Effects of Erosion Control Practices on Nutrient Loss

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Elements of Soil Erosion

Soil erosion by water is the detachment of soil particles by the direct action of raindrops and runoff water, and the transport of these particles by splash and very shallow flowing water to small channels or rills. Detachment of soil particles also occurs in these rills due to the force exerted by the flowing water. When rills join together and form larger channels, they may become gullies. These gullies can be either temporary (ephemeral) or permanent (classical). Non-erodible channels might be grassed waterways, or designed channels that limit flow conditions so that channel erosion does not occur.

Gross erosion includes sheet, rill, gully and channel erosion, and is the first step in the process of sediment delivery. Because much eroded sediment is deposited in or near the field of origin, only a fraction of the total eroded soil from an area contributes to sediment yield from a watershed. Sediment delivery is affected by a number of factors including soil properties, proximity to the stream, man made structures-including sediment basins, fences, and culverts, channel density, basin characteristics, land use/land cover, and rainfall-runoff factors. Coarse-textured sediment and sediment from sheet and rill erosion are less likely to reach a stream than fine-grained sediment or sediment from channel erosion. In general, the larger the area, the lower the ratio of sediment yield at the watershed outlet or point of interest to gross erosion in the entire watershed, defined as the sediment delivery ratio (SDR). The SDR for many watersheds ranges between about 15 and 40 percent (Novotny and Olem, 1994).

Practices to Control Soil Erosion and Sediment Delivery

Practices to control sheet and rill erosion modify one or more of the factors affecting erosion processes: slope length, slope steepness, cropping and management practices and support practices that slow runoff water or cause deposition. In contrast, rainfall erosivity and soil erodibility, dominant factors affecting soil erosion, cannot be easily modified. In this discussion, erosion control practices are grouped as conservation tillage, which reduces sheet and rill erosion, and other practices which reduce slope length and runoff (contouring, contour strip cropping and terraces). Other practices to control channel and gully erosion (grassed waterways, grade-control structures, terraces and water and sediment control basins) reduce the velocity of flowing water (which reduces both erosion and sediment transport in channels) or diverts flow into stable channels or pipes.

Conservation tillage is defined as a tillage system that leaves 30% or more of the land surface covered by crop residue after planting. Currently, conservation tillage is used on about 40% of all U. S. cropland. In the Midwest, no-till and strip-till soybeans continue to be more common than no-till corn. Tables 1 and 2 show current tillage practices for soybean and corn from the seven corn belt states (CTIC, 2004). Illinois, Indiana, Iowa, Ohio, Minnesota, Missouri, and Wisconsin planted 17.6 million acres of no-till soybeans in 2004, while only 6.3 millions acres of corn were planted using no-till practices in those seven states

Table 1. Tillage practices in seven corn belt states for soybean production (CTIC, 2004).

State	Soybean Acres	No-Till	Mulch-Till (30% residue)	Reduced-Till (15-30% residue)	Conventional-Till (0-15% residue)
Illinois	10,316,344	46.2%	20.9%	19.2%	13.7%
Indiana	5,487,069	61.5%	15.2%	10.0%	13.2%
Iowa	10,179,278	33.1%	47.3%	14.6%	4.3%
Minnesota	7,176,774	7.1%	46.1%	24.6%	21.4%
Missouri	5,143,354	40.1%	9.5%	19.9%	30.1%
Ohio	4,630,915	63.7%	9.0%	8.3%	19.0%
Wisconsin	1,540,605	36.6%	21.4%	15.8%	26.2%
Total	44,474,339	39.6%	27.8%	16.7%	15.6%

Table 2. Tillage practices in seven corn belt states for corn production (CTIC, 2004).

