PHOSPHORUS
TRANSPORT TO AND AVAILABILITY IN SURFACE WATERS

COLLEGE OF AGRICULTURAL, FOOD AND ENVIRONMENTAL SCIENCES
Gyles Randall, Dave Mulla, George Rehm, Lowell Busman, John Lamb, and Michael Schmitt

Sources of phosphorus (P) contamination of surface waters are numerous and include agriculture, municipal sewage treatment plants, individual septic treatment systems, decaying plant material, runoff from urban areas and construction sites, stream bank erosion, and wildlife. In some areas and under certain conditions, P losses from agriculture can be a major source of the P entering lakes and streams. This bulletin will address the mechanics and the sources of P loss from agricultural systems.

Phosphorus enters lakes and streams in runoff from landscapes that drain to surface water bodies. Phosphorus may be dissolved in runoff water (soluble or dissolved P) or be associated with particles such as soil or organic matter particles (particulate P) carried in the runoff. Factors affecting P losses from the landscape and movement to surface water can be divided into transport factors and P source/management factors.

Transport Factors

Erosion

The main factors affecting the transport of P to surface waters are erosion and runoff. Because P is attached to soil materials, erosion largely determines the particulate P (PP) movement in the landscape. Sources of PP in streams include eroding surface soil, stream banks, channel beds, and plant material (leaves, etc.). Thus, controlling erosion is of prime importance in minimizing P movement, especially in fertile agricultural landscapes. In landscapes with permanent vegetative cover, such as forest or pasture, the primary source of sediment is from stream bank erosion. This sediment will have characteristics similar to the subsoil of the parent material, which is often low in P content.

The contribution of eroded soil materials to P enrichment of surface waters is very complex. First, part of the sediment eroded from the landscape will be deposited at the toe slope, in depressional areas, along field boundaries, or in grassy riparian zones. Thus, sediment yield from the field to a water body is only a portion of that eroded from the slope. Second, during the movement of sediment, smaller particles (fine fractions) of material are preferentially transported while the larger particles tend to settle out. Therefore, the P concentration and reactivity of eroded particulate material is usually greater than the source soil. The enrichment of P may increase as much as six-fold as the relative movement of fine to coarser particles increases. For this reason, the fine-textured soils (clay loam, silty clay loam, silty clay, and clay soils) of Minnesota have a high potential of supplying P to surface water bodies if erosion occurs and the soil particles are not kept on the soil landscape.

Runoff

Runoff of water either across the soil surface or via subsurface flow can contain significant concentrations of dissolved P (DP). As rainfall or snow melt moves across the soil surface, the water interacts with a thin layer of soil. During this process, P is extracted from the soil and plant material and dissolved in the runoff water. DP can also be lost from standing vegetation (e.g., CRP, alfalfa, native prairies) via spring snowmelt because P contained in the tissue is released due to breakdown of plant cells by freezing and thawing. The removal of P from plant residue by rainfall or runoff may account for differences among watersheds and seasonal fluctuations in P movement. Concentrations of DP in subsurface flow are low because the P-deficient subsoils sorb (absorb and adsorb) much of the

UNIVERSITY OF MINNESOTA
Extension
SERVICE

soluble P contained in the water percolating through the soil profile. Exceptions may occur in organic, permeable coarse, and waterlogged soils with low ability to retain P. Thus, the accelerated eutrophication of surface waters by P is mostly associated with inputs from surface rather than subsurface flow.

The relationship between the DP and PP fractions of total P in runoff as a function of erosion is shown in **Fig. 1.** As erosion increases, the PP fraction of total P increases, while the DP fraction decreases significantly.

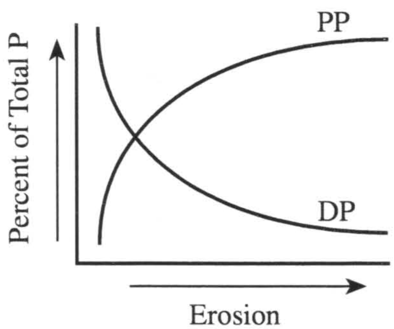

Fig. 1. Effect of erosion on the percentage of total P as dissolved P and particulate P in runoff.

Reducing P Loss by Erosion and Runoff Control

Phosphorus losses from erosion and runoff may be reduced by increasing residue cover on the soil surface through conservation tillage. Results from a flat, tiled, clay loam site in Michigan show significantly lower losses of sediment, total P, and soluble P for chisel tillage compared to moldboard plow tillage **(Table 1)**. However, sediment reductions were much greater than the reductions in total P or soluble P. Water flow, a combination of surface runoff and tile drainage, was not greatly different between the two tillage systems. In other research, DP concentration in the runoff from no-till practices has often been greater than from conventional practices.

Table 1. Edge of field loss from adjacent chisel and moldboard plow plots on flat, tiled, clay loam soils in Michigan (adapted from Gold and Loudon, 1989)[1/].

Parameter	Tillage		Change
	Moldboard	Chisel	%
Sediment (lb/A)	832	347	-58
Total P (lb/A)	1.07	0.74	-31
Soluble P (lb/A)	0.48	0.35	-21
Water flow (inches)	16.2	15.0	-8

[1/] Includes losses by erosion, surface runoff, and tile drainage (no surface intakes).

