EVALUATION OF AGRICULTURAL SEDIMENT CONTROL PRACTICES RELATIVE TO WATER QUALITY PLANNING

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Abstract. Control of sediment has become increasingly important as an element of many water quality improvement programs. An analytical method using the universal soil loss equation and linear programming to determine the cost-effectiveness of alternative sediment control practices is developed. Applications of this method to four case study farms and a hypothetical watershed are analyzed. The analyses illustrate the need for developing priorities so as to achieve greatest reduction in sediment losses per dollar of cost. The costs per unit of sediment reduction vary greatly with area, soil, and strategy or technique used.

INTRODUCTION

Long term preservation of the soil resource base has been the principal objective of Soil Conservation Service (SCS) programs for decades. Recently, the potential effects of soil erosion on water quality have been emphasized by federal and state agencies involved in water quality management. Continued planning and implementation of programs for controlling pollutants from nonpoint sources are likely to sustain interest in practices for controlling soil erosion and sediment delivery to water courses.

One problem in allocating resources toward achieving erosion and (or) sediment control objectives is selection of practices and treatment areas appropriate for those objectives. This article focuses on estimating the relative cost-effectiveness of alternative control practices within the treatment area. Cost-effectiveness is defined as the reduction in estimated soil erosion or sediment delivery per dollar expended on and (or) imputed to adopting control practices.

The soil erosion and sedimentation processes represent one major pathway for movement of potential pollutants to watercourses. Sediment control measures decrease not only the loading of soil particles but also substances such as ammonium, inorganic particulate phosphorus and some pesticides absorbed by the particles. The effect of a reduction in these loadings on water quality also depends on loadings from other nonpoint and point sources as well as the limnological characteristics of the receiving waters.

THE COST-EFFECTIVENESS OF SEDIMENT CONTROL ALTERNATIVES

Schneider and Day, and White and Partenheimer demonstrated that the cost of adopting erosion controls varies appreciably among farms within and between different agricultural regions. Their research indicates that controls based on the variability in an area's physical and topographic features and farmers' flexibility in adjusting activities to implement those controls are less costly than imposing one erosion control limit throughout the area.

McGrann and Meyer estimated a wide variation in costs for controlling erosion on various soils in Iowa. Alt and Heady reported that given a particular farm operation, certain practices are very cost-efficient in sediment control while others can result in severe reductions in farm income even though the practices are essentially equally effective in controlling sediment delivery.

Examination of the cost-effectiveness of sediment control alternatives requires estimation of the reduction in soil erosion and sediment delivery if the practice were adopted and the cost of implementing a particular practice or set of practices. Cost estimates should include practice installation and maintenance costs; changes in fixed and variable farm production costs associated with adoption of sediment control practices; and the public cost of program administration, technical assistance, and cost sharing. Public costs have not been estimated; no cost sharing is assumed. Consequently, costs will include expenditures to install and maintain practices and the estimated changes in net farm income if the practices were adopted. Implementation of control practices is assumed to have no impact on prices received and paid by farmers.

A widely used method for estimating average annual soil erosion is the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965).

$$A = RK(LS)CP$$

Where: A = average annual gross sheet erosion (tons/acre)
R = regional rainfall erosivity factor
K = soil erodibility factor
LS = slope length factor
C = cropping practice factor
P = conservation practice factor

Specific values for R and K are available for different regions of the country. Values for the remaining parameters are site specific (Wischmeier and Smith, 1978).

The USLE is used to estimate gross sheet erosion and not the soil transported from field to stream. The fraction of eroded soil actually reaching a point in the stream divided by the total sheet erosion of the area draining to that point is the sediment delivery ratio (SDR) for that area. Methods for estimating sediment transport are less well developed than the USLE, but considerable research has been accomplished (Onstad and Foster). The method used to calculate delivery ratios here was derived from Renfro. Using this method, sediment delivery rates were developed as a function of the distance between a field and a stream (Walter and Black). Figure 1 illustrates this relationship.

CASE STUDY FARMS AND NONPOINT SOURCE CONTROL OPTIONS

To demonstrate the effects of imposing soil erosion and sediment delivery constraints on land-use decisions and farm incomes, four dairy farms representing significantly different soil and cropping conditions in New York were analyzed. Farm A is a 70 cow operation in central New York on Kendaia/Lansing/Ovid soils (3-5% slopes). Farm B in northern New York on Rhinebeck/Benson/Elmwood soils (0-3% slopes) has 67 cows. Farms C and D in central New York have 80 and 55 cow herds, respectively. Farm C is on Bath/Valois-Howard/Langford soils