State	Corn Acres	No-Till	Mulch-Till (30% residue)	Reduced-Till (15-30% residue)	Conventional-Till (0-15% residue)
Illinois	11,165,908	14.0%	12.1%	22.2%	51.8%
Indiana	5,350,414	18.8%	8.6%	17.3%	55.1%
Iowa	12,348,317	14.4%	26.6%	36.5%	22.2%
Minnesota	7,388,154	1.5%	15.7%	34.1%	48.1%
Missouri	2,887,237	20.2%	7.4%	23.2%	48.9%
Ohio	3,527,939	23.5%	9.9%	13.1%	53.4%
Wisconsin	3,520,402	14.5%	18.1%	20.7%	46.5%
Total	46,188,371	13.7%	16.1%	26.6%	43.2%

Contouring is the practice of performing field operations on the contour. Usually, there are ridges developed when the land is tilled or at planting, and these ridges trap excess rainfall. When there is a mild slope to the row, water may travel along the row to an outlet. Contouring is particularly effective when rainfall amounts and intensities are low, when ridges are high, and

when slopes and slope lengths are not excessive. As slopes and slope lengths increase, and as rainfall amounts and intensities increase, contouring loses much of its effectiveness, and may have no impact on soil erosion.
Stripcropping is the practice of growing alternate strips of different crops along the contour. Alternating strips are crops that have different growing and harvest times. These might be a strip of row crop, with the next strip being either a small grain or permanent grass. These strips reduce water erosion by being on the contour, and with runoff passing from highly erodible row crops into small grains or grass where considerable deposition may take place.

Grassed waterways and grade control structures are designed to keep erosive forces in channels carrying surface runoff below critical values where erosion might occur. Water and sediment control basins are constructed basins that temporarily store runoff water and release it at controlled rates through underground drain lines. The temporary impoundment of runoff water reduces downstream runoff rates, preventing gullying and greatly reducing downstream sediment delivery.

Terraces are broad channels across the slope. Runoff water above the terrace follow these broad channels to an outlet. Terraces reduce slope length and deliver surface runoff through terrace channels that are designed to be non erodible and to prevent deposition of sediment. A well designed terrace system will use grassed waterways or underground outlets to prevent channel erosion as surface runoff exits the area. Some terraces do not follow the contour, and water is stored in small impoundments until discharged through underground outlets.

Potential Benefits

Although significant gains in erosion control have been made over the last 20 years, soil erosion continues to be an important environmental concern. It is estimated that over 423 million tons of topsoil eroded from the seven corn belt states in 1997, while in 1982 the estimated loss was approximately 707 million tons. Individual states vary considerably in the rate of soil loss. In 1997, average annual sheet and rill erosion rates on cropland for Illinois, Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin were 4.1, 3.0, 4.9, 2.1, 5.6, 2.6, and 3.7 tons/acre/year, respectively (USDA, 2000)

Contouring and contour strip cropping can be very effective in reducing soil erosion. Where it is most effective, contouring can reduce soil erosion about 50%, and contour strip cropping will reduce erosion further in most cases. However, both have limits of application. As slope increases, the maximum slope length decreases, and when erosion is most severe, such as slopes exceeding 9%, much of the effectiveness is lost, and the length of slope to which it can be applied becomes quite low.

Terraces are an effective means for controlling slope length and reducing soil erosion on erodibile areas. Terraces may discharge water through surface channels, by infiltration in a pondage area, or through underground drain lines. They have a negligible effect on crop yields, but a major effect on sediment delivery. Terraces that drain by surface channels are designed to have no erosion in the terrace channels. Controlling slope length will reduce soil erosion and channel erosion between terraces, but to greatly impact sediment delivery, practices that further reduce soil erosion-such as conservation tillage, should be used between terraces. Cropping is generally on the contour for surface drained terraces. Depending on design, deposition may occur in surface drained terraces.

Terraces that drain through underground outlets are very effective at reducing sediment delivery of eroded material. Laflen et al (1972) estimated that about 95% of material eroded between terraces was deposited in pondage areas around underground outlets, and that material discharged was almost all less than 0.016 mm in diameter. This type of terrace lends itself to modern farming techniques because rows are parallel to field boundaries, avoiding point rows and small areas that are difficult to farm. Since farming for this type of terrace is generally not done on the contour, other practices-such as conservation tillage, are needed to reduce erosion between terraces.

Terraces that drain via surface channels work well on gently sloping lands with long slopes. They require some routine maintenance to ensure that they drain adequately. They also work nicely when small grains are grown because it is easier to farm over the terraces.

