MEASURING EROSION RATE AND ONSITE DAMAGE USING GIS: A POLICY APPLICATION

David J. Walker and
Kathleen M. Painter

A.E. Research Series 94-9

Selected paper for
1994 Annual Meeting of the American
Agricultural Economics Association,
August 7-10, San Diego, CA.

Authors are Professor and Post-Doctoral Research Associate, respectively, Dept. of Agricultural Economics, University of Idaho, Moscow, Idaho, 83843.

MEASURING EROSION RATE AND ONSITE DAMAGE USING GIS: A POLICY APPLICATION

ABSTRACT

Mathematical modeling with field-level erosion and erosion damage estimates showed current farm program provisions reduce predicted erosion rate by nearly 5 tons per acre compared to a No Farm Programs scenario for a watershed in northern Idaho. A convenient method for calculating field-specific erosion damage is presented.

MEASURING EROSION RATE AND ONSITE DAMAGE USING GIS: A POLICY APPLICATION

Introduction

Soil erosion is generally recognized as an environmental problem associated with agricultural production which varies by topography, climate, soils, and cropping practices. Measuring economic damage attributable to soil erosion is a complex task because of site variability and confounding technical progress in crop yields. Nationally, onsite erosion damage has been estimated at $1.3 billion as measured by crop productivity losses (Alt and Putman, 1987).

Aggregate studies of erosion often fail to capture the site-specific nature of erosion impacts. Analytical software using Geographic Information Systems (GIS) data allows representation of landscape-specific characteristics. In this analysis, grid-based GIS data for topsoil depth, soil type, percent slope, slope length, and other erosion factors were overlaid with vector-based GIS data representing field boundaries in a watershed. Erosion estimates were then extracted on a field-level basis for a number of rotation, tillage, and conservation practices. Erosion estimates and site-specific topsoil depth data were used to calculate onsite erosion damage. The damage model incorporates nonlinear yield damage, topsoil depth and technical progress in yields, yet is easy to use.

Precise, landscape-specific watershed erosion damage estimates are an essential tool for conservation policy. Critical areas need to be targeted for cost-effective erosion control. Appropriate erosion control policies and implementation of practices can then be planned based on the characteristics of a specific region.

Increasing awareness of erosion damage and the benefits of different erosion control measures can help promote implementation of conservation practices.

Study Area

The Tom Beall watershed in northern Idaho is located near Lewiston, within an area of severe soil erosion and water quality problems as identified by the Soil Conservation Service (USDA). Elevation in the 11,000-acre watershed ranges from about 900 feet to over 2300 feet, reflecting steeply sloped fields. Three-fourths of the 7,205 cropland acres are classified as highly erodible.

Average rainfall in this semi-arid dryland farming region is 12 inches per year. Approximately 60% of the land is planted in winter wheat every year. Other crops include dry peas and lentils, barley, and small amounts of canola, buckwheat, and bluegrass. Winter wheat is quite vulnerable to erosion, as most precipitation occurs in the winter months on the planted seedbed. Rain and snowmelt on partially frozen soil cause particularly severe runoff and erosion as the soil cannot absorb this moisture.

Concepts for Measuring Erosion Damage

The basis for measuring the cost of erosion damage is the "with versus without" comparison common to economic analysis. Erosion damage is the present value of lost income from reduced yields over a future damage horizon due to current year erosion. Initially erosion damage will be discussed in terms of yield damage for clarity but ultimately it will be measured in terms of the economic cost of yield damage. Erosion damage assessment is complicated by the impact of yield-enhancing technical progress. Assuming the rate of technology is independent of erosion (exogeneous technical progress in Walker and Young), erosion damage should not be based on an absolute decline in historical yield. Erosion damage in any one year is measured as the difference in potential future yield with technology and initial topsoil depth versus realized future yield with technology and topsoil depleted by current year erosion. In order to avoid a measure of technical progress that is confounded by erosion, one must separate the projected effects of erosion and technology. Separation of these effects also debunks the myth that erosion damage is of no consequence when technical progress boosts crop yields more than erosion reduces them.