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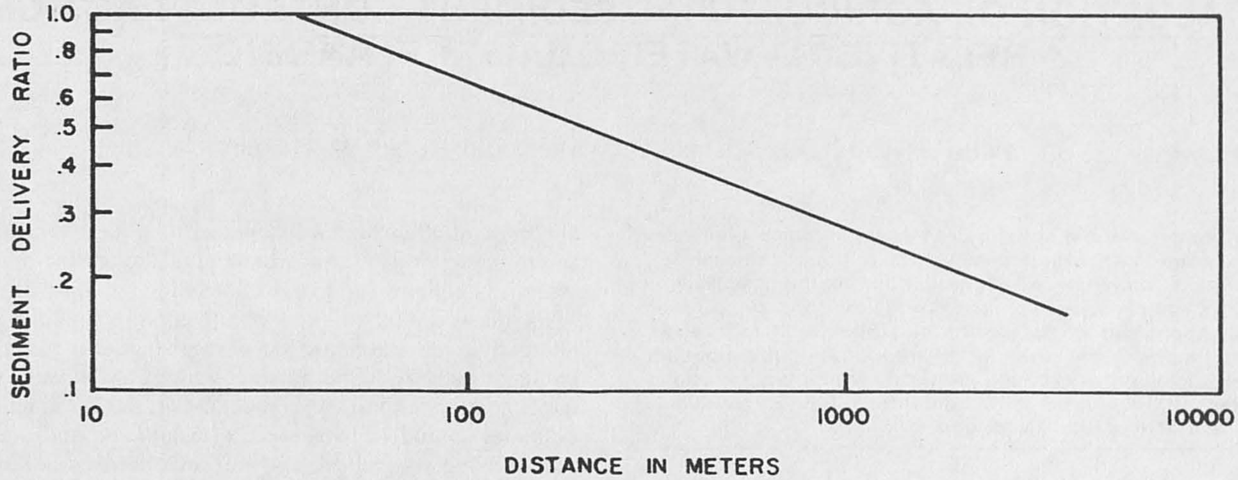

Figure 1.
Sediment delivery ratio as a function of distance between field and stream.

(0-25% slopes) while Farm D comprises Madrid/Lima/Bombay soils (0-15% slopes).

A linear programming model was developed to estimate changes in farm income associated with meeting specified erosion and sediment loss limits. The model maximizes net farm income subject to specified constraints on land, labor, capital and soil loss. Each crop and livestock activity on a given farm was represented by a combination of tillage practice, field type, crop, and conservation practice. Individual fields were grouped into field types according to erosion potential and the feasibility of implementing contouring and diversions. Types 1, 2, and 3 represented fields with potential for low, moderate, and high erosion respectively. Field size, slope, and shape determined the feasibility of implementing contouring and diversions.

Each dairy farm was assumed to grow enough corn and hay to meet herd feed requirements. Buying and selling activities were only allowed for corn grain. A base solution was calculated for each farm to reflect resource use and production patterns when profits are maximized and no constraints on soil loss are imposed.

Three types of soil erosion or sediment delivery constraints were considered:

Field Limited Erosion—soil erosion limits on each field type on each farm.

Farm Limited Erosion—limits on total soil erosion from the farm. Individual field levels could vary considerably if the specified farm limit were met.

Farm Limited Sediment Delivery—similar to Farm Limited Erosion except sediment delivery was constrained.

Based on a literature review, it was concluded that variations in farm income resulting from changing tillage methods were generally much greater than was the case for other conservation practices. Conventional, minimum, and no-tillage, were included in the analyses. Smith *et al.* indicate that appreciable changes in yield can be expected when using reduced tillage systems on certain soil types and for particular levels of management. Although the direction of change in yield is somewhat predictable for a particular soil and management level, data were not available to predict the level of change in New York. For the soils and management levels on the farms analyzed, no change in average yield was assumed. But it should be pointed out that comparisons of the cost-effectiveness between tillage practices are sensitive to these yield assumptions, as Smith *et al.* have demonstrated.

FARM ADJUSTMENTS AND EROSION AND SEDIMENT DELIVERY ABATEMENT COSTS

Five major points resulted from or were supported by the case studies. First, the structure of some farming operations allows for significant adjustments in cropping enterprises such that soil erosion and sediment delivery can be significantly reduced at little cost to the farmer. Conversely, other farms have little flexibility in reallocating resources to meet erosion and sediment delivery constraints. For example, significant reductions in farm income were estimated for Farm A where most land has a high erosion potential (Figure 2). Decreases in income (increases in cost of erosion control) begin at relatively high erosion limits (25 metric tons/hectare/year) for Farm A while on Farm B, little change in income is observed until allowable erosion is limited to 6 Mt/ha/yr or less.