Practice Effectiveness

Table 3 summarizes the results of simulations of the effects of various erosion control practices on soil and nutrient losses compared to a tillage system typically used in the Corn Belt. WEPP (Laflen et al., 1997) was used to calculate runoff and soil loss for all tillage systems and to calculate enrichment ratios for sediment. The typical tillage system for a corn-soybean rotation leaves 20% residue cover after corn planting and 40% residue after soybean planting. For all practices except water and sediment control basins, simulated losses are to the end of the slope; for water and sediment control basins, the values represent losses at the end of the outlet for the basin. The values also are not adjusted for sediment deposition or ponding of runoff water prior to reaching a stream. For specific fields, the SDR may range between 0 and 95% depending primarily on distance to a stream.

For reference, the base soil loss of 7.8 tons/acre/year is about twice the 1997 average annual soil loss in the Corn Belt. (2004 estimates for Illinois indicate less than 10 percent of fields have erosion rates > 7.5 tons/acre/yr.) In many watersheds in the region, total phosphorus yields from intensively cropped watersheds are about 1 lb/acre/year (Goolsby et al. 1999).

Total nitrogen yields vary greatly, but are typically less than 10 lb/a/y in non-tiled drained watersheds and greater than 20 lb/a/y in tile-drained watersheds. The majority of the N lost in eroded soil is organic nitrogen. Due to sediment deposition in the field and in reservoirs and because organic N is refractory, this form of N is not likely to be a major contributor to eutrophication in the Gulf of Mexico. In tile-drained watersheds and in large rivers, most of the N (>70%) is in the form of nitrate (McIsaac and Hu, 2004; Goolsby et al., 1999).

In our simulations, all erosion control practices considered increased losses of dissolved nutrients compared to the moldboard plow system. The effect of erosion control practices in increasing runoff losses of nitrate is probably not practically significant because the dominant path for nitrate loss is leaching and nitrate concentrations in runoff are usually low compared to subsurface drainage waters. The impacts of increased losses of dissolved phosphorus and decreased losses of particulate phosphorus due to the widespread adoption of conservation tillage systems less certain. In some settings, dissolved inorganic phosphorus is likely to be more biologically available than sediment bound phosphorus. In other settings, dissolved phosphorus may become sediment bound and relatively unavailable. On the other hand, sediment bound phosphorus can become desorbed in anaerobic environments, and thus become more biologically available for phytoplankton.

Table 3. Estimated annual soil and nutrient losses under various erosion control practices. Central Iowa climate, average over 10 Iowa soils and a 72.6 foot long slope of 9% and a 300 foot long slope of 5%)

Practice	Runoff	Soil erosion/ Sediment yield	Nutrient enrichment ratio*		Losses in surface runoff water (lb/ac)		Losses in eroded soil (lb/ac)		Total water and soil losses (lb/ac)	
	(in)	(t/a/y)	Sediment	Water	NH_4-N + NO_3-N	PO_4-P	Total N	Total P	N	P
Moldboard plow	5.2	15.0	0.6	0.4	2.2	0.1	53.4	20.9	55.6	21.0
Typical tillage	4.8	7.8	1.0	1.0	3.0	0.4	32.8	12.7	35.8	13.1
No till	4.2	1.0	1.5	1.7	3.6	0.7	6.1	2.4	9.7	3.1
Contour farming	4.4	3.9	0.8	1.3	3.5	0.5	12.5	4.8	15.9	5.3
Strip cropping	4.4	2.9	0.8	1.3	3.5	0.5	9.5	3.7	12.9	4.2
Terraces surface-drained	4.4	2.3	0.8	1.3	3.5	0.5	7.4	2.9	11.0	3.4
Water and sediment control basins	3.9	0.4	1.5	1.7	4.0	0.6	2.5	1.0	6.5	1.6

*Nutrient enrichment ratios, relative to the typical tillage practice, were calculated based on concentrations taken from Baker and Laflen (1983), and on soil erosion and sediment yields.

Important Factors affecting Nutrient Loss

Soil erosion and associated nutrient transport is driven by surface runoff, which is generated disproportionately from soils that have low infiltration capacity as a consequence of such factors as high clay content, surface crusting, high water table, or shallow bedrock. Phosphorus transport in runoff tends to increase with increasing phosphorus concentration at the soil surface and increasing runoff (Sharpley et al. 2003). Thus, practices that reduce phosphorus concentrations in the soil surface and/or reduce surface runoff are most effective in controlling P transport. When tillage is reduced or eliminated, particulate phosphorus loss in surface runoff usually declines, but dissolved P losses may increase if phosphorus becomes more concentrated near the soil surface unless P fertilizers or manure are injected or incorporated into the soil. Thus, timing and methods of application of P fertilizer become more important to controlling phosphorus transport in runoff from reduced tillage systems.

