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Minnesota Phosphorus Site Risk Index

Technical Guide

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Minnesota Phosphorus Site Risk Index

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Executive Summary

Surface water quality is an important issue in a state where this resource provides a major economic engine. Phosphorus can be a major factor in lake eutrophication. Phosphorus (P) is the nutrient limiting algae growth in most fresh water systems. When P in runoff is allowed to enter surface waters the resultant algal bloom leads to depleted dissolved oxygen levels and the associated degradation in water quality. Phosphorus is also an important plant nutrient. Fertilizer, manure, and other organic P sources are land applied to support adequate plant growth. The challenge for people who make land use decisions is to balance economic and environmental risks.

The Minnesota Phosphorus Index is a management tool for individual fields or landscapes that provides a relative (unitless) assessment of the risks to surface waters of P losses from erosion, rainfall runoff, and snowmelt runoff. It also allows the user to evaluate management options that can reduce the risk. It is not intended to be used as a regulatory tool, nor to estimate changes in surface water quality measurements. The Minnesota P Index does not consider the sensitivity of the receiving waters, nor the environmental costs of entry of P to surface waters. It also does not consider the cost of adoption of different practices to reduce P losses from specific fields.

Other states have developed similar tools. As with other states, Minnesota's P Index addresses its unique climate, soils, landscapes, and land use practices to develop a risk assessment. For example, it is currently the only index that assesses the risk associated with snowmelt P losses. This would have little value in Florida or Texas, but, in Minnesota, snowmelt can be a major source of P entering surface waters. All current indices assess P source levels and the probability of transport across the landscape.

There are two basic approaches to P indices: the matrix method and the pathway method. The matrix method uses a table in which the rows represent P source and transport issues and columns represent different levels of risk related to each issue. Weighting factors for source, transport, and P loss risk are assigned to different practices based on the opinion of experts. Often the risk increases by doubling as you move from one level to the next. The matrix model was considered during the development of the Minnesota P Index and was also used to estimate risk on a regional scale (Birr and Mulla, 2001). A second, less common approach is the pathway model. This is a more physically based model using algorithms from published data that estimate P source levels and risk of transport across the landscape to surface water. Multiple pathways are assessed and added to yield an overall risk. This is the approach that was chosen for the Minnesota P Index.

Three pathways are considered in the Minnesota pathway approach. The first is the transport of sediment-bound P associated with the eroded particles in rainfall runoff. The second is the transport of dissolved P by rainfall runoff. The third is the transport of dissolved P by snowmelt. Losses from these three pathways are added, giving a total P index (unitless) for the given site. This index value represents the relative long-term average risk of P losses for a given site and set of management practices. Actual P losses depend on the quantity and timing of precipitation. For this reason, the Minnesota P Index should not be compared with or used to estimate watershed-scale water quality monitoring data.

Evaluation of test scenarios revealed that there are multiple ways to lower the P Index. Best management options can be evaluated for a specific site using the Minnesota P Index. P losses can be lowered using some combination of reduced P application rates, improved methods of P application, or adoption of practices such as conservation tillage or buffer strips that reduce the risk of P transport across the landscape. Usually one pathway (erosion, rainfall runoff, or snowmelt runoff) is much more important than all other pathways, and management changes that address that pathway will be the most effective method for reducing the overall risk.

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Introduction

Environmental policies of the past three decades have significantly reduced the amount of phosphorus entering surface waters from point sources. However, eutrophication of fresh waters is still a major environmental concern due to transport of excessive amounts of phosphorus from non-point sources such as municipal and agricultural activities.

Phosphorus (P) is an economically important input in both crop and livestock production systems (Mallarino and Blackmer, 1992; Valk et al., 2000). A challenge in agriculture is to supply adequate P for economical production while minimizing losses to surface and ground water. Application of phosphorus in fertilizer and manure in excess of the quantities removed by crops has elevated phosphorus levels in many agricultural soils above agronomically optimum levels. Runoff and erosion from these soils can transport phosphorus into surface waters if there is a hydrological connection.

Recognizing the fact that high phosphorus soils can contribute to eutrophication of surface waters, many states have established threshold soil test phosphorus levels that limit application of additional phosphorus in soils exceeding the threshold (Sharpley et al., 1996). However, the movement of phosphorus from agricultural soils to water bodies is influenced by many factors and a more holistic approach is needed for protection of vulnerable water bodies. In response to that need, a group of researchers from universities and government agencies in the early 1990's developed the concept of a phosphorus site index.

The concept of a phosphorus site index is to use a combination of landscape and land management factors to assess the risk of P movement off-site from fields or watersheds (Birr and Mulla, 2001; Gburek et al., 2000, Lemunyon and Gilbert, 1993). The factors in the P site risk index consider sources of P as well as transport of P to water. The original phosphorus index by Lemunyon and Gilbert (1993) has been shown to relate to off-site transport of phosphorus from small agricultural watersheds in Texas, Oklahoma, and other regions (Sharpley, 1995). Modified versions of the original phosphorus index have been used by many states and governmental agencies to apply to local climate and land management conditions. A phosphorus index developed for Minnesota will be an important means of accomplishing water quality goals by focusing resources and efforts on areas with the highest potential for transport of phosphorus to surface waters.

Development Process

A team from the University of Minnesota, the USDA-Agricultural Research Service (ARS), the USDA-Natural Resources Conservation Service (NRCS), and the Minnesota Pollution Control Agency (MPCA) worked together for approximately 18 months to develop the Minnesota P Site Risk Index. The development process involved the following steps.

- P Index literature review
- Establishment of soil critical levels
- The MN P Index description
- Testing and evaluation
- Sensitivity analysis
- Professional review
- Field pilot testing

Phosphorus Index Literature Review

The purpose of the literature review was to provide background on the development of the various phosphorus indices used or being developed in the U.S, before designing the

Minnesota index. We evaluated eight P site indices (details in Appendix A). From this critique, we identified factors used for computing site risk that have relevance for Minnesota conditions (Table 1).

The original phosphorus index (USDA-NRCS, 1994, Lemunyon and Gilbert, 1993) was based on the concept that phosphorus loss from agricultural land is governed by the combination of "source factors" and "transport factors." Each factor was assigned a weight based on expert opinion. The factors and respective weight from the Original P Index are:

Source Factors: agronomic soil test phosphorus (1.0), inorganic phosphorus application rate (0.75) and method (0.5), and organic phosphorus application rate (1.0) and method (1.0).

Transport Factors: soil erosion (1.5), irrigation erosion (1.5), and runoff class (0.5).

The authors of the original phosphorus index acknowledged the need for individual states to modify the index and its algorithms for specific uses or locations. In fact, many versions of the P Index have been developed using the same core factors to evaluate risk as the original version. Some indices use additional factors that are of local importance. Most indices have included a term to account for proximity of the field to surface water.

The various P indices differ widely in how factors are weighted and in how risk is computed. Many states have modified the original index by combining source and transport factors in a multiplicative approach rather than the original additive approach. No uniform scale has been developed for phosphorus indices, which complicates direct comparison of the various approaches. In most indices, the outcome is a relative level of the risk of off-site phosphorus transport. Only in the Iowa index was the computed index value an estimate of phosphorus delivery (lb/ac) rather than a relative risk level.

Among the indices evaluated there were two distinct approaches in the way the index is formatted. The majority of the indices use a matrix approach, with rows representing risk factors and columns representing categorical risk levels. The other approach makes a quantitative estimate of the phosphorus loss from a site by modeling the P source and transport pathways. We initially considered both a matrix approach and a quantitative approach (hereafter referred to as a pathway approach). Although there were advantages and disadvantages to each, a modified pathway approach (unitless) was selected as best for use in Minnesota.

In addition to risk factors used in other P indices, we identified unique factors of importance for evaluating P transport in Minnesota. Specifically, we included a snowmelt runoff factor and an incorporated manure factor.

Characterization of Phosphorus in Minnesota Soils

An extensive characterization of P in Minnesota soils was performed to establish criteria of risk and correlations for use in the Minnesota P Site Risk Index. Specifically, relationships were defined between soil test P and organic matter content, on the one hand, and the concentrations of total P in soil and soluble P in runoff water, on the other.

The characterization was accomplished through a combination of laboratory extraction studies and a simulated rainfall study using the plow layer of 160 agricultural soils from across Minnesota. Soils represented major agricultural regions, cropping systems, and soil management practices prevailing in the state (Figure 1). Appendix B summarizes methods and results of the soil characterization.

The Minnesota P Index Description

The Minnesota P Index is based on the concept of independent pathways of P delivery from a field to water. The index combines input factors within each pathway to compute a risk score. The three pathways considered are 1) sediment-bound P from rainfall runoff, 2) soluble P from rainfall runoff, and 3) total P from snowmelt runoff. Sources and justifications of equations are explained here. All equations and factor values are in the "Minnesota P Index Worksheet User's Guide."

I. Sediment-bound P, Rainfall

Sediment-bound P = Field erosion X manure factor X sediment delivery factors X soil total P concentration.

The risk of sediment-bound P loss is a function of the amount of sediment lost as erosion and the amount of P attached to the sediments.

Sheet and rill erosion. Sediment delivery is used for the erosion component of the P index. The long-term average annual sediment delivery (tons/acre/year) is estimated using the Revised Universal Soil Loss Equation 2, RUSLE2 (USDA-NRCS, 2003). RUSLE2 estimates sheet and rill erosion based on soil type (K factor, erodibility), climatic erosivity (R, amount and intensity of rainfall), slope length and steepness (LS), cover management practices (C), and support practices that reduce erosion (P). Where soil type and topography vary across a field, RUSLE2 and P Index values should be based on the "most limiting area of significant extent," i.e., the area that represents the highest potential for erosion and P loss and occupies at least 20% of the treatment unit (Minnesota Natural Resources Conservation Service, 2004). Using RUSLE2 to estimate sediment delivery (soil loss minus deposition) is somewhat different from using it to estimate soil loss for conservation planning purposes. Whereas soil loss is estimated for a simple slope (a single gradient), sediment delivery should be estimated for a complex slope (multiple segments with different gradients) from the most limiting area of significant extent. By using a complex slope, RUSLE2 will estimate deposition that occurs on the toeslope.

Wind erosion and gully erosion are not currently accounted for in the Minnesota P Index, but they may be significant sources of P to some surface waters.

Manure factor. The sediment delivery prediction is reduced by up to 25% (multiplied by 0.75) if manure was injected or incorporated during the previous 3 years.