Technical progress has actually been shown to increase erosion damage for crops and regions with multiplicative yield response to technological change because technical gains are greater on deeper soil. This increase in erosion damage is illustrated by Figure 1. In the absence of technology, erosion over a period of decades reduces topsoil depth from 18 to 5 inches, which decreases yield from 70 to 51 bushels (C to A) along a constant yield function, Y_0. The difference, 19 bushels, measures the yield damage from erosion in the absence of technology. Allowing for technical progress in yields shifts the yield function to Y_n. Because technology boosts yield from C to A′ in spite of erosion, one might erroneously conclude that technology had eliminated erosion damage. The correct measure of erosion damage is based on a "with versus without" erosion comparison of yield along the technology augmented yield function, Y_n. Potential yield declines from C′ at the starting soil depth to A′ at

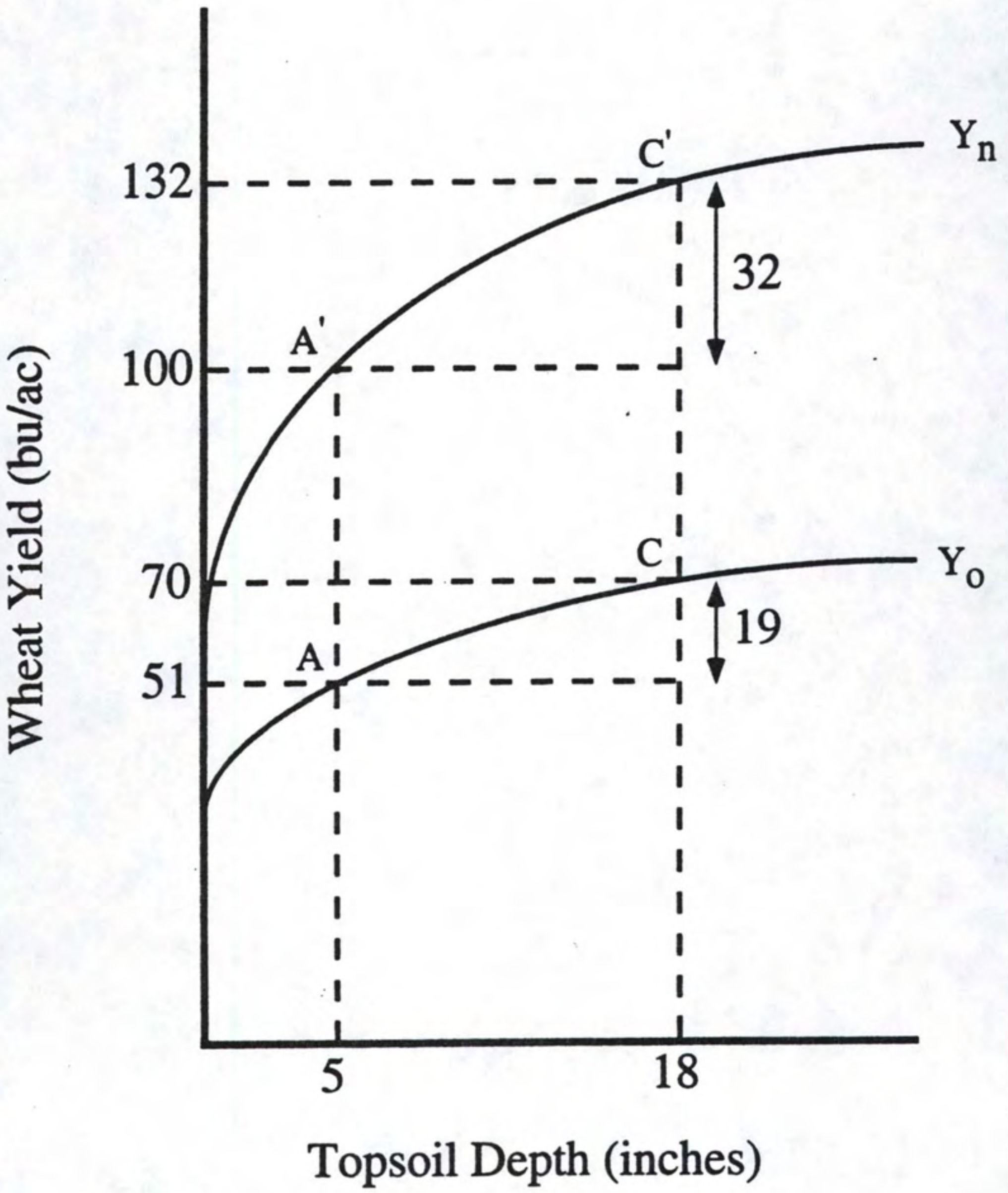

Figure 1. Impact of Technology on Erosion Damage.

the eroded soil depth, giving a yield damage measure of 32 bushels after a period of erosion. Since research in this region supports a multiplicative shift in the yield function from technology (Young, Taylor, and Papendick), erosion damage increases with technology.

Erosion Damage Model

A spreadsheet model incorporating the above concepts assesses the economic cost of erosion damage by projecting the impact of current erosion on future crop yields. Topsoil depth serves as a proxy for soil properties such as organic matter content and bulk density that are correlated with topsoil depth and in turn impact crop yields. In addition to projecting the negative impact of erosion on crop yields, the model also projects the positive impact of technical progress on yields. The correct measure of erosion damage requires establishing how much higher yields would be with the new technology if soil were conserved.

The economic assessment of erosion damage cost estimates the present value of lost future income over a relevant damage horizon from reduced future yields due to erosion in the current year. A damage horizon of 75 years is used because that is long enough to incorporate the management periods of current operators, their children and their grandchildren. With family farms it seems reasonable an operator would be concerned about those future consequences. With a 4% real private rate of discount, a 75-year time horizon captures 95 percent of the present value of erosion damage into perpetuity.

