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EROSION AND THE LOSS OF SOIL PRODUCTIVITY
ON THE TERRIL SOIL SERIES IN MINNESOTA

by

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by

Frank Hao Wen and K. William Easter*

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, it remains a severe problem. Two aspects of the soil erosion problem are of particular economic importance. First is the loss in soil productivity and second is the downstream damages caused by soil erosion. This paper 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 many 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; Fornberg and

Swanson, 1979; and Taylor, et al., 1979). However, this represents a potentially serious oversimplification (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, this neglects 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 changes in soil productivity and soil erosion is still a subject of considerable controversy. To help fill this gap, we estimate the relationship of crop yield to both topsoil depth and subsurface conditions. Several different nonlinear functional forms are tried. The study area is southeast Minnesota which is the region in Minnesota with the most serious water related soil erosion problem. The study focuses on corn, soybeans and wheat which are the dominant grain crops in the region.

Past Research

Harker, et al., found that the appropriate yield response function relating wheat yield, Y, and topsoil depth X, is asymptotic at a yield of 83 bushels. The regression equation they estimated was:

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

Thus when all topsoil is gone, wheat yields decreased to 36 bushels. With this functional form successive reductions in

topsoil depth due to soil erosion cause increasing yield reductions. Walker and Young, 1981, using the same functional form as Harker, et al., found that the yield of peas approaches a limit of about 22 cwt per acre with deep soil and decreases to 7 cwt with the loss of all topsoil.

Langdale, et al., 1979, estimated the corn yield-soil depth relationship of the southern Piedmont soil. They related soil depth to grain, stover, and dry matter by using a quadratic model and found that: (a) the soil depth-corn yield relationship was nonlinear, and (b) each centimeter of eroded topsoil costs the producer 2.34 bushels of corn grain per acre per year.

Burt, 1981, applied control theory to the farm level economics of soil conservation in the Palouse wheat area. He used topsoil depth and percentage of organic matter in the top 6 inches of soil as the two state variables and derived the following production function for wheat:

$$Y(\text{wheat/bu}) = A + 35.1 (1 - 0.9^X) (1 - 0.6^Y)$$

Where parameter "A" is a constant representing yield theoretically obtained when all topsoil is gone, X is the depth of topsoil and y is percentage of organic matter in the top 6 inches of soil.

Bhide, et al., 1982, estimated the economic optimum levels of soil loss, primarily from the individual farmer's viewpoint. A control theory model with the following three components was developed: (a) an equation relating net returns per acre to the level of soil loss per acre 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. These three equations were estimated for three erosive soils in central Iowa. 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, the subsoil characteristics have been largely ignored. However, Neill (1979) and Pierce, et al. (1983) pointed out that not only favorable surface horizons (topsoil depth) but also the subsurface horizons are crucial to soil productivity. "The relative productivity of soil and its rate of change due to erosion depends on the presence of favorable rooting characteristics in the soil profile" (Pierce, et al., 1983). This concept is illustrated by the following figures (Figure 1).

Case A represents a soil with favorable characteristics with reference to both surface and subsurface soil texture. Case B corresponds to soils with favorable surface horizons but unfavorable subsoils because of too fine or coarse texture, low pH value and/or low water holding capacity. Case C depicts soil with favorable surface horizons and consolidated or very coarse-fragment (rock or gravel) subsoils.

Neglecting either subsurface or surface characteristics will tend to oversimplify the soil erosion-productivity relationship. As soil is eroded, not only will topsoil depth change, but also

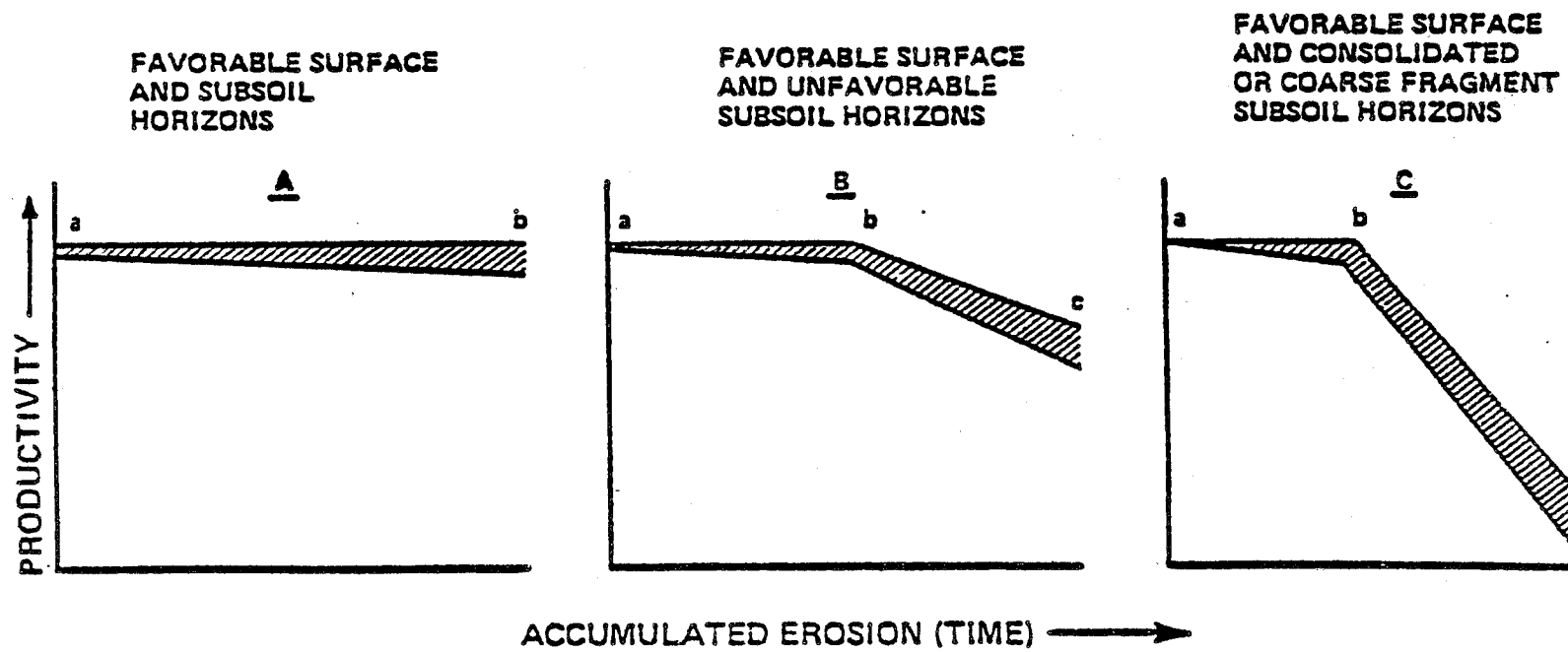


FIGURE 1. Diagram of Potential Productivity Change with Accumulated Erosion

SOURCE: Pierce, et al., 1983

the subsurface soil characteristics such as water holding capacity, will change. Pierce, et al. (1983) used a model which incorporated both the surface and the subsurface horizons to describe the soil loss-soil productivity relationship. The model includes the following factors: sufficiency of available water holding capacity, sufficiency of bulk density, sufficiency of pH value, and the weighting factor which is a function of soil depth. From these factors productivity indices were developed for major land groups. They assumed that nutrients, climate, management and plant differences did not limit plant growth. Their 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 in southeast Minnesota includes the following five counties: Goodhue, Steele, Freeborn, Olmstead, and Waseca. 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 which affect soil productivity, the study is limited to the Terril soil series.^{3/} It is the most common soil series in the study area, although it is not the dominant soil series in any county within the study area. The Terril soil series, with slope ranging from 0 percent to 25 percent, is

suitable for a wide range of crops. Thus within the area there are a range of soil erosion conditions which affect soil productivity. Table 1 shows some characteristics of the Terril soil series.