Field monitoring data in Minnesota and elsewhere have shown that applied manure (incorporated or injected) reduces erosion compared to soils without manure (Gilley and Risse, 2000). However, RUSLE2 estimates are not sensitive to this reduction. Literature suggests the reduction in erosion after applied manure could range from zero to 75%, with the majority of reports showing reductions of 25-50%. Thus, a 25% percent reduction was chosen as a representative, but conservative estimate. Erosion rates in the Minnesota P Index are not reduced in response to surface applications of manure. The cover effect of surface manure can be handled within RUSLE2.

Sediment delivery adjustment factor. The sediment delivery factor reduces the RUSLE2 sediment delivery estimate by as much as 95% to account for three types of deposition not accounted for in the RUSLE2 estimate: 1) in-field and field edge sediment traps, including buffers, filter strips, and terraces; 2) deposition occurring as runoff flows over the landscape between the field and the nearest surface water body; and 3) deposition associated with standing water, including sediment control basins, other impoundments, and natural landscape depressions (with or without surface tile inlets). Each of these are further discussed below.

Buffers and filter strips that meet NRCS Practice Standards are assigned sediment delivery factors of 0.5, and terraces, 0.4. The NRCS Practice Standard states that filter strips must be at least 30 feet wide (depending on slope), and are unsuitable if more than 50% of the runoff is channelized, if erosion from the contributing area is >10 t/ac/yr, or if the slope is >12% (Minnesota NRCS, 2002). Buffers, filter strips, and terraces should not be included in the RUSLE2 calculation. In test runs, RUSLE2 generated trapping efficiencies for filter strips ranging from 90% to nearly 100%. In contrast, field research showed typical efficiencies of 50-95% (Castelle and Johnson, 2000; Chauby, et al., 1994; Daniels and Gilliam, 1996; Dillaha, 1989; Dillaha et al., 1989; Lee, et al. 1999; Munoz-Carpena et al., 1993; Robinson et al., 1996). Efficiencies may be even lower in actual field settings if flow is channelized or if vegetation is not well-maintained over time. Thus, by including filter strips in RUSLE2, users would get an unrealistic impression of the reduction in erosion and P loss risk.

A sediment delivery ratio (SDR) is the proportion of sediment leaving the field that reaches surface water. The relationship between distance and SDR used in the Minnesota P Index was based on Ouyang and Bartholic (1997). To determine the distance to surface water, the user must decide which surface waters are of interest. Generally, a permanent stream, lake, or wetland is the primary water quality concern, but any water course that is wet most of the year (e.g., drainage ditches or intermittent streams) should be considered surface water for purposes of the P Index, because they eventually lead to streams and lakes. Sinkholes are also considered surface water.

Impoundments and sediment control basins are assigned sediment delivery factors of 0.05 and 0.2, respectively (Iowa NRCS, 2001).

The P Index accounts for sediment deposition occurring in the natural depressions characteristic of the Prairie Pothole regions of Minnesota. Users select a sediment delivery factor of 0.05 for depressions with no outlets, 0.02 for those with surface tile inlets, and 0.15 for those with rock/gravel inlet structures (Ginting, et al., 2000; Gieseke, 2000; and Ranaivoson, 2004). That factor is then multiplied by the fraction of the field draining to depressions. Other sediment delivery factors (i.e., sediment delivery ratio based on distance to water, or any sediment traps) are multiplied by the fraction of the field not draining to depressions. The two numbers are added together to arrive at a weighted sediment delivery factor.

Soil total P concentration. The concentration of total P associated with delivered sediment (lbs P/ton of sediment) is estimated based on soil organic matter levels and soil test P levels measured within the past 3 years. Commonly available soil P tests (Bray, Mehlich, Olsen) measure levels of P available for crop production. The regression equation describing the relationship between Olsen P and total P was based on tests from over 160 soil samples taken from agricultural fields in Minnesota (Appendix B). The same soil samples were used to define the relationships between Olsen P and Bray P or Mehlich P.

For high P soils (>100 ppm Bray, >100 ppm Mehlich, or >50 ppm Olsen), standard soil test P analysis will not provide an accurate measure of soil test P concentration. In these cases, a "Nutrient Management Phosphorus Test" (http://soiltest.coafes.umn.edu/methods.htm) is recommended. This test is a modification of the Olsen P procedure, with a sample dilution that allows more accuracy for high P soils. The Olsen method is recommended for this test because it can be used on all soils in the state, while the Bray and Mehlich methods cannot be accurately used on calcareous soils.

In earlier versions of the P Index, total soil P was based only on soil test P, but better correlations were achieved by including a soil organic matter

(SOM) component. The relationship used in the Index is:

Total P (ppm) = 316.1 + 2.483 * Olsen + 36.266 * SOM   ($R^2 = 0.71$)

Total P (lbs/ton) = 0.6322 + 0.00497 * Olsen + 0.0725 * SOM

where Olsen P is in ppm and SOM is in percent.

This suggests that, on average, SOM is 0.36% P and that in a native soil with 5% SOM and low soil test P about 36% of the P is organic. This corresponds with what others have found for soils in this region.

The effect of calcium carbonate was considered, but running the regression for soils with carbonate contents of less than 2% only increased the R^2 to 0.76. The role of calcium carbonate in fixing P is small, except possibly in prairie pothole rim soils that are high in finely divided calcium carbonates.

Only a portion of soil P is immediately bioavailable in aquatic systems, but the model accounts for all P associated with sediments based on the assumption that all soil P will eventually become available. Thus, P Index results are not as sensitive to changes in soil test phosphorus as some users expect. Soil tests represent only a fraction of total soil P, so as soil test increases, the risk of P loss due to erosion does not increase proportionally. For example, the equations given above show that, for a soil with 3% organic matter, raising the Olsen soil test from 10 to 50 ppm – a five-fold increase – will only raise the total soil P from 450 to 549 – a 22% increase.

Optional soil test adjustment. In most situations, the change in total P due to fertilization or crop removal is small for periods of 3 years or less and these changes are not critical for the purposes of the P Index. However, if P application rates are very high, or if the P Index will be used to project the effects of management several years ahead, it may be useful to consider changes in total soil P since the last soil test. For these situations, an optional procedure is included to adjust the Olsen P value to account for additions and/or removals of P. The procedure combines a P application rate (fertilizer or manure), an "average" crop removal factor (Randall et al., 1997) of 30 lbs. P_2O_5/acre, and a ***Soil P Buffer Factor*** of 0.05 for sandy loam or coarser textured soils, 0.03 for finer textured soils, and 0.02 for calcareous soils (pH >7.3). For CRP, pastures, woodland, and similar areas, the crop removal factor is zero. The computerized version of program uses crop removal estimates based on crop type and yield, using values from the Minnesota Department of Agriculture (1999). The Soil P Buffer Factors are based on Minnesota research (Moncrief and Evans, 1994) and other supporting data (Peck et al., 1971). The units for the buffer factors are ppm Olsen soil test P per lb of P_2O_5 added or removed.

II. Soluble P, Rainfall

Soluble P, Rainfall = Base runoff volume X Runoff adjustment factor X (Soluble soil P + Applied P) X 0.22.

The risk of soluble P loss in rainfall runoff is a function of the estimated runoff volume and the concentration of soluble P in rainfall runoff. The two sources of soluble P in rainfall runoff are the soil solution (including P fertilizer and manure applied since the last soil test), and P solubilized directly from unincorporated manure or fertilizer P applied during the current crop year. (Crop years are defined as the period between harvest of one crop and harvest of the succeeding crop).

Base runoff volume. The base runoff values in inches were based on historical rainfall records and the NRCS Runoff Calculation method (USDA-NRCS, 1990), assuming soil group B and row crop production. A runoff curve number for an average hydrologic condition was taken as the average between: straight row –no residue, poor hydrologic condition; and straight row – residue management, good hydrologic condition, or 78 for "B" soils. Using an RCN of 78, the runoff amount for each day was determined for each NOAA Cooperative Climate Station using 1961 through 1990 daily precipitation data for the long term average frost free dates (24 degrees F base). This data was used to create an isoline map of the average annual runoff values.

Runoff adjustment factor. Applying the same procedure to other hydrologic groups and cover conditions, adjustment factors were calculated to convert the base runoff values to represent different cropping conditions.

Hydrologic soil groups are a function of soil texture and permeability and relate to the tendency of water to runoff from the given soil. Hydrologic soil groups are reported in County Soil Survey manuals as group A, B, C, or D. Runoff potential ranges from group A soils with low runoff potential to group D soils with high runoff potential. In Minnesota, many group C and D soils have been artificially drained. For purposes of the P Index, these artificially drained soils should be considered hydrologic group B.

Soluble P concentration in runoff. Soluble P in runoff may come from the soil or directly from recent manure or fertilizer applications.

The concentration of **soluble P from soil** can be predicted based on a phosphorus soil test taken within the last three years. A linear relationship between Olsen P and runoff soluble P was defined for Minnesota soils (Appendix B) as 0.01 ppm of P in runoff for every ppm of soil test P. As explained in the section about estimating soil total P concentration (page 8), results of Bray or Mehlich soil tests should be converted to an equivalent Olsen test value, older soil tests should be adjusted using the Optional Soil Test Adjustment, and the Nutrient Management Phosphorus Test is recommended for high P soils.

The **applied P factor** accounts for non-winter (April 1 to November 14) direct losses of soluble P from fertilizer and manure applications. (Winter applications are accounted for in Pathway 3.) To determine the rate of P applied from manure, both the manure application rate and the concentration of P in manure are needed. It is recommended that a manure analysis be performed for each application period. If a manure analysis is not available, the P content can be estimated from the table of typical values provided in the User Guide (Midwest Plan Service, 2001 and 1993). The amount of applied fertilizer and manure is reduced by a factor that estimates the fraction of applied P left at the soil surface after incorporation by different tillage tools, with injected P applications having a risk of zero. The incorporation efficiency figures were determined based on data illustrating the stratification of soil test P for various tillage systems and on the effect of tillage on surface residue (Randall et al., 1983). For example, the percent of applied P remaining at the soil surface is 0, 5, 50, and 100 for injection, moldboard plow, disk, and no tillage, respectively.

The applied P factor is calculated as 0.1 ppm of P in runoff for every pound of applied P at the surface. This relationship was defined by calculating the concentration of P when 3% of surface-applied P is lost in 1.35 inches of runoff. Published data sources relating P application rates to P losses show that approximately 3% of applied P potentially can be lost when high intensity rainfall occurs shortly following surface P application without incorporation (Edwards and Daniel, 1994; Edwards and Daniel, 1992; Mueller et al., 1983). Assuming good infiltration, 1.35 inches of runoff is the amount lost during a 1.8-inch rainfall.

