ILLINOIS AGRICULTURAL ECONOMICS STAFF PAPER.

Series E Agricultural Economics

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July 1985 No. 84 E-311 (rev.)

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Efficiency of Sediment Control Policies*

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* The authors are grateful for the assistance of Jeong Lim, Changwoo Pyo, and Pei-Ing Wu in the research reported here. Support for this work came from Project No. 1-1-11381 of the Illinois Water Resources Center and Project No. 1-6-53491 of the Illinois Agricultural Experiment Station, College of Agriculture, University of Illinois.

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I. Introduction

Efforts to reduce nonpoint water pollution from agriculture have typically been keyed to erosion indicators (rates of soil loss) and standards (erosion tolerance - "T"- values). Many economists have observed that the program goals and management indicators are incongruous because the relationship between water pollution and erosion is quite complex. This incongruity may be a source of inefficiency in agricultural pollution control efforts.

In this paper, we compare the economic consequences of performance standards based on T-values to the impacts of policies based on efficient reduction of agricultural effluents. This comparison allows inference on the magnitude of inefficiencies resulting from using erosion rates as proxies for pollutants delivered to streams. Our focus is on sediment pollution.

Section II contains a theoretical model which makes clear the potential for inefficiency in erosion-based sediment control policies. A simulation/optimization model that can be used to test for inefficiency is described briefly in Section III. An empirical application to a small area in the Lake Decatur watershed of Central Illinois is presented in Section IV. Conclusions are drawn in Section V.

II. Erosion Rates and Efficient Pollution Control

Assume that the objective of agricultural nonpoint pollution control policy is to achieve a prescribed water quality standard (z^*) at least cost. Also assume, for simplicity, that the water quality standard of concern involves gross loadings of sediment delivered to a stream or lake. The pollution management agency must induce changes in land use to achieve z^*. Let $\underline{y}_i$ denote a vector of management practices applied to land unit i ($i=1,\ldots,m$). Each vector $\underline{y}_i$ must be contained in a set of feasible combinations of practices, Y_i. Let $\underline{y}$ be the vector containing all $\underline{y}$'s, i.e., $\underline{y} = [\underline{y}_1, \ldots, \underline{y}_n]$. For analytical ease in this theoretical presentation, each $\underline{y}_i$ is defined over continuous elements ($j=1,\ldots,m$), such as the percentage of acreage in reduced tillage or the percentage in a particular crop rotation. Let the vector $\underline{s}_i$ represent the soil type, slope conditions, relative location, and climatic circumstances of unit i, and let $g(\underline{y}_i;\underline{s}_i)$ be a scalar-valued erosion function. A scalar-valued surface transport function $f[g(\underline{y}_1,\underline{s}_1),\ldots,g(\underline{y}_n,\underline{s}_n); \underline{y}_1,\ldots,\underline{y}_n;\underline{s}_1,\ldots,\underline{s}_n]$ translates erosion rates into cumulative loadings entering the water body. The function $f[\bullet]$ captures topographic features and spatial relationships between land units. Both $g(\bullet)$ and $f[\bullet]$ are assumed to be continuously differentiable. Finally, $\underline{y}_i^o$ denotes the vector of profit maximizing land management practices that would occur in the absence of pollution control policies, and $\pi_i(\underline{y}_i;\underline{s}_i)$ is a profit function for land unit i.

With these assumptions and definitions, the pollution control policy problem may be expressed as follows:

$$\min_{\underline{y}} \; R(\underline{y}) = \sum_{i=1}^{n} \pi_i(\underline{y}_i^o;\underline{s}_i) - \pi_i(y_i;\underline{s}_i) \tag{1}$$

$$\text{s.t.} \quad f[g(\underline{y}_1;\underline{s}_1),\ldots,g(\underline{y}_n;\underline{s}_n);\underline{y}_1,\ldots,\underline{y}_n;\underline{s}_1,\ldots,\underline{s}_n] \le z^*, \quad \underline{y}_i \in Y_i \;,\; i=1,\ldots,n. \tag{2}$$

