Soil Erosion and the Loss in Productivity: An Example of the Terril Soil Series in Minnesota

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Contents

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ABSTRACT. Two regression models were used to estimate functional relationships between crop yields and soil characteristics for corn, soybeans, and wheat in southeastern Minnesota. The relationships between topsoil depth and yield were found to be nonlinear for all three crops. The high level of significance of soil depth (SD) in explaining yield differences indicates that subsoil characteristics are important in determining corn and soybean yields.

The analysis of conservation practice shows that strip cropping does not become profitable until SD drops to between 50 cm and 11 cm depending on crop prices and discount rates. Terracing is shown to not be profitable unless topsoil is very shallow, crop prices are high and discount rates are low. Generally for deep topsoils, productivity losses from soil erosion are minor and adoption of conservation practices is not profitable for most farmers. Conservation practices only become profitable when the topsoil becomes relatively shallow.

Soil erosion has been recognized as a serious natural resource problem in the United States for at least a half century. Yet even after 45 years of cooperative efforts by farmers and the federal government to reduce erosion, it remains a severe problem. Two aspects of the soil erosion problem are of particular economic importance: the loss in soil productivity and the downstream damages caused by soil erosion. This bulletin focuses on estimating the relationship between soil loss due to erosion and soil productivity.[1] The concern is that, with other inputs held constant, crop yields will decline as topsoil is lost and/or its associated soil chemistry and organic and structural components are changed. Crop yield response functions estimated from field observation on yields, topsoil depth, and organic matter content have tended to support this contention.

In 1940, Ibach identified topsoil in the Corn Belt as the critical resource determining crop yields, the quantity of fertilizer used, and the value of agricultural land. Since then, it has been popular in economic studies of long-run costs of soil erosion to specify constant yield reductions per inch of soil loss or per volume of organic matter lost (Buntley and Bell, 1976; Eck et al., 1967; Culver, 1963; Horner, 1960; Forhberg and Swanson, 1979; and Taylor et al., 1979). However, this represents a potentially serious oversimplification for several reasons (Browning et al., 1947; and Thomas and Cassel, 1979). First, the relationship between soil loss or organic matter loss and crop yields may be nonlinear. Second, the assumption ignores the characteristics of subsoil such as water-holding capacity, bulk density, and sufficiency of the pH value, which can significantly affect crop yields. According to Neill's 1979 study, both the surface and subsurface soil conditions are crucial in determining crop yield.[2]

The actual relationship between soil productivity and soil erosion is still a subject of considerable controversy. To help fill this gap, we tested three different nonlinear models as predictors of the relationship of crop yield to both topsoil depth and subsurface conditions. The study area is southeastern Minnesota, which is the region in the state with the most serious water-related soil erosion problem. The study focuses on corn, soybeans, and wheat, the dominant grain crops in the region.

Past Research

Harker et al. (n.d.) and Walker (1982) expressed the yield response function relating wheat yield Y and topsoil depth X as:

$$Y(\text{bu}) = 36.44 + 47.01\,[1 - (\text{Exp})^{-0.09864X}]$$

The maximum yield is thus 83 bu/ac. Successive reductions in topsoil depth due to soil erosion cause increasing yield reductions. When all topsoil is gone, wheat yields decreased to 36 bu/ac. Walker and Young (1981) using the same functional form found that the yield of peas approaches a limit of about 22 cwt/ac with deep soil and decreases to 7 cwt/ac with the loss of all topsoil.

Langdale et al. (1979) estimated the corn yield-soil depth relationship of southern Piedmont soils. They related soil depth to grain, stover, and dry matter using a quadratic model and found that the relationship was nonlinear, and at existing production levels a centimeter of eroded topsoil cost the producer 2.34 bu/ac of corn grain per year.

Burt (1981) applied control theory to the farm-level

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[1]Soil productivity is defined as the capacity of a soil to produce a specified plant or sequence of plants under a physically defined set of management practices.

[2]Neill's (1979) study considered the following subsoil conditions: available water capacity (AWC), aeration, bulk density, pH value, electrical conductivity, weighting factor, and number of horizons in depth of rooting under ideal conditions.

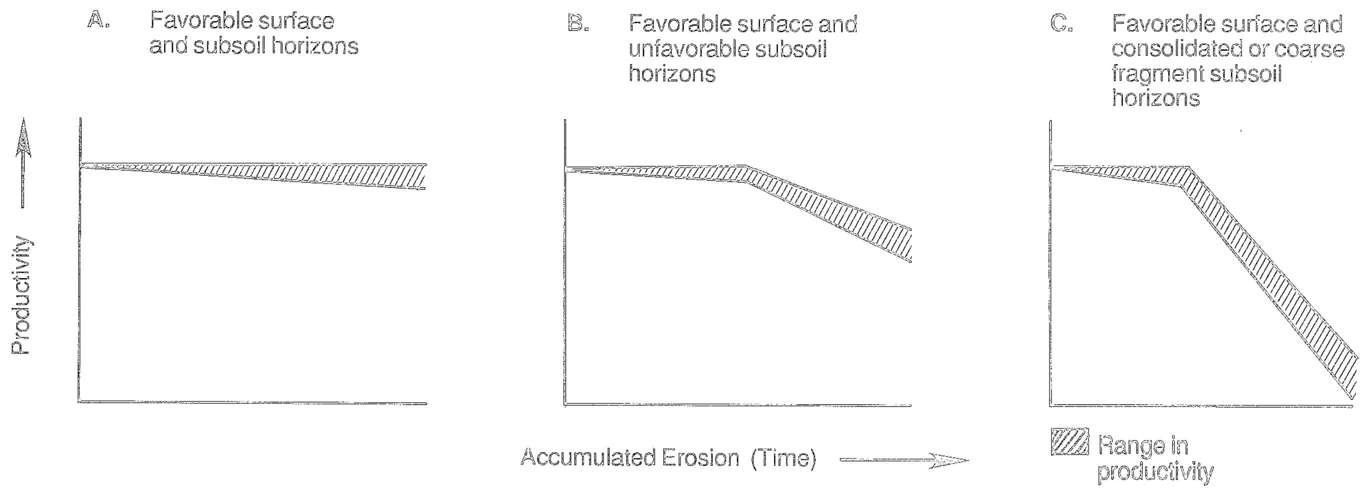

Figure 1. Change in potential productivity with accumulated erosion.

economics of soil conservation in the Palouse wheat area. Using topsoil depth and percentage of organic matter in the top 6 inches of soil as the two state variables he derived the following production function for wheat:

$$Y(bu/ac) = A + 35.1\,(1 - 0.9^{X})\,(1 - 0.6^{y})$$

where:

A = a constant representing theoretical yield when all topsoil is gone
X = the depth of topsoil
y = percentage of organic matter in the top 6 inches of soil.

Bhide et al. (1982) estimated the economic optimum levels of soil loss for three erosive soils in central Iowa, primarily from the individual farmer's viewpoint. They developed a control theory model with three components: (a) an equation relating net returns per acre to soil loss with time as a proxy for technological progress; (b) an equation relating change in net returns to topsoil depth and technological progress; and (c) an equation relating soil loss and soil depth. Their results are quite consistent with past studies: the returns to soil conservation efforts are positively related to a longer planning period, shallower soils, a lower discount rate, and technological progress.

Although topsoil depth has been accepted as a crucial factor that affects soil productivity, subsoil characteristics have been largely ignored. This, however, oversimplifies the soil erosion- productivity relationship: as topsoil erodes, subsurface soil characteristics such as water-holding capacity also change. Neill (1979) and Pierce et al. (1983) show that favorable surface horizon (topsoil depth) and subsurface horizon conditions are both crucial to soil productivity. This concept is illustrated in Figure 1.

Pierce et al. (1983) used a model that incorporated both surface and subsurface horizons to describe the soil loss-soil productivity relationship. The model includes the following factors: sufficiency of available water-holding capacity (SWC), sufficiency of bulk density, sufficiency of pH value, and a weighting factor (WF) (a function of soil depth). From these factors productivity indices were developed for major land groups, assuming that nutrients, climate, management, and plant differences did not limit plant growth. The results strongly suggest that any study of the effect of soil erosion on productivity should consider the impact of both surface and subsurface soil characteristics.