The **constant** of 0.22 converts runoff inches to million pounds or runoff per acre.

III. Total P, Snowmelt

Total P, snowmelt = Snowmelt runoff factor X Fall soil condition factor X (Fall residue P + fall/winter surface applied P) X 0.18.

The risk of P being carried to water via snowmelt is a function of the amount of snowmelt runoff, the roughness of the soil as it affects snowmelt runoff, and the amount of P in surface residue and surface applied fertilizer and manure.

Snowmelt runoff. The map of potential maximum snowmelt runoff in inches is based on historical snow records across the state. In Minnesota, most snowmelt runoff occurs during the spring thaw, usually in mid- to late-March. The base snowmelt runoff was determined by taking 65% of the average maximum snowpack for the period March 16 through March 31 (USDC). The 65% figure is based on observations in small plot research done in Minnesota (Hansen et al., 2000; Munyankusi, 1999). The base snowmelt runoff volume represents the potential maximum runoff for a geographic area.

Fall soil condition factor. This factor is determined by the type and direction of fall tillage. The fall soil condition affects both the amount of snow retained and surface storage of water from melting snow, both of which can result in wide differences in snowmelt runoff and associated P loss (Ginting et al., 1998; Hansen et al., 2000; Hansen et al., 2001; Munyankusi, 1999). Snow is trapped by crop residue, especially standing corn stalks in no till fields. The larger accumulations of snow increase the potential for snowmelt runoff. A rough soil surface, created by tillage, leaves depressions that can store water and reduce the volume of snowmelt runoff compared to the smoother surface of untilled fields. The combination of crop residue and surface roughness results in three to four times the volume of snowmelt runoff following no fall tillage compared to fall moldboard plowing. Tillage and planting direction also affect the volume of snowmelt runoff, with smaller amounts moving from fields that are farmed across the slope than up and down the slope.

Soluble P concentration in snowmelt. Phosphorus in snowmelt can originate from crop residue or from winter applied fertilizer or manure. The amount of surface available P (lbs P/ac) in **crop residue** is based on crop, crop yield, and tillage practice (Halsey, 1986; Wischmeier, 1973; Hanway and Olsen, 1980; Mays et al. 1980). **Winter applied P** is defined as any unincorporated application occurring between November 15th and March 31st. Determining the amount of manure P applied requires the manure application rate and the concentration of P in manure. It is recommended that a manure analysis be performed for each application period. If a manure analysis is not available, the P content can be estimated from the table provided in the "Minnesota P Index Worksheet User's Guide."

The snowmelt risk calculation is based on the assumption that 18% of the applied P and crop residue P will be lost with one inch of runoff. In general, risk of P loss from crop residue is small relative to loss from winter applied P. When risk of snowmelt runoff is estimated to be more or less than one inch, the risk of P loss will vary accordingly.

The **constant** of 0.18 represents the percentage of surface available P lost per inch of runoff.

Overall Risk

The overall P site risk score is the sum of the risk values for each of the three pathways. When the calculated risk is "very low" (<1), no changes in management are recommended. Minor changes may be recommended if risk is "low" (1-2). In the "medium" risk category (2-4), small improvements in management may be necessary, and the producer should avoid management practices that increase the risk of P losses. In the "high" risk category (4-6), moderate improvements in management are recommended to lower the risk of P losses. In the "very high" risk category (>6), multiple (and possibly large) improvements in management practices are recommended. Results from the P Index identify the causes of risk and suggest management practices that will be most effective in reducing risk. Maximum flexibility should be given to the producer to reduce risk in the most logical and economical way for them.

Results from the Minnesota P Index represent the relative risk of P loss from one site compared to another, or the relative value of one practice compared to another at a particular site. In this way, it can be used to effectively target conservation efforts. P Index results do not represent actual P loads leaving a field for several reasons. The various components of the model are based on different scales of research that may not be absolutely comparable. The P Index calculation is based on the RUSLE2 sediment delivery estimate, which may not match actual sediment losses. The concentration of P in rainfall runoff is based on a single scenario of heavy runoff immediately after P application. Actual event intensity, timing, and preceding conditions will result in quite different P loss amounts. Rainfall and snowmelt runoff volumes vary widely from year to year, so the long term average runoff estimates used in the P Index may not reflect runoff rates over a few years.

Results from the Minnesota P Index do not represent the impacts to surface water quality. Receiving waters vary in their sensitivity to P loading, and this sensitivity should be considered when interpreting results of the Minnesota P Index.

Factors not Included in the MN P Index

Gully erosion. The sediment-bound P pathway is based on a RUSLE2 sediment delivery estimate, and thus only accounts for sediment transported by sheet and rill erosion. Ephemeral and permanent gullies can be substantial sources of sediment in some situations, but the Minnesota P Index does not address gullies for several reasons.The impact of gully erosion on P loss is unclear due to a lack of data describing the extent of gully erosion and the P content of the transported sediments. Gully sediments are likely to include a large proportion of subsoil particles, which generally have substantially lower P levels than does surface soil.

Gully erosion is estimated by measuring the volume of the gully, estimating the density of the soil, estimating the number of years it took to build the gully, and dividing by the acreage of the field to prorate the total to a per acre figure. Thus, the measurement looks backward, in contrast to RUSLE2 sheet erosion estimates which project average annual losses. Combining the two measurements assumes that the rate of gully erosion will continue into the future.

Any estimate of P loss from gullies should be a separate calculation in which the gully erosion estimate is multiplied by an estimate of subsoil P based on landscape type. Because flow is already channelized, a different sediment delivery ratio will be necessary.

Sediment enrichment ratio. Hydrologic research has shown that concentrations of particulate contaminants such as P are higher in eroded sediments than in the original soil. Enrichment ratios can be used to estimate the higher concentrations. However, enrichment factors are small and have little effect on relative risk rankings of sites.

Subsurface drainage. Soluble phosphorus can leach through soil and be delivered to surface water via subsurface drainage tiles or through natural subsurface recharge. Data from southern Minnesota (Randall et al., 2000) suggest that these losses are small relative to other sources of P loss and thus were not included in estimating total risk of P loss to surface water. Drainage losses can be significant under organic soils, which cannot adsorb P as well as do mineral soils; under fractured soil that provides preferential flow channels directly to the tile lines (e.g. in the case of newly installed drainage tiles); and on coarse, irrigated soils where soil test P or P applications are very high.

Testing and Evaluation

Water quality research from Minnesota was used to test and evaluate the Minnesota P Site Risk Index. Four specific studies were used as the primary data for the testing and evaluation. The **Cedar Lake** study was a paired watershed study conducted in Scott County, Minnesota from 1995-2000 (Hansen et al., 2001). This study compared P losses in snowmelt and rainfall runoff as affected by tillage practice in a continuous corn rotation. The **Nytes** study was a paired watershed study, also conducted in Scott County, Minnesota from 1996-2001, that compared P losses in snowmelt and rainfall runoff as affected by tillage practice in a corn-soybean rotation. The **Lancaster** study was replicated plot research conducted in Lancaster, Wisconsin from 1994 to 1995 (Munyankusi, 1999). The study evaluated P loss in runoff as affected by tillage practice and timing of manure application. Finally, the **Morris** study was conducted in Morris, Minnesota from 1994 to 1996 (Ginting et al., 1998). This was a replicated plot study that evaluated the effects of tillage and manure application on P losses.

From each of these studies, the annual loss of total P was compared against the risk calculated by the Minnesota P Site Risk Index. For this comparison, measured values of runoff volume and soil loss were used, rather than estimated values.

The annual loss of total P from these sites was linearly related to the P Index risk score (r^2=0.68). Thus, P Index risks are proportional to the loss of P from these sites. At most study sites, the Sediment-bound P losses were dominant, and the risk from this pathway was well correlated with measured particulate P losses. Losses of soluble P by rainfall or snowmelt at these sites represented a small fraction of the total annual P loss, and the P Index was not as accurate in predicting these risks as in predicting sediment P loss risk. There are, however, management practices and site conditions not investigated at these sites that can lead to situations where P losses in rainfall runoff or snowmelt runoff exceed the losses of particulate P.

Sensitivity Analysis

Hypothetical scenarios using a wide range of inputs that represent the range of conditions in Minnesota were created to evaluate the sensitivity of the Minnesota P Site Risk Index. A base scenario was created and then each input was varied independently. The purpose of the sensitivity analysis was to isolate the effect of model components, even though resulting scenarios may not be realistic. For example, in reality a change in tillage would be associated with a change in the erosion rate.

Two site conditions – soil texture and soil hydrologic group – were not varied in any of the selected scenarios. A soil with silt loam texture in hydrologic group B (moderate infiltration rates, moderately well- to well-drained) was assumed in all cases. This was done to make it easier to compare management practices across a more uniform set of conditions. Differences in soil texture and hydrologic group will affect P transport through their effects on factors including soil erosion and surface runoff of water, but we wanted to focus on evaluating the parameters that can be changed through management.

Results of the sensitivity analysis runs are shown in Figures 2 through 6. Some observations are that P loss risk drops off quickly with distance (Figure 2), but near and distant sites can both have low or high risk ratings. Increases in STP significantly increase P loss risk, but not proportionally (Figure 3). Erosion rate is one of the most significant determinants of P loss risk (Figure 3). High P applications can dominate the P loss risk if they are not incorporated (Figure 4).

Field Pilot Testing

Field pilot testing of the Minnesota P Index was performed to evaluate usability, the availability of required inputs, and the logic and usefulness of results. The production farm at the University of Minnesota, West Central Research and Outreach Center (WCROC) in Morris, MN was chosen as the location for the field pilot test.

Site Description. The WCROC farm consists of approximately 1,300 acres of crop and pasture land. Crop production consists primarily of corn and soybeans in rotation, with smaller areas of small grain and alfalfa production. Manure from dairy and swine is land applied in the cropping system. Pastures are managed to maintain a mixed stand of grasses and legumes and are rotationally grazed by both cows and sheep. Soils at the WCROC are formed in calcareous loamy glacial till historically under native tall grass prairie. The Pomme de Terre River flows through a section of the farm and is a tributary of the Minnesota River. Landscape is typical of glacial till, with rolling hills and variable slopes. Many of the soils are prone to erosion.