The Yield Response Function

A yield response function or a production function portrays an input-output relationship. It describes a 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 will vary among soil types, animals, technology levels, rainfall amounts 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:

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

where:

Y = output

$X_1 \dots X_n$ = variable inputs

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

In this study yield response functions are estimated for corn, soybeans, and wheat with respect to both subsoil and surface soil characteristics such as slope, topsoil depth (SD), productivity index (PI), weighting factor (WF), available water holding capacity (AWC), and sufficiency of water holding capacity (SWC), while other inputs such as level of technology (T),

TABLE 1. Terril Soil Series, Physical and Chemical Properties

| Properties | Depth from surface | Soil Texture | Permea- bility | Available Water | Reaction | Bulk Den- sity | Erosion Factor | Organic Matter |
|------------------|--------------------------|-----------------|-------------------|--------------------|----------|----------------------|-------------------|-------------------|
| Terril Series | (Inch) | | (inch/hr) | (in/in) | (PH) | (g/cm ³) | (K) (T) | % |
| | 0-5 | Sandy | 2.0 | 0.10 | 6.1 | 1.35 | 0.32 5 | 4 |
| | | Loam | 6.0 | 0.15 | 6.5 | 1.40 | | 5 |
| | 5-10 | Loam | 0.6 | 0.15 | 5.6 | 1.35 | 0.32 NA | NA |
| | | | 2.0 | 0.19 | 6.0 | 1.40 | | |
| | 10-15 | Clay | 0.6 | 0.20 | 5.6 | 1.35 | 0.32 NA | NA |
| | | Loam | 2.0 | 0.22 | 6.0 | 1.40 | | |
| | 15-30 | Sandy | 0.6 | 0.11 | 5.6 | 1.40 | 0.32 NA | NA |
| | | Loam | 2.0 | 0.16 | 6.0 | 1.65 | | |
| | 30-50 | Fine | 6.0 | 0.05 | 5.6 | 1.65 | 0.10 NA | NA |
| | | Sand | 20.0 | 0.07 | 6.0 | 1.75 | | |

SOURCE: Table (15), Page 196, "Soil Survey of Olmstead County," March 1980.

fertilizer utilization (F), and management (M) are assumed constant.^{4/} The yield response function can be expressed as:

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

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 associated crop yields. In fact, one might expect linear relationships to be the exception rather than the rule. However, 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.

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, that is,

$$\text{Log } Y = \text{Log } A + b \text{ Log } X$$

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

choice of a transformation to achieve linearity will depend largely on the nature of the variables, and other considerations.

The rankit plots for crop yield versus each independent variable indicated that nonlinear relationships exist between topsoil depth and associated 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,

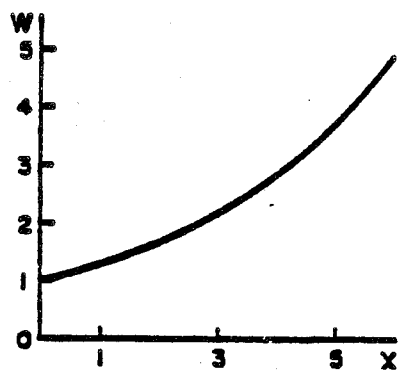
X_2 = slope,

X_3 = subsoil characteristics.

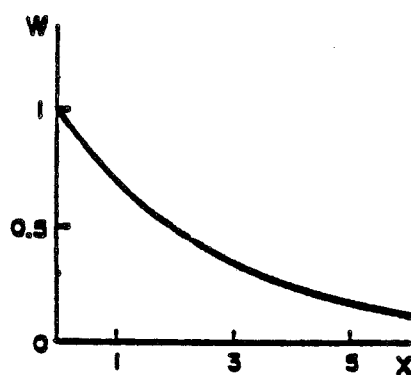
Nonlinearizable Models

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; and Narayanan, et al., 1974). The four most common nonlinear relationships are shown in Figure 2. The most appropriate relationship suggested by past studies appears to be the Asymptotic Regression Type, i.e. $\text{Yield} = A - B(C^X)$.

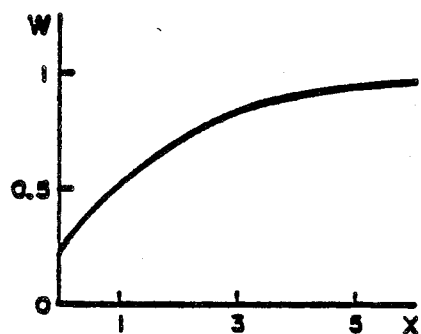
A nonlinearizable model means that the regression analysis involves an estimation of parameters that appear in the regression model in a nonlinearizable fashion.^{5/} The following nonlinearizable models are estimated for corn, wheat and soybeans:



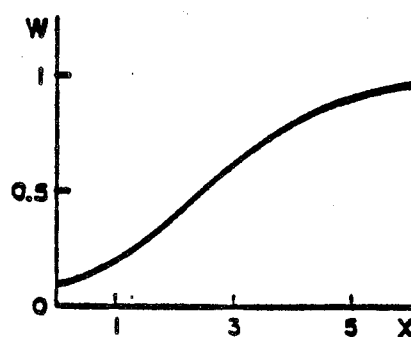
(a) Exponential Growth Law
 $W = A(B^X) = A(e^{cX})$



(b) Exponential Decay Law
 $W = A(B^{-X}) = A(e^{-cX})$



(c) Asymptotic Regression
 $W = A - B(\rho^X) = A - B(e^{-cX})$



(d) Logistic Growth Law
 $W = A/(1+B\rho^X)$

FIGURE 2. Four Most Common Nonlinear Relations

Model Type I

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

where:

X = topsoil depth

K = $\text{Exp } B_3$

B₁, B₂, and B₃ are estimated parameters

Model Type II

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

where:

X = topsoil depth

Z = one of the soil characteristics, i.e., slope
AWC, SWC, WF, or PI

K = $\text{Exp } B_4$

B₁, B₂, B₃, and B₄ are estimated parameters

Data and Farm Survey

The response functions are estimated based on data obtained from farmers who participated in the Southeastern Minnesota Farm Records Project in 1982 and who had a significant amount of the Terril soil series on their farms. The amount of Terril soil on each farm was determined from soil survey maps.

A farm survey was conducted 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. Once fields were identified on the soil survey maps, information concerning slope and subsoil characteristics such as water holding capacity, and pH value could be obtained.