Minnesota Study

The study area comprised Goodhue, Steele, Freeborn, Olmsted, and Waseca counties in southeastern Minnesota. These were the counties for which soil survey maps were available and where a significant number of farmers were active members of the Southeastern Minnesota Farm Management Association.

Because different soil series have different physical and chemical properties that affect soil productivity, the study was limited to the Terril soil series.[3] It is the most common soil series in the study area, although it is not the

[3]The Terril soil series consists of gently sloping, deep, well-drained soils on concave foot slopes at the base of valley walls. These soils were formed in loamy sediment and the native vegetation was tall prairie grasses. In a representative profile the surface layer is very dark, grayish-brown, sandy loam, and about 28 in thick. The upper 6 in of subsoil is dark yellowish-brown, friable clay loam; the lower 8 in is a dark yellowish-brown, heavy sandy loam. Light yellowish-brown, loose sand occurs at a depth of 48 in. Permeability is moderate and available water-holding capacity is high. The content of organic matter is moderate. Available phosphorus content is medium and potassium content is low. Most of the acreage is used for crops or pasture. This soil is well-suited for corn, soybeans, small grains, and hay. The main limitations of this soil series are hazards of erosion from runoff and siltation in cultivated fields. Surface runoff is medium to rapid and the primary management need is to control surface runoff. Soil conservation and maintenance of fertility are important.

Table 1. Physical and chemical properties of the Terril soil series.

Depth from Surface (in)	Soil Texture	Permeability (in/hr)	Available Water (in/in)	pH	Bulk Density (g/cm^3)	Erosion Factor (K)	(T)	Organic Matter (%)
0-5	Sandy Loam	2.0 - 6.0	0.10 - 0.15	6.1 - 6.5	1.35 - 1.40	0.32	5	4-5
5-10	Loam	0.6 - 2.0	0.15 - 0.19	5.6 - 6.0	1.35 - 1.40	0.32	NA	NA
10-15	Clay Loam	0.6 - 2.0	0.20 - 0.22	5.6 - 6.0	1.35 - 1.40	0.32	NA	NA
15-30	Sandy Loam	0.6 - 2.0	0.11 - 0.16	5.6 - 6.0	1.40 - 1.65	0.32	NA	NA
30-50	Fine Sand	6.0 - 20.0	0.05 - 0.07	5.6 - 6.0	1.65 - 1.75	0.10	NA	NA

SOURCE: SCS *Soil Survey of Olmsted County,* March 1980, Table 15, p. 196.

Table 2. Farmers Surveyed by Crop and County, 1983.

	Number Reporting Yields:			Number Reporting Soil Depth:		
County	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
Goodhue	9	13	15	9	11	13
Steele	8	11	10	7	6	9
Freeborn	5	4	7	5	5	4
Olmsted	15	12	11	13	11	8
Waseca	12	4	7	9	4	7
Total	49	44	50	43	37	41

dominant soil series in any county within the study area. The series has a slope ranging from 0 percent to 25 percent and is suitable for a wide range of crops, so it provided a range in soil erosion conditions affecting soil productivity. Table 1 shows some characteristics of the Terril soil series.

Data were obtained from farmers who participated in the Southeastern Minnesota Farm Records Project in 1982 and who had a significant acreage of the Terril soil series on their farms. The acreage of Terril soil on each farm was determined from soil survey maps.

Farmers were surveyed during the winter of 1983 using mail questionnaires with follow-up telephone calls to elicit information concerning soil depth and field locations. Farmers were asked to identify their fields on soil survey maps or provide a legal description of the fields so that information concerning slope and subsoil characteristics such as available water holding capacity (AWC) and pH could be obtained.

The survey sample distribution is shown in Table 2. Farmers who did not know their topsoil depth were dropped from the sample, leaving a final sample size of 43 for corn, 37 for soybeans, and 41 for wheat.

The Yield Response Function

A yield response or production function portrays an input-output relationship in which resources are transformed into products. There are numerous input-output relationships in agriculture because the rate at which inputs are transformed into outputs varies with soil type, technology level, rainfall amount, and other variables. Any given input-output relationship specifies the quantities and qualities of resources utilized to produce a particular product. Mathematically, a production function can be expressed as follows:

$$Y = f(X_1, X_2, X_3 \ldots X_n / X_{n+1}, X_{n+2} \ldots X_{n+k})$$

where:

Y = output

$X_1 \ldots X_n$ = variable inputs

$X_{n+1} \ldots X_{n+k}$ = fixed inputs

In this study, yield response functions are estimated for corn, soybeans, and wheat with respect to the surface soil characteristics of slope and topsoil depth (SD) and the subsoil characteristics measured by the productivity index (PI), WF, AWC, and SWC, while other inputs such as

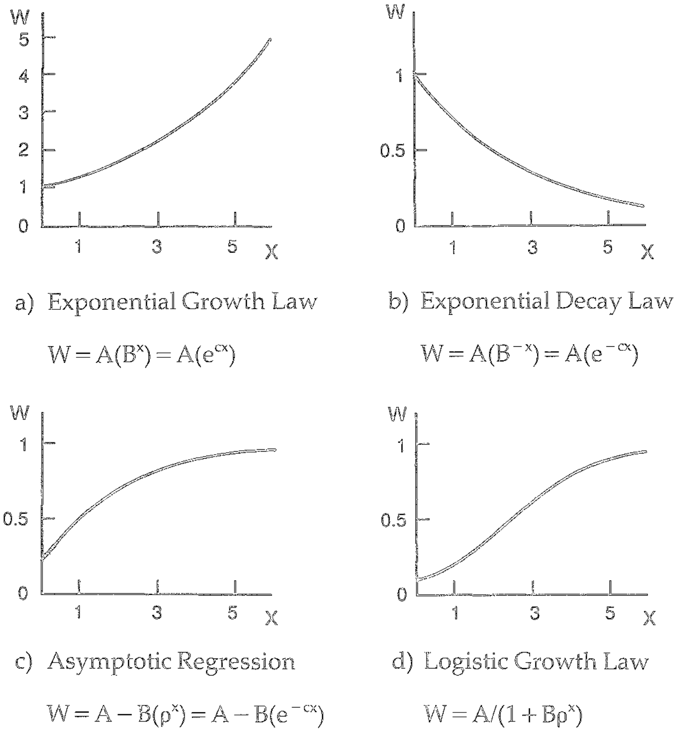

Figure 2. The four most common nonlinear relationships.

level of technology (T), fertilizer utilization (F), and management (M) are assumed constant.[4] The yield response function can be expressed as:

$$Y = f\,(\text{slope, SD, AWC, WF, PI, SWC/M,F,T})$$

Detailed definitions of the variables are presented in the appendix.

Linearizable Models

Not all relationships between a dependent variable and a set of predictors are linear. This is especially true in the relationship between soil characteristics and crop yields. In fact, one might expect linear relationships to be the exception rather than the rule.

Nonlinearity can often be discovered by examining plots of residuals versus the fitted value Y or other variables for systematic relationships. In general, nonlinearity will be indicated by a curved relationship when the residuals are plotted against Y or one of the X's.

Suitable transformations of data can frequently be found that will reduce a theoretically nonlinear model to a linear form. These transformation models are defined as *linearizable* models. In practical work, the specific choice of a transformation to achieve linearity will depend largely on the nature of the variables and other considerations.