An optimal solution to the preceding problem must satisfy the following Kuhn-Tucker conditions:

$$- \delta\pi_i/\delta y_{ij} - \mu(f_g \bullet \delta g/\delta y_{ij} + \delta f/\delta y_{ij}) \ge 0 \text{ , and}$$

$$\{y_{ij} - y_{ij}^o\}\{- \delta\pi_i/\delta y_{ij} - \mu(f_g \bullet \delta g/\delta y_{ij} + \delta f/\delta y_{ij})\} = 0 \; ; \tag{3}$$

and

$$z^* - f[\bullet] \le 0 \text{ , and}$$

$$\mu\{z^* - f[\bullet]\} = 0 \; . \tag{4}$$

In expressions (3) and (4), μ is the Lagrangian multiplier corresponding to inequality constraint (2)and f_g is a partial derivative. The signs of $\delta g(\bullet)/\delta y_{ij}$ and $\delta\pi_i(\bullet)/\delta y_{ij}$ are indeterminant because the management variables are not defined to be monotonically related to erosion or profit rates. The term f_g must be non-negative; all other things equal, more erosion cannot be associated with less cumulative sediment delivered to the water body.

In the problem formulation above, a policy that does not account for the sediment delivery function, $f[\bullet]$, would lead to a solution equivalent to setting $f_g=1$ and $\delta f/\delta y_{ij}=0$ in expression (3). These are unreasonable restrictions, for they imply that the sediment deposited in the water body is the simple sum of all the soil that erodes from all n units. This fails to reflect the potential for spatial interrelationships, such as the sediment-trapping effect of grassed waterways and buffer strips. Thus, such a policy would almost surely be inefficient. The magnitude of the inefficiency can be determined only empirically. To that end, we now describe a model for making the necessary calculations and then apply the model to a case that is representative of conditions in Central Illinois.

III. Optimal Sediment Management: The SEDEC Model

It is evident from the preceding discussion that information on farm profit functions, erosion functions, and spatial sediment movement functions is required if sediment control policies are to be efficient. These three elements have been joined in the SEDEC (SEDiment EConomics) simulation/optimization model [Braden, Johnson, and Martin]. The financial and erosion relationships are simulated using the SOILEC program developed by Dumsday and Seitz (see also Eleveld, Johnson, and Dumsday). This program determines long-term annual operating profits and sheet and rill erosion rates associated with various cropland management practices. (Meadow is included as a cropping choice.) The annual financial results are expressed as annualized averages for the entire planning period. The Universal Soil Loss Equation (USLE) [Wischmeier and Smith] is used as the basic erosion model. Wind erosion and channelized-flow erosion are excluded from consideration in the application reported here. Soil depth is related to productivity using approximating techniques developed by Bost. Representative farming cost data are derived from the U.S. Soil Conservation Service budget generator.

In SEDEC, the financial and erosion relationships are embedded in a spatial model. Runoff and sediment move downslope across land management units toward a stream channel or impoundment. Soil that becomes eroded on one land management unit may settle out downhill if decreasing steepness or denser vegetative stands cause the runoff water to lose momentum. A relationship proposed tentatively by C. D. Clarke of the U. S. Soil Conservation Service is used in SEDEC to simulate the sediment delivery process. Assume now that the elements of $\underline{y}$ take on discrete values and include crop rotations, tillage practices, and structural conservation measures. Let $C_i = C(\underline{y}_i)$, $P_i = P(\underline{y}_i)$, and $S = S(\underline{s}_i)$ denote, respectively, the USLE coefficients for crop rotation and tillage practice, mechanical control practice, and steepness of slope. The Clarke relationship entails computing the following ratio at each point of significant slope change or transition in land management practices:

$$d_{i-1}(\underline{y}_i, \underline{y}_{i-1}; \underline{s}_i, \underline{s}_{i-1}) = (C_{i-1}/C_i) \bullet (S_{i-1}/S_i) \bullet (P_{i-1}/P_i) \quad , (5)$$

such that

$$C_{i-1}/C_i \leq 1, \; S_{i-1}/S_i \leq 1, \; P_{i-1}/P_i \leq 1 \; , \text{ and } d_0 = 1 \; . \qquad (6)$$

Expression (5) gives the proportionate relationship between the sediment "transport capacity" of land unit i-1 and the adjacent uphill unit i. The inequality constraints in (6) prevent an increase in slope or more erosive management practices on unit i-1 (relative to i) from translating into a sediment transport capacity that is greater than the rate of erosion from unit i. The equality constraint in (6) requires that all erosion from the land unit adjacent to the water body (i=1 on a given drainage path) is deposited in the water.