P Index Calculations. Risk calculations were performed on 35 individual fields, each found in one of 4 divisions of the WCROC farm. The four divisions are referred to as North Farm, Sommers Farm, East Farm, and East Pastures/Farm. Calculations were based on information from the 2001 crop year. For most fields, soil test P results were available within the last 3 years. Soil Olsen P values ranged from 5 to 69 ppm and averaged 20 ppm (Figure 7). Soils with Olsen P values greater than 20 ppm generally reflect a history of manure application. The fields on the North Farm have not had manure applied in the recent past.

Soil erosion calculations were done for each field as an input to the P Index. Soil erosion varied from 0.25 to 4.7 t/ac/yr and averaged 0.80 t/ac/yr (Figure 8). The North and East farms are managed in corn and soybeans, but erosion is low because the fields are flat. The Sommers Farm is also managed in corn and soybeans, but has moderate slopes. Fields from the East Pastures/Farm have the steepest slopes at the WCROC farm. Three fields are cropped to corn and soybeans and have the highest erosion risk for the WCROC farm. Fields from the East Pastures also have steep slopes, but erosion risk is low because of the permanent vegetation.

Runoff risk was determined for the farm using a base runoff of 1.3 in/yr. Soil hydrologic group was B for all soils at the WCROC. Runoff adjustment factors were 1.0 for row crops, 0.67 for small grains, and 0.30 for pastures. As a result, fields with the highest runoff risk generally corresponded with the fields ranked highest for erosion risk.

The P Index risk assessment is shown in Figure 9. The P Index scores ranged from 0.2 to 11 and averaged 0.9. Eighty percent of the fields had P Index values less than 1.0. This illustrates that management practices on most fields at the WCROC posed little risk of P loss, while risk was high for a few fields. Improvements would be best accomplished by changing management practices on four individual fields having P Index scores greater than 4.0. For each of these sites, the risk was high due to surface application of manure without incorporation. Changing manure application methods would reduce the risk at each site to a value below 4.0.

Usability of the Excel Worksheet. A junior scientist at the WCROC performed the pilot testing. An orientation and training session was required in order for this person to utilize the P Index. After orientation, the staff member was able to understand and execute the calculations effectively. On occasion, he required some additional clarification. Feedback was used to improve and clarify the documentation.

The P Index computations for all 35 fields were relatively time consuming, requiring approximately 10 hours of time. A large percentage of the time was spent obtaining necessary input data for the calculations. Another time-consuming element was managing the data in a spreadsheet. Since a large percentage of the fields was found to have little risk, it would be desirable to develop a simpler initial screening tool that would be used to determine if the entire P Index calculation was needed. Several other states have proposed use of some kind of screening tool.

The field pilot testing clearly identified the need to create a user-friendly interface for the P Index. Since this field test, a Windows-based interface has been developed that hides much of the complexity to the user and simplifies the data handling.

Availability of Required Inputs. The inputs for the P Index were obtained from a combination of the P Index User Guide and all the following resources:

- County Soil Survey (soil types, soil hydrologic group)
- USDA-NRCS field office (RUSLE prediction based on R, K, C, LS factors)
- Farm records (STP, P application rates, manure analysis, cropping system)
- Map and personal knowledge (distance from field edge to water body)

All of the inputs required were available for P Index calculations at the WCROC. However, it may be anticipated that many land managers will lack STP, manure analysis, and records of P application history.

Logic and Usefulness. The results of the P Index Pilot Test were reviewed with the WCROC farm management team. The reaction of the team was very positive. The only concern expressed surrounded the high P Index scores for fields on the East Farm. The farm management team agreed that risk scores there would be higher due to manure application without incorporation, but thought that the flat slope at these sites would lower the risk. After obtaining P Index results, WCROC farm management team reviewed their current manure management plans and identified alternative management practices that would reduce the P Index scores on all fields where it was high. The management solutions identified were incorporation of manure and a change in timing of manure application.

Field Pilot Test Summary. The field pilot test illustrated the utility of the Minnesota P Site Risk Index for differentiating risk of off-site P movement based on landscape and land management factors. The necessary inputs for these sites were available from a combination of sources. It is anticipated that in practice, many land owners will lack soil and manure analysis data. The P Index requires some technical skills and training for the user and is somewhat time consuming to use. However, the Windows-based user-interface has reduced these concerns and made the P Index more user friendly.

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Tables and Figures

Table 1. Comparison of factors used in several phosphorus indices (as of 2002).

	INDEX DEVELOPER OR STATE							
	Lemunyon & Gilbert	Gburek et al.	Sharpley	MD	VT	FL	WI	IA
Source factors								
Soil Test Phosphorus	X	X	X	X	X	X	X	X
Fertilizer P application rate	X	X	X	X	X	X	X	X
Fertilizer P application method	X	X	X	X	X	X	X	X
Organic P application rate	X	X	X	X	X	X	X	X
Organic P application method	X	X	X	X	X	X	X	X
Transport factors								
Soil erosion	X	X	X	X	X	X	X	X
Irrigation erosion	X	-	-	-	-	-	-	-
Runoff	X	X	X	X	X	X	X	X
Leaching potential	-	-	X	X	-	X	-	-
Distance to water body	-	X	X	X	-	-	X	X
Buffer strip	-	-	-	-	X	-	X	X
Subsurface drainage	-	-	X	X	-	-	-	X
Hydrological return period	-	X	-	-	X	-	-	-
Sensitivity of receiving water	-	-	-	X	-	X	-	-
Index Mathematical Processing	additive	multiply	multiply	multiply	multiply	multiply	multiply	additive

Figure 1. Counties represented in soil sampling and number of samples from each county (total of 160 soils).

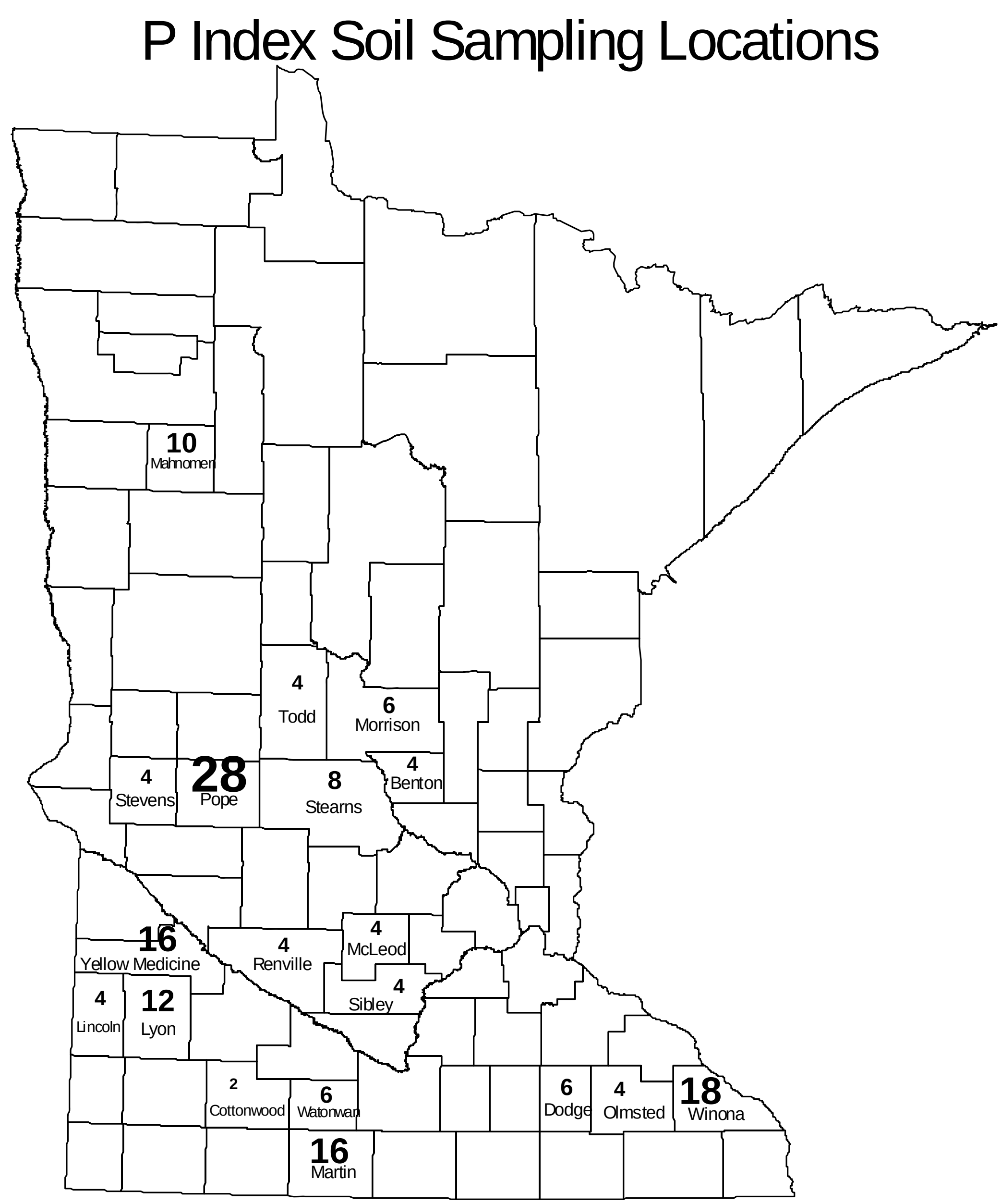


Figure 2. Sensitivity of the MN P Index to distance from water.
(Other attributes: Houston Co., silt loam, 4 t/a/y soil loss, 4% OM, 30 ppm Olsen, corn after soybeans, fall chisel, no contouring, no P applications.)