Second, the increase in marginal costs associated with more stringent erosion controls also corresponds to a particular pattern of control practices. The relationships in Figure 3 are typical of this phenomenon. For the unrestricted case (Base Solution), reductions in sediment delivery limits, and indirectly in soil erosion limits, are met by shifting from principally continuous cultivation to contouring and strip cropping. These latter practices enter the optimal farm management systems even when sediment delivery is only moderately limited at 5.5 to 6.0 Mt/ha/yr. For the four farms, the marginal cost of sediment delivery control increased materially when diversions were included in the optimal management plan, as on Farm D when sediment delivery was restricted to 2.5 Mt/ha/yr or less (Figure 3). In all cases, a very dramatic increase in the marginal cost of sediment control was observed as cropland was idled to need constraints on sediment delivery, such as 1.0 Mt/ha/yr in Figure 3.

Third, a farm limit constraint on soil erosion could generally be met at a lower cost than restricting soil losses to the same level on each field. The farm limit approach allows erosion increases on some fields and decreases on others as long as the farm average does not exceed some specified level. This approach is not necessarily consistent with a goal of maintaining soil productivity on individual tracts of land but may be appropriate for water quality management. A comparison of the farm limit and field limit analyses for Farm B is given in Table 1. The differences in estimated costs associated with these two approaches when soil erosion is

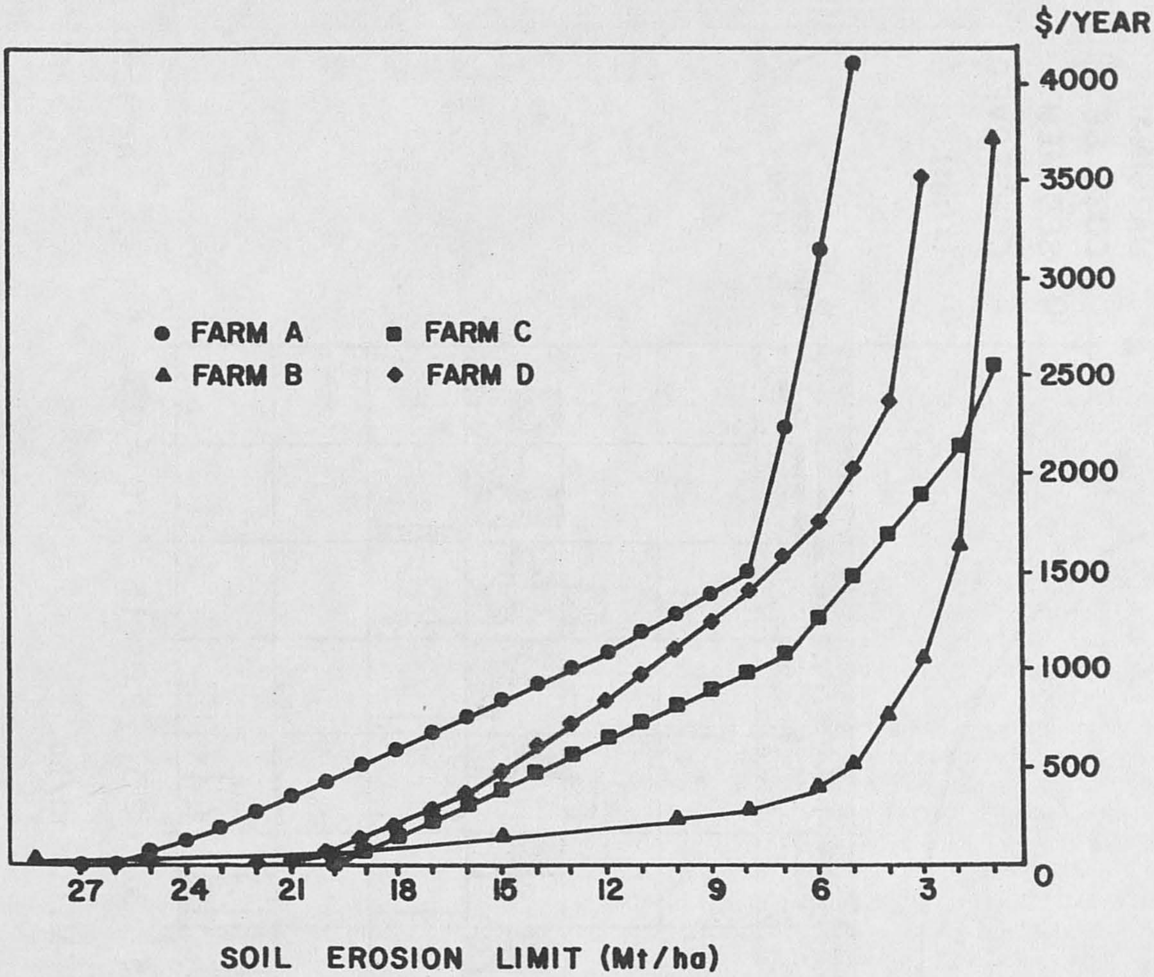

Figure 2.
Costs of controlling soil erosion to specified field limit levels when conventional tillage is used.