Now let $\underline{s}$ denote a vector of all physical characteristics of the watershed, i.e., $\underline{s}^T = [\underline{s}_1, \ldots, \underline{s}_n]$. Given the preceding relationships, the cumulative sediment delivered to a stream along a drainage route is [Braden, Johnson, and Martin]:

$$f[g(\underline{y};\underline{s})] = \sum_{i=1}^{n} \prod_{k=0}^{i-1} d_k(\underline{y}_k,\underline{y}_{k+1};\underline{s}_k,\underline{s}_{k+1}) \bullet g(\underline{y}_i;\underline{s}_i) \quad , \qquad (7)$$

where Π is the product operator. Use of this delivery model permits recursive solution to identify land management practices that meet a constraint on cumulative loadings (from one or more delivery paths) with minimal reduction in profits.

IV. Policy Inefficiency in a Central Illinois Case Study

As the centerpiece of its agricultural nonpoint source pollution control strategy, Illinois requires that soil losses on agricultural land not exceed soil loss tolerance levels beyond the end of this century [Illinois Department of Agriculture]. This standard must be met on gently sloped land by 1988, while erosion on most other land must not exceed two times the tolerance levels by 1988 and 1.5 times T levels by 1994.

To investigate the potential for inefficiency in this policy approach, we used SEDEC to evaluate the cost of compliance with erosion tolerance levels versus the cost of optimal sediment management that would achieve the same level of gross loadings. The analysis was performed for a small area in the Long Creek drainage of the Lake Decatur watershed in Macon County, Illinois. Sediment deposition is a major problem in Lake Decatur [U. S. Soil Conservation Service].

The study area contains 259 acres involving parts of 15 fields on six different farms. Most slopes are 3% or less, although slopes of 5% and more are present in the area. Crops are grown on virtually all of the land in the study area. Corn and soybeans are dominant, but hay crops, small grains, and meadow are sometimes grown.

The study area was divided into 22 land management units according to farm field boundaries and major topographic features. Four major drainage zones were identified from topographic maps and field reconnaissance. A typical drainage profile was determined for each zone. Every management unit was associated with one zone.

Soil types were identified from Soil Conservation Service (SCS) soil maps. Soil depth and productivity characteristics were obtained from the SOILS 5 data base. Budgets for representative farms in Central Illinois were obtained from the SCS. Crop prices were assumed fixed in real terms over a 50 year planning horizon at the following levels: corn-$3.00/bu.; soybeans-$7.00/bu; oats-$3.50/bu; and alfalfa - $60.00/ton. An 8% real discount rate was used in determining the present value of the 50 year income stream and the equivalent annualized annuity value.

Seventy-two management regimes were considered, including four crop rotations (continuous corn; corn-soybeans; corn-soybeans-oats; and corn-soybeans-oats-alfalfa), six tillage options (fall plowing; spring plowing; spring disking; till-planting; fall chiseling; and no-till), and three cultural practices (plowing up and down slopes, on contours, or in contoured strips of different crops). A corn-soybean rotation with chiseling up and down slopes in the fall was most profitable throughout the area.

For most soils in the study area, soil loss tolerance values are between two and four tons/acre/year (t/a/y). In this study, we assumed first that a uniform limit of three t/a/y would apply to each management unit in the area under Illinois' regulations. SEDEC was used to determine the least cost means of meeting that limit and the associated sediment deposition. Then, we used SEDEC again to determine an economically optimal set of management practices that would achieve an average annual sediment load no greater than that produced with the three t/a/y restriction. In all cases, management units in one field were required to be utilized identically, and the same tillage practice had to be used on all fields belonging to a particular farm.