Strategically placed and properly designed filter strips have been shown to effectively reduce erosion and P movement, especially PP. The strips must be level to prevent channelization of surface runoff water and sufficiently wide to effectively filter out contaminants in the runoff. These strips have had little consistent effect on reducing DP concentrations, however. Other measures to reduce the potential for P movement by erosion and runoff include terracing, contour tillage, cover crops, tile drainage, and impoundments or small reservoirs. Most of these practices are more effective at reducing PP than DP movement in runoff.

Surface intakes installed in depressional areas within the landscape serve as direct conduits from the land surface through the subsurface tile system to drainage ditches, streams, and lakes. Thus, preventing erosion or any lateral movement of nutrients or organic materials within the area drained by the surface intake is critical. Because this is not always possible, the potential for P loss into drainage systems with surface tile intakes is quite high.

P Source/Management Factors

Soil Test P

Decades of fertilization at rates exceeding those of crop removal have resulted in widespread increases in soil test P (STP), often above levels required for crop production. In south-central Minnesota, for example, about 65% of the soil samples tested low or medium in extractable P in 1956. In 1991-93, 69% of the soil samples tested by the University of Minnesota Soil Testing Laboratory had soil test values > 21 ppm (very high). Once STP levels become excessive, further applications of P will increase the potential for P movement and not provide any potential agronomic benefits.

While STP levels in the top 6 to 8 inches of the soil profile have increased with time due to fertilization, the adoption of conservation tillage systems has also influenced the level of STP in runoff from the soil surface (top inch). Stratification of STP occurs with reduced tillage due to the lack of incorporation of broadcast fertilizer and manure and from recycling of subsoil nutrients to the soil surface by plant growth. As a rule, the lesser the amount of tillage the greater the stratification of STP near the soil surface. Land application of livestock manure also elevates STP. This is a significant concern wherever livestock density is concentrated and volume of manure produced exceeds the land area available for long-term application of manure at agronomic rates.

Accumulation of STP near the soil surface increases the concentration and loss of P in runoff. Highly significant linear relationships similar to that shown in **Fig. 2** are frequently seen between the amount of STP in the surface soil and DP concentration in surface runoff.

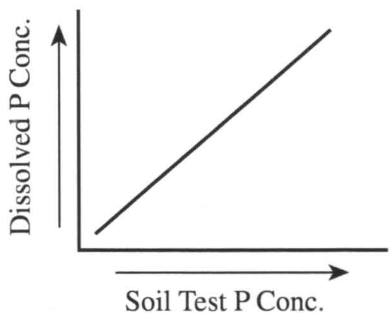

Fig. 2. Effect of soil test P concentration on dissolved P in runoff.

Though various methods have been developed to accurately assess plant availability of STP, the relationship between soil P and the potential enrichment of bioavailable P (BAP) in runoff water is less clear. Recently developed resin accumulators and iron-oxide impregnated strips have been shown to be independent of soil type; thus allowing the estimation of BAP in both acid and alkaline soils. Further testing of these methods is necessary before they can be widely used as an environmental test for soil P bioavailability.

Rate, Method, and Time of P Application

Loss of P in runoff is influenced by the rate, method, and the time of P application; source of P used; amount and duration of rainfall; and vegetative cover. Increased loss of P in runoff is frequently reported with increasing application rates of fertilizer P, dairy manure, swine manure, and poultry litter. The DP concentration in runoff from areas receiving broadcast fertilizer P has been found to average as much as 100 times greater than from areas where comparable rates were applied 2 inches below the soil surface. Incorporation of dairy manure has been reported to reduce the total P (TP) loss in runoff five-fold compared with areas receiving broadcast applications.

Timing between application of P and the first runoff event is also important, especially in situations involving manure. Losses of P from surface-applied poultry and swine manure have been reduced by up to 90% due to P sorption by the soil when rainfall did not occur for three days after application. The major portion of annual P loss in runoff is generally caused by one or two intense storms. If broadcast P applications are made during periods of the year when intense storms or runoff is most likely, then the percentage of applied P lost will generally be greater than if applications are made when runoff probabilities are less. Runoff of P is greatest during the planting season, a time of intense rain and minimum crop cover. Under some conditions, winter applications of manure to frozen, sloping soils also greatly increases the potential for loss during spring runoff events. Within the Minnesota River Basin, this combination of transport and P source/management factors has led to higher TP loadings in the river during March to June than in all other months.

Conservation tillage systems, especially no-till, can reduce sediment (particulate) forms of P losses on nearly level, somewhat poorly-drained soil, but may have quite variable effects on soluble P losses depending on how the P fertilizer is applied. Switching from full-width tillage systems like chisel-field cultivator to conservation tillage systems must be accompanied by practices which place P fertilizers and manure below the soil surface or BAP in runoff may actually increase.