The calculation of the cost of erosion damage in the convenient spreadsheet damage model is represented by Equation 1:

$$(1)\ \delta = \sum_{t=1}^{n} \frac{D(1+\phi)^{t}}{(1+r)^{t}}$$

$$= D \sum_{t+1}^{n} (1+g)^{t}$$

$$\textit{where } g = \frac{\phi - r}{1+r}$$

$$= D\ [\frac{(1+g)^{n+1} - (1+g)}{g}]$$

where **ϕ** represents the technical progress rate, **r** equals the discount rate, and **D** equals P(ΔY), the nominal value of yield damage. The net growth rate **g** combines the effect of growth in yield damage from technology and the discount rate. This single growth rate will represent positive or negative growth in the present value of damage in each year of the damage horizon depending on whether technical progress rate is greater or less than the discount rate. Normally, it would be less. The final expression in brackets in Equation 1 calculates the sum of the geometric series over the damage horizon using the net rate **g**. This is a measure of annual erosion damage that assumes nominal damage is constant in each year of the damage horizon except for the effect of technology.

Methods

For this study, site-specific estimates of erosion and erosion damage were determined under a variety of cropping, tillage, and conservation practices. Erosion was calculated at the cell level for each agricultural practice using the Universal Soil Loss Equation (USLE). The cell size for this study was 3.3 acres; each cell represents a data point. A digitized elevation map (DEM) was created and used to construct GIS maps with the L and S (slope length and slope gradient) components of the USLE. Soil types were also digitized for the watershed in order to estimate the average soil erodibility factor by field (K factor). Maps were created for the remaining USLE components, some of which varied by field and crop choice such as the P (conservation practice) factor and some that were constant across the landscape and did not vary by farming practice such as the R (rainfall) factor. Erosion factor maps were multiplied using GIS software (IDRISI Project, Clark Labs, Clark University, Worcester, MA) in order to obtain a map with erosion value by cropping system for each cell.

Field-level erosion estimates were needed to model erosion in the watershed assuming profit-maximizing behavior for farmers. A GIS map for each field was overlaid on the erosion maps in order to extract an average erosion value for the cells within each field. Field-level erosion estimates for each cropping system were used for policy analysis in a mixed integer linear programming model (MIP).