The survey sample distribution is shown in Table 2. A number of farmers did not know their topsoil depth and these observations had to be dropped from the sample. Thus the final sample size was lowered to 43 observations for corn, 37 observations for soybeans and 41 observations for wheat.

Comparison of Results

Linearizable Model

The linearizable models provide reasonably good estimates of yield responses for all three crops. For corn, the slope, soil depth (SD) and $(SD)^2$ are all significant at the 5 percent level or higher in explaining yields while for soybeans SD and SD^2 and available water holding capacity (AWC) are significant at the 5 percent level or higher (Table 3). In the wheat model $(SD)^2$ and slope are significant at the 1 percent level or higher. 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 are the most significant variables explaining yields in all three cases.

TABLE 2. Farmers Surveyed by Crop and County, 1983

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

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) |
| Soil Depth | - - - | 2.50 (3.96)**** | 1.51 (4.35)**** |
| Soil ² Depth ² | 0.007 (5.09)**** | -0.028 (-1.77) ⁺ | -0.031 (-2.79)** |
| Slope | -0.371 (02.75)** | -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 |
| Degree of Freedom | 37 | 39 | 33 |

Figures in parenthesis are the t statistics

****p < 0.001

*** p < 0.005

** p < 0.01

* p < 0.025

+ p < 0.05

The three estimated equations support the argument that the relationship between land productivity and soil erosion should be nonlinear. This conclusion is based on the following evidence:

- The "square of topsoil depth" term SD^2 appears in all the estimated linearizable regression models and is statistically significant at the 5 percent level or better.
- 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.

Among the three crops, corn has the largest yield drop when topsoil depth is reduced. The regression results show that a one inch loss (2.54 cm per inch) of topsoil will reduce corn yield by about 6.35 bu (2.5×2.54). The next most affected crop is soybeans, where a one inch topsoil loss will reduce soybean yield by 3.8 bu per acre. After all the topsoil has been removed, the theoretical corn yield on the subsoil is about 68 bu which is about half of the highest corn yield. In the case of soybeans, with all the topsoil removed, yield is only about 10.5 bu which amounts to less than one-third of the expected soybean yield for a deep topsoil. Both corn and soybean yields are dramatically affected by the amount of topsoil.

For wheat, yield is not very sensitive to soil characteristics such as topsoil depth, slope, and AWC. This can be seen from the constant term of the equation for wheat. It is 31.26 which indicates that if there is no topsoil, wheat yield will be 31.26 bu per acre. Comparing this figure with the average wheat

yield from the sample (38.75 bu per acre), there is only a 7.5 bu yield difference.

The steepness of slope and the loss in topsoil affect the crop yield in the same direction. 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 ($12.2 = (11)(0.535) + (2.54)(2.5)$). When steepness of slope increases, erosion potential increases since topsoil removal is easier.

For both wheat and soybeans, the regression equations show that available water holding capacity (AWC), a subsoil characteristic, can also be an important independent variable in determining yields. The coefficient of AWC for soybeans is significant at the 5 percent level but for wheat it is only significant at the 40 percent 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 for wheat and 10 bu for soybeans. The most important is the 5 bu yield differences for wheat which accounts for more than 50 percent of total yield variation. The 10 bushels yield difference for soybeans accounts for more than 30 percent of total yield variation. The impact of AWC suggests 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 topsoil depth is included. The regression equation for wheat shows no statistically reliable relationship between yield and soil depth since all of the estimated parameters are not significant at the 20 percent 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 1 percent level or better. Moreover, the R^2 of 0.79 indicates a good fit. The regression results for soybeans are equally as good. All parameters except the constant term are significant at the 0.5 percent level or better and the $R^2 = .80$.

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

Comparing these results for wheat with the linearizable model one finds that the constant term explains most of the yield variation in the linearizable model but not in the Type I

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 |
| Degree of Freedom | 38 | 40 | 34 |

Figures in parentheses are the t statistics.

**** p < 0.001

*** p < 0.005

** p < 0.01

* p < 0.20

nonlinearizable model. The average sample yield for wheat is 38.75 bu per acre while the constant terms are 31.26 and 17.85 for the linearizable and nonlinearizable models, respectively. The limit value of wheat yield asymptotically approaches 370 bu per acre under the nonlinearizable Type I model which indicates that the wheat data is 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.

Two of the Type II nonlinearizable regression models estimated for wheat provided the best fit to the data. In the first equation Z is available water holding capacity (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 5 percent level (see Table 5). Only the coefficient for slope was close to being significant at the 5 percent level.

For corn, the two type II nonlinearizable regression equations explain about 80 percent of the yield variation. In the first Z is the weighting factor (WF) and in the second Z is the slope. Statistically, WF is not significant at the 20 percent level while soil depth is highly significant. In the second regression equation, the slope is significant at the 1 percent level but the topsoil depth parameter B₄ is only significant at the 20 percent level.

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 (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 | | |
| Degree of Freedom | 37 | | 39 | | 33 | | |

The figures in parentheses are the t statistics.

**** p < 0.001
 *** p < 0.005
 ** p < 0.01
 * p < 0.025
 + p < 0.05

For soybeans there are three type II nonlinearizable regression equations with Z being AWC, sufficiency of available water holding capacity (SWC) and the productivity index (PI). The constant terms B_1 are not statistically significant at the 5 percent level, except for the equation with PI as the soil characteristic. The coefficients for soil characteristics are significant at the 2.5 percent level for AWC and at the 10 percent level for SWC. In contrast, all of the coefficients for topsoil depth are statistically significant at the 0.5 percent level or better.

The regression equations based on the Type II nonlinearizable model suggest that incorporating other soil characteristics 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 such as AWC, WF, SWC, PI are not significant in the equations except for slope with corn and AWC and SWC for soybeans. Where slope is significant for corn the parameter for topsoil depth 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 suggest 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

By using the estimated functional relationship between topsoil depth and crop productivity one can calculate the benefits associated with different soil conservation practices and evaluate their relative profitability.^{6/} Since the Type I nonlinear 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 following 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 of the asymptotic nature of the yield response functions with respect to topsoil depth, 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 depth is relatively shallow, below 20 cm, soil conservation practices offer significant yield advantages and the adoption of conservation practices will become more attractive to farmers.