Linearizing may require transforming both the independent and dependent variables. An important class of linearizable functions are power or multiplicative models of the form

$$Y = A\,(X^b).$$

This form can be linearized by taking logarithms:

$$\log Y = \log A + b \log X$$

The plots of crop yield versus each independent variable indicated that a nonlinear relationship exists between topsoil depth and crop yield. Therefore, the following linearizable model was fitted for crop yields with respect to subsoil characteristics, topsoil depth, and slope:

$$\text{Yield} = B_1 + B_2X_1 + B_3(X_1)^2 + B_4(X_2) + B_5(X_3) + e$$

where:

X_1 = topsoil depth
X_2 = slope,
X_3 = subsoil characteristics
e = error term
$B_1 \ldots B_2$ = unknown parameters

Nonlinearizable Models

Not all functions are linearizable, nor in some cases is it desirable to transform for linearity. In fact, a number of authors have argued that the relationship between topsoil depth and crop yields should be nonlinearizable (Ibach, 1940; Narayanan et al., 1974). Of the four most common nonlinear relationships (Figure 2), the most appropriate to describe the relationship between soil depth and yield appears to be the asymptotic regression type, i.e., Yield = $A - B(C^x)$.

A nonlinearizable model means that the regression analysis involves an estimation of parameters that appear in the regression model in a nonlinearizable fashion.[5] The

[4] Due to the lack of data, management and fertilizer were not included as variable inputs. This may not be too serious a problem since the variation in fertilizer use appeared to be small among farmers on the Terril soil and the level of technology and management were also very similar within the region.

[5] A nonlinearizable regression consists of minimizing the sum-of-squares function. The dependent variable Y is defined by $Y_1 = f_1(X,b) + e_i$, $i = 1, 2, 3 \ldots, N$ where $f_1(X,b)$ stands for the chosen model function and e_i is the error term. Note that the model is defined as an arithmetic expression combining the independent variables (X) and the parameters (b).

The sum-of-squares function can then be written as:

$$S\,(B) = \sum_{i=1}^{n} (e_i)^2 = \sum_{i=1}^{n} (Y_i - f_i\,(X,b))$$

This function is minimized and, in doing so, the model f(X,b) describes as closely as possible the behavior of the dependent variable Y. Note that in the sum-of-squares function, S(B), the parameters (b's) are the only unknown quantities.

Nonlinearizable regression can only be used if the functional form of the regression model is known explicitly. This information may come from theoretical consideratons, from solutions of differential equation systems, from graphical representations of the data, or from models of analogous systems.

Table 3. Linearizable model of yield response to soil characteristics for the Terril soil in southeastern Minnesota, 1983.

	Wheat	Corn	Soybeans
Constant	31.26 (3.12)***	72.41 (4.35)****	3.25 (1.01)
SD	—	2.50 (3.96)****	1.51 (4.35)****
SD^2	0.007 (5.09)****	−0.028 (−1.77)$^+$	−0.031 (−2.79)**
Slope	−0.371 (2.75)**	−0.535 (2.50)*	—
AWC	38.26 (0.91)	—	79.43 (1.86)$^+$
R^2	0.72	0.77	0.79
Sample Size	41	43	37
Degrees of Freedom	37	39	33

Figures in parentheses are the t statistics; ****$p < 0.001$; *** $p < 0.005$; ** $p < 0.01$; * $p < 0.025$; $^+$ $p < 0.05$

following nonlinearizable models were used in this study:

Model Type I:

$$\text{Yield} = B_1 + B_2 (1 - \text{Exp}^{B_3 X}) = B_1 + B_2 (1 - K^X)$$

where:

X = topsoil depth

$K = \text{Exp}^{B_3}$

B_1, B_2, and B_3 = estimated parameters

Model Type II:

$$\text{Yield} = B_1 + B_2 Z + B_3 (1 - \text{Exp}^{B_4 X}) = B_1 + B_2 Z + B_3 (1 - K^X)$$

where:

X = topsoil depth

Z = one of the soil characteristics (slope, AWC, SWC, WF, or PI)

$K = \text{Exp}^{B_4}$

B_1, B_2, B_3, and B_4 = estimated parameters

Comparison of Results

Linearizable Model

The linearizable model provides reasonably good estimates of yield responses for all three crops. For corn, slope, SD, and SD^2 are all significant at the 0.05 level or better in explaining yields, while for soybeans SD, SD^2, and AWC are significant at the 0.05 level or better (Table 3). In the wheat model SD^2 and slope are significant at the 0.01 level or better. For cases where SD is significant (corn and soybeans) and positively related to yield, SD^2 is negative. As expected, slope has a negative effect on yield while AWC has a positive effect. Soil depth or its square best explain yields in all three cases.

The results of applying the linearizable model support the argument that the relationship between land productivity and soil erosion should be nonlinear for two reasons. First, the "square of topsoil depth" term SD^2 appears in all the estimated linearizable regressions and is statistically significant at the 0.05 level or better. Second, the high R^2 for all three estimated equations suggests that the selected independent variables explain most of the yield variation, and that statistically the models provided good regression estimations.

Both corn and soybean yields are dramatically affected by the amount of topsoil. The regression results show that a one- inch loss (2.54 cm) of topsoil will reduce corn yield by about 6.35 bu/ac (2.5 x 2.54). The next most affected crop is soybeans, in which a one-inch topsoil loss reduces soybean yield by 3.8 bu/ac.

After all the topsoil has been removed, the theoretical corn yield on the subsoil is about 68 bu/ac, about half of the highest corn yield. In the case of soybeans, with all the topsoil removed, yield is only about 10.5 bu/ac, less than one-third of the expected yield for a deep topsoil.

Table 4. Nonlinearizable Type I model of yield response to topsoil depth for the Terril soil in southeastern Minnesota, 1983.

	Wheat	Corn	Soybeans
B_1 (constant)	17.854 (7.34)****	45.792 (7.33)****	15.792 (1.45)*
B_2 (soil depth)	351.246 (1.05)	89.436 (2.37)**	38.765 (3.79)****
B_3 (soil depth)	−0.0026 (−0.25)	−0.0415 (−2.56)**	−0.0643 (−3.22)***
K	0.9974 (0.25)	0.9594 (2.56)**	0.9377 (3.22)***
R^2	0.73	0.79	0.80
Sample Size	41	43	37
Degrees of Freedom	38	40	34

Figures in parentheses are the t statistics ****$p < 0.001$ ***$p < 0.005$ **$p < 0.01$ *$p < 0.20$

Wheat yield, on the other hand, is not very sensitive to soil characteristics such as SD, slope, and AWC. The constant term of the equation, 31.26, indicates that if there is no topsoil, wheat yield will be only 7.5 bu/ac less than the average wheat yield from the sample (38.75 bu/ac).

Increased slope also reduces crop yield. The regression result for corn shows that a 10 percent increase in slope together with a one-inch decrease in topsoil will reduce corn yield by as much as 12.2 bu/ac [12.2 = (11)(0.535) + (2.54)(2.5)]. When slope increases, erosion potential increases since topsoil removal is easier.

For both wheat and soybeans, the regression equations show that AWC, a subsoil characteristic, can also be an important variable in determining yields. The coefficient of AWC for soybeans is significant at the 0.05 level but for wheat it is only significant at the 0.40 level. Although t statistics are not very high for AWC and the range in AWC values is fairly narrow, a change in AWC can cause a yield difference as large as 5 bu/ac for wheat and 10 bu/ac for soybeans. For wheat this yield difference accounts for more than 50 percent of total yield variation, while for soybeans it accounts for more than 30 percent of total yield variation. These results suggest that AWC might be the most significant soil characteristic affecting crop yields. It, rather than topsoil depth, may be directly affecting crop yields, since AWC is directly related to topsoil depth.

Nonlinearizable Models

The *Type I* nonlinearizable regression estimations are limited since only SD is included. The regression equation for wheat shows no statistically reliable relationship between yield and SD since none of the estimated parameters is significant at the 0.20 level except for the constant term (see Table 4).

For both corn and soybeans, the Type I nonlinearizable regressions provide statistically reliable relationships. In the equation for corn, all parameters including the constant term are significant at the 0.01 level or better. Moreover, the R^2 of 0.79 indicates a good fit. For soybeans all parameters except the constant term are significant at the 0.005 level or better and the $R^2 = 0.80$.