Onsite erosion damage was estimated with production functions that describe the relationship between topsoil depth and yield for the major crops in this region (Peng). Mitscherlisch-Spillman equations were fitted for yield and topsoil depth measurements for winter wheat, barley, and peas or lentils using the general form:

(2) $\mathbf{y = a + b(1 - c^D)}$

where **y** is yield, **a** represents yield when soil depth is zero, **b** represents the maximum increase in yield from deeper topsoil (asymptote for yield), **c** ($0<\mathbf{c}<1$) reflects the change in marginal product with respect to topsoil depth, and **D** represents topsoil depth.

For wheat and peas, dynamic versions of the production functions representing multiplicative technical progress in yields (Walker and Young) are:

(3) $\mathbf{y(t) = a + b(1 - c^D)e^{\phi t}}$

where **e** is the exponential operator, ϕ is the rate of technical progress and **t** is time. For barley, a different functional form provided a better fit for technical change in barley yields over time. More detail on barley yield response to topsoil depth and technological change as well as rates for technical progress in crop yields were based on Painter, 1992. Values for **a**, **b**, **c**, and ϕ by crop are presented in Table 1.

The change in topsoil depth attributable to one year's erosion varies by rotation, tillage, and conservation practice. The reduction in yield depends on both the original topsoil depth and the predicted annual decrease in topsoil depth. The present value of future yield losses reflects discount rate and crop price assumptions. A discount rate of 4% was used for this study to reflect the real long term return to farming. Crop prices, based on 1989-1993 farm-gate average prices for Idaho, were $3.24 per bushel for wheat, $89.80 per ton for barley, and $8.91 per pound for dry peas. Deficiency payments were calculated using 1989-1993 national average crop prices and legislated target prices. On paid base acres, deficiency payments were $0.85 per bushel for wheat and $5.67 per ton for barley. Under the 1990 Farm Bill, 15% of base acreage is no longer eligible for payments ("flex" acreage).

Results

Erosion rates and onsite erosion damage were calculated for five rotations, two tillage choices, and two conservation practices for a total of 20 options per field. Rotations consisted of winter wheat and dry peas (WP); winter wheat and spring barley (WB); winter wheat, spring barley, and dry peas (WBP); winter wheat, spring barley, and summer fallow (WBF), and winter wheat, dry peas, winter wheat, and summer fallow (WPWF). Tillage options included conventional and reduced tillage. For this study, the main difference between the two is that under reduced tillage the chisel replaces the moldboard plow. In order to meet conservation compliance provisions of the 1985 Farm Bill, farmers are required to meet certain residue levels on their fields, which is typically achieved through reduced tillage. Of the two conservation practices examined in this study, cross slope farming is a widespread practice while use of divided slopes is less common. However, more farmers are using divided slopes as part of their conservation plans for meeting compliance.

Weighted average erosion rates for the watershed ranged from a high of 15.4 tons per acre per year for WPWF with conventional tillage and cross slope farming to a low of 4.33 tons per acre per year for WBP under reduced tillage and divided slopes. The average field-level erosion rate over 86 fields was 8.95 tons per acre per year with a standard deviation of 3.48 tons. Field-level rates ranged from 0.49 tons per acre per year for WBP with reduced tillage and divided slopes to 37.85 tons per acre per year for WPWF with conventional tillage and cross slope farming. Obviously, targeted application of erosion control strategies is needed on a field-level basis.

Weighted average onsite erosion damage values were highest for rotations with 50% of the land in winter wheat, as this is the highest value crop in this area. For the whole watershed, the WP rotation under conventional tillage and cross slope farming had the highest weighted average onsite erosion damage of nearly $8 per acre. Weighted average damage was lowest at $1.47 per acre for the WBF rotation with reduced tillage and divided slopes. The maximum damage sustained at the field level averaged $21.52 per acre for WP under reduced tillage and cross slope farming.