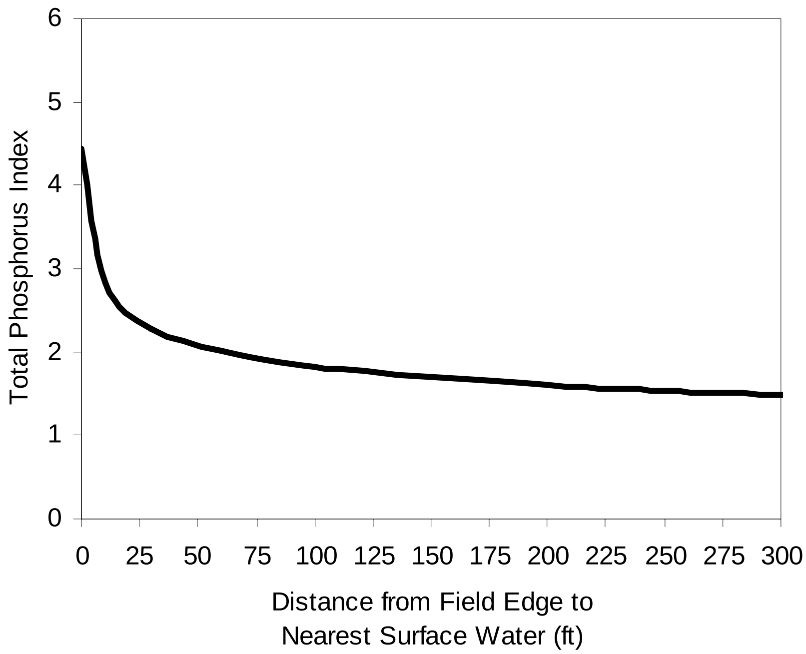


Figure 3. Sensitivity of the MN P Index to soil test P and soil loss.
(Other attributes: Houston Co., silt loam, 4% OM, 100 ft to water, corn after soybeans, fall chisel, no contouring, no P applications.)

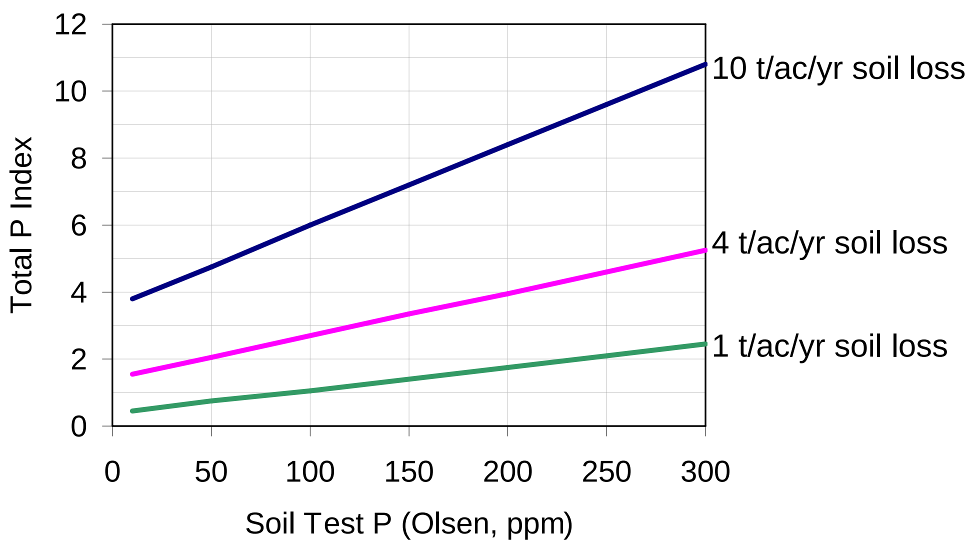


Figure 4. Sensitivity of the MN P Index to manure application rate, method, and timing. (Other attributes: Houston Co., silt loam, 4% OM, 4 t/ac/yr soil loss, 100 ft to water, corn after soybeans, fall chisel, no contouring.)

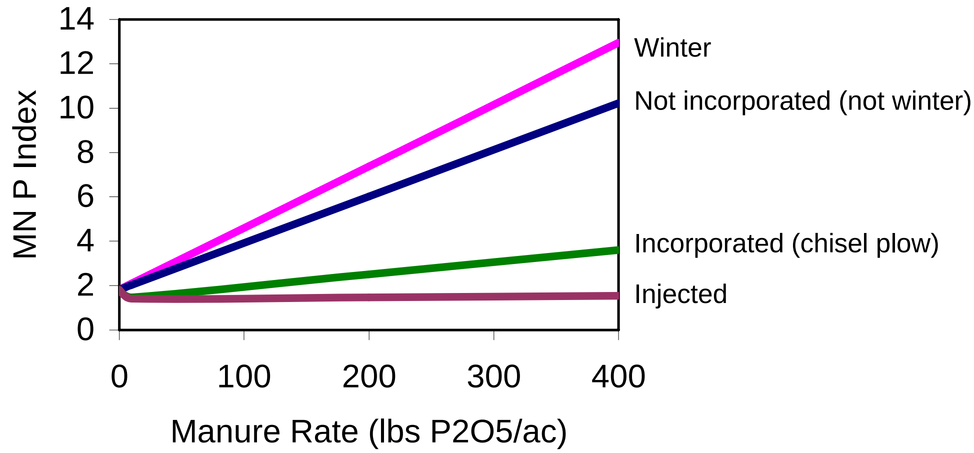


Figure 5. Sensitivity of the snowmelt P loss risk to fall tillage type and orientation. (Other attributes: Houston Co., silt loam, 4% OM, 4 t/ac/yr soil loss, 100 ft to water, corn after soybeans.)

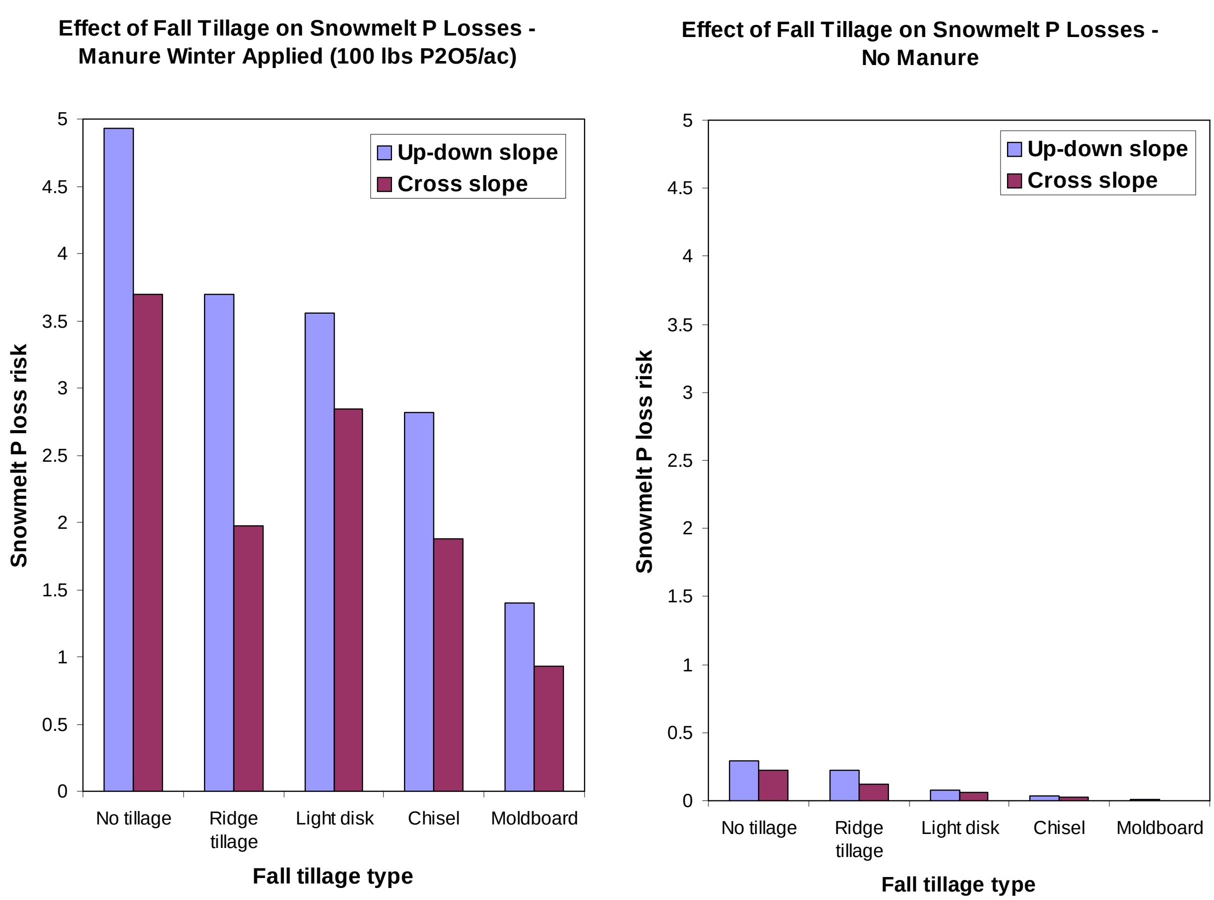


Figure 6. Sensitivity of the snowmelt P loss risk to fall tillage type and orientation. (Other attributes: Houston Co., silt loam, 4% OM, 4 t/ac/yr soil loss, 100 ft to water, corn after soybeans, fall chisel, no contouring.)

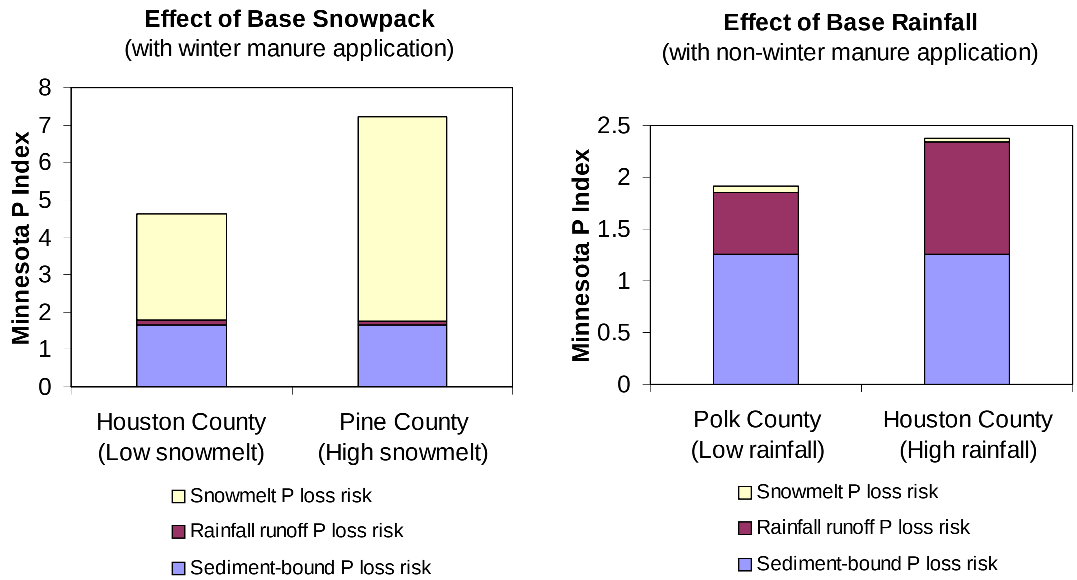


Figure 7. Soil test P (Olsen) for 35 production fields at the University of Minnesota, West Central Research and Outreach Center, Morris, MN.