All agricultural cropland has the potential for contributing nutrients to surface waters; however, some sites are more likely to contribute significant amounts than others. Highly erodible cropland enriched with fertilizer and manure nutrient inputs has a higher probability of degrading surface water quality due to greater runoff and soil losses. Other highly probable sites for P contribution to surface waters are nearby feedlots and barnyards in close proximity to surface waters. These sites with highest probability for P loss merit specific management practices to minimize their contribution to the enrichment of surface water.

P Availability in Surface Waters

The eutrophication process is accelerated with the addition of nutrients to surface water bodies. Elevated nutrient levels within the water often causes abnormally high production of algae and aquatic plants. The eventual decomposition of increased amounts of organic matter can deplete the dissolved oxygen content of surface water resulting in the death of fish and other aquatic organisms. Of all cropland nutrients inputs, P has been identified as the most important to prevent from reaching surface water bodies. Due to low natural levels of P, biological productivity in surface waters is usually limited by P availability.

Phosphorus movement in runoff and erosion from the landscape occurs as PP and DP. In general, PP is the major portion (75 to 90%) of P transported in runoff and erosion from cultivated land. The PP is primarily associated with sediment and organic matter and contains both organic and inorganic P. Although not immediately available, PP represents a major reservoir of P to aquatic vegetation and algae. Portions of PP may come into solution with time, especially as dissolved P levels are depleted. Some researchers have estimated that 20 to 40% of sediment inorganic P is potentially available. Additionally, PP can be transported as part of the suspended sediment load, potentially affecting aquatic systems located downstream.

Dissolved P is considered most available for plant uptake and can have an immediate impact on aquatic vegetation and algal growth. Total P is the total amount of PP and DP contained in the water system. Several studies have shown little decrease in algal growth in lakes in which total P inputs were reduced. This suggests that other forms of P would be a better index for P bioavailability.

The bioavailable form of P (BAP) includes all of the DP and the portion of the PP that comes into solution (ranges from 10 to 90% of the PP). Levels of BAP have been estimated to represent 98% of the P that can be utilized by algae. Thus, BAP measurements, although more difficult to determine, are a more accurate estimate of long-term P availability to aquatic plants and algae.

P Concentrations in the Minnesota River

Phosphorus concentrations and loading in the Minnesota River and its tributaries were monitored intensively from August, 1989, through September, 1992, and are reported in the Minnesota River Assessment Project Report, Vol. II, 1994, Minnesota Pollution Control Agency. Their data show that the tributaries frequently transport P-enriched water to the main stem. TP in the main stem ranged from 0.04 to 0.48 mg/L with a median value of 0.22 mg/L. Three to 89% of the TP was DP with at least 33% as DP in 50% of the samples. DP ranged from 0.01 to 0.34 mg/L with a medium of 0.07 mg/L. These levels of DP suggest that the Minnesota River is enriched with P in amounts that exceed growth requirements of algae.

TP concentrations and river flows were lower in the headwaters of the Minnesota River Basin than in the lower portions, indicating less P loading from this region. This was likely due to lower rainfall and reduced transport of P from the landscape to the river in the western end of the basin. On the other hand, TP concentrations were significantly higher in the Blue Earth, LeSueur, and Lower Minnesota Basins due to greater rainfall and steeper slopes in portions of these basins. During runoff events, TP concentrations were about two times greater than the median value and about five times greater than concentrations collected during low flow in the Blue Earth River. TP concentrations often reached peak values during the rising portion of the stream hydrograph.

Analysis of stream flow data from the Minnesota River and its tributaries from 1974 through 1994 by the University of Minnesota, Department of Soil, Water, and Climate, also shows much higher P loading from the lower portions of the river basin. About two-thirds of the TP in the Minnesota River at Fort Snelling was produced in the Lower Minnesota, LeSueur, and Blue Earth watersheds. Thus, streams in the high rainfall and runoff areas of the basin contribute a relatively large portion of the annual P load to the Minnesota River.

Conclusion

Phosphorus losses from agriculture can be a significant source of P entering lakes and rivers. However, P budget and management information indicates that P losses in runoff represent a small portion (1 to 2%) of annual P inputs to agricultural land. Many watersheds contain acreage that does not contribute appreciably to runoff of P, and most of the annual P loss occurs during a few high-runoff events. These characteristics suggest that management strategies to remediate water quality problems associated with P losses from the landscape will be most effective if used on high-risk, sensitive or source areas within a watershed rather than implementing general strategies over a broad area. General management practices that can be focused in these high-risk areas include minimizing erosion and runoff, avoiding P additions to very high testing soils where a crop response is unlikely, and incorporating or injecting P inputs (fertilizer and manure) below the soil surface.

Partial funding for this publication was provided by the Metropolitan Council and the Minnesota Board of Water and Soil Resources.

FO-6796-B
Reviewed 1998

www.extension.umn.edu

Additional copies of this item can be ordered from the University of Minnesota Extension Service Distribution Center, 20 Coffey Hall, 1420 Eckles Avenue, St. Paul, MN 55108-6069, e-mail: order@extension.umn.edu or credit card orders at 800-876-8636 or 624-4900 (local calls).

Produced by Communication and Educational Technology Services, University of Minnesota Extension Service.