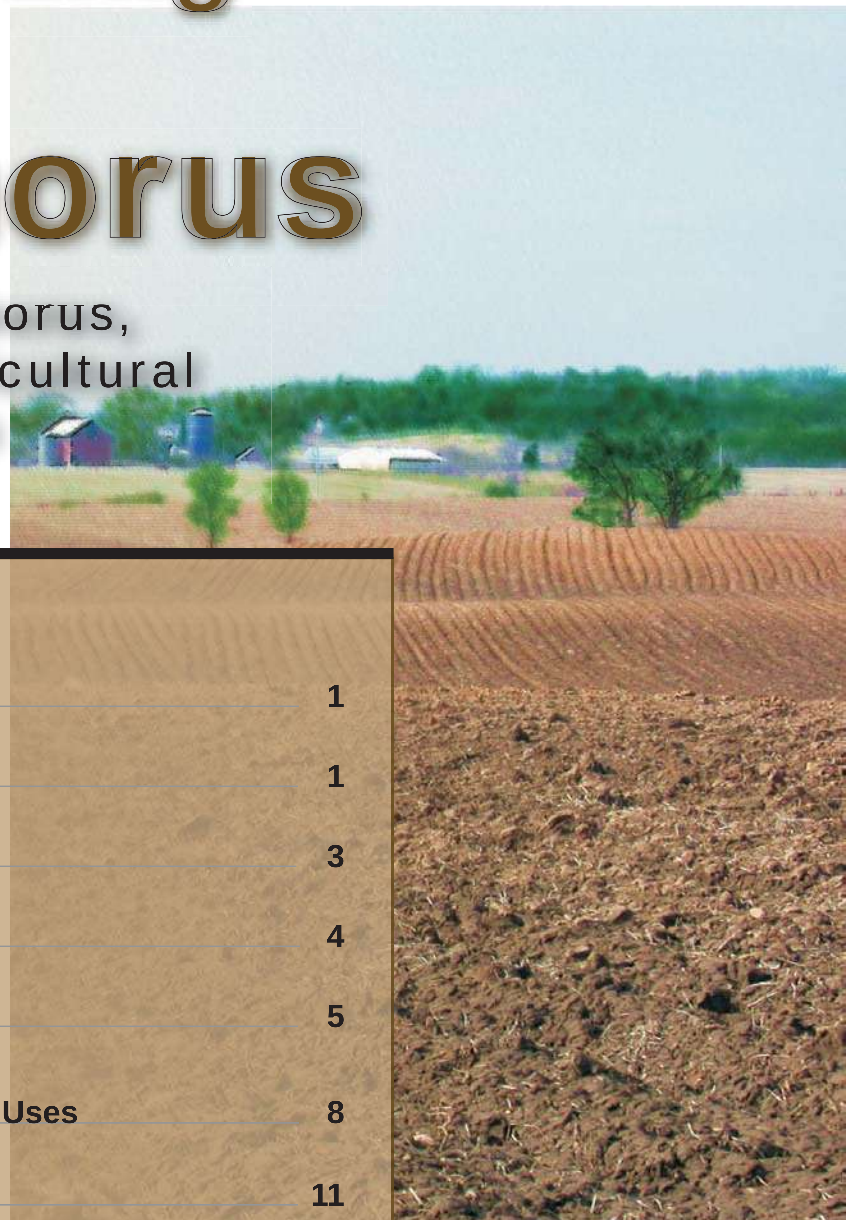
Understanding Soil Phosphorus

An Overview of Phosphorus, Water Quality, and Agricultural Management Practices



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Introduction

Phosphorus (P) is a naturally occurring, essential plant and animal nutrient. In plants, P is required for photosynthesis, respiration, seed production, root growth and other critical functions. In animals, P is critical for proper bone and muscle growth, metabolism, reproduction, and overall animal performance. Supplemental additions of P beyond naturally occurring levels are necessary for productive agricultural cropping and livestock enterprises. These supplementary P inputs come in the form of fertilizers for crops and feed additives for animals.

Phosphorus can also be a pollutant. Movement of P from fertile landscapes to lakes and streams is an environmental concern affecting the quality of surface water resources. Similar to its impact on land, P additions to waters can increase the biological productivity of lakes and streams - often to the point of degrading water quality.