The above relationship can be readily understood by referring to the results from 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 6. Crop Yields and Soil Depth Over Time Under Three Soil Conservation Practices

| Crops: | CORN | | | SOYBEANS | | | WHEAT | | |
|---------------------------------|--------------------|----------------|--------------------|------------|----------------|--------------------|------------|----------------|--------------------|
| | Contouring | Strip Cropping | Contouring Terrace | Contouring | Strip Cropping | Contouring Terrace | Contouring | Strip Cropping | Contouring Terrace |
| Practices: | Contouring | Cropping | Terrace | Contouring | Cropping | Terrace | Contouring | Cropping | Terrace |
| Planning period (years) | | | | | | | | | |
| 1 | 40 ^a | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | 118.2 ^b | 118.2 | 118.2 | 51.6 | 51.6 | 51.6 | 52.2 | 52.2 | 52.2 |
| 5 | 39.0 | 39.5 | 39.8 | 39.0 | 39.5 | 39.8 | 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 | 37.8 | 38.9 | 39.6 | 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 | 36.6 | 38.3 | 39.3 | 36.6 | 38.3 | 39.3 |
| | 115.7 | 117.0 | 117.9 | 50.9 | 51.3 | 51.5 | 49.5 | 50.9 | 51.7 |
| 1-16 Subtotal (bu.) | 1874.9 | 1883.4 | 1888.3 | 821.0 | 823.3 | 824.7 | 817.4 | 824.5 | 832.0 |
| 20 | 35.4 | 37.7 | 39.1 | 35.4 | 37.7 | 39.1 | 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 | 34.2 | 37.1 | 38.9 | 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 | 33.0 | 36.5 | 38.6 | 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 | 31.8 | 35.9 | 38.4 | 31.8 | 35.9 | 38.4 |
| | 111.7 | 115.1 | 117.0 | 49.6 | 50.7 | 51.3 | 45.5 | 48.9 | 50.9 |
| 40 | 30.6 | 35.3 | 38.1 | 30.6 | 35.3 | 38.1 | 30.6 | 35.3 | 38.1 |
| | 110.1 | 114.6 | 116.9 | 49.2 | 50.7 | 51.2 | 44.5 | 48.4 | 50.7 |
| 45 | 29.4 | 34.7 | 37.9 | 29.4 | 34.7 | 37.9 | 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 | 28.2 | 34.1 | 37.7 | 28.2 | 34.1 | 37.7 |
| | 107.5 | 113.5 | 116.5 | 48.3 | 50.2 | 51.1 | 42.5 | 47.4 | 50.3 |
| 1-50 Total (bu.) | 5682.3 | 5805.8 | 5871.5 | 2512.1 | 2550.2 | 2568.9 | 2385.0 | 2498.8 | 2566.5 |
| % of production decrease (1-50) | 9.0 ^c | 4.0 | 1.5 | 6.5 | 2.6 | 1.0 | 18.7 | 9.3 | 3.7 |
| % of production decrease (1-16) | 2.2 ^d | 1.0 | 0.4 | 1.4 | 0.7 | 0.3 | 5.3 | 2.6 | 1.1 |

^aTopsoil depth (cm).^bCrop yield (bu/acre).^c(Yield in the 50th year - yield in the 1st year)/yield in the 1st year.^d(Yield in the 16th year - yield in the 1st year)/yield in the 1st year.

TABLE 7. Crop Yields and Soil Depth Over Time for Shallow Topsoil Under Three Soil Conservation Practices

| Crops: | CORN | | | SOYBEANS | | | WHEAT | | |
|---------------------------------|-------------------|----------------|--------------------|------------|----------------|--------------------|------------|----------------|--------------------|
| Practices: | Contouring | Strip Cropping | Contouring Terrace | Contouring | Strip Cropping | Contouring Terrace | Contouring | Strip Cropping | Contouring Terrace |
| Planning period (years) | | | | | | | | | |
| 1 | 20 ^a | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| | 96.2 ^b | 96.2 | 96.2 | 43.8 | 43.8 | 43.8 | 35.5 | 35.5 | 35.5 |
| 5 | 19.0 | 19.5 | 19.8 | 19.0 | 19.5 | 19.8 | 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 | 17.8 | 18.9 | 19.6 | 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 | 16.6 | 18.3 | 19.3 | 16.6 | 18.3 | 19.3 |
| | 90.4 | 93.4 | 95.1 | 41.3 | 42.6 | 43.4 | 32.4 | 34.0 | 34.9 |
| 1-16 Subtotal (bu.) | 1490.6 | 1515.8 | 1530.2 | 680.0 | 691.2 | 697.5 | 543.7 | 555.4 | 562.8 |
| 20 | 15.4 | 17.7 | 19.1 | 15.4 | 17.7 | 19.1 | 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 | 14.2 | 17.1 | 18.9 | 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 | 13.0 | 16.5 | 18.6 | 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 | 11.8 | 15.9 | 18.4 | 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 | 10.6 | 15.3 | 18.1 | 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 | 9.4 | 14.7 | 17.9 | 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 | 8.2 | 14.1 | 17.7 | 8.2 | 14.1 | 17.7 |
| | 71.7 | 85.5 | 92.2 | 31.7 | 38.9 | 42.1 | 25.2 | 30.4 | 33.5 |
| 1-50 Total (bu.) | 4294.4 | 4588.4 | 4720.9 | 1949.9 | 2086.2 | 2152.9 | 1538.2 | 1657.2 | 1727.6 |
| % of production decrease (1-50) | 25.5 ^c | 11.2 | 4.2 | 27.6 | 11.2 | 4.0 | 28.9 | 14.4 | 5.7 |
| % of production decrease (1-16) | 6.5 ^d | 3.1 | 1.2 | 6.4 | 3.0 | 1.1 | 8.7 | 4.4 | 1.8 |

^aTopsoil depth (cm).^bCrop yield (bu/acre).^c(Yield in the 50th year - yield in the 1st year)/yield in the 1st year.^d(Yield in the 16th year - yield in the 1st year)/yield in the 1st year.

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. In both tables annual depth of topsoil at the end of each year is calculated with the Universal Soil Loss Equation (USLE) for different crops and soil conservation practices. The average annual crop yield is then calculated for the three crops based on the yield-topsoil depth relationships shown in the last section. Table 6 indicates that for a 50 year planning period expected total per acre corn production will be 5,682 bu if the farm field is contoured. If the soil conservation practice is strip cropping, expected total corn production increases to 5,806 bu per acre for the 50 year planning period. Under contour terraces, corn production increases to 5,871 bu per acre. The expected difference in corn production between contouring and contour terraces for the 50 year period is 189 bu (5,871 - 5,682).

If one focuses on corn production in the first 16 years the correspondent difference in corn production between contouring and contour terraces is only 13 bu per acre (1,888 - 1,875). The production difference from soil conservation practices in the first 16 years accounts for only 7 percent of expected difference in production for the 50 year planning period.

For soybeans, expected total production per acre over the next 50 years will be 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 per acre. In the

first 16 years, the production advantages with terraces is only 4 bu which amounts to 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 will increase production by only 15 bu over contouring for the first 16 years. This difference accounts for 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. Soil erosion 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.

When initial topsoil is shallow, i.e. only 20 cm, contour terracing offers significant yield advantages during a much shorter time period. For corn contour terraces on shallow soil will reduce productive losses by 40 bu per acre over the 16 year period. The productive difference will be 17 bu and 20 bu for soybeans and wheat, respectively. Comparing the last two rows in Table 6 and Table 7, which are the percent drop in productivity for both planning periods and soil depths, shows that conser-

vation 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 physical relationship between topsoil depth 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. The farmer's decision rule is to choose the advanced soil conservation practices such as strip cropping or contour terracing to reduce losses in productivity when the benefits from these conservation practices exceed costs. Mathematically, the private farm decision model is as follows:

$$\text{Max NPV} = \sum_{t=0}^T \left\{ \frac{(P_{t+1}) \cdot Y_{t+1}}{(1+r)^{t+1}} \right\} - \left\{ \frac{\text{ICCP}_i}{(1+r)^i} + \sum_{t=0}^{T-1} \frac{\text{MC}_{t+1}}{(1+r)^{t+1}} \right\}$$

where:

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

$t = 0$, 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 .