Average per acre returns assuming profit maximization by farm unit for fields within the Tom Beall watershed are presented in Table 2. These represent returns to management and land, using slightly modified budgets from the Palouse region to represent this lower rainfall region (Painter, Granatstein, and Miller). Policy scenarios included basic 1990 Farm Bill provisions plus several variations on conservation compliance; 1990 Farm Bill provisions with Natural Resource Accounting, in which on-site soil erosion damage is subtracted from farmers' profit functions; and a No Programs option.

For the baseline 1990 Farm Bill scenario, conservation compliance is interpreted as requiring reduced tillage. A more targeted approach is also modeled, in which farmers cannot exceed the soil tolerance factor T (or a multiple of T) in order to receive deficiency payments. Under this policy farmers will target erosion control practices to the more highly erodible fields where erosion exceeds "T." The original 1985 Farm Bill legislation restricted erosion to T. As can be seen in Table 2, this goal was unrealistic for this highly erodible region. The participation rate is projected to fall from 100% to 38% under this scenario, and average erosion rises relative to the 1990

Farm Bill baseline. Given the voluntary nature of farm programs, the expected erosion control was not achieved because this erosion limit was too restrictive. Also, a targeted erosion limit may not be economically feasible on all fields. Profit-maximizing farmers can choose to not participate in the farm program, which releases them from any erosion constraints and increases overall erosion.

The final version of conservation compliance, interpreted as requiring reduced tillage for this study, outperforms any of the T level restrictions on erosion in this watershed in terms of erosion control. The various T targets all have higher overall erosion and onsite erosion damage. Farm income is slightly higher than the baseline for 1.5 X T, averaging $3.69 per acre across 14 farm units. For a 2 X T erosion limit, income rises to an average of $6.58 per acre, but erosion averages 50% higher than for the baseline at nearly 2 X T. Government cost in terms of deficiency payment outlays is lower under the various T targets, however (Table 2).

For the 1990 Farm Bill Plus Natural Resource Accounting scenario, onsite erosion damage is subtracted from farmer profit for each farm unit. Onsite erosion damage reflects the loss in future crop revenue due to erosion in the present year. All other provisions are identical to the baseline. Although net returns fell an average of $3 per acre, the erosion rate was reduced an average of 0.5 tons/acre/year and average onsite damage declined by $0.45 per acre. This scenario provides a more complete picture of net farm income due to the incorporation of the resource depletion cost. Farmer behavior is modified to reflect this cost for each activity since these costs are included in the profit calculation.

Under a No Programs scenario in which farmers have no planting or conservation restrictions and receive no government payments, average net returns of -$6.30 per acre were $9.75 per acre lower than under the 1990 Farm Bill. Erosion averaged nearly 5 tons more per acre, at 11.46 tons annually. Onsite erosion damage increased 44% over the 1990 Farm Bill and 73% over the 1990 Farm Bill Plus Natural Resource Accounting. These results show the dramatic impact of conservation compliance restrictions in this region of highly erodible land and high participation rates in the government farm program. Both farm income support and erosion control are greatly impacted by the federal program.

Conclusions

Site-specific erosion levels can be estimated over a large area and with a variety of production practices using GIS software. Economic data plus site-specific topsoil depth and erosion data were used to calculate the discounted present value of yield loss due to this year's erosion. Since many of the parameters needed to estimate the economic impact of erosion damage are subject to change, including crop price, discount rate, and individual time horizon, a versatile spreadsheet application is used to estimate erosion damage. This large volume of physical and economic data can be easily accommodated in mathematical modeling using GAMS (General Algebraic Modeling System, see Brooke, Kendrick, and Meeraus).

Results of profit-maximizing models showed government farm program payments are clearly an important component of farmers' profits in this region. Farmers are willing to comply with conservation compliance provisions in order to receive government payments. Although net returns to land and management are fairly low under the baseline policy scenario, averaging $3.45 per acre, average returns are negative at -$6.30 per acre without the farm program. In addition, erosion is predicted to increase an average of 73% over the watershed without the current farm program, assuming profit-maximizing behavior by farm managers.

