil depth decreases (Figures 3a and 3b). These damages will reach a maximum at zero topsoil depth.

For the "S" shaped increasing proportion M-S yield-topsoil function on Cecil soils, the yield damage is very small at low topsoil depth. It then increases over some range of topsoil depth and reaches a maximum at the inflection point (A, Figures 4a and 4b). For soil depths greater than at the inflection point, the yield damage decreases until it becomes close to zero for the deepest soils (Figure 4b). Hence, farmers with severely or slightly eroded soil will have less incentive to conserve the soil than those with moderately eroded topsoils.

The economic feasibility of a particular soil conservation practice is greatly influenced by the shape of the yield damage function. If the single factor M-S function exhibited by Palouse soils is applicable, and a soil conservation practice is used which costs C_1 dollars per ton of erosion control, it would be profitable to adopt the practice only if the value of the soil saved is greater than the conservation costs. This occurs if the topsoil depth is X_1 or less, as shown in Figure 4b. In contrast, farmers with soils exhibiting characteristics of the "S" shaped function, as on Cecil soils, will find it profitable to employ the conservation practice with cost C_1 for soil depths between X_1 and X_3. If the practice costs C_2 per ton of erosion control, the farmer with the single factor M-S function (e.g. Palouse soils) will find it unprofitable to employ the practice at any topsoil depth, while it will be profitable for a farmer with a "S" shaped M-S function (e.g. Cecil soils).

Thus it has been shown that the interaction of conservation practice costs and the yield-topsoil depth functions can have a significant impact on the economic feasibility of conservation practices. Practices economically feasible on one soil may not be so on another. Economists and soil scientists need to recognize that one yield-topsoil depth function shape does not fit all soils.

A recognition of these regional differences is needed in evaluating alternative policies to promote soil conservation. Policies effective in one region may be ineffective in others. Additional studies on the effects of soil depth and composition on crop yields for other soils, crops, and areas of the country are needed to provide better information to assist the formulation of soil conservation policies.

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