NPV = net present value.

r = discount rate.

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

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

Farmers make these decisions concerning adoption of additional conservation practices and timing of adoption based on the difference between net present value of contouring $(NPV)_C$ and net present value of strip cropping $(NPV)_{SC}$ or contour terracing $(NPV)_{TC}$. It is assumed that with or without advanced conservation practices, only the amount of soil erosion and topsoil depth will change while variable production costs are held constant.

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

The analysis shows that when topsoil depth 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 the strip cropping conservation practice (see Table 9 and Figure 3).^{8/} For wheat, the strip cropping practice is profitable with deep soil, and the benefit increases linearly as soil is eroded. This is because the data for wheat does 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, the adoption of strip cropping will be delayed by about 100 years for corn producers and 130 years for

TABLE 8

Cost, Price and Erosion Rate Data Used
in the Cost-benefit Analysis

| | <u>Corn</u> | <u>Soybeans</u> | <u>Wheat</u> |
|-------------------|------------------------|-----------------|--------------|
| <u>Crop Price</u> | \$2.50/bu ^a | \$6.40 | \$3.50 |
| 25% decrease | \$1.88 | \$4.80 | \$2.63 |
| 25% increase | \$3.13 | \$8.00 | \$4.38 |

| | <u>Strip Cropping</u> | <u>Contour Terraces</u> |
|---|-------------------------|--------------------------|
| Installation cost | \$24.89/ac ^b | \$447.60/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 |

| | <u>Contouring</u> | <u>Strip Cropping</u> | <u>Contour Terraces</u> |
|---------------------------------------|-------------------|-----------------------|-------------------------|
| Annual soil erosion rate ^d | 14.52 t/a/yr | 7.26 | 2.90 |
| | 0.24 cm/yr | 0.12 | 0.048 |

^a"Farm Planning Prices," University of Minnesota, Agricultural Extension Service, 1980.

^b"An Analysis of On-farm Impacts of Soil Conservation and Non-point Source Pollution Abatement Practices and Policies on Representative Farms in Southeast Minnesota," Merritt Merrill Padgitt, 1980.

^c"The Economics of Soil and Water Conservation Practices in Iowa: Model and Data Documentation," August 1982, C. Arden Pope III, Shashanka Bhide and Earl O. Heady.

^dSee footnote 5.

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% | B/C ^a | 12% | B/C ^b | 4% | B/C ^a | 12% | B/C ^b | 4% | B/C ^a | 12% | B/C ^b |
| | Corn (\$2.50/bu.) | | | | Soybeans (\$6.40/bu.) | | | | Wheat (\$3.50/bu.) | | | |
| 100 | 6.87 | 0.102 | 1.03 | 0.025 | 1.35 | 0.020 | 0.20 | 0.005 | 95.74* | 1.415* | 15.73 | 0.380 |
| 52 | 50.30 | 0.744 | 7.79 | 0.188 | 29.65 | 0.438 | 4.41 | 0.106 | 108.33 | 1.602 | 17.80 | 0.430 |
| 46 | 64.53 | 0.954 | 10.00 | 0.241 | 43.61 | 0.645 | 6.48 | 0.156 | 110.02 | 1.627 | 18.08 | 0.437 |
| 40 | 82.77* | 1.224* | 12.82 | 0.310 | 64.15 | 0.948 | 9.53 | 0.230 | 111.73 | 1.652 | 18.36 | 0.443 |
| 34 | 106.17 | 1.569 | 16.45 | 0.397 | 94.34* | 1.395* | 14.01 | 0.338 | 113.47 | 1.678 | 18.65 | 0.450 |
| 22 | 174.68 | 2.582 | 27.05 | 0.653 | 198.08 | 2.928 | 30.31 | 0.732 | 117.03 | 1.730 | 19.23 | 0.464 |
| 16 | 224.06 | 3.313 | 34.70 | 0.838 | 300.16 | 4.438 | 44.58* | 1.077* | 118.85 | 1.757 | 19.53 | 0.472 |
| 10 | 281.62 | 4.164 | 44.34* | 1.071* | 431.49 | 6.379 | 65.27 | 1.576 | 118.75 | 1.756 | 19.78 | 0.478 |
| | Corn (\$3.13/bu.) | | | | Soybeans (\$8.00/bu.) | | | | Wheat (\$4.38/bu.) | | | |
| 100 | 8.58 | 0.127 | 1.33 | 0.032 | 1.69 | 0.025 | 0.25 | 0.006 | 119.67* | 1.769* | 19.67 | 0.475 |
| 52 | 62.89 | 0.929 | 9.73 | 0.235 | 37.06 | 0.548 | 5.50 | 0.133 | 135.42 | 2.002 | 22.25 | 0.537 |
| 46 | 80.66* | 1.192* | 12.49 | 0.302 | 54.51 | 0.806 | 8.09 | 0.195 | 137.52 | 2.033 | 22.60 | 0.546 |
| 40 | 103.46 | 1.529 | 16.02 | 0.387 | 80.18* | 1.185* | 11.90 | 0.287 | 139.66 | 2.065 | 22.95 | 0.554 |
| 22 | 218.35 | 3.228 | 33.82 | 0.817 | 255.10 | 3.771 | 37.89 | 0.915 | 146.29 | 2.163 | 24.04 | 0.581 |
| 16 | 280.07 | 4.141 | 43.38* | 1.048* | 375.20 | 5.547 | 55.73* | 1.346* | 148.56 | 2.196 | 24.42 | 0.590 |
| | Corn (\$1.88/bu.) | | | | Soybeans (\$4.80/bu.) | | | | Wheat (\$2.63/bu.) | | | |
| 100 | 5.14 | 0.076 | 0.80 | 0.019 | 1.02 | 0.015 | 0.15 | 0.004 | 71.81* | 1.062* | 11.80 | 0.285 |
| 52 | 37.73 | 0.558 | 5.84 | 0.141 | 22.23 | 0.329 | 3.30 | 0.080 | 81.25 | 1.201 | 13.35 | 0.322 |
| 40 | 62.07 | 0.918 | 9.62 | 0.232 | 48.10 | 0.711 | 7.15 | 0.173 | 83.80 | 1.239 | 13.77 | 0.333 |
| 34 | 79.62* | 1.177* | 12.33 | 0.298 | 70.76* | 1.046* | 10.50 | 0.254 | 85.10 | 1.258 | 13.98 | 0.338 |
| 16 | 168.04 | 2.484 | 36.03 | 0.629 | 225.12 | 3.328 | 33.44 | 0.808 | 89.14 | 1.318 | 14.65 | 0.354 |
| 10 | 211.22 | 3.123 | 33.26 | 0.803 | 323.62 | 4.784 | 48.96* | 1.182* | 89.06 | 1.317 | 14.83 | 0.358 |

a. Strip cropping cost is \$67.64 per acre.

b. Strip cropping cost is \$41.41 per acre.

*. Critical topsoil depth at which strip cropping is profitable.