The results of our analysis are summarized in Table 1. A three t/a/y limit would reduce annualized net operating revenues in this 259 acre area by about $1,116. This is equivalent to a present value sum of about $13,653. The per acre costs ranged from zero to $30.11 and averaged $4.30. The overall costs amounted to about 1.8% of net annualized operating revenues for the area.

With adherence to the three tons/acre/year limit, sediment loads were reduced by about 72%, on average, relative to levels associated with the profit-maximizing management regime. Erosion was reduced by about 40%. Sixty-nine percent of the land was affected by some kind of management change. In all of the affected portion, a till-plant system replaced fall chiseling. Fifty-six percent of the land was managed with continuous corn, while 13% was shifted to a corn-soybeans-wheat-oats rotation. Contour strip cropping was implemented on about one percent of the area.

The management regime that lowered the sediment load by at least 72 percent in an optimal fashion reduced the annualized net operating revenues by only $628, or 56% of the loss associated with the three t/a/y policy. The annualized cost is equivalent to a present value sum of about $7,683. The costs per acre ranged between zero and $18.20 and average $2.42. Gross erosion was reduced by about 30%, compared to 40% with land meeting erosion tolerances. Under the optimal sediment management regime, only 98 acres, about 38 percent of the study area, had to be shifted to practices that yielded less than maximum net operating revenues. All changes entailed a till-plant system and continuous corn. Contour strip cropping was adopted on about 12 acres of steep land along the Creek.

The preceding results indicate that optimal management of sediment could be considerably less costly and involve altered management of far fewer acres than a comparable erosion standard. Specifically, costs could be reduced nearly 44%, by about $1.90/acre in annualized value (equivalent to a present value sum of $23/acre). Much of these savings could translate into lower public subsidies for soil conservation efforts.

There are other potential advantages of distinguishing sediment management policies from erosion standards. One would be to separate water quality goals from soil productivity concerns. Say, for instance, it is agreed that sediment loads need not be reduced by 72% in our study area; a 40% reduction will satisfy water quality goals. According to results from SEDEC, this could be achieved for about $255 in annualized costs by changing management practices on less than 10% of the study area. In such a case, over 75% of the expenditures entailed by a program keyed to soil loss tolerance values would be superfluous for meeting water quality goals.

V. Conclusions

Cases where careful land management in a relatively small area can reduce overall sedimentation significantly are almost surely the norm. If so, our analysis indicates that very significant savings may be available in aggregate by shifting away from erosion tolerance limits and toward efficiently directed sediment management. Efficient sediment control efforts would also affect far less land than would a uniform standard. We conclude that requiring erosion rates to be at or below tolerance levels on all agricultural land can be a very inefficient way to control nonpoint pollution.

Table 1. Comparison of Three Tons/Acre/Year Erosion Limits and Equivalent Optimal Sediment Controls: Long Creek Basin Case Study*

	Erosion Limited to 3 t/a/y on average	Equivalent Optimal Management of Sediment
Avg. Ann. Sediment Load	127 tons	125 tons
(% of Profit Max. Load)	(28.3%)	(27.9%)
Avg. Ann. Gross Erosion	431 tons	507 tons
(% of Profit Max. Load)	(59.7%)	(70.2%)
Annualized Avg. Net Operating Losses	$1,116	$ 628
(% of Profit Max. Net Operating Income)	(1.8%)	(1.0%)
Percentage of Acreage in:		
Continuous Corn	56%	38%
Corn-Soybeans	31	62
Corn-Soybeans-Wheat-Oats	13	0
Fall Chiseling	31%	62%
Till Planting	69	38
Up and Down Plowing	99%	95%
Contour Strip Cropping	1	5

* Optimal unconstrained management of all 259 acres involved a corn-soybean rotation and fall chiseling up and down slopes. Average annualized net operating revenues were $60,494 and average gross sediment loads were 448 tons/year. Assumptions are discussed in the text.

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