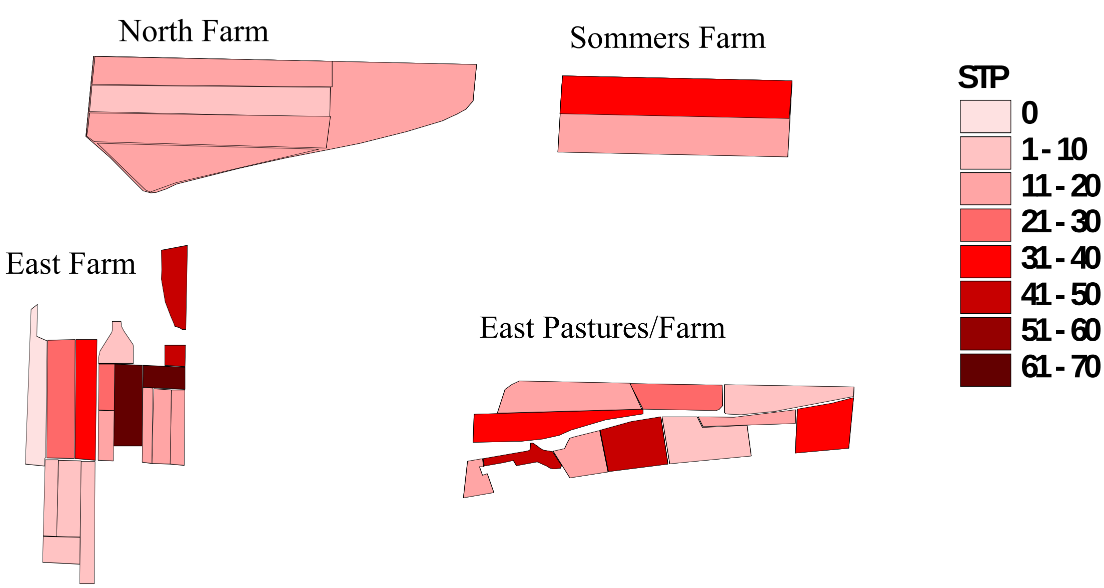


Figure 8. Soil Erosion estimated with the Revised Universal Soil Loss Equation for 35 production fields at the University of Minnesota, West Central Research and Outreach Center, Morris, MN.

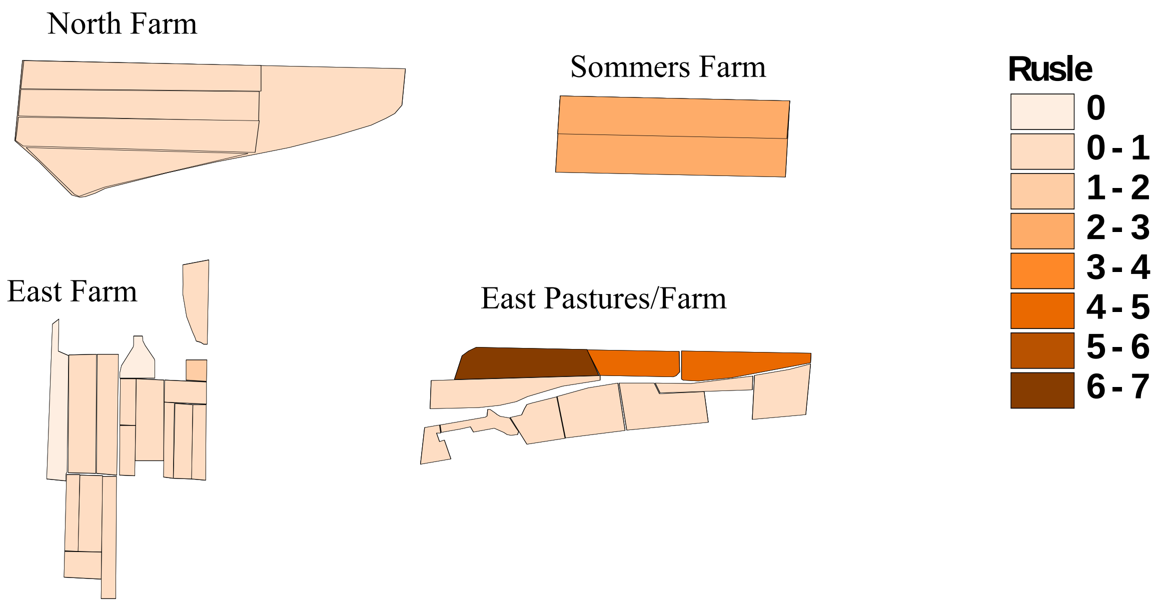
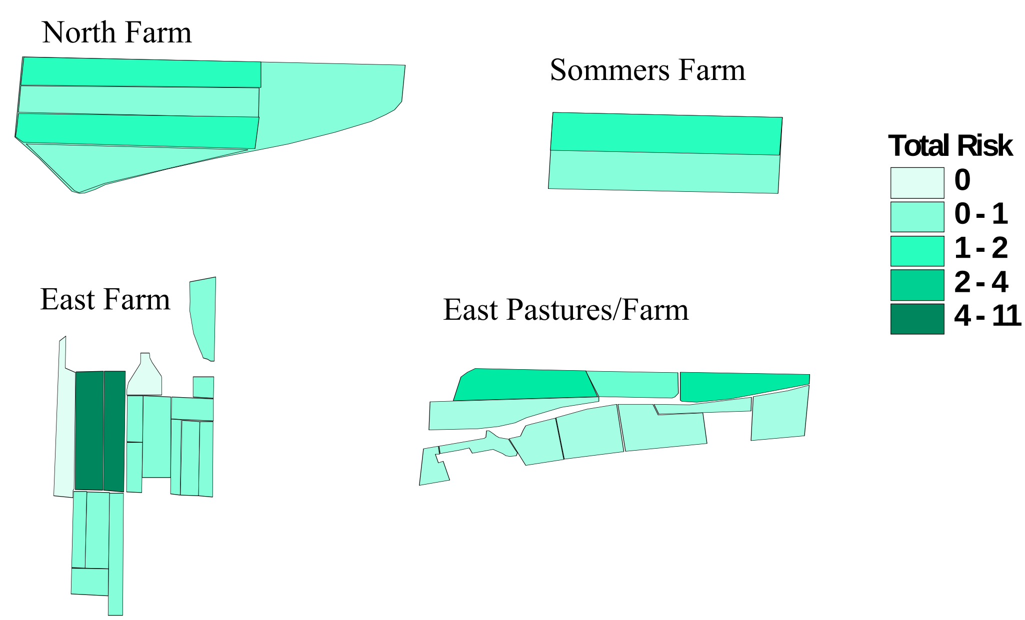


Figure 9. Phosphorus site risk index scores for 35 production fields at the University of Minnesota, West Central Research and Outreach Center, Morris, MN.



Appendix A:
Details of Phosphorus Indices Evaluated in the Literature Review

The purpose of this review was to provide background on the development of the various phosphorus indices used or being developed in the U.S. at the time the Minnesota P Index was being developed. From the review, we considered all of the factors used in the various indices for determining risk of phosphorus loss to surface water. Each factor was considered for relevance under Minnesota conditions. Additional factors unique to Minnesota were also considered, such as phosphorus movement by snowmelt runoff.

The original phosphorus index

The original phosphorus index (Lemonyon and Gilbert, 1993) was based on the concept that phosphorus loss from agricultural land is governed by the combination of "source factors" and "transport factors." The index was an eight-by-five weighted matrix that related the source and transport factors to the potential for phosphorus loss from a site (NRCS, 1994). Each factor is assigned a weighting factor based on its potential impact on the overall export of phosphorus from a field. The factors and their respective weights are:

Source Factors: agronomic soil test phosphorus (1.0), inorganic phosphorus application rate (0.75) and method (0.50), organic phosphorus application rate (1.0) and method (1.0).

Transport Factors: soil erosion (1.5), irrigation erosion (1.5), and runoff class (0.5).

The values of the weighting factors were at the time based on the professional judgment of the group that developed the index. Each site characteristic had a range of numerical value ratings of Low (1), Medium (2), High (4), or Very High (8) (a base 2 system) (Sims et al., 2000). To calculate the phosphorus loss rating for each characteristic, the value of that characteristic was multiplied by its respective weighting factor. For example, the weighted soil erosion value for a site with medium erosion was 2 * 1.5 = 3. The overall risk was then calculated by summing the weighted values. When the source and transport matrices are combined by adding their respective values, it is referred to as an *additive* index. The quantitative phosphorus loss score was then converted into a qualitative rating of site vulnerability to phosphorus loss as follows: Site phosphorus vulnerability rating: Low (<8), Medium (8-14), High (15-32), Very High > 32.

In the original phosphorus index, water erosion was calculated from the Revised Universal Soil Loss Equation (RUSLE) and wind erosion was calculated from the Wind Erosion Equation (WEQ). Runoff class was calculated from soil saturated hydraulic conductivity and the percentage slope of the site.

The authors of the original phosphorus index acknowledged the need for individual states to modify the index and its algorithm for specific uses or locations. The additive nature of the original index makes the value of such a rating questionable. It is possible to have a field with a high source value and low transport potential rated as a medium to high risk for phosphorus loss. Also, the original phosphorus index does not consider proximity of the field to receiving waters. For this reason, it evaluates risk of phosphorus delivery to the field edge and not necessarily the risk of actual delivery to a water body.

A multiplicative phosphorus index

Gburek et al. (2000) evaluated hydrologic and chemical factors controlling phosphorus export from a 39.5 acre mixed watershed in Pennsylvania (using GIS modeling) and modified the original phosphorus index. The index assembled by Gburek et al. makes several adjustments to the original phosphorus index. The two most significant modifications made are:

1. The phosphorus source and transport matrices are combined in a *multiplicative* manner rather than using the additive approach.

2. Risk of phosphorus delivery from field edge to a water body is included by means of the hydrologic return period.

The inclusion of these two factors improved the utility of the index and provided a better fit with the water quality monitoring data from the watershed. The multiplicative approach provides a better way to identify sites at risk for off site movement of phosphorus due to the combination of source and transport properties. Further, when considering the impact of phosphorus on water quality, including a means to evaluate the connectivity of the field to surface water is important.