Conservation tillage practices that leave crop residue on the soil surface protect fine textured soils from forming surface crusts, and thereby have the potential to reduce runoff in soils where crust formation is a major limitation to infiltration. There are some reports of dramatic reductions in runoff from continuous no-till on well drained soils, where after three or four years, accumulations of organic matter and/or earthworms develop and maintain high porosity at the soil surface (Shipitalo et al. 2000). But in some settings, no-till has not had much influence on runoff (Gihdey and Alberts 1996). Residue cover also reduces evaporation from the soil surface, thereby increasing soil moisture content, which may increase runoff. Additionally, infiltration can be limited by factors other than the soil surface condition and residue. Residue cover may have little influence on runoff or dissolved phosphorus transport where infiltration is limited by a claypan, shallow bedrock, high water table, or seasonal precipitation patterns that saturate most soils, Conservation tillage is probably most effective in reducing runoff, soil loss and nutrient transport in well drained fine textured soils, and where phosphorus fertilizer and manure are injected or incorporated into the soil.

The interaction of tillage systems and nutrients in tile drainage is unclear. Tile drainage reduces surface runoff and thereby soil loss and particulate P transport. Phosphorus concentrations in tile drainage water can be high, however, if P concentrations in the soil are high or if soil macropores result in preferential flow (Sharpley et al. 2003). Although phosphorus and ammonia tend to be adsorbed in the top 15 to 30 cm of soil, they can also move through soil and can be found in tile drainage waters, particularly during high flow events when significant quantities of water move rapidly to the tile through macropores such as large cracks or holes in the soil. This results in minimal contact between the water and soil so less adsorption takes place. Dissolved phosphorus concentrations in excess of 50 ppb have been observed in tile drainage waters when soil phosphorus concentrations are high.

In contrast to P, nitrate is highly soluble and generally does not adsorb to soils. Rather, when water infiltrates into soil, nitrate tends to move with water into the soil profile. Consequently, there are usually low nitrate concentrations at the soil surface during runoff events and in runoff. In sandy soils and in tile drained fields, nitrate can be rapidly leached out of the root zone to ground water, to tile drains and, ultimately, to streams and rivers. As a result, tillage practices seem to have little influence on the quantity of nitrate leached (Zucker and Brown 1998). An exception may occur when fall tillage is followed by warm and wet conditions in the winter and early spring, which may promote mineralization, tile flow and high nitrate flux (Randall and Goss, 2001)

Most of the soil and nutrients losses in surface runoff tend to occur in a few rare events that involve large quantities of runoff. Most conservation measures are most effective at reducing runoff and erosion from smaller and more frequent events, and are less effective as the amount of precipitation and runoff increases. Soils can be especially vulnerable to runoff and erosion when a moderately large quantity of rain occurs in late winter when frost prevents percolation of water into the soil. If P fertilizers and manure had been surface applied when the soils were frozen, the resulting runoff may be very high in P. Soils are also vulnerable to erosion in the spring planting season, before the crop has developed. Soils tend to have high water content at this time of year and a moderate rainfall event can produce significant quantities of runoff and erosion. As the season progresses, the crop canopy and the extraction of water from the soil tend to reduce runoff and erosion. The pattern of runoff and erosion that occurs in a given year depends on the timing of precipitation and canopy development, which is highly variable from one year to the next. Thus, the effectiveness of soil conservation practices in reducing runoff and erosion is highly variable and difficult to accurately determine from short-term experiments. A commitment to intensive long-term monitoring is needed to quantify the impacts of conservation practices on water quality

In many streams and rivers, sediment from the erosion of past decades is stored in stream channels. This sediment becomes mobilized during high flow events, and will probably be a source of turbidity for decades (Trimble 1999). Agricultural practices that reduce peak runoff rates are may also reduce the problems related to the remobilization of this stored sediment.