FIGURE 3. Benefit-Cost Ratio for Strip Cropping Conservation Practices

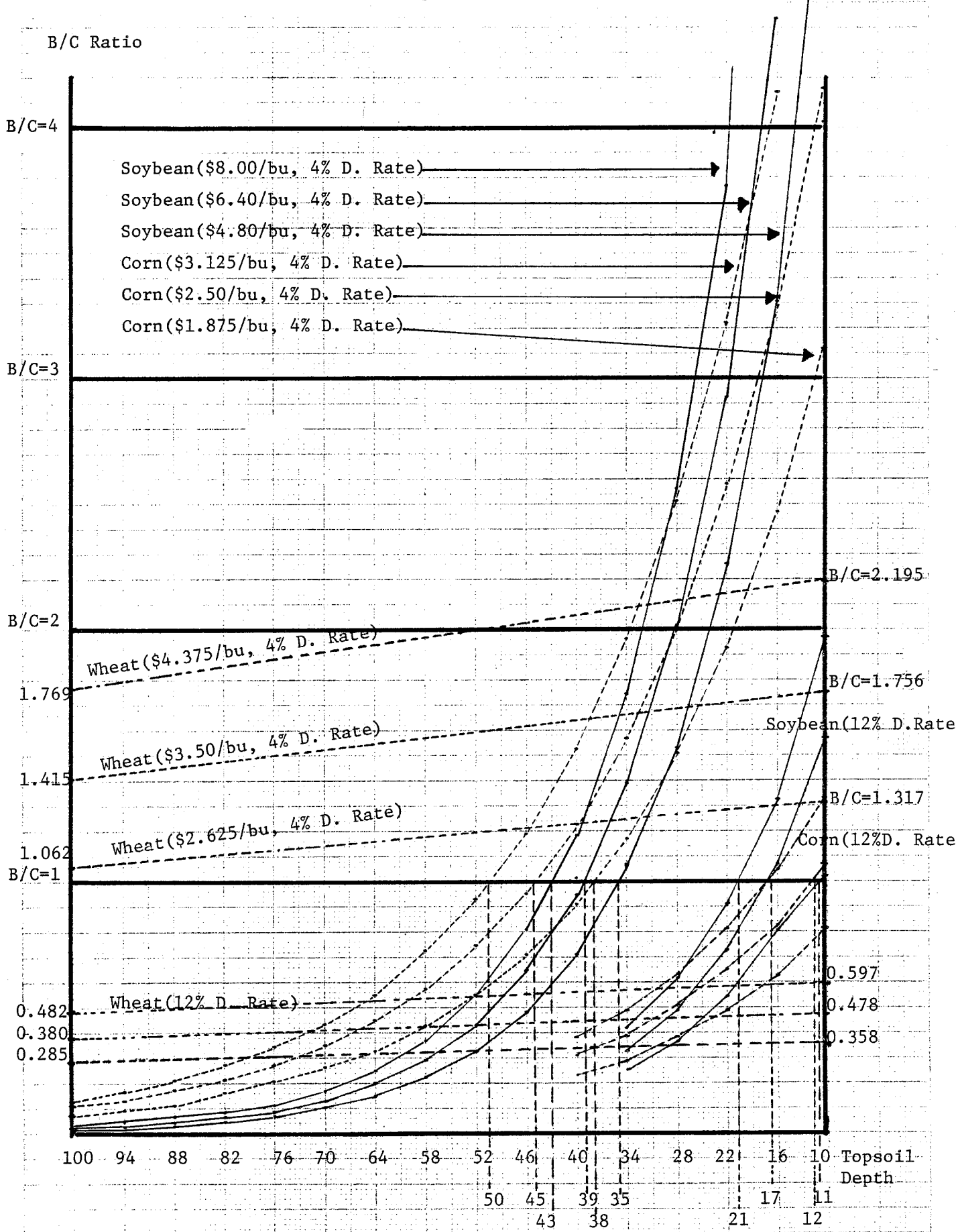


TABLE 10. Topsoil Depth at Which Contour Terracing is Profitable for Alternative Crops, Prices and Discount Rates

| 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 |
| <hr/> | | | | | | | | | | | | |
| | Corn (\$2.50/bu.) | | | | Soybeans (\$6.40/bu.) | | | | Wheat (\$3.50/bu.) | | | |
| 100 | 10.56 | 0.013 | 1.66 | 0.003 | 2.04 | 0.00252 | 0.30 | 0.0005 | 152.80 | 0.189 | 16.13 | 0.027 |
| 52 | 83.04 | 0.103 | 12.15 | 0.021 | 44.63 | 0.05522 | 6.77 | 0.0115 | 172.91 | 0.214 | 28.44 | 0.048 |
| 22 | 268.67 | 0.332 | 42.19 | 0.072 | 307.19 | 0.38007 | 46.59 | 0.0794 | 186.79 | 0.231 | 30.72 | 0.052 |
| 10 | 436.28 | 0.540 | 69.24 | 0.118 | 654.55 | 0.80985 | 100.49 | 0.1712 | 190.70 | 0.236 | 31.63 | 0.054 |
| | Corn (\$3.13/bu.) | | | | Soybeans (\$8.00/bu.) | | | | Wheat (\$4.38/bu.) | | | |
| 100 | 13.20 | 0.016 | 2.07 | 0.004 | 2.55 | 0.003 | 0.39 | 0.0007 | 191.01 | 0.236 | 31.42 | 0.054 |
| 52 | 96.73 | 0.119 | 15.18 | 0.026 | 55.78 | 0.069 | 8.46 | 0.0144 | 216.13 | 0.267 | 35.55 | 0.061 |
| 22 | 335.84 | 0.416 | 52.74 | 0.090 | 383.99 | 0.475 | 58.24 | 0.0992 | 233.49 | 0.289 | 38.40 | 0.065 |
| 16 | 430.78 | 0.533 | 67.64 | 0.115 | 564.78 | 0.699 | 85.65 | 0.1459 | 237.12 | 0.293 | 39.00 | 0.066 |
| 10 | 545.35 | 0.675 | 86.56 | 0.147 | 818.19* | 1.012* | 105.62 | 0.1799 | 238.38 | 0.295 | 39.54 | 0.067 |
| | Corn (\$1.88/bu.) | | | | Soybeans (\$4.80/bu.) | | | | Wheat (\$2.63/bu.) | | | |
| 100 | 7.92 | 0.0098 | 1.25 | 0.0021 | 1.53 | 0.0019 | 0.23 | 0.0004 | 114.61 | 0.142 | 18.85 | 0.032 |
| 52 | 58.03 | 0.0718 | 9.11 | 0.0155 | 33.47 | 0.0414 | 5.08 | 0.0087 | 129.68 | 0.160 | 21.33 | 0.036 |
| 10 | 327.21 | 0.4048 | 51.93 | 0.0885 | 490.92 | 0.6074 | 75.37 | 0.1284 | 143.02 | 0.177 | 24.02 | 0.041 |

a. Contour terracing cost is \$808.24 per acre.

b. Contour terracing cost is \$586.96 per acre.

*. Critical topsoil depth at which contour terracing is profitable.

soybean producers. Therefore, the adoption year 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. First, projected crop prices were allowed to both increase and decrease by 25 percent. With the price of corn increased to \$3.13/bu, farmers will adopt strip cropping 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 25 percent 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 will be further delayed by about 30 years.