Multiplicative phosphorus index for northeastern US

Sharpley (2000) introduced a modified multiplicative phosphorus index for the Northeastern U.S. This index maintained the separation of source and transport factors with a multiplicative approach. Two additional tables were added to simplify the interpretation of the index score. The rating interpretation table relates the index score to the risk level (low, medium, high, very high) and the management options table assigns specific management choices depending upon the risk level. For example, if the risk is low, then nutrients can be managed on a nitrogen basis, while if the risk is high, phosphorus application is recommended at or below crop removal rates. Other important features of this index are the inclusion of factors for leaching potential, subsurface drainage, and distance from the edge of the field to surface waters.

Maryland phosphorus index

Scientists at the University of Maryland modified the above multiplicative phosphorus index for the state of Maryland (Maryland Cooperative Extension, 2000). The Maryland phosphorus index was one of the most developed phosphorus indices in the U.S. and its use is required for sites meeting certain criteria. The basic structure of that index is similar to the one presented by Sharpley. However, the addition of a vulnerability ranking for the water body that receives the drainage water from the site makes it a more comprehensive index. The transport factor matrix has provisions for ranking the site with respect to distance from surface water and presence of vegetative buffers. The index has eight supplemental tables for calculating phosphorus loss ratings for various factors.

Vermont phosphorus index

The Vermont phosphorus index is a modification of the original phosphorus index (Lemunyon and Gilbert, 1993). Several unique features important in Vermont have been incorporated (Jokela,1999). In the Vermont index, rather than using a categorical approach to calculating the index, a formula is used for both source and transport factors. The results of the two formulas are then combined in a multiplicative approach and the numerical outcome is translated into a qualitative phosphorus loss rating.

Another unique feature of the Vermont index is the inclusion of a soil analysis result other than soil test phosphorus. Specifically, Vermont researchers included a factor related to the amount of extractable aluminum in their phosphorus index. This is because the amount of extractable aluminum in the soil plays a significant role in phosphorus availability. In general, soils with higher aluminum have a higher capacity for phosphorus than those with lower aluminum (Jokela, 1999).

Florida phosphorus index

The Florida phosphorus index is another good example of adapting and modifying the original phosphorus index to address the needs of a specific region (NRCS-Florida, 2000). A number of additional site and transport factors are included in the Florida phosphorus index. Similar to other indices, the Florida index divides the index into a source and a transport matrix and combines them with a multiplicative process. The quantitative score is then converted to a qualitative ranking from low to very high. Unique features of the Florida index are the inclusion of wastewater application as a separate factor and also the inclusion of a sensitivity factor for surface water bodies.

Wisconsin phosphorus index

At the time when the Minnesota P Index was being developed the Wisconsin index was composed of two matrices, one for *transport factors* and one for *site management factors* or phosphorus *source* (Bundy and Kaap, 1999). Weighting factors were used within each of the two matrices and the matrices were combined in a multiplicative manner. The Wisconsin index used somewhat different weights for individual transport factors than those for other indices. The soil erosion factor was more heavily weighted. Also, a separate factor was included for the slope of the site and for distance to water. In the source factor matrix, more attention was focused on the nutrient management options than was apparent in other indices. This was based on the assumption that phosphorus loss potential was lower when manure was incorporated within one week after application compared to when it was left on the field over the winter. The value of the Wisconsin method-timing factor varies from 0.4 to 1.0, where 0.4 was used when phosphorus was incorporated 2" deep or more and 1.0 was used when phosphorus was incorporated greater than one week after application or was not incorporated for winter-applied manure. Also in the source matrix, the measured soil phosphorus level at the site was divided by 30 to obtain a comparison of the soil test value with an agronomically optimum value of 30 mg/kg for Bray phosphorus (Bundy and Kaap, 1999). This index has subsequently been replaced by a pathway-approach index (http://wpindex.soils.wisc.edu/).

Iowa phosphorus index

The Iowa phosphorus index is fundamentally different in philosophy than the original phosphorus index (Mallarino, 2000). This index does away with the categorical approach found in the other indices with the intent of developing a phosphorus index that generates a rough quantitative estimate of the phosphorus loss from a site. The developers argue that "lack of consideration of estimates of phosphorus loads that leave the field complicates the comparison (or normalization) of the different indices developed in various states" (Iowa NRCS, 2001).

The Iowa index is field based. While it acknowledges the importance of the interaction of the source and transport factors, it attempts to deal with these interactions internally within three components of the index: the *erosion* component, the *runoff* component, and the *subsurface* *drainage* component. Each of these components estimates the phosphorus lost from the field by that transport mechanism. When the three components are added together, the index is an estimate of the phosphorus lost from the field in lbs P/acre. The Iowa phosphorus index is unique in other ways as well. It puts more emphasis on bioavailable phosphorus than the other indices by including an availability factor for sediment P. It attempts to account for distance to receiving waters by using a sediment delivery ratio based on the distance from the edge of the field to the water. These additional considerations of the Iowa index lead to a complex, heavily developed phosphorus index that operates on several assumptions. The technical documentation for the index includes all the details necessary to calculate the index value in eight tables and four figures.

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Appendix B:
Soil Characterization Methods and Critical Data

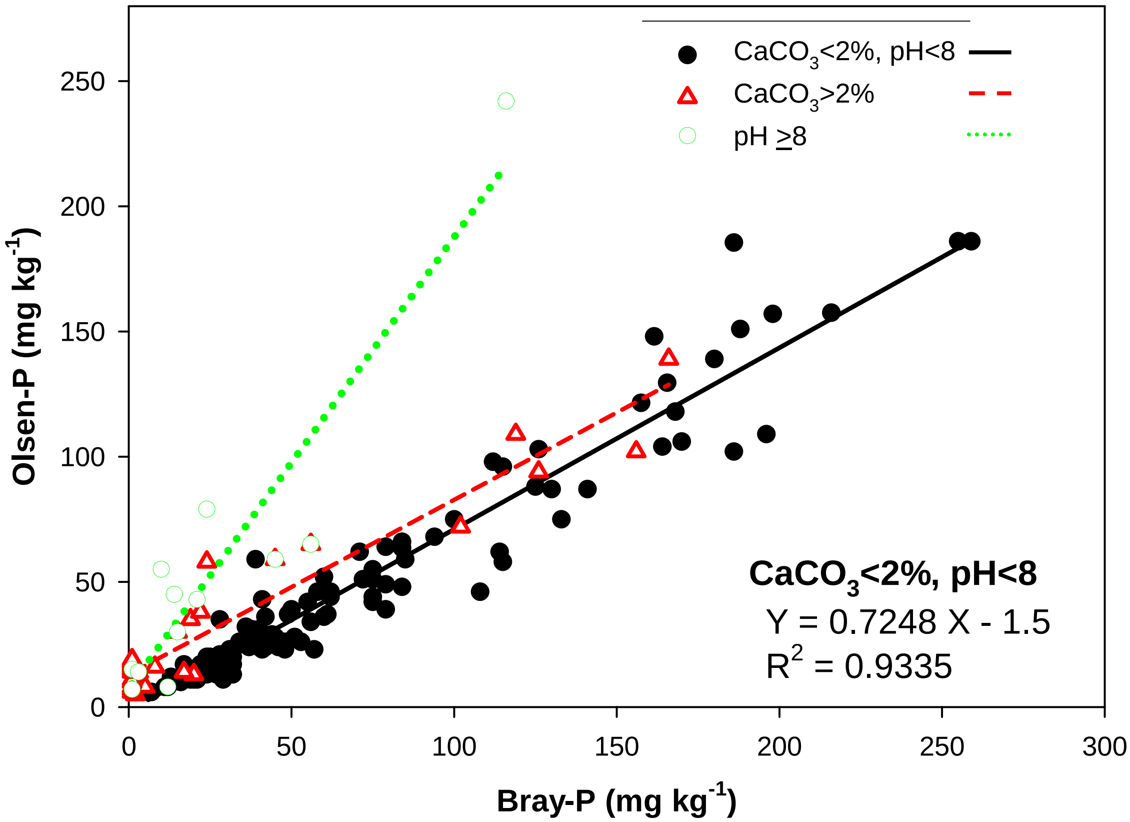
Since the total P concentration (P_{total}) in surface soils is a major factor determining P loss, mainly through runoff, this parameter is an essential input to the PI model. However, P_{total} is usually not available to farmers and land owners, hence soil-test P (STP), which is commonly used for fertility assessment for crop production, was tested for its accuracy in predicting P_{total}. The Olsen-, Bray-, and Mehlich-P methods of assessing STP are commonly used in various fields or regions of Minnesota. To allow use of different STP indices, the correlations between these three methods were tested. Other soil properties were tested by stepwise regression to improve the prediction of P_{total}.

Soils were sampled from the plow layer of 160 agricultural sites across Minnesota. Soils represented major agricultural regions, cropping systems, and soil management practices prevailing in the state (Figure 1). A subset of 38 soils was used in a simulated rainfall study to assess the effect of various soil properties on P loss.

The soils were tested by standard methods (Klute et al., 1986; Sparks et al., 1996) for the following general characteristics: texture, pH (in H_2O), and content of organic matter (OM) and $CaCO_3$. Phosphorus was tested by an array of procedures (Pierzynski, 2000) to determine: total P content, Olsen-P, Bray-P, Mehlich 3-P, water soluble P, and P sorption index (PSI).

The protocol for the simulated rainfall runoff study was modified from the USDA-NRCS national phosphorus project protocol. Soils were dried, sieved, and then packed into 60 x 15 x 10-cm PVC boxes. Prior to applying rainfall, soil was saturated from the bottom using a Marriott bottle apparatus. The boxes were adjusted to a uniform slope of 4%, typical of much of the landscape in Minnesota. Rainfall was applied for 30 minutes at a rate of 6 cm hr^{-1}– the average 30-minute rain intensity with a 5-year return frequency in Minnesota. Deionized water was used as the source water for the rainfall simulator. Runoff from each soil sample for an entire rain event was composited in an acid-washed 3-L plastic container. A 50-mL aliquot was immediately filtered through a 0.45 µm syringe filter unit and stored at 4^{o} C for analysis of soluble P. The unfiltered runoff was stored at 4^{o} C and later analyzed for biologically available phosphorus (Fe-strip method), total P, and total suspended sediment.