Table 1
Total Soil Erosion and Cost of Erosion Control when Soil Erosion Is Restricted to Specified Levels for Field and Farm Limits with Conventional Tillage Used on Farm B

Soil Erosion Limit	Total Soil Erosion Field Limit	Total Soil Erosion Farm Limit	Cost of Erosion Control Field Limit	Cost of Erosion Control Farm Limit
(Mt/ha/yr)	(Mt)	(Mt)	($/year)	($/year)
15	290	750	175	0
11[a]	240	550	255	0
7[b]	170	350	325	50
3	75	150	1075	400

[a]Approximately 5 tons/acre.
[b]Approximately 3 tons/acre.

restricted to 11 and 7 Mt/ha/yr on case study farms are given in Table 2. For Farms A and D, the difference in cost was not appreciable.

A fourth observation was that converting from conventional tillage to reduced tillage systems could have a dramatic effect on reducing gross soil erosion while incurring only a small cost as some equipment must be converted. Recall that the impact of changes in tillage systems on yields is uncertain and that no effects on yields have been assumed. Chisel plowing or no-till planting leaves more residue on the ground surface than does conventional tillage. The decrease in soil erosion is directly linked to this surface residue which reduces runoff and increases infiltration and surface storage of water. In most cases, variable and fixed machinery costs are lower with reduced tillage systems, but herbicide and insecticide costs are greater (Smith *et al.*). The estimated net cost to the farmer in changing from conventional to reduced tillage systems is relatively small and can, in some cases, even result in net savings. Consequently, reduced tillage options always shifted cost curves downward, as indicated in Figure 4 for Farm A. The results for the four case study farms support the proposition that reduced tillage systems are a low cost sediment control technique (Table 3).

Finally, expenditures for sediment control are likely less with a direct focus on controlling sediment delivery rather than an indirect

Table 2
Cost of Reducing Soil Erosion from Unrestricted Levels to 11 Mt/ha/yr and 7 Mt/ha/yr Under Field and Farm Limits when Conventional Tillage is Used on Case Study Farms

Farm	11 Mt/ha/yr Field Limit	11 Mt/ha/yr Farm Limit	7 Mt/ha/yr Field Limit	7 Mt/ha/yr Farm Limit
A	$1,220	$1,120	$2,270	$2,230
B	230	0	330	70
C	760	560	1,100	960
D	1,000	910	1,610	1,510