Discussion of the impact of P on water quality is complicated due to many factors. For example, the visible impact of P on water quality can occur miles away from the point where P leaves the land and enters a body of water. Controlling P additions to water bodies is further complicated by the fact that lakes, streams, and sources of P input often cross political boundaries (states, counties, etc.). In addition, the complex chemistry of P and the various reactions it may undergo affects the forms, availability, and transport of P. Inconsistent nomenclature in the P research literature can also be confusing. The intent of this publication is to provide a better understanding of the effect of phosphorus on the environment.

Phosphorus and Water Quality

Eutrophication

Eutrophication is the natural aging of lakes or streams. The eutrophication process is accelerated by nutrient additions to water bodies. Elevated nutrient levels in water can lead to abnormally high production and growth of algae and aquatic vegetation resulting in reduced aesthetic and recreational value of lakes. Reduced water clarity, unpleasant swimming conditions, objectionable odors, and interference with boating and fishing can all be consequences of nutrient contributions to lakes and streams. The economic implications of highly eutrophic lakes on tourism, recreation, etc. can be significant (Newton and Jarrell, 1999). The eventual decomposition of the increased amount of organic matter can deplete the dissolved oxygen content of lakes resulting in the death of fish and other aquatic organisms. Additionally, certain blue-green algae in waters have been found to form potent toxins that can cause taste and odor problems, interfere with treatment of drinking water, and may pose a health hazard to humans and livestock (Lawton and Codd, 1991; Martin and Cooke, 1994; Sharpley and Beegle, 1999). The Environmental Protection Agency (US EPA, 1996) has identified eutrophication as the main cause of impaired surface water quality in the United States.

Phosphorus has been identified as the most limiting nutrient in freshwater environments (Correll, 1998). Biological productivity in surface waters increases in relation to P additions. From a water quality protection standpoint, it is very important to prevent P from reaching surface waters. Runoff water and eroded sediment from fertile landscapes are major contributors of P to lakes and streams. Agricultural land use has been identified by the EPA as the major source of nutrients causing accelerated eutrophication in the nation's lakes and rivers (Parry, 1998; USEPA, 1996).

Critical values for P in waters

No clear guidelines exist regarding the concentration of P in surface waters that will induce or accelerate eutrophication. However, numerous recommendations and reference criteria have been suggested relative to critical P concentrations. An example of

the range in values for various forms of P and types of water bodies is summarized in **Table 1**. These values are expressed in terms of total P (TP) or dissolved / soluble P (DP). *See the P Terminology section (page 11) for a discussion on the forms of P and their importance to water quality.*

The EPA's approach to dealing with the variability in critical P concentration values is described in the agency's *Nutrient Criteria Technical Guidance Manual for Lakes and Reservoirs* (USEPA, 2000). The custom of developing a single pollutant concentration number for nationwide application is **not** appropriate for nutrients. The EPA recognizes the variety of regional factors that need to be reflected in the setting of critical concentration levels. Individual states and tribes are developing water quality criteria, including P concentration levels, to support designated uses of waters. This "ecoregion" approach attempts to recognize the diversity in the nation's soils, geology, precipitation patterns, water body characteristics, and other site-specific factors.

Table 1. Reported critical phosphorus concentrations for surface waters.

Form of P	Water Body	P Concentration (ppm)	Source of Information
TP	Lakes	0.01	USEPA, 2000
TP	Lakes	0.03	Newton & Jarrell, 1999
TP	Streams	0.05	Newton & Jarrell, 1999
TP	Lakes & streams	0.02	Correll , 1998
TP	Streams entering lakes	0.05	USEPA, 1986
TP	Streams not entering lakes	0.10	USEPA, 1986
TP	Lakes	0.025	USEPA, 1986
TP	Lakes & streams	0.02	Sawyer, 1947; Vollenweider, 1968
DP	Lakes & streams	0.01	Sawyer, 1947; Vollenweider, 1968