The estimated regression results for the Type I nonlinearizable models suggest that the relationship between SD and soil productivity is asymptotic nonlinear, i.e., yields approach some upper limit. The yield of corn asymptotically approaches a limit of about 135 bu/ac with deep soil while removal of all topsoil could reduce yields by about 65 percent to 45 bu/ac. The soybean yield approaches a limit of about 54.5 bu/ac with deep soil, while yield drops by about 70 percent to 16 bu/ac with topsoil removed.

In contrast to the linearizable model, in the Type I nonlinearizable model the constant term does not explain most of the wheat yield variation. The average sample yield for wheat is 38.75 bu/ac while the constant terms are 31.26 and 17.85 for the linearizable and nonlinearizable models, respectively. Wheat yield asymptotically approaches 370 bu/ac under the nonlinearizable Type I model, indicating that the wheat data are actually linearizable and the nonlinearizable estimation misspecifies the data structure. This is also the reason why all the t statistics of nonlinearizable models for wheat are not statistically significant except for the constant terms.

Table 5. Nonlinearizable Type II model of yield response to soil characteristics of Terril soil in southeastern Minnesota, 1983.

	Wheat		Corn		Soybeans		
	AWC	Slope	WF	Slope	SWC	AWC	PI
B_1 (constant)	17.36 (4.28)****	28.43 (5.03)****	47.262 (3.15)***	67.843 (6.43)****	0.205 (1.72)	0.452 (1.25)	4.725 (2.01)+
B_2 (soil characteristics)	12.321 (1.01)	−0.173 (−1.73)	9.45 (0.72)	−0.595 (−2.71)**	10.721 (1.97)+	57.843 (2.39)*	4.35 (1.1)
B_3 (soil depth)	475.51 (0.52)	488.69 (0.93)	98.745 (7.8)****	64.531 (4.81)****	55.379 (3.32)***	43.26 (5.21)****	48.213 (6.21)****
B_4 (soil depth)	−0.0016 (−0.076)	−0.0014 (−0.089)	−0.0415 (−4.23)****	−0.0575 (−1.35)	0.0514 (−4.13)****	−0.0593 (−3.99)****	−0.0551 (−4.76)****
K	0.9984 (0.076)	0.9985 (0.089)	0.9593 (4.43)****	0.9441 (1.35)	0.9499 (4.13)****	0.9424 (3.99)****	0.9464 (4.76)****
R^2	0.75	0.77	0.80	0.80	0.82	0.83	0.81
Sample Size	41		43		37		
Degrees of Freedom	37		39		33		

Figures in parentheses are the t statistics
****$p < 0.001$ *** $p < 0.005$ ** $p < 0.01$ * $p < 0.025$ + $p < 0.05$

For corn, two Type II nonlinearizable regression equations explain about 80 percent of the yield variation. In the first Z is WF, and in the second Z is the slope. Statistically, WF is not significant at the 0.20 level while SD is highly significant. In the second regression equation, the slope is significant at the 0.01 level but the SD parameter is only significant at the 0.20 level.

Two of the *Type II* nonlinearizable regressions estimated for wheat provided the best fit to the data. In the first equation Z is AWC and in the second equation Z is the slope. As with the Type I nonlinearizable model, all the estimated parameters except the constant term were insignificant at the 0.05 level (Table 5). Only the coefficient for slope was close to being significant at the 0.05 level.

For soybeans there are three Type II nonlinearizable regression equations, with Z being AWC, SWC, and PI. The constant terms B_1 are not statistically significant at the 0.05 level except for the equation with PI as the soil characteristic. The coefficients for soil characteristics are significant at the 0.025 level for AWC and at the 0.10 level for SWC. In contrast, all of the coefficients for topsoil depth are statistically significant at the 0.005 level or better.

The regression equations based on the Type II nonlinearizable model suggest that incorporating other soil characteristics besides SD does not significantly improve the nonlinearizable estimates. The addition of another independent variable raises the R^2's only marginally. Statistically the soil characteristic variables AWC, WF, SWC, and PI are not significant in the equations except for slope with corn and AWC and SWC for soybeans. Where slope is significant for corn, SD is not. When AWC and SWC are significant for soybeans, the constant terms are not.

Thus, both the linearizable models and the Type I nonlinearizable models provide better empirical estimates than the Type II models. The comparison of the different models suggests that:

(a) when dealing only with the topsoil depth-soil productivity relationship, the best model is the Type I nonlinearizable model.
(b) when incorporating other soil characteristics, the linearizable model is the best choice.

Application of Results

The estimated functional relationship between topsoil depth and crop productivity can be used to calculate the benefits and the relative profitability of various soil conservation practices.[6] Since the Type I nonlinearizable regression models were the best for estimating the simple topsoil depth-yield relationship, they are used to estimate the topsoil erosion impacts on crop yield. The fol-

[6]Soil loss is calculated under the following conditions: a farm with Terril soil series in southeastern Minnesota where (1) the soil erodibility factor for Terril soil is X = 0.32 ton/ac/year; (2) the length of slope (h) is 400 ft and the slope is 10 percent, so the LS factor is 2.8; (3) the crop management factor (C) is 0.18 assuming a corn-corn-oats-meadow rotation; and (4) the soil conservation practice factors (P) are 0.6, 0.3, and 0.12, respectively, for contouring, strip cropping or contour terracing. Substituting the above information into the Universal Soil Loss Equation (USLE), an estimated average annual soil loss is obtained for different soil conservation practices.

If *contouring* is adopted on the farm field, the estimated average annual soil erosion is (150) (2.8) (0.6) (0.32) (0.18) = 14.52 tons/ac/year (approximately 0.24 cm/year). For *strip cropping* the soil loss is (150) (2.8) (0.3) (0.32) (0.18) = 7.26 tons/ac/year, about 0.12 cm/year. For *contour terraces* the soil loss is (150) (2.8) (0.12) (0.32) (0.18) = 2.90 tons/ac/year, or about 0.048 cm/year.

If no conservation is practiced the soil conservation practice factor P in the USLE will be 1.0. Hence, the estimated annual soil erosion rate is (150) (2.8) (1.0) (0.32) (0.18) = 24.2 tons/ac/year, about 0.4 cm/year.

lowing three yield response functions are used for wheat (W), corn (C), and soybeans (S): $Y_w = 17.8541 + 351.2455 (1 - 0.9974^X)$, $Y_c = 45.792 + 89.4357 (1 - 0.9549^X)$, and $Y_s = 15.792 + 38.7653 (1 - 0.9377^X)$. For the three models X is the topsoil depth measured in cm.

Asymptotic Yield Response Functions

Because the yield response functions are asymptotic with respect to SD, the estimated yields are increasingly reduced by successive reductions in topsoil depth. Thus, when topsoil is relatively deep (over 40 cm), soil conservation practices will not result in large productivity differences even with a long planning period. In contrast, if topsoil is relatively shallow (below 20 cm), soil conservation practices offer significant yield advantages and conservation practices become more attractive to farmers.

The above relationship can be readily understood by referring to Tables 6 and 7. The assumed initial conditions for Table 6 are that topsoil depth is 40 cm at the end of the first year and the planning period is 50 years. For Table 7 the assumed initial conditions are that topsoil depth is 20 cm at the end of the first year and the planning period is 50 years. The tables show depth of topsoil at the end of each year (calculated with the Universal Soil Loss Equation, USLE) for different crops and soil conservation practices, and the average annual crop yield based on the yield-topsoil depth relationships shown in the previous section.

Table 6 indicates that for a 50-year planning period, expected total corn production will be 5,682 bu/ac if the farm field is contoured. Expected total corn production for the 50-year planning period increases to 5,806 bu/ac for strip cropping and to 5,871 bu/ac for contour terraces. The expected difference in corn production between contouring and contour terraces for the 50-year period is thus 189 bu/ac.

In the first 16 years the difference in corn production between contouring and contour terraces is only 13 bu/ac (1,888 - 1,875). This accounts for only 7 percent of expected difference in production for the 50-year planning period.

For soybeans, expected total production per acre over 50 years is 2,512 bu, 2,550 bu, and 2,569 bu, respectively, under contouring, strip cropping, and contour terraces. The expected soybean production difference for the 50-year period between contouring and terraces is only 57 bu/ac. In the first 16 years, the production advantage of terraces is 4 bu/ac, only 6.5 percent of the difference in production for the 50-year planning period.