Additionally, it should be recognized that reducing sediment concentrations in streams may allow for greater light penetration into the water column, which may allow for more algae growth where phosphorus concentrations are sufficiently high. This possibility should not discourage conservation efforts, but should inform expectations and strategies of conservation programs.

Limitations of Erosion Control Practices

<u>Conservation tillage</u> systems that leave a great deal of crop residue on the soil surface for erosion control can be successfully used for almost any land, and any crop or crop rotation. Recent work by Buman et al. (2004) demonstrated that profits from conservation tillage systems for a corn-soybean rotation in the Corn Belt were greater than for conventional tillage systems. While yields were slightly lower for no-till systems for corn production as compared to other tillage systems (including a strip tillage system), the reduced production costs for no-till more than offset the yield advantage of conventional tillage systems.

Conservation tillage has a significant effect on soil erosion and water quality. Changes in soil structure, water infiltration, and distribution of nutrients and pesticides in the soil profile are all influenced by the type and extent of tillage. Although balancing water quality goals and adjusting tillage practices to address specific water concerns are important considerations, modifying other management practices may have more immediate impacts. Nutrient application rates, timing, placement, cropping systems, and the extent and management of subsurface drainage could have a greater influence on water quality than tillage practices.

Conventional tillage with a moldboard plow that buried nearly all crop residue has virtually disappeared from American agriculture. The moldboard plow has been replaced with the chisel plow, or other full width tillage tools, that can leave considerable residue on the soil surface- even though when it is combined with secondary tillage system on a number of crops, it may not leave 30% of the surface covered with plant residue after planting, the minimum level to be considered conservation tillage. These tillage tools have become the “conventional” tillage tools of modern agriculture and have few limitations. There is a wide variety of these systems that can be adapted to many situations and used in such a way as to have a major impact on reducing soil erosion. Even small amounts of residue may reduce soil erosion considerably on many lands in the Corn Belt.

While many conservation tillage tools have virtually no constraints as far as costs, production risks, or machinery shortcomings, the best system for conserving soil, the no-till system, may have major constraints in some situations. In cool climates and wet poorly drained soils common in the northern Corn Belt, delayed planting, emergence, and plant growth may reduce yields in some years. While long term results using no-till might be satisfactory, yields are more variable than for other conservation tillage systems, restricting acceptance by farmers in some areas.

Contouring is an effective practice capable of reducing soil erosion on land that does not suffer from severe soil erosion. However, since farm equipment has increased in size, it is less frequently used because it is difficult to follow the contour with large equipment, and it is difficult to farm the small portions of fields that result when fields are rectangular and rows curve to follow the contour of the land. True contouring is seldom practiced; generally it is practiced as cross slope farming with machines traveling parallel to field boundaries.

Contouring is effective in small and medium sized storms, and has little effectiveness for large storms. It diminishes in effectiveness as annual rainfall increases, and as slopes increase. At its maximum effect, contouring will reduce erosion about 50%. However, on long slopes, or very steep slopes, this practice is not very effective. Contouring has no impact on crop yields, unless ridges are high and it is used in areas where yields are limited by soil moisture availability. In these cases, yields may be increased because of moisture conservation.

Terraces that drain via underground drain lines trap sediment so that pondage volume will be reduced over time, rendering the terraces ineffective because of overtopping. Use of conservation tillage systems that reduce soil erosion between terraces may extend the life of such terraces. An additional benefit of such terraces is that much runoff is stored in the impoundments, and released at very low rates, reducing down stream channel erosion and off-site damages due to flooding. However, such terraces are usually designed to store a limited amount of runoff, and storms that are larger than the usual 10-year design period may lead to overtopping, causing damage not only to the terrace, but to channels and structures downstream. Terraces are expensive to construct, some designs remove land from production, and interfere with farming operations. Unfortunately, terraces have a relatively short span of effectiveness because they are designed to hold a limited amount of runoff water. Few terraces in the Corn Belt constructed prior to 1970 are still functional.

Water and sediment control basins perform very similarly to terraces with underground outlets, but do not reduce slope length or erosion losses in the field. It is very important to have soil erosion control on the watershed above the sediment control basin to ensure a long effective life of the basin.