In the case of soybeans, when the price of soybeans is \$8.00/bu and \$4.80/bu, the topsoil depth at which strip cropping will be adopted is 43 cm and 35 cm, respectively. For wheat changing the price by 25 percent, i.e. \$4.38/bu or \$2.63/bu, will 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, it is finally profitable to adopt contour terracing when the topsoil is 11 cm. Table 10 also shows that, as the corn price increases to \$3.13/bu and topsoil decreases to about 5.6 cm, contour terracing will become profitable. But as topsoil depth 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.

Second, 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 and Figure 3). Farmers have no 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 one 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 farmers with shallow topsoil than they are for those with 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

Because the results are for one soil series, the Terril series in southeastern Minnesota, the outcome could vary greatly for different soil types across different regions. Our estimated results suggest that the Terril series is most like Case B shown in Figure 1. For soils belonging to Case C, where the relationship between topsoil depth and crop yield tends to be discon-

tinuous 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 of the 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 and 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 decision makers 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 of 8 percent would be to subsidize farmers to apply soil conservation practices. Using results from the Type I nonlinear model, the amount of subsidy can be estimated. 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.

The results from our analysis suggest a general rule for targeting soil conservation practices based on topsoil depth and the susceptibility to soil erosion. The target should be those soils which have 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. 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 topsoil depth

as well as subsoil characteristics such as available waterholding capacity were found to affect crop yield. The data on topsoil depth is based on farmer interviews. The calculations and choice of the subsoil characteristics are mostly based on Neill's 1979 thesis and the research paper by Pierce, et al. (1983).

Two regression methods, linearizable and nonlinearizable, are used to estimate functional relationships between the crop yields and soil characteristics. There are two types of nonlinearizable models, one which only includes topsoil depth while the other incorporates additional subsoil characteristics. Two hypotheses have been tested: (1) a nonlinear relationship exists between crop yield and the topsoil depth and (2) the subsoil characteristics are crucial in determining soil productivity. In regards to the first hypothesis, the relationship between topsoil depth and yield was nonlinear for all three crops. This is best shown by the Type I model for corn and soybeans which includes topsoil depth as the only independent variable. However, for the wheat data the best fit is obtained with the linearizable model which includes slope and SD^2 as independent variables.

Concerning the second hypothesis, subsoil characteristics are important in determining soybean and corn yields as shown by the significance of soil depth in the response functions. For wheat soil depth was only important in the linearizable model. In addition, AWC and SWC significantly affect soybean yields. Yet they were not significant in the corn or wheat response functions. Thus the data for corn and soybeans more strongly support the second hypotheses than does the wheat data.

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

The analysis indicates that strip cropping will become profitable as topsoil depth drops to between 50 cm and 11 cm depending on crop prices and discount rates. The sensitivity analysis reveals that the critical topsoil depth 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 are 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, as a means of controlling soil erosion, has been vigorously promoted in this country over the last 50 years and has almost become a symbol of erosion control efforts. However, terracing is shown not to be a profitable farming practice unless topsoil is very shallow while crop prices are high and discount rates low.

The analysis could be expanded to consider:

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

There are a range of 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 inputs such as fertilizer, as well as differences in technology and management that directly affect yields but not by saving topsoil, need to be considered. Finally, precise measurement of topsoil depth and research on other soils concerning the relationship between yield and soil characteristics are a prerequisite for more specific recommendation.

FOOTNOTES

* The authors would like to thank Ford Runge, Steve Taff and Burt Sundquist for their very helpful comments on an earlier draft.

1/ The capacity of a soil to produce a specified plant or sequence of plants under a physically defined set of management practices.

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

3/ The Terril soil series consist 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 a 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. The content of available phosphorus is medium and that of potassium 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 run-off and siltation in cultivated fields. Surface run-off is medium to rapid and the primary management need is to control surface run-off. Soil conservation practices and maintenance of fertility are important.

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 $Y_i = f_i(X, b) + e_i$, $i = 1, 2, 3, \dots, N$ where $f_i(X, b)$ 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, the X's, and the parameters, the b's.

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

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

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 in the expression.

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

representations of the data or from models used to describe analogous systems.

6/ The 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 is $h = 400$ ft and the slope = 10 percent, therefore, the LS factor is 2.8, (3) the crop management factor $C = 0.18$ assuming a corn-corn-oats-meadow rotation and (4) depending on whether the specific farm field is to be contoured, strip cropped or contour terraced, the soil conservation practice factors would be $P_c = 0.6$, $P_{sc} = 0.3$ and $P_{tc} = 0.12$. Substituting the above information into the 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/acre/year. This amounts to approximately a 0.24 cm loss of topsoil per year. For strip cropping the soil loss is $(150)(2.8)(0.3)(0.32)(0.18) = 7.26$ tons/acre/year which is about 0.12 cm of topsoil lost per year. For contour terraces the soil loss is $(150)(2.8)(0.12)(0.32)(0.18) = 2.90$ tons/acre/year, or about 0.048 cm of topsoil lost per year.

If there is no conservation practice at all 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/acre/year, which is about 0.4 cm of topsoil lost per year.

7/ Contouring often costs only a few dollars an acre. The major expenses include 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 base line and farmers compare it with other advanced conservation practices. However, this means that we will underestimate the benefits from adopting soil conservation practices for those farmers not applying any conservation measures.

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 25-30 percent of the land out of row crop production on a per acre basis 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 making this adjustment. 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.

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APPENDIX

Variables Used to Estimate the Yield-Soil Loss Relationship

The soil is one of the important variables which pre-determines a fairly large part of crop yield variations in response to inputs. Therefore, to estimate the soil loss impacts on crop yield, one needs yield data from a given soil type. Thus, crop yields are required for the Terril soil series. However, average yield for the Terril soil series on each sample farm is difficult to obtain since many farmers do not know their crop yields for each field let alone for each soil type. Thus, crop yield for each field, which is predominantly the Terril soil series, had to be estimated based on average farm yield. The following is an example of how these yields were calculated.

- | | |
|---------|---|
| Step 1. | The average corn yield per acre for the whole farm obtained from the survey is 108 bu/ac. |
| Step 2. | The farm is located on the soil survey map and the acreage of different soil types on that farm is calculated. |
| Step 3. | The estimated crop yield for different soil types is obtained from the soil survey map of that county as shown in the table for corn below. |

| <u>Clarion Loam</u> | <u>Lester Loam (2-6%)</u> | <u>Terril Soil (15%)</u> |
|---------------------|---------------------------|--------------------------|
| 35 acres | 40 acres | 95 acres |
| 120 bu/ac* | 115 bu/ac* | (X) |

*The average corn production, 120 bu/ac for Clarion Loam soil and 115 bu/ac for Lester Loam soil are SCS estimates.

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

The slope data for each field with the Terril soil can be directly read from the Soil Conservation Service soil survey map for each individual farm.

The topsoil is soil material in the A horizon. For the Terril soil series the topsoil generally ranges from 0-38 cm for Goodhue County to 0-30 cm for Steele County. The average topsoil depth, as reported by the farmers for each field, is used in the analysis.