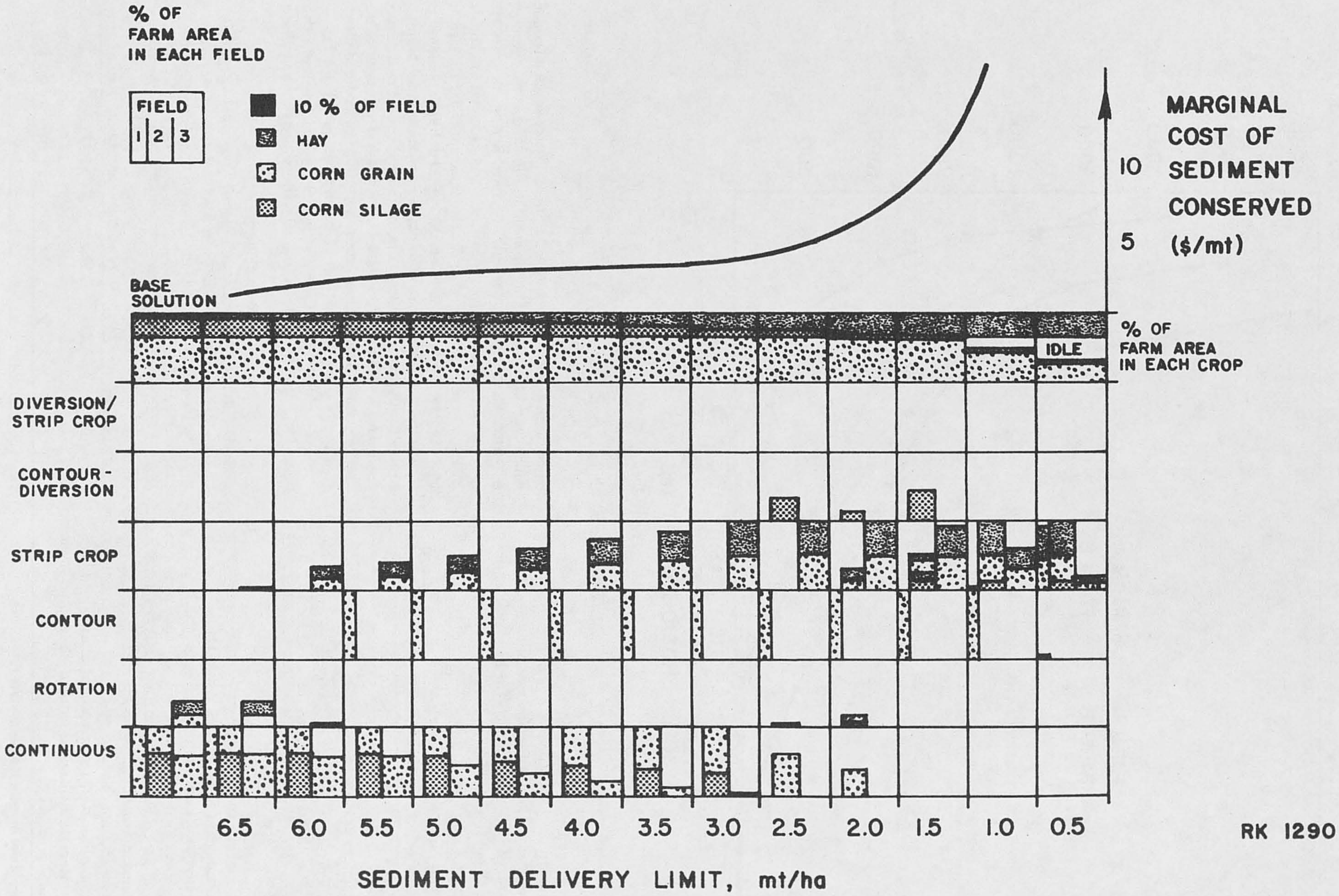

Figure 3.
Crop patterns, control practices, and marginal costs associated with controlling sediment delivery to specified farm limit levels when conventional tillage is used on Farm D.

approach through reducing soil erosion. As indicated in Figure 5, reductions in soil erosion eventually reduce sediment delivery. However, this is not a one-to-one correspondence on most farms. Reducing gross soil erosion in areas where sediment delivery rates are low results in relatively small reductions in sediment delivered. For example, reducing erosion from 17 Mt/ha/yr to 12 Mt/ha/yr on Farm D does not decrease total sediment delivery. Likewise, a reduction in soil erosion of 3 Mt/ha/yr on Farm A from 23 to 20 Mt/ha/yr does not materially decrease sediment delivery. Given this variability in relationships among farms, a judicious choice of fields within a farm for initial treatment can greatly reduce sediment delivery at a lower cost than uniform reductions of gross erosion on all fields.

Table 3
Cost of Reducing Sediment Delivery from Unrestricted Levels to Farm Limits of 4.5 Mt/ha/yr and 2.5 Mt/ha/yr According to Specified Tillage Practice on Case Study Farms

Farm	4.5 Mt/ha/yr Conventional	4.5 Mt/ha/yr Reduced	4.5 Mt/ha/yr No-Till	2.5 Mt/ha/yr Conventional	2.5 Mt/ha/yr Reduced	2.5 Mt/ha/yr No-Till
A	$1,340	$530	$150	$3,330	$2,120	$1,190
B	0	0	0	150	0	0
C	690	90	0	1,270	720	180
D	700	0	0	1,540	700	0

Table 4
Levels of Sediment Delivery and Associated Costs for Alternative Strategies for Reducing Sediment Delivery when Case Study Farms Comprise a Watershed