Contouring, strip cropping, and contour terraces result in total expected wheat production per acre of 2,385 bu, 2,499 bu, and 2,567 bu, respectively, for the 50-year period. Terracing would increase production over contouring by 15 bu/ac for the first 16 years, only 8 percent of the total expected wheat output difference over the 50-year period.

Thus, for deep topsoil, soil erosion will not reduce soil productivity very dramatically. It will reduce soil productivity by 18.7 percent for wheat, 6.5 percent for soybeans, and 9 percent for corn under contour farming over 50 years (Table 6). This is only an average loss in productivity of 0.37 percent, 0.13 percent, and 0.18 percent annually for these three crops.

In contrast, when initial topsoil is shallow (20 cm), contour terracing offers significant yield advantages during a much shorter period. Contour terraces on shallow soil will reduce losses over the 16-year period by 40 bu/ac for corn, 17 bu/ac for soybeans, and 20 bu/ac for wheat. A comparison of the last two rows in Tables 6 and 7, which show the percent drop in productivity for both planning periods, illustrates that conservation practices are much more attractive to farmers with shallow topsoil. This is true even when the planning period is short.

Adoption of Conservation Practices

Given the above relationship between SD and crop yield, at what point is it profitable for farmers to adopt conservation practices? Assume that farmers are already farming on the contour[7] and the planning period is 50 years. Farmers will adopt advanced soil conservation practices such as strip cropping or contour terracing to reduce losses in productivity when the benefits exceed costs. Mathematically, the private farm decision model is as follows:

$$\text{Max NPV} = \sum_{t=o}^{T} \left\{\frac{(P_{t+1}) \circ Y_{t+1}}{(1+r)^{t+1}}\right\} - \left\{\frac{ICCP_i}{(1+r)^i} + \sum_{t=o}^{T-i} \frac{MC_{t+1}}{(1+r)^{t+1}}\right\}$$

where:

NPV = net present value

T = planning period, in this case T = 0, 1, 2 ... 50

t = 0, indicating the beginning of the first year

P_{t+1} = crop price in year t + 1

Y_{t+1} = crop yield in year t + 1. Here Y_{t+1} is a function of topsoil depth (X_t) in year t.

r = discount rate

$ICCP_i$ = cost of installing soil conservation practices in year i, $0 \leq i \leq T$; i = 0 indicates conservation practices adopted in the current year, i > 0, future years

MC_{t+i} = soil conservation maintenance cost in year t + i

Farmers generally decide whether and when to adopt additional conservation practices based on the difference between net present value of contouring $(NPV)_c$ and net present value of strip cropping $(NPV)_{sc}$ or contour terrac-

[7]Contouring often costs only a few dollars an acre. The major expenses are additional labor, time, and managerial skills required to plow according to the field topography. These costs, however, can increase significantly where there is highly variable topography and when the farmer is using larger, wide machinery. Generally, contouring is a profitable farm practice on sloping lands. We assume that it is a conservation baseline and farmers compare it with other advanced conservation practices. However, this means that we will underestimate the benefits from adopting soil conservation practices for farmers not applying any conservation measures.

Table 6. Crop yields and soil depth over time under three soil conservation practices.

Planning period (years)	Soil Depth (cm)			Crop Yields (bu/ac)								
				Corn			Soybeans			Wheat		
	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces
1	40	40	40	118.2	118.2	118.2	51.6	51.6	51.6	52.2	52.2	52.2
5	39.0	39.5	39.8	117.5	117.9	118.1	51.4	51.5	51.6	51.4	51.8	52.1
10	37.8	38.9	39.6	116.6	117.4	117.9	51.2	51.4	51.5	50.5	51.3	51.9
15	36.6	38.3	39.3	115.7	117.0	117.8	50.9	51.3	51.5	49.5	50.9	51.7
Subtotal (1-16)				1,874.9	1,883.4	1,888.3	821.0	823.3	824.7	817.4	824.5	832.0
20	35.4	37.7	39.1	114.7	116.5	117.6	50.6	51.1	51.4	48.5	50.4	51.5
25	34.2	37.1	38.9	113.6	116.1	117.4	50.3	51.0	51.4	47.5	49.9	51.3
30	33.0	36.5	38.6	112.5	115.6	117.2	49.9	50.9	51.3	46.5	49.4	51.1
35	31.8	35.9	38,4	111.4	115.1	117.0	49.6	50.7	51.3	45.5	48.9	50.9
40	30.6	35.3	38.1	110.1	114.6	116.9	49.2	50.6	51.2	44.5	48.4	50.7
45	29.4	34.7	37.9	108.9	114.1	116.7	48.7	50.4	51.2	43.5	47.9	50.5
50	28.2	34.1	37.7	107.5	113.5	116.5	48.3	50.2	51.1	42.5	47.4	50.3
Total (1-50)				5,682.3	5,805.8	5,871.5	2,512.1	2,550.2	2,568.9	2,385.0	2,498.8	2,566.5
% production decrease (1-50)[a]				9.0	4.0	1.5	6.5	2.6	1.0	18.7	9.3	3.7
% production decrease (1-16)[b]				2.2	1.0	0.4	1.4	0.7	0.3	5.3	2.6	1.1

[a](Yield in the fiftieth year – yield in the first year)/yield in the first year.
[b](Yield in the sixteenth year – yield in the first year)/yield in the first year.

Table 7. Crop yields and soil depth over time for shallow topsoil under three soil conservation practices.

Planning period (years)	Soil Depth (cm)			Crop Yields (bu/ac)								
				Corn			Soybeans			Wheat		
	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces	Contouring	Strip Cropping	Contour Terraces
1	20	20	20	96.2	96.2	96.2	43.8	43.8	43.8	35.5	35.5	35.5
5	19.0	19.5	19.8	94.6	95.4	95.9	43.2	43.5	43.7	34.7	35.1	35.3
10	17.8	18.9	19.6	92.6	94.4	95.5	42.3	43.1	43.5	33.6	34.6	35.1
15	16.6	18.3	19.3	90.4	93.4	95.1	41.3	42.6	43.4	32.4	34.0	34.9
Subtotal (1-16)				1,490.6	1,515.8	1,530.2	680.0	691.2	697.5	542.7	555.4	562.8
20	15.4	17.7	19.1	88.1	92.4	94.7	40.2	42.2	43.2	31.5	33.5	34.7
25	14.2	17.1	18.9	85.7	91.3	94.3	39.0	41.7	43.0	30.5	33.0	34.5
30	13.0	16.5	18.6	83.2	90.2	93.9	37.8	41.2	42.8	29.5	32.5	34.3
35	11.8	15.9	18.4	80.5	89.1	93.5	36.5	40.6	42.7	28.4	32.0	34.1
40	10.6	15.3	18.1	77.7	87.9	93.1	35.0	40.1	42.5	27.4	31.4	33.9
45	9.4	14.7	17.9	74.8	86.7	92.7	33.4	39.5	42.3	26.3	30.9	33.7
50	8.2	14.1	17.7	71.7	85.5	92.2	31.7	38.9	42.1	25.2	30.4	33.5
Total (1-50)				4,294.4	4,588.4	4,720.9	1,949.9	2,086.2	2,153.0	1,538.2	1,657.2	1,727.6
% production decrease (1-50)[a]				25.5	11.2	4.2	27.6	11.2	4.0	28.9	14.4	5.7
% production decrease (1-16)[b]				6.5	3.1	1.2	6.4	3.0	1.1	8.7	4.4	1.8

[a](Yield in the fiftieth year – yield in the first year)/yield in the first year.
[b](Yield in the sixteenth year – yield in the first year)/yield in the first year.

Table 8. Price, cost, and erosion rate data used in the cost-benefit analysis.