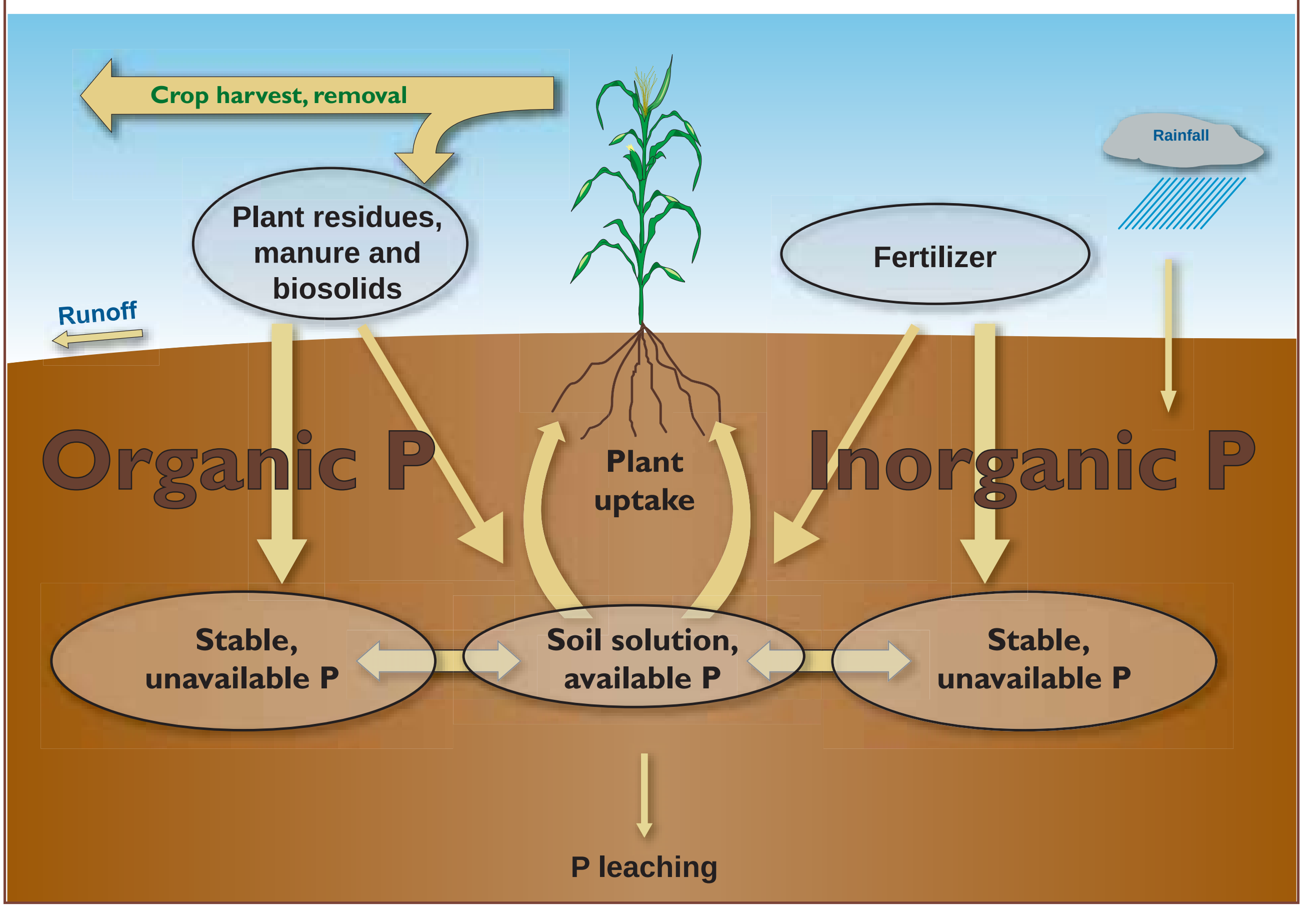
The Phosphorus Cycle

Phosphorus, like most soil nutrients, moves through a series of cycles from soil to plant to animal (**Fig. 1**). The P cycle consists of a complex relationship of chemical and biological reactions that control the availability of P. Phosphorus in soil originates from the weathering of minerals and from additions of P in the form of fertilizers, animal manure, plant residues, and other biosolids, such as sludge. Phosphorus can be removed or lost from soil by crop uptake and subsequent harvest, soil erosion, and runoff (the overland flow of water). In some instances – such as areas of very sandy soils, high organic matter soils, or P-saturated soils - P can move with water through the soil (a process called leaching) and is transported via groundwater flow to surface water bodies (Sims et al., 1998). However, P leaching is relatively rare because P is tightly held (or "fixed") by soil particles (Heckrath et al., 1995; Sims et al., 1998; Hesketh and Brookes, 2000). Practically all soluble P from fertilizer or manure is converted to soil-bound, water-insoluble P within a few hours of application (Schulte and Kelling, 1992).