Strategy	Sediment Delivery: Total	Sediment Delivery: Watershed Average	Cost: Change in Farm Income	Cost: Cost per Mt of Sediment Conserved
	(Mt/yr)	Mt/ha/yr)	($)	($/Mt)
No sediment control practices implemented	1,520	5.5		
Watershed treatment				
1. Nonstructural practices implemented on all farms	870	3.1	-2,400	3.7
2. Reduce sediment delivery to 2.5 Mt/ha/yr (farm limit) on all farms	680	2.5	-4,350	5.2
Selective area treatment				
Treat farms with highest SDR (Farms A and D, 52% of area)				
3. Nonstructural practices implemented	1,100	4.0	-1,400	3.4
4. Reduce sediment delivery to 2.5 Mt/ha/yr (farm limit)	860	3.1	-3,500	5.3
Treat farms with lowest marginal treatment costs (Farms B and C, 44% of area)				
5. Nonstructural practices implemented	1,080	3.9	-1,200	2.7
6. Reduce sediment delivery to 2.5 Mt/ha/yr (farm limit)	1,030	3.7	-1,500	3.1
Watershed treatment—change tillage and implement nonstructural practices				
7. Convert conventional tillage to no-till on all farms	940	3.4	-1,250	2.2
8. Convert conventional tillage to no-till and implement nonstructural practices on all farms	560	2.0	-2,900	3.0
Selective area treatment—change tillage and implement nonstructural practices				
Treat farms with highest SDR (Farms A and D)				
9. Convert conventional tillage to no-till	1,100	4.0	-400	1.0
10. Convert conventional tillage to no-till and implement nonstructural practices	900	3.2	-1,450	2.4
Treat farms with lowest marginal treatment costs (Farms B and C)				
11. Convert conventional tillage to no-till	1,090	3.9	+100	0
12. Convert conventional tillage to no-till and implement nonstructural practices	890	3.2	-700	1.1
13. Convert conventional tillage to reduced tillage[a]	1,250	4.5	+1,250	0
14. Convert conventional tillage to reduced tillage[a] and implement nonstructural practices	770	2.8	-900	1.2

[a]Reduced tillage is represented by chisel plowing

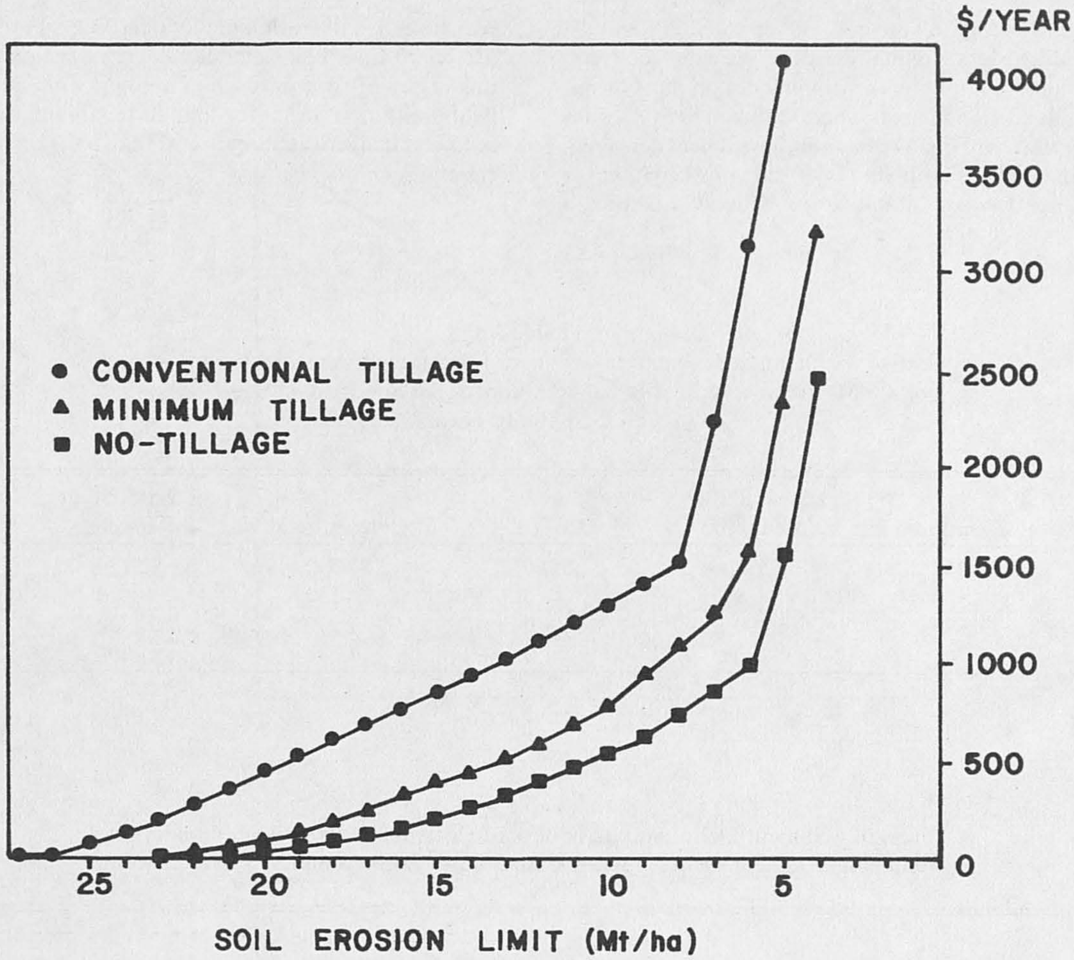

Figure 4.
Costs of controlling soil erosion to specified field limit levels when alternative tillage practices are used on Farm A.