	Corn	Soybeans	Wheat
Crop Price ($/bu)	$2.50[a]	$6.40[a]	$3.50[a]
25% decrease	$1.88	$4.80	$2.63
25% increase	$3.13	$8.00	$4.38

	Strip Cropping	Contour Terraces
Installation cost	$24.89/ac[b]	$477.60/ac[c]
Annual maintenance cost (MC)	$1.99/ac	$16.79/ac
4% discount rate—50-year planning period present value (MC)	$42.75/ac	$360.64/ac
12% discount rate—50-year planning period present value (MC)	$16.52/ac	$139.36/ac
Total cost 4%	$67.64/ac	$808.24/ac
12%	$41.41/ac	$586.96/ac

		Contouring	Strip Cropping	Contour Terraces
Annual Soil Erosion Rate[d]	ton/ac/yr	14.52	7.26	2.90
	cm/yr	0.24	0.12	0.048

[a]*Farm Planning Prices*, University of Minnesota, Agricultural Extension Service, 1980.
[b]Merritt Merrill Padgitt, "*An Analysis of On-farm Impacts of Soil Conservation and Non-point Source Pollution Abatement Practices and Policies on Representative Farms in Southeast Minnesota*," 1980 unpublished PhD thesis, Department of Resource Development, Michigan State University, East Lansing, Michigan.
[c]C. Arden Pope III, Shashanka Bhide and Earl O. Heady, "*The Economics of Soil and Water Conservation Practices in Iowa: Model and Data Documentation*, August 1982, Card•Report No. 108 SWCQ Series I, Iowa State University, Ames, Iowa.
[d]See footnote 5.

ing $(NPV)_{tc}$. It is assumed that with or without advanced conservation practices, only the amount of soil erosion and topsoil depth will change (variable production costs are constant).

The information needed to complete the cost-benefit analysis is presented in Table 8. All the benefit and cost data are in 1980 prices.

The analysis shows that when topsoil is very deep, there is no private profit incentive to adopt additional soil conservation practices. Not until topsoil depth has declined to 45 cm for corn and 39 cm for soybeans, is it profitable to adopt strip cropping (Table 9, Figure 3).[8] For wheat, strip cropping is profitable with deep soil, and the benefit increases linearly as soil is eroded. This is because the data for wheat do not exhibit the asymptotic relationship.

Because of high installation costs ($447.60/ac) and annual maintenance costs ($16.79/ac), contour terracing is not profitable even when the topsoil is very shallow (Table 10).

Another way to interpret the results is that, if initial topsoil depth is 70 cm, strip cropping will not be economical for about 100 years for corn producers and 130 years for soybean producers. Therefore, the adoption of soil conservation practices is very dependent on the initial topsoil depth for each farm field.

Sensitivity analysis was conducted to see how changes in model parameters would affect outcomes (Table 9 and 10).

Case 1. Projected crop prices were increased and decreased by 25 percent. With the price of corn increased to $3.13/bu, strip cropping is economically justified when topsoil depth is 50 cm. This is equivalent to adopting strip cropping about 25 years earlier than in the case of no price increase. When the price of corn is decreased to $1.88/bu, the critical soil depth at which strip cropping is profitable drops to 38 cm. This means that adoption of strip cropping would be further delayed by about 30 years.

[8]Strip-cropping entails planting strips of close-growing crops such as alfalfa and meadow grasses as buffers between strips of row crops such as corn. Therefore, strip cropping usually takes 25 to 30 percent of the land out of row crop production depending on width and frequency of strips. The net farm output and revenue effect is not always clear; hence, the benefits for strip cropping were calculated without adjusting for the acreage taken out of row crops. The benefits from strip cropping are therefore likely to be overestimated. However, since the example is only to illustrate the effect of soil depth on the adoption of soil conservation practices, the direction of change is still quite clear. Strip cropping is not profitable until topsoil is fairly shallow.

Table 9. Topsoil depth at which strip cropping is profitable for alternative crops, prices, and discount rates.

Topsoil Depth (cm)	Discount Rates				Discount Rates				Discount Rates			
	4%		12%		4%		12%		4%		12%	
	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]
	Corn ($2.50/bu)				Soybeans ($6.40/bu)				Wheat ($3.50/bu)			
100	$ 6.87	0.10	$ 1.03	0.02	$ 1.35	0.02	$ 0.20	0.00	$ 95.74[c]	1.42	$15.73	0.38
52	50.30	0.74	7.79	0.19	29.65	0.44	4.41	0.11	108.33	1.60	17.80	0.43
46	64.53	0.95	10.00	0.24	43.61	0.64	6.48	0.16	110.02	1.63	18.08	0.44
40	82.77[c]	1.22[c]	12.82	0.31	64.15	0.95	9.53	0.23	111.73	1.65	18.36	0.44
34	106.17	1.57	16.45	0.40	94.34[c]	1.39[c]	14.01	0.34	113.47	1.68	18.65	0.45
22	174.68	2.58	27.05	0.65	198.08	2.93	30.31	0.73	117.03	1.73	19.23	0.46
16	224.06	3.31	34.70	0.84	300.16	4.44	44.58[c]	1.08[c]	118.85	1.76	19.53	0.47
10	281.62	4.16	44.34[c]	1.07[c]	431.49	6.38	65.27	1.58	118.75	1.76	19.78	0.48
	Corn ($3.13/bu)				Soybeans ($8.00/bu)				Wheat ($4.38/bu)			
100	$ 8.58	0.13	$ 1.33	0.03	$ 1.69	0.02	$ 0.25	0.01	$119.67[c]	1.77[c]	$19.67	0.48
52	62.89	0.93	9.73	0.23	37.06	0.55	5.50	0.13	135.42	2.00	22.25	0.54
46	80.66[c]	1.19[c]	12.49	0.30	54.51	0.81	8.09	0.20	137.52	2.03	22.60	0.55
40	103.46	1.53	16.02	0.39	80.18[c]	1.19[c]	11.90	0.29	139.66	2.06	22.95	0.55
22	218.35	3.23	33.82	0.82	255.10	3.77	37.89	0.91	146.29	2.16	24.04	0.58
16	280.07	4.14	43.38[c]	1.05[c]	375.20	5.55	55.73[c]	1.35[c]	148.56	2.20	24.42	0.59
10	352.03	5.20	55.43	1.34	539.36	7.97	81.60	1.97	148.44	2.19	24.72	0.60
	Corn ($1.88/bu)				Soybeans ($4.80/bu)				Wheat ($2.63/bu)			
100	$ 5.14	0.08	$ 0.80	0.02	$ 1.02	0.02	$ 0.15	0.00	$ 71.81[c]	1.06[c]	$11.80	0.28
52	37.73	0.56	5.84	0.14	22.23	0.33	3.30	0.08	81.25	1.20	13.35	0.32
40	62.07	0.92	9.62	0.23	48.10	0.71	7.15	0.17	83.80	1.24	13.77	0.33
34	79.62[c]	1.18[c]	12.33	0.30	70.76[c]	1.05[c]	10.50	0.25	85.10	1.26	13.98	0.34
16	168.04	2.48	36.03	0.63	225.12	3.33	33.44	0.81	89.14	1.32	14.65	0.35
10	211.22	3.12	33.26	0.80	323.62	4.78	48.96[c]	1.18[c]	89.06	1.32	14.83	0.36

[a]Strip cropping cost is $67.64/ac.
[b]Strip cropping cost is $41.41/ac.
[c]Topsoil depth at which strip cropping is profitable.