The majority of soil P is located in the topsoil as a complex mixture of mineral (inorganic) and organic materials. Both organic and inorganic forms of P are important sources for plant growth, but their availabilities are controlled by soil characteristics and environmental conditions (Schulte and Kelling, 1992). Plant roots adsorb dissolved or soluble P from the soil solution in the form of orthophosphate ($H_2PO_4^-$ or $HPO_4^=$). The $H_2PO_4^-$ form is dominant in acidic soils with pH levels below 7.2 and the $HPO_4^=$ form is prevalent in alkaline soils with pH levels greater that 7.2 (Lindsay, 1979). The concentration of P in the soil solution of fertile soils is typically very low – ranging between less than 0.01 and 1 ppm (Wood, 1998; Mullins, 2000). A value of 0.2 ppm is commonly accepted as the concentration of soluble P needed to meet the nutritional needs of most agronomic crops (Wood, 1998). Soils generally contain 500-1,000 ppm of total P (inorganic and organic), but most of this is bound to soil particles ("fixed") and is unavailable for plant use (Schulte and Kelling, 1992).

The solubility of P is controlled by the concentrations of calcium (Ca), iron (Fe), aluminum (Al), and manganese (Mn) in the soil solution and by the

Figure 1. The phosphorus cycle.



nature and amount of soil minerals. Phosphorus is strongly bound onto the surfaces of these elements. It is also strongly bound to the surfaces of Fe, Al, and Mn oxides and clay minerals (PPI, 1979; Stanford et al., 1970). Organic forms of P can be converted to plant-available inorganic forms of P during the decomposition of organic matter – a process called mineralization. Mineralization of organic P is more rapid in warm, well-aerated soils. Because of this and the fact that root growth and plant development are slowed at low temperatures, crops grown in cold, wet soils often respond to starter fertilizer applications containing P (Schulte and Kelling, 1992). Phosphorus has been added to most agricultural soils to ensure that soil concentrations are adequate for optimum growth and yield of crops. Conversion of stable forms of soil-P to plant-available forms of P often occurs too slowly to meet crop needs.

The amount of P necessary to cause water quality problems is very small compared to the amount of P required for crops or the amounts contained in manure and fertilizer-P applications. Surface water concentrations of total P in the range of 0.01 to 0.02 ppm are an order of magnitude lower than P concentrations in soil solution that are needed for plant growth – typically 0.2 to 0.3 ppm (Tisdale et al., 1985; Sharpley et al., 1999). Comparing these concentrations illustrates the importance of limiting any amount of P losses from the landscape to surface waters (Daniel et al., 1998; Sharpley et al., 1999) and complicates strategies relative to management practice recommendations for agriculture.

Phosphorus Transport

Phosphorus enters lakes and streams mainly in runoff and erosion from landscapes draining to them (**Fig. 2**). Runoff is the gravity-induced movement of water across the surface of soils. As rainfall or snow melt travels along the landscape, the water interacts with the topsoil and any materials on the soil surface. During this process P can be added to the runoff water from soil, plant material, manure and other soil amendments. The runoff water contains P in both the soluble (or dissolved) form as well as the particulate (or sediment-bound) form. Particulate P (PP) is bound to the eroded soil and organic particles carried in the runoff. In general, PP is the major portion of the P removed from agricultural land. Sharpley et al. (1992) estimates PP makes up 60 to 90% of the total P load transported in runoff from cropland. However, the impact of the soluble P (SP) portion of runoff can

Figure 2. Phosphorus movement from landscapes.