Cost Effectiveness of Erosion Control Practices

Even though some structural practices may be more effective than cropping system practices in reducing sediment and nutrient losses, the cost per unit of soil or nutrient saved is typically much greater (Table 4) .The cost estimates shown in Table 4 should be considered as order of magnitude estimates of the cost-effectiveness of various erosion control practices. If a producer adopts a practice a cropping system practice as a result of an incentive payment or for cost-savings, e.g. no-till soybeans, the per-ton or per-pound cost of the practice will rapidly approach zero.

The incentive payments for changes in management practices, such as zero till or contouring, is usually offered at a specific rate per acre. Therefore, the cost per ton of soil loss and associated nutrient reduction is dependent on the change of the erosion rate on the field after implementing the practice. The costs of structural practices vary more widely based on site conditions and the assumed life of the practice. Forster and Rausch (2002) reported costs in two Ohio watersheds of about $2.50/ton for no till and more than $40/ton for sediment or water control structures. At erosion rates equal to the 1997 NRI estimates for average soil loss rates in the Corn Belt states, the per-ton or per-pound costs double.

The effective cost of erosion control practices in reducing losses of sediment and nutrients to a stream will also vary greatly depending on the delivery of runoff water and sediment to the stream. A field immediately adjacent to a stream may deliver almost all of the sediment and nutrients to that stream, while a field several miles away may contribute only a small portion. Consequently the cost of reduction per ton of soil or per pound of nutrient may be significantly different, depending on location.

Table 4. Estimated annual costs for reductions in soil and nutrient losses for various erosion control practices compared to typical tillage. Practice effectiveness from Table 3 used for estimates of cost effectiveness. For each constituent, annual costs are calculated based on total practice cost.

Practice	Incentive payment/ construction cost ($/ac)	Practice life-span (years)	Annual cost erosion reduction ($/t/yr)	Annual cost nitrogen reduction ($/lb/yr)	Annual cost phosphorus reduction ($/lb/yr)
No-till	$20	2	$1.46	$0.38	$1.00
Contouring	$10	5	$0.51	$0.10	$0.26
Stripcropping	$25	5	$1.03	$0.22	$0.56
Terrace with vegetative outlet	$550	20	$5.00	$1.11	$2.84
Water and sediment control basin	$600	10	$8.10	$2.05	$5.22

Summary

The maximum annual amount of soil that can be removed before the long-term natural soil productivity is adversely affected is referred to as T or the tolerable soil loss level. However, reducing soil erosion losses to T, typically 3 to 5 tons per acre per year for Corn Belt soils, may not adequately protect water quality. Erosion control practices can substantially reduce particulate phosphorus and nitrogen loss from fields, but may increase dissolved phosphorus losses if fertilizer or manure is not effectively incorporated into the soil. Erosion control practices have relatively little impact on inorganic nitrogen losses. The fraction of the nutrient and sediment losses delivered to surface water are affected by practices in the field as well as the distance and path traveled between the field and stream. For example, a field with high concentrations of phosphorus in the soil surface adjacent to a stream and eroding at half the T value may have greater impacts on water quality than a field with low phosphorus levels eroding at >3T, but four miles from the stream.

One significant benefit of erosion control practices is the maintenance of the soil productivity. Grass waterways and conservation tillage also provide food and habitat for birds and small mammals. Continuous no-till systems may sequester five times more carbon than conventional tillage.

In order to accurately assess the costs and benefits of erosion control practices, they should be considered as part of an overall system. Conservation systems need to consider individual landscapes, watershed conditions, and production resources. In addition, the cost of water quality improvements may not be uniform across production systems. For example, the cost effectiveness for reducing sediment, nitrogen, or phosphorus will produce a greater return when practices are targeted to vulnerable areas. In contrast, the incremental cost of water quality improvements may become limiting if current conditions are already favorable.

The most immediate research needs regarding the effectiveness of erosion control practices in reducing nutrient losses are 1) accounting for the ultimate fate of the various forms of phosphorus leaving the edge of field and 2) quantifying the environmental significance of those forms within surface water. While the greatest losses of phosphorus from many fields are attached to sediment, some erosion control practices, such as conservation tillage systems, may increase losses of dissolved phosphorus. The bioavailability of particulate and dissolved phosphorus within different water body types must be better understood to ensure that efforts to reduce total phosphorus losses do not increase losses in a form that may have more negative impacts on water quality.

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