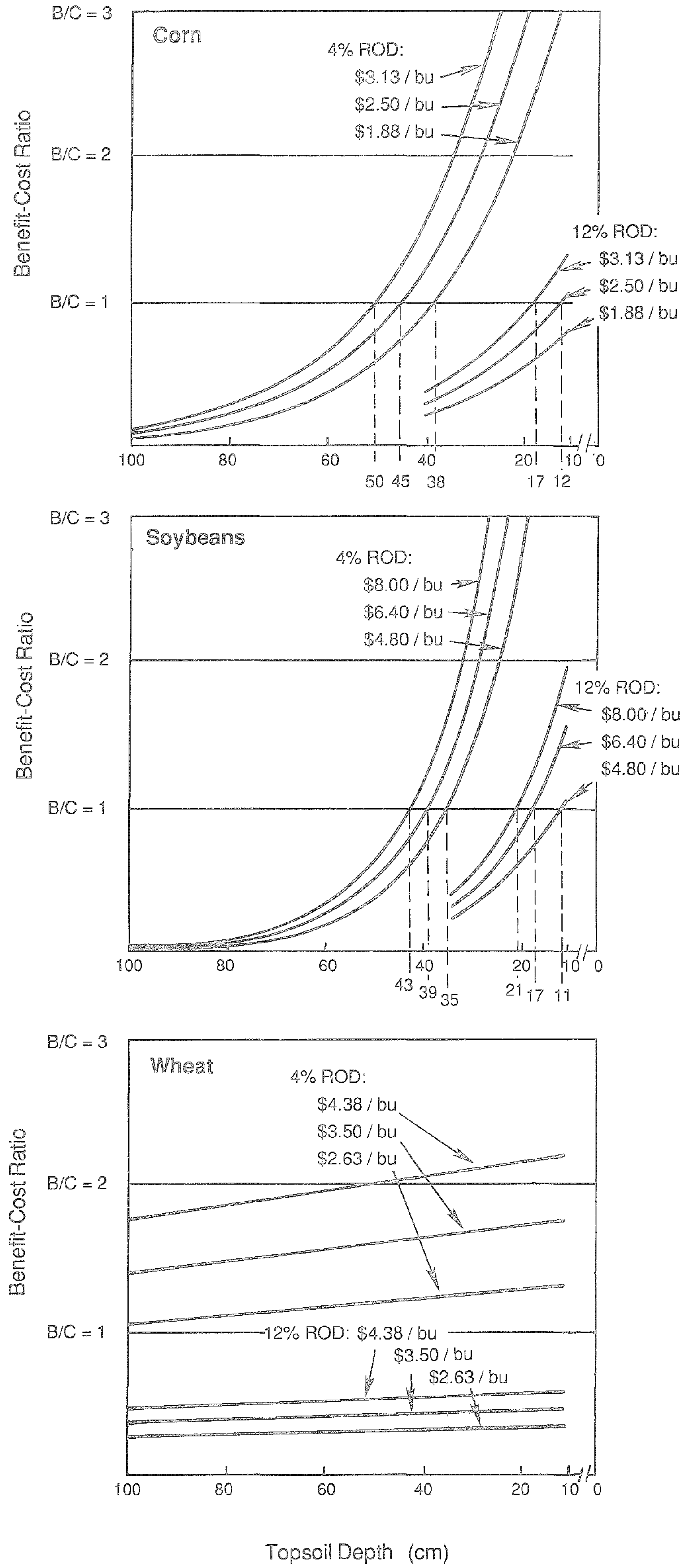

Figure 3. Benefit-cost ratio for strip cropping conservation practices for wheat, soybeans and corn at different prices and rates of discount (ROD).

Table 10. Topsoil depth at which contour terracing is profitable for alternative crops, prices, and discount rates.

Topsoil Depth (cm)	Discount Rates 4%		Discount Rates 12%		Discount Rates 4%		Discount Rates 12%		Discount Rates 4%		Discount Rates 12%	
	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]	Benefits/ac	B/C[a]	Benefits/ac	B/C[b]
	Corn ($2.50/bu)				Soybeans ($6.40/bu)				Wheat ($3.50/bu)			
100	$ 10.56	0.01	$ 1.66	0.00	$ 2.04	0.00	$ 0.30	0.00	$152.80	0.19	$16.13	0.03
52	83.04	0.10	12.15	0.02	44.63	0.06	6.77	0.01	172.91	0.21	28.44	0.05
22	268.67	0.33	42.19	0.07	307.19	0.38	46.59	0.08	186.79	0.23	30.72	0.05
10	436.28	0.54	69.24	0.12	654.55	0.81	100.49	0.17	190.70	0.24	31.63	0.05
	Corn ($3.13/bu)				Soybeans ($8.00/bu)				Wheat ($4.38/bu)			
100	$ 13.20	0.02	$ 2.07	0.00	$ 2.55	0.00	$ 0.39	0.00	$191.01	0.24	$31.42	0.05
52	96.73	0.12	15.18	0.03	55.78	0.07	8.46	0.01	216.13	0.27	35.55	0.06
22	335.84	0.42	52.74	0.09	383.99	0.48	58.24	0.10	233.49	0.29	38.40	0.07
16	430.78	0.53	67.64	0.12	564.78	0.70	85.65	0.15	237.12	0.29	39.00	0.07
10	545.35	0.67	86.56	0.15	818.19[c]	1.01[c]	105.62	0.18	238.38	0.29	39.54	0.08
	Corn ($1.88/bu)				Soybeans ($4.80/bu)				Wheat ($2.63/bu)			
100	$ 7.92	0.01	$ 1.25	0.00	$ 1.53	0.00	$ 0.23	0.00	$114.61	0.14	$18.85	0.03
52	58.03	0.07	9.11	0.02	33.47	0.04	5.08	0.01	129.68	0.16	21.33	0.04
10	327.21	0.40	51.93	0.09	490.92	0.61	75.37	0.13	143.02	0.18	24.02	0.04

[a]Contour terracing cost is $808.24/ac.
[b]Contour terracing cost is $586.96/ac.
[c]Critical topsoil depth at which contour terracing is profitable.

In the case of soybeans, when the price of soybeans is $8.00/bu and $4.80/bu, the topsoil depths at which strip cropping is profitable are 43 cm and 35 cm, respectively. For wheat, changing the price by 25 percent to $4.38/bu or $2.63/bu does not change the result that strip cropping is profitable no matter how deep the topsoil as long as the discount rate is 4 percent.

With a 25 percent price increase for soybeans, contour terracing is finally profitable when the topsoil is 11 cm. For corn, contour terracing becomes profitable as the price increases to $3.13/bu and topsoil depth decreases to about 5.6 cm. But as topsoil is further eroded to 3.2 cm, the cost of contour terracing exceeds the benefits because there is not enough topsoil left to make further conservation profitable.

Case 2. The private discount rate is usually much higher than 4 percent. When the rate of discount (ROD) is increased to 12 percent the topsoil depth at which strip cropping becomes profitable drops to 17 cm and 12 cm for corn with prices of $3.13/bu and $2.50/bu (Table 9, Figure 3). Farmers have no economic incentive to adopt strip cropping if corn prices decline to $1.88/bu. For wheat, at a 12 percent discount rate, the benefit-cost ratios are all below 1.0 for both strip cropping and terracing. In contrast, with a 12 percent discount rate the topsoil depth at which strip cropping is adopted for soybeans is 21 cm, 17 cm, and 11 cm, depending on soybean prices.

Due to the asymptotic relationship between topsoil depth and crop yield, soil conservation benefits are higher for shallow topsoil than they are for deep topsoil. But once topsoil depth decreases to the critical level where adoption of conservation practices becomes profitable, there is no economic advantage in further delaying adoption, given a farmer's finite planning horizon.

Further Considerations

These results are just for one soil series, and the outcome could vary greatly for different soil types across different regions. The results suggest that the Terril series is most like Case B in Figure 1. For soils belonging to Case C, where the relationship between topsoil depth and crop yield tends to be discontinuous and yields without topsoil are very low, extra topsoil will be more valuable.

Annual soil erosion estimated with USLE suggests a total loss of the eroded soil. However, most eroded soil has simply been moved from a higher place on the farm to a lower place. Thus, benefit calculations based on the USLE tend to overestimate soil conservation benefits within a finite planning period because it takes longer to actually erode soil from the field.

The costs of conservation practices are assumed to be the same across all farms even though there are differences in topsoil depth. In many situations slope and land class vary inversely with the existing topsoil depth, while installation and maintenance costs of conservation practices tend to increase with slope. Thus, further studies might consider varying the cost of conservation practices.

The net present value model and yield response function reflect only the private profitability from soil conservation practices. There are social benefits from reduced off-site soil erosion damages which may be twice as large as productive losses (Clark et al., 1985). These social benefits should be incorporated with productivity benefits in the net present value model to determine optimum levels of soil conservation for society.