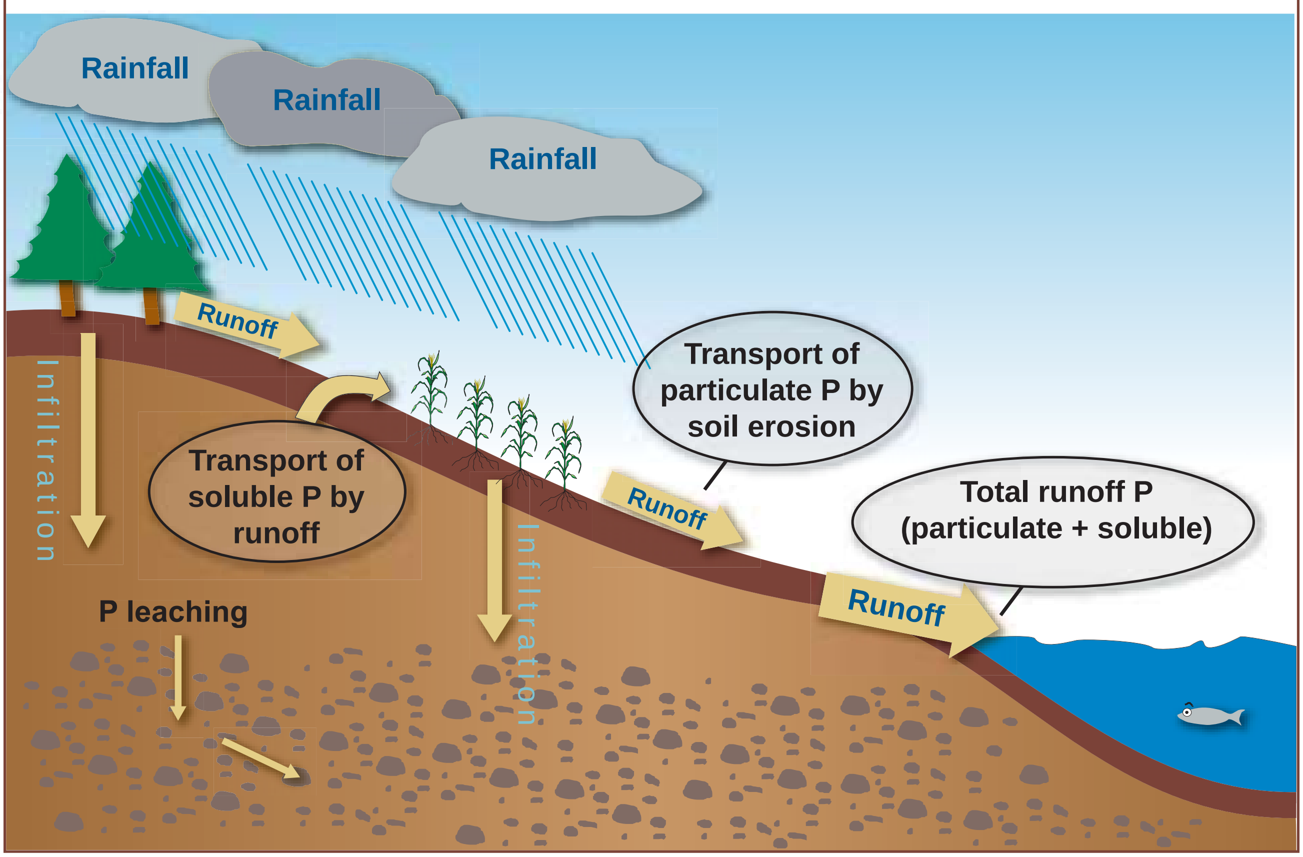
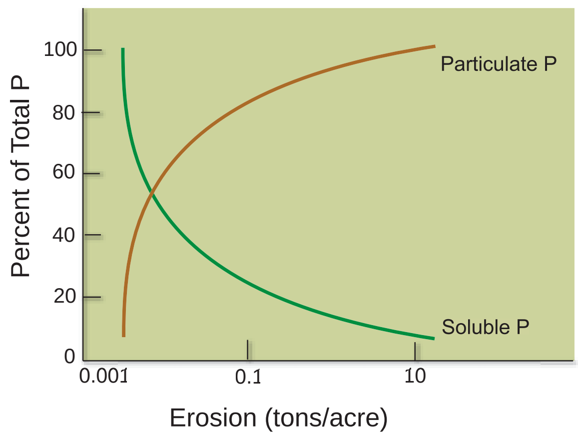
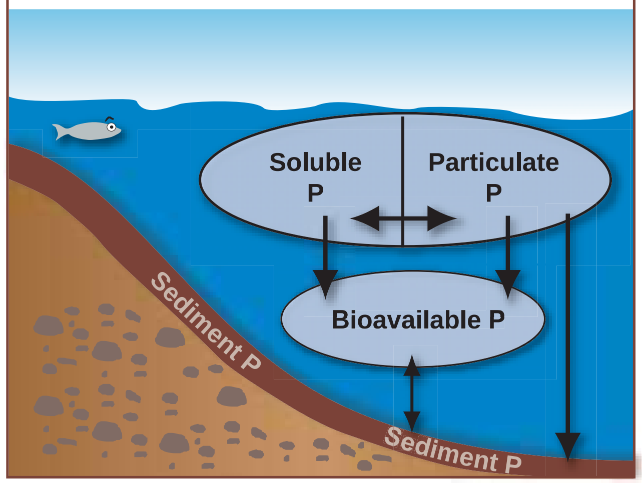