These research results show that overly restrictive farm policy provisions can be counterproductive under voluntary farm programs. Under the original legislation for the 1985 Farm Bill, farmers of highly erodible land were required to reduce tillage to the soil tolerance factor T for their area. Under this policy scenario, farmer participation in the farm program falls to 38% and average erosion rises to 8.9 tons per acre in the Tom Beall watershed. In comparison, average erosion is 6.6 tons per acre and all farmers participate in the government program under the revised conservation compliance provisions modeled in this research.

Prior to the 1985 Farm Bill, federal farm policy was criticized for encouraging erosion through base-building incentives. To build base acreage that was eligible for deficiency payments, growers might plant marginal lands that were highly erodible and resist soil conserving rotations that included nonprogram crops. Revised base acreage provisions and conservation compliance in the 1985 and 1990 Farm Bills were designed to make farm policy more environmentally kind. Results of this study suggest that environmental gains are being realized.

Table 1. Coefficients for Equation 3 by Crop.

Crop	a	b	c	ϕ
Wheat (bu/ac)	47.3	33.34	0.92	0.008
Peas (cwt/ac)	1140.39	1431.48	0.96	0.0175
Barley (lb/ac)	2043.39	1440.06	0.92	N/A

Table 2. Results of Profit-Maximimizing Policy Models for Farms in the Tom Beall Watershed.

POLICY:	Average Net Returns ($/ac/yr)	Average Erosion Rate (t/ac/yr)	Average Onsite Damage ($/ac/yr)	Farm Program Partici-pation (%)	Govern-ment Cost ($/ac/yr)
1990 Farm Bill[1]	3.45	6.62	3.04	100	25.79
1990 Farm Bill, erosion limit of:					
1 X T	-1.57	8.93	3.44	38	14.96
1.5 X T	3.69	8.60	3.46	85	21.69
2 X T	6.58	9.66	4.35	100	24.59
1990 Farm Bill + Natural Resource Accounting[2]	0.47	6.17	2.52	100	24.59
No Government Programs	-6.30	11.46	4.37	N/A	N/A

[1]Requires use of reduced tillage on highly erodible farmland.
[2]Onsite damage is subtracted from farmers' profits.

REFERENCES

Alt, Klaus, and John Putman. "Soil Erosion: Dramatic in Places but Not a Severe Threat to Productivity." In *Agricultural Outlook*. Econ. Res. Serv., U.S. Dept. Agr., Washington, D.C., 1987.

Brooke, Anthony, David Kendrick, and Alexander Meeraus. *GAMS: A User's Guide.* Scientific Press, San Francisco, CA, 1988.

Painter, Kathleen. *Farm Level Economic and Environmental Impacts of Farm Policy Proposals: An Interregional Comparison.* Ph.D. dissertation, Dept. of Agr. Econ., Wash. State U., Pullman, May 1992.

Painter, Kathleen, David Granatstein, and Baird Miller. *1992 Alternative Crop Rotation Enterprise Budgets, Eastern Whitman County, Washington State*. EB 1725, Cooperative Extension, Wash. State U., Pullman, 1992.

Peng, Ming. *Cost of Erosion Damage and the Economic of Conservation: A Comparison between Two Idaho Wheat Regions.* M.S. Thesis, Dept. of Agr. Econ. and Rural Sociology, University of Idaho, Moscow, 1990.

U.S. Dept. Agr. *Soil, Water, and Related Resources in the United States: Status, Conditions, and Trends, 1980 RCA Appraisal, Part I*. Washington, D.C., 1981.

Walker, David and Douglas Young. "Assessing Soil Erosion Productivity Damage." In *Soil Conservation: Assessing the National Resources Inventory, Vol. 2* National Academy Press, Washington, D.C. 1986.

Young, Douglas, Daniel Taylor, and Robert Papendick. "Separation of Erosion and Technology Impacts on Winter Wheat Yields in the Palouse: A Statistical Approach." In American Society of Agricultural Engineers, *Erosion and Soil Productivity*. St. Joseph, Michigan, 1985, pp. 130-142.