Also, the social discount rate may be lower than the one used by private decisionmakers, which implies that society would desire an earlier adoption of soil conservation practices. For example, the social rate of discount might be 4 percent and the private rate 12 percent. One way to make up for this difference would be to subsidize farmers to apply soil conservation practices.

The amount of subsidy can be estimated using results from the Type I nonlinear model. In the case of corn, with 4 percent discount rate, strip cropping would be adopted at a topsoil depth of 45 cm. However, at 12 percent the adoption depth is 12 cm. At a cost of $41/ac for strip cropping and private benefits of only $10/ac with topsoil depth of 45 cm, a subsidy of $31/ac or more would be required to induce farmers to adopt strip cropping at the point desired by society.

This analysis suggests that external incentives for adopting soil conservation practices should be targeted at soils with high rates of erosion but low resulting losses in productivity. Thus, high priority should be given to deep but highly erosive soils, particularly those close to streams or rivers where farmers would have no economic incentive to prevent soil erosion and downstream damages. For shallower soils, farmers would have a greater economic incentive to apply conservation practices and prevent losses in soil productivity.

Summary and Conclusions

Yield response functions were estimated for corn, soybeans, and wheat based on farm survey data from five counties in southeastern Minnesota for the Terril soil series. The data on topsoil depth are based on farmer interviews. The calculations and choice of the subsoil characteristics were mostly based on Neill (1979) and Pierce et al. (1983).

Two regression methods, linearizable and nonlinearizable, were used to estimate functional relationships between crop yields and soil characteristics. Two types of nonlinearizable model were tested; one only includes topsoil depth (SD) while the other incorporates subsoil characteristics. Two hypotheses were tested: (1) a nonlinear relationship exists between crop yield and SD, and (2) the subsoil characteristics are crucial in determining soil productivity.

In regards to the first hypothesis, the relationship between SD and yield was nonlinear for all three crops. This was best shown by the Type I nonlinearizable model for corn and soybeans, in which SD was the only independent variable. However, for the wheat data the best fit was obtained with the linearizable model, which includes slope and SD^2 as independent variables.

Concerning the second hypothesis, subsoil characteristics were important in determining soybean and corn yields as shown by the significance of SD in the response functions. For wheat SD was only important in the linearizable model. AWC and SWC significantly affected soybean yields but were not significant in the corn or wheat response functions. Thus, the data for corn and soybeans more strongly support the second hypotheses than do the wheat data.

The optimal timing of soil conservation practices was simulated for corn, wheat, and soybeans over a 50-year planning period. The net present values for strip cropping and terracing were calculated based on the soil depth-yield relationship. Type I response functions were used to estimate the yields since they provided the "best" predictions when SD was the only independent variable.

The analysis indicated that strip cropping becomes profitable as SD drops to between 50 cm and 11 cm, depending on crop prices and discount rates. The sensitivity analysis revealed that the critical SD at which strip cropping becomes profitable is highly sensitive to the discount rate but less sensitive to crop price variations. Generally, for deep topsoils, productivity losses from soil erosion are minor and adoption of conservation practices is not profitable for farmers. Conservation practices become more profitable as productivity losses increase with topsoil erosion. Once conservation practices become profitable, there is little incentive for farmers to delay adoption.

Terracing has been vigorously promoted in this country over the last 50 years as a means of controlling soil erosion and has almost become a symbol of erosion control efforts. However, terracing is shown to not be profitable unless topsoil is very shallow, crop prices are high, and discount rates are low.

The analysis could be expanded to consider two additional factors:

(1) how risk perceptions influence farmers' conservation decisions, and
(2) how benefits from reducing downstream soil erosion damages change the social optimum depth of topsoil at which conservation practices should be adopted.

There are numerous applications of the above model for conservation decisions. However, before specific recommendations can be made, more reliable yield data by field and soil type are needed. The variation in other factors such as fertilizer, technology, and management, that directly affect yields but not by saving topsoil, needs to be considered. Finally, precise measurement of SD and research on other soils concerning the relationship between yield and soil characteristics are a prerequisite for more specific recommendations.

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Appendix

Variables Used to Estimate the Yield-Soil Loss Relationship

Yield. The soil is one of the important variables which predetermines a fairly large part of crop yield variations in response to inputs. Therefore, to estimate the soil loss impacts on crop yield, we require crop yields for the Terril soil series. However, average yield for the Terril soil series on each sample farm was difficult to obtain since many farmers do not break down crop yields for each field let alone for each soil type. Thus, crop yield for the Terril soil series had to be estimated based on average farm yield as shown in the following example:

1. The average corn yield per acre for the whole farm is obtained from the survey (108 bu/ac).
2. The acreage of different soil types on the farm is calculated using soil survey maps.
3. The estimated crop yield for different soil types is obtained from the Soil Conservation Service (SCS).

Clarion Loam	Lester Loam (2%-6%)[b]	Terril Soil (15%)[b]
35 acres	40 acres	95 acres
120 bu/ac[a]	115 bu/ac[a]	(X)

[a]SCS estimates.
[b]Slope.

4. The yield (X) for the Terril soil is obtained by solving the following equation: 108 bu/ac = [(120)(35) + 115 (40) + 95(X)]/(35 + 40 + 95). X = 101 bu/ac.

Slope. The slope data for each field with the Terril soil were directly read from the SCS soil survey map for each individual farm.

Topsoil Depth. The topsoil is soil material in the A horizon. For example in the Terril soil series the topsoil generally ranges from 0 to 38 cm for Goodhue County and 0 to 30 cm for Steele County. The average topsoil depth (SD) as reported by the farmers for each field is used in the analysis.

Available Water-holding Capacity. The available water- holding capacity (AWC) is the capacity of soils to hold water available for use by most plants. It is commonly defined as the difference between the amount of soil water at field capacity and the amount at the wilting point and is expressed as inches of water per inch of soil.

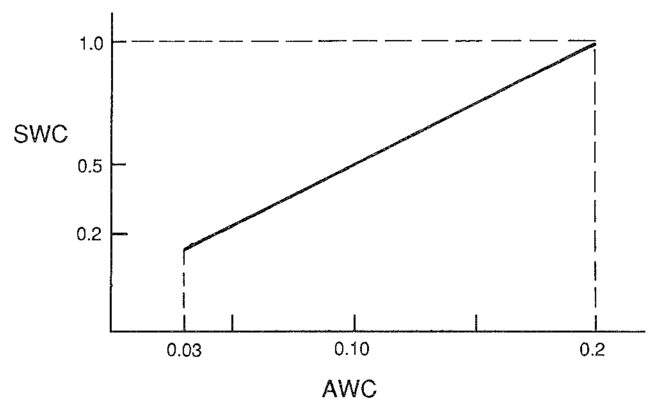

Figure A1. Relationship between AWC and SWC.

Sufficiency of Water-holding Capacity. The sufficiency of water-holding capacity (SWC) is a linear transformation of AWC to a scale of 0 to 1 (Figure A1). The AWC of the Terril soil for different soil textures was obtained from the soil survey map. The estimated SWC was then calculated using Figure A1 (Pierce et al., 1983). For example, if the AWC for a Terril soil field is 0.15 the associated SWC is about 0.75.

Weighting Factor. The formula for deriving the weighting factor is:

$$WF = \int_0^X 0.35 - 0.152 \log \sqrt{(Depth + Depth^2 + 6.45)}$$

The total area under the curve can be normalized to a value of 1.0, the integral solved, and the results displayed in a table.

Productivity Index. The productivity index (PI) drops if the subsoil has characteristics less favorable than the soil above it. The PI was constructed by Pierce et al. (1983) and Neill (1979). It is the product of WF, SWC, sufficiency of pH, and sufficiency of bulk density, and can be used to describe a linear relationship between soil productivity and soil erosion. Since for the Terril soil series the sufficiency of pH for all soil textures is 1.0 and the sufficiency of bulk density is 0.8782, the only variables changing its PI are SWC and WF.