Figure 3. Effect of erosion on the percentage of total P as soluble P and particulate P in runoff.



Source: Pote et al., 1996.

Figure 4. Phosphorus dynamics within a body of water.



be immediate on algae and aquatic weeds in lakes and streams (Sharpley et al., 1996). The relationship between the SP and PP proportion of the total P in runoff varies as a function of erosion rates (**Fig. 3**). As erosion rates increase, the PP fraction of total P content increases while the SP fraction decreases significantly (Pote et al., 1996).

Once eroded sediment has reached a lake, it eventually settles to the bottom where it may serve as a reservoir of P (Correll, 1998). The release of P from bottom sediments is a complex process dependant upon numerous factors (**Fig. 4**). Biological activity can gradually mineralize organic P and release SP. This SP may diffuse into the lake water or it may become bound to the surfaces of lake bottom particles before it can reach the overlying water.

In addition to runoff and erosion delivery mechanisms, other sources of P can be groundwater leaching and precipitation. These sources of P are often negligible when compared to runoff inputs in most parts of the country including Wisconsin (Heckrath et al., 1995; Sims et al., 1998; Hesketh and Brookes, 2000). Groundwater flow has been documented as a P transport mechanism to surface waters only under conditions of high water tables, soils that are extremely high in P (P has saturated the soil's adsorption capacity), and/or sandy (highly permeable) soils (Wood, 1998; Correll, 1998; Eghball et al., 1996; Sims et al., 1998). Groundwater contributions of P are all in the soluble or dissolved form.

Runoff and eroded sediment that reaches a lake or stream often originates from limited areas within a watershed. These "source areas" vary in location and magnitude of P contribution due to climatic conditions such as the intensity and duration of rainfall, as well land characteristics such as soil moisture conditions, soil erodability, soil water storage capacity, topography, etc. (Gburek and Sharpley, 1998). The multitude of factors influencing P movement from the landscape complicates the ability to predict P losses and adds to the challenge of developing effective surface water quality protection practices and programs.

Sources of Phosphorus

Natural

Phosphorus is a naturally occurring element found in soil, water and all living organisms. It is one of 16 essential elements for plant growth. Standing vegetation, both native vegetation and agricultural crops, can be a source of P in runoff. Researchers have noted alfalfa, grasses, and crop residues to be contributors of P contained in spring runoff (Wendt and Corey, 1980). In cold climates, P is released from vegetative tissue as freezing and thawing ruptures plant cells. This source of P is generally dominated by the dissolved (or soluble) form of P (Daniel et al., 1998). Forest leaf litter is also a contributor of P in runoff (Singer and Rust, 1975). The period of greatest forest-P loss is spring snowmelt. Similar to vegetative losses, the mechanism of P loss from leaf litter is the freezing and thawing processes during the fall and early winter. Studies have found P losses from forested watersheds to be significantly lower than losses from agricultural watersheds (Vaithiyanathan and Correll, 1992).

Precipitation additions of P have been measured and found to be a contributor in some watersheds. Research by Correll et al. (1992) found that about 7% of the total P input was from precipitation in an Atlantic Coastal Plain watershed. Menzel et al. (1978) found annual inputs of P to be 0.13 lb per acre per year in Oklahoma precipitation.