COST-EFFECTIVENESS OF ALTERNATIVE SEDIMENT CONTROL STRATEGIES

If water quality is to be improved through reductions in sediment delivered from farms to watercourses, fields and practices should be chosen so that sediment delivery is reduced the most per dollar of cost. The choice of areas and (or) fields should be related to an identified water quality problem. Given, for example, that sedimentation of water channels and reservoirs is a problem, how might practices and fields be chosen in such a way that selected sediment delivery constraints are realized at minimum cost?

Using analyses of the case study farms, costs and effects of different sediment control strategies can be examined. To demonstrate the differences among strategies, the four farms are assumed to comprise a watershed. Minimum tillage is assumed to be practiced on Farms A and D, conventional tillage on Farms B and C, and farmers are profit maximizers. Changes in farm income, cropping systems, sediment control practices, and sediment delivery were developed through linear programming.

To illustrate the effects of various sediment control options, fourteen strategies were developed (Table 4). Three sets of practices were applied—nonstructural, structural and tillage. The nonstructural measures consisted of contouring, strip cropping and changes in crop rotations. These practices were allowed to be implemented as long as the total crop acreage and the ratio of cropland to hay acreage remained the same as in the base solution. The only structural practice considered was diversion ditches. Tillage systems included conventional moldboard plowing, chisel plowing and no-till planting.

In Strategies 1 and 2, all farms are treated similarly. Only nonstructural measures are implemented with Strategy 1; the second allows any means to reduce sediment delivery to 2.5 Mt/ha/yr (farm limit).

Strategies 3-6 are based on the premise that for whatever reason, only part of the watershed can be treated. In Strategies 3 and 4, farms with the highest initial sediment delivery rates were treated to reduce sediment delivery to 2.5 Mt/ha/yr. Farms with the lowest marginal treatment costs were selected for Strategies 5 and 6. Changing tillage systems and implementing nonstructural practices were components in the remaining strategies.

Implementing nonstructural practices on all farms (Strategy 1) reduced sediment delivery from the watershed by 43 percent at an estimated cost of $2,400 ($3.70/Mt). To reduce sediment delivery to 2.5 Mt/ha/yr (farm limit) on all farms, contour-diversions and reductions in corn acreage were needed. The resulting cost of reducing sediment delivery from the 5.5 Mt/ha/yr average base level for the watershed to a uniform level of 2.5 Mt/ha/yr (farm limit) on each farm was $5.20/Mt.

Treating only farms with the highest initial sediment delivery rates—Strategies 3 and 4—resulted in unit costs of sediment control similar to the first two strategies. Reductions in sediment