Olsen vs. Bray P for Minnesota Soils

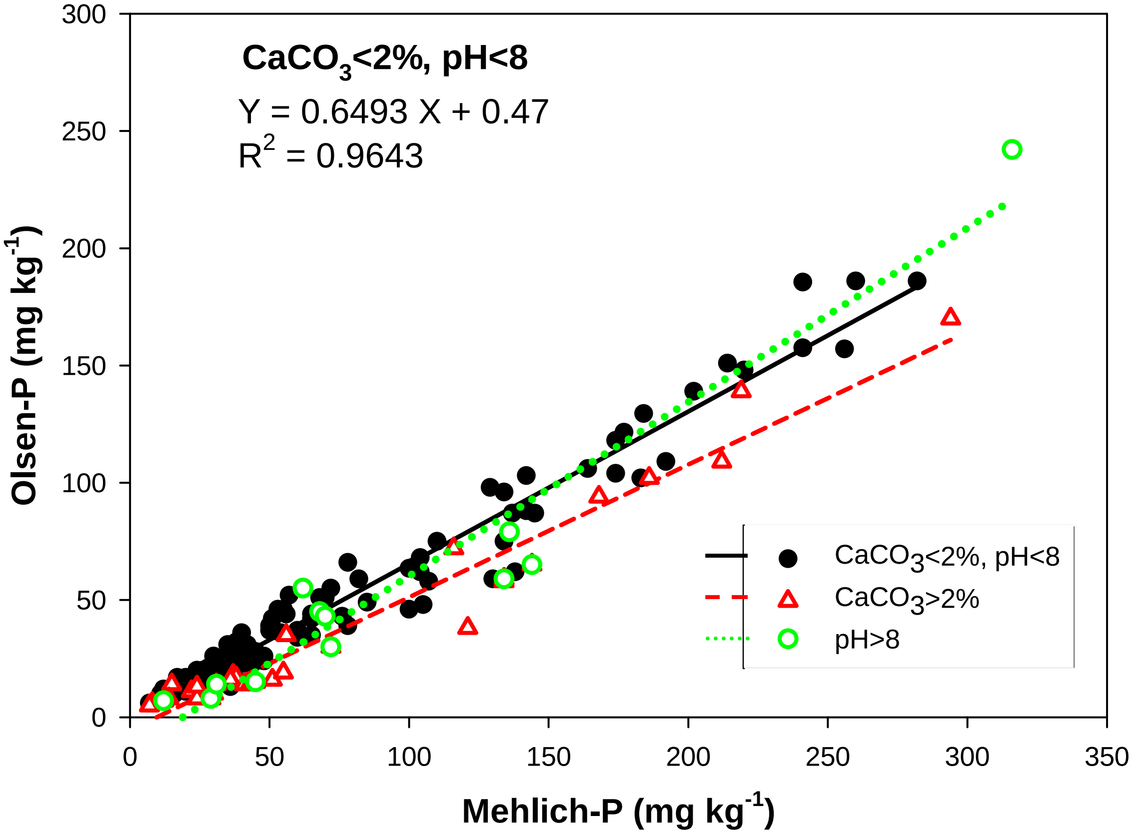


High carbonate and very high pH values, even in non-carbonate soils, usually give low Bray P results due to Bray failure. At $CaCO_3$<2% and pH<8, which apply to the majority of Minnesota soils, the significant correlation allows prediction of Olsen-P (mg kg^{-1}) from available data of Bray-P (mg kg^{-1}) according to the linear regression (intercept forced through 0,0; N=119):

Olsen-P = 0.7117·Bray-P

Calculated intercept is -1.4 mg kg^{-1}, but forcing the regression through the origin was selected to ease calculations.

Olsen vs. Mehlich P for Minnesota Soils

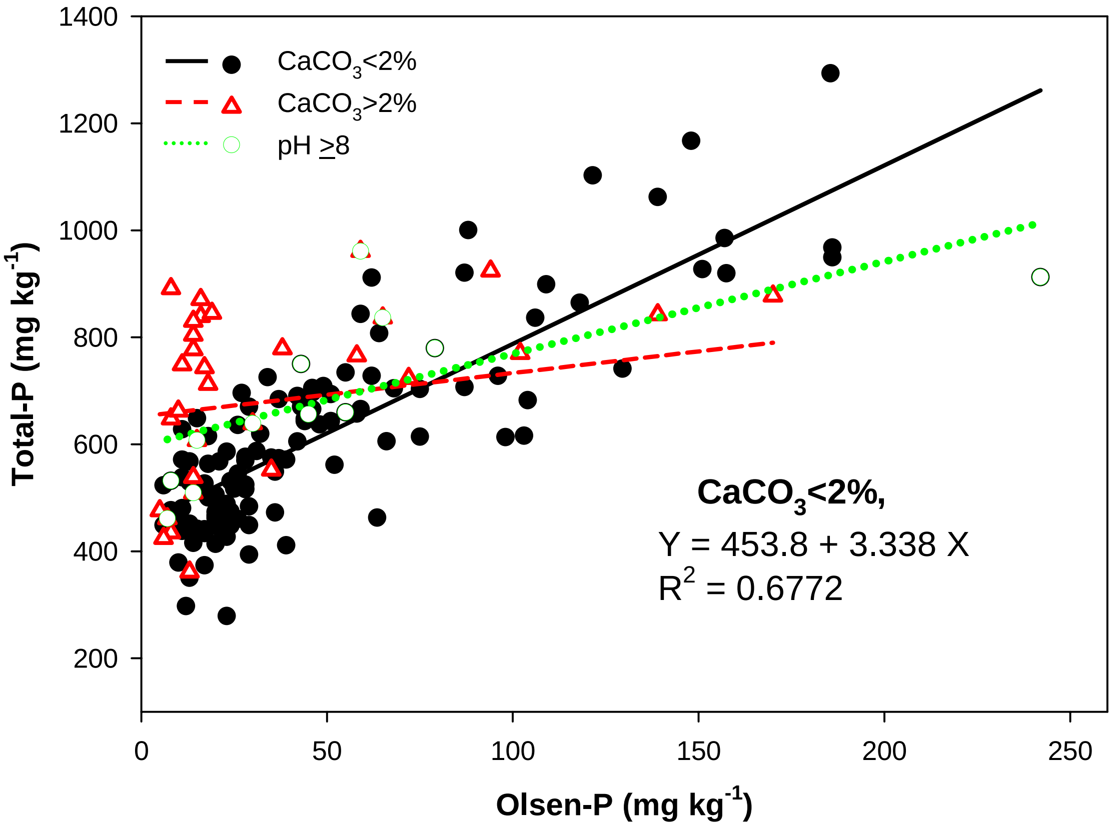


Mehlich tolerates more pH buffering than Bray but for consistency the same population of soils was used for this regression as for Bray vs. Olsen. The significant correlation (119 soils, $CaCO_3$<2% and pH<8) allows prediction of Olsen-P (mg kg^{-1}) from available data of Mehlich-P (mg kg^{-1}, intercept forced through 0,0):

Olsen-P = 0.653·Mehlich-P

Calculated intercept is 0.47 mg kg^{-1}, but forcing the regression through the origin was selected to ease calculations.

Total P vs. Olsen P for Soils of Minnesota



Some soils with high $CaCO_3$ have a lot of occluded P and can have rather high total P with low Olsen P. The bioavailablity of this occluded P should be very low and thus it is appropriate to remove these points from the regression. The significant correlation found in 121 soils with $CaCO_3$<2% allows prediction of Total-P (mg kg^{-1}) from available or predicted (by Bray- or Mehlich-P) data of Olsen-P (mg kg^{-1}):

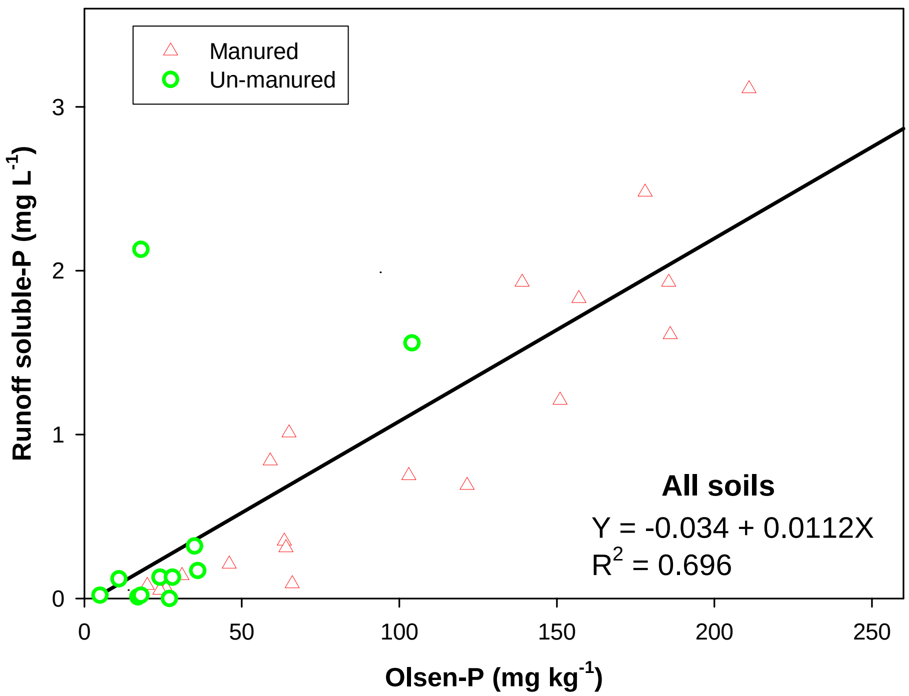
Total-P = 453.8 + 3.338· Olsen-P

A combined model that includes OM content (%) was suggested by stepwise regression:

Total-P = 321.9 + 2.785·Olsen-P + 29.11·OM

By including OM in the regression, R^2 increased from 0.677 to 0.757. Other general soil properties did not enter the regression (at $p<0.05$).

Runoff Soluble P vs. Olsen P Concentration



This regression was made for soils used in the laboratory rainfall simulation. The regression allows prediction of the concentration of soluble P in runoff that originates from soil P, not from recently applied P, as indicated by the relation of the manured and un-manured soils to the regression line of all soils.

Based on these results (31 soils) P concentration in runoff water is predicted from available or predicted (by Bray- or Mehlich-P) data of Olsen-P by the equation:

$$\textbf{Runoff soluble-P (mg L}^{-1}\textbf{)} = 0.011 \cdot \textbf{Olsen-P (mg kg}^{-1}\textbf{)}$$

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