Fertilizers

Crop fertilization is the greatest use of P in agriculture (Mullins, 2000). Many native soils were naturally low in P and most cropping systems required supplemental P additions to maximize yield potential. The long-term use of manufactured, commercial fertilizers has increased the P levels of many cropland fields to levels adequate for crop growth and beyond. Rock phosphate is the original source of nearly all P fertilizer soil in the U.S. (Schulte and Kelling, 1992). Rock phosphate alone is not an effective P source for most soils. It is treated with acid in the fertilizer manufacturing process and converted to more soluble forms that can be taken up by plants. A listing of common phosphate fertilizers can be found in **Table 2**. Phosphate fertilizers are usually manufactured or blended with nitrogen, potassium, or both to form mixed fertilizer blends (Schulte and Kelling, 1992).

Manure

Land application of manure to cropland recycles nutrients, but can also lead to the build-up of P in soils, which in turn, increases the potential for P losses via runoff and soil erosion. Manure is often applied to cropland at rates that attempt to meet the nitrogen (N) need of the crop. The available nitrogen and P contents of dairy and other animal manures are about equal (**Table 3**). However, the N need of corn, for example, is 3-5 times greater than the P need (**Table 4**). The consequence of applying manure at rates to meet the N need of corn is that P applica-

Table 2. Fertilizer sources of phosphorus.

Fertilizer Type	Chemical Formula	Fertilizer Analysis	Water Solubility
		N-P_2O_5-K_2O	- - - - % - - - -
Ammonium polyphosphate	$NH_4H_2PO_4 + (NH_4)_3HP_2O_7$		
Liquid		10-34-0	100
Dry		15-62-0	100
Diammonium phosphate (DAP)	$(NH_4)_2HPO_4$	18-46-0	95+
Monoammonium phosphate (MAP)	$NH_4H_2PO_4$	11-48-0	92
Triple superphosphate	$Ca(H_2PO_4)_2$	0-46-0	87
Ordinary superphosphate	$Ca(H_2PO_4)_2 + CaSO_4$	0-20-0	85
Rock phosphate	$3Ca_3(PO_4)_2CaF_2$	0-32-0	<1

Source: Schulte and Kelling, 1992.

Table 3. Available nutrient content from solid and liquid dairy manure.

	N surface applied	N incorporated	P_2O_5	K_2O
	- - - - - - - - lb/ton - - - - - - - -			
Solid	3	4	3	8
Liquid	8	10	8	21

Source: Kelling et al., 1998.

Table 4. Recommended nutrient application rates for corn grain at optimum soil test levels.

	N	P_2O_5	K_2O
	- - - - - - - lb/a/yr - - - - - -		
Corn (yield - 200 bu/a)	160	75	55
Corn (yield - 160 bu/a)	160	60	45
Corn (yield - 120 bu/a)	160	45	35

Source: Kelling et al., 1998.

tions will exceed crop removal **(Fig. 5)**. The result is a build-up of P in cropland soils. Long-term manure applications have elevated the soil P level of many soils above the range necessary for optimum crop growth. This trend is especially prevalent in areas where concentrated livestock operations are common (Sims, 1993).

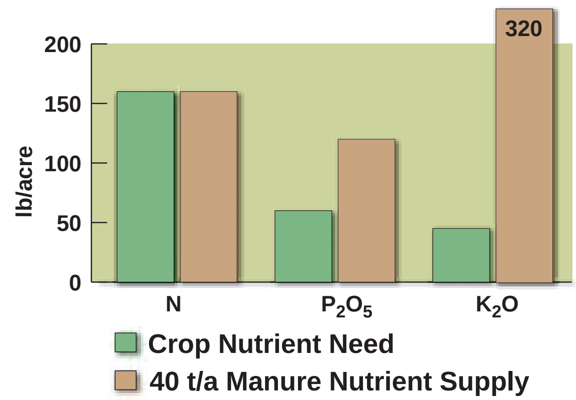
Concentrated Livestock Operations

On individual farms and in many areas of Wisconsin and the nation, P inputs in feed and fertilizer exceed P outputs contained in crop and animal produce leaving the farm or region (**Fig. 6**). This is especially true in areas where concentrated livestock production is prevalent (Daniel et al., 1998). The rapid growth and intensification of animal farming operations in many areas has created local imbalances of P inputs and outputs. The National Research Council (1993) estimates that only 30% of the fertilizer and feed P imported onto farms is exported in crops and animal produce. The surplus 70% of the P is remaining on-farm and leading to the excessive enrichment of soil P.