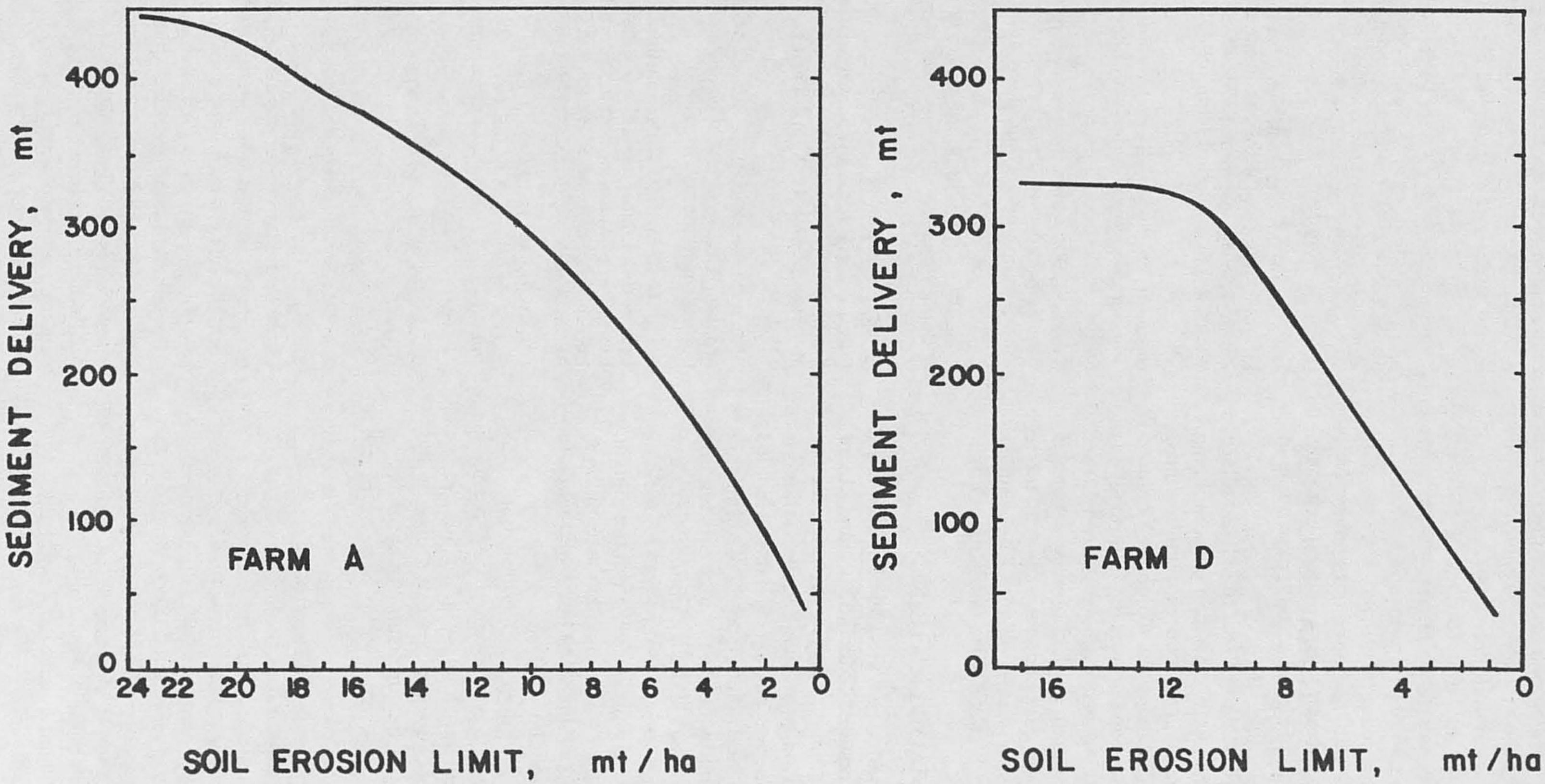

Figure 5.
Relationships between reducing soil erosion to specified field limit levels and total sediment delivery from Farms A and D.

delivery with Strategies 3 and 4 are less but so are reductions in farm incomes. Unit costs associated with implementing practices on farms having relatively lower marginal treatment costs—Strategies 5 and 6—were substantially lower than those associated with the previous alternatives. Strategies 5 and 6 reduced total sediment delivery from the watershed by about 30 percent for an estimated $1,200 to $1,500 reduction in farm income.

Converting all farms to no-till cultivation (Strategy 7) reduced sediment delivery by nearly 40 percent at a relatively low unit cost of $2.20/Mt of sediment conserved. Implementing no-till in selected areas resulted in marked sediment delivery reductions at little or no expense (Strategies 9 and 11). Converting conventional tillage to no-tillage on Farms B and C reduced total sediment delivery by almost 30 percent and resulted in a slight increase in farm income (Strategy 11).

Converting Farms B and C from conventional to reduced tillage so that all farms in the watershed were practicing reduced tillage increased farm income by $1,250 and reduced total sediment delivery by about 18 percent (Strategy 13). Combining reduced tillage with nonstructural practices on Farms B and C (Strategy 14) was accomplished for $900 and reduced sediment delivered from the watershed by 50 percent. A greater reduction resulted only if no-till and nonstructural practices were implemented on all farms (Strategy 8), or if sediment delivery rates were restricted to 2.5 Mt/ha/yr on all farms (Strategy 2), but both at much higher costs.

SUMMARY AND IMPLICATIONS

The case study farms and watershed analyses illustrate some important points helpful to planners of water quality management programs, particularly where sedimentation has been identified as contributing to degradation of water quality. Sedimentation is a consequence of soil erosion. The two phenomena are interrelated but with differing geographical focal points. Control of soil erosion tends to be conducted on a field by field basis with emphasis on reducing soil movement within the field. Programs for controlling sedimentation are not necessarily geared toward field boundaries but toward soil movements off groups of fields to watercourses. Where fields are adjacent to or transected by watercourses, individual fields can be the units of analysis whether the goal is to control soil erosion or sedimentation.

These analyses illustrate the need for prioritizing areas contributing most to sedimentation and identifying practices controlling sedimentation from farmland so as to achieve the greatest reductions per dollar of control costs. Costs of erosion and sediment control vary appreciably among farms. An absolute soil erosion limit could, in some cases, have severe effects on farm incomes. A variable limit, perhaps keyed to total crop production or corn/hay ratios, would mitigate some of the negative income effects. Total treatment costs and unit sediment reduction costs will vary greatly within a watershed depending on the type of control practice and the areas treated. Analyses of fourteen strategies for controlling sediment delivery in a hypothetical watershed resulted in cost variations of 0 to over $5/Mt of sediment conserved.

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