The Subsoil Characteristics

The estimated subsoil characteristics are based on the work of Neill (1979) and Pierce, et al. (1983). 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. The sufficiency of water holding capacity (SWC) is a linear transformation of AWC to a scale of 0 to 1 (Figure A-1). The AWC of the Terril soil for different soil

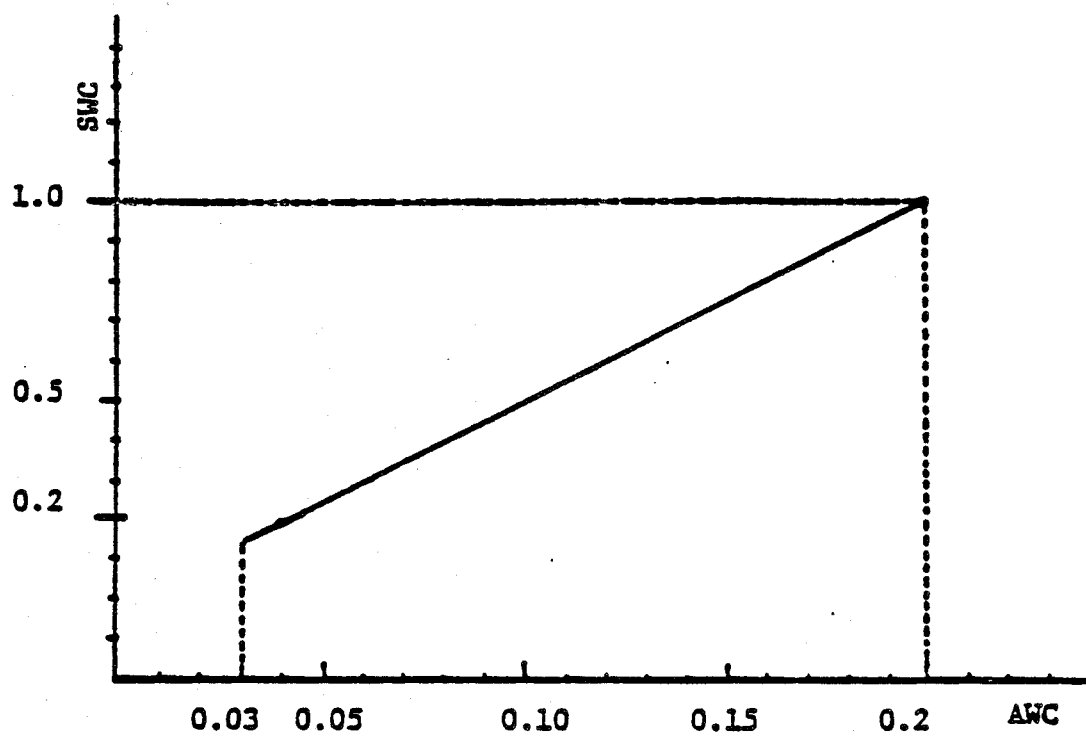


FIGURE A1. Relationship between AWC and SWC

textures was obtained from the soil survey map. The estimated SWC was then calculated using Figure A-1 (Pierce, et al., 1983). For example, if the AWC for a Terril soil field is 0.15 the associated SWC is about 0.75.

The weighting factor (WF) for any horizon is the integral of the curve between the upper and lower boundary of the soil horizon (Figure A-2). The formula for deriving the weighting factor is:

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

The total area under the curve can be normalized to a value of 1.0 (Figure A-3), the integral solved and the results displayed in a table.

Figure A-4 shows the concept of the sliding weighting factor. As erosion occurs, the curve shifts down the soil profile. The productivity index (PI) drops if the subsoil has characteristics less favorable than the soil above it. If a limiting layer is encountered that portion of the curve below the limiting layer (slashed area below 100 cm in Figure A-4) is lost and the PI declines.

The (PI) is constructed by Pierce and Neill. It is the product of (SWC) (SUFF PH) (WF) (SUFF BD) 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 (SUFF PH) for all soil textures is equal to one and the sufficiency of bulk density (SUFF BD) is equal to 0.8782, $PI = (SWC)(WF)$.

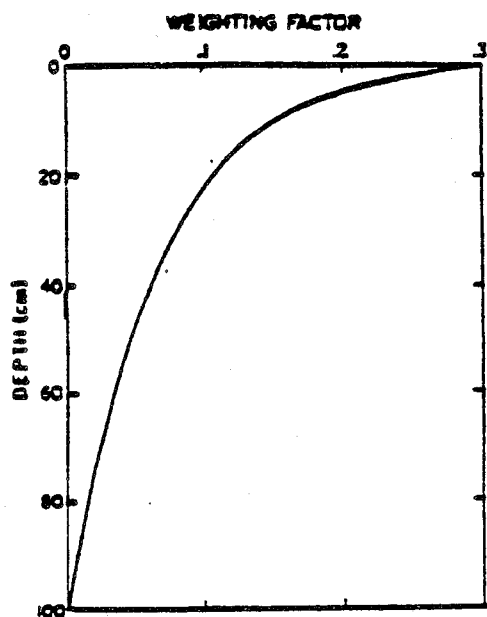


FIGURE A2. Assumed rooting pattern (weighting factor) for 100 centimeter depth in an ideal soil.

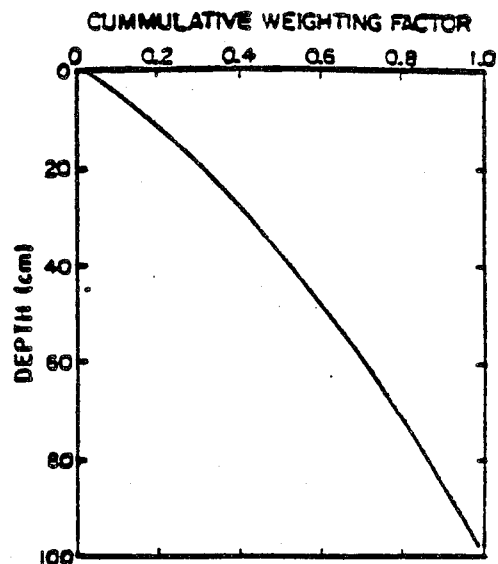


FIGURE A3. Plot of the cumulative weighting factor used in the productivity model

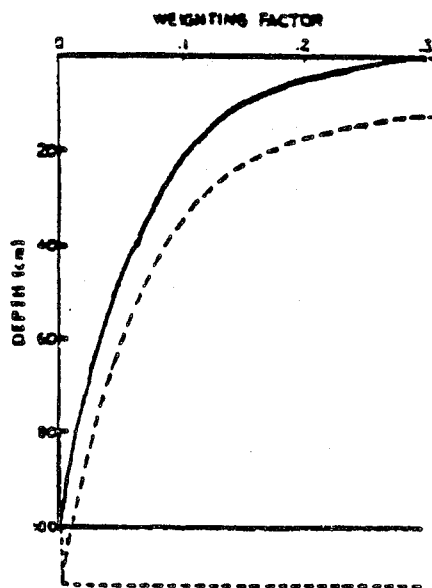


FIGURE A4. Concept of the sliding weight factor. As erosion occurs, the curve shifts down the soil profile.