Two factors come into play with livestock operations and the build-up of soil P: 1) The import of P via feed transported to livestock-producing areas, and 2) the increase in size of individual livestock facilities and the regional concentration of livestock operations. Many confined animal operations do not produce sufficient feed for their livestock. Feed and the associated nutrients are imported to these operations. On a national scale, Lanyon & Thompson (1996) point out the disparity between grain and animal production in the U.S. by noting that in 1995 the major animal producing states imported over 80% of their grain for feed. The USDA (1989) states that less than a third of the grain produced on farms today is fed on the farm where it is grown. Both these observations point out the fragmentation of crop and animal production and the tendency for nutrient accumulation on livestock operations.

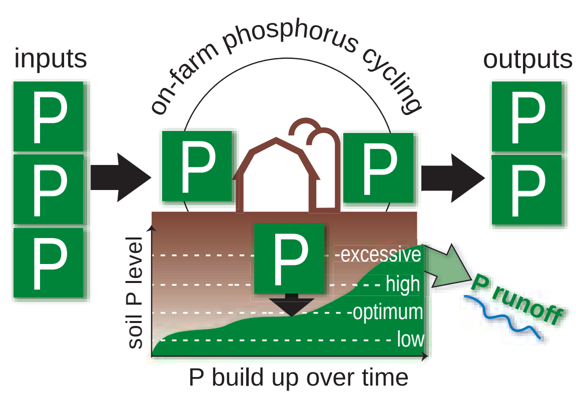
The second factor contributing to the build-up of P on livestock operations is the fact that manure generated by concentrated livestock operations is disposed by application to surrounding land. Land application of manure is a sound agronomic and economic management option. However, larger animal operations often do not have sufficient land available to use the P contained in the manure in an environmentally acceptable manner. The result is often large amounts of manure being applied on relatively few acres. Manure-nutrients accumulate in soil as a consequence of limited distribution. The cost of transporting manure from its site of production often exceeds the nutrient value for the manure. This fact further limits manure distribution and results in it being applied in close proximity of its production. The combination of the limited distribution of the manure from confined livestock operations along with the import of P often results in P surpluses on farms and build-up of soil P to excessive levels over time.

Figure 5. Nitrogen-based manure application strategy for corn.



Source: Bundy, 1998.

Figure 6. On-farm phosphorus cycle.



Livestock Feed

Livestock feed inputs have been found to be a major contributing factor to on-farm P surpluses (Satter and Wu, 1999; Powell et al., 2002; Sharpley et al., 1999). Soil build-up of P is accelerated when livestock are overfed P in dietary rations. Phosphorus excretion in manure is directly related to the level of P intake (Ternouth, 1989; Morse et al., 1992;

Khorasani et al., 1997; Metcalf et al., 1996). High P in livestock dietary intake directly correlates with higher bypass P as reflected in elevated P content of livestock manure (**Table 5**). Overuse of dietary P supplements accelerates the build-up of soil test P to excessive levels and increases the potential for P losses from manured fields (Ebeling et al., 2002). Another consequence is an increase in land required for application of manure ***if*** P-based rate limitations are to be met.

In regards to dairy production, many dairy herds are fed dietary P at levels that exceed U.S. National Research Council (NRC) recommendations. The NRC recommends that the typical dairy cow diet contain between 0.32 and 0.38% P, depending on milk production (NRC, 2001). In a survey of Wisconsin dairy producers by Powell et al. (2001) the reported P content of animal diets was found to range from 0.23 to 0.85% P with the average being 0.40%. Approximately 85% of the surveyed dairy farms were feeding P in excess of NRC requirements and over half of all cows were being fed P in excess of 0.38%. Other surveys have found dietary P levels between 0.5 and 0.6% for high producing herds (Howard and Shaver, 1992; Keuning et al., 1999; Satter and Wu, 1999). It has been estimated that the U.S. dairy industry, alone, over-supplements P in the diet of cows by an unnecessary $100 million annually (Satter and Wu, 1999).

Table 5. Annual phosphorus fed to and excreted by a lactating cow.

Dietary P Level	Supplemental P	Fecal P
(%)	------- lb/cow/year -------	
0.35	0	42
0.38	5.5	47
0.48	23	65
0.55	36	78

Source: Powell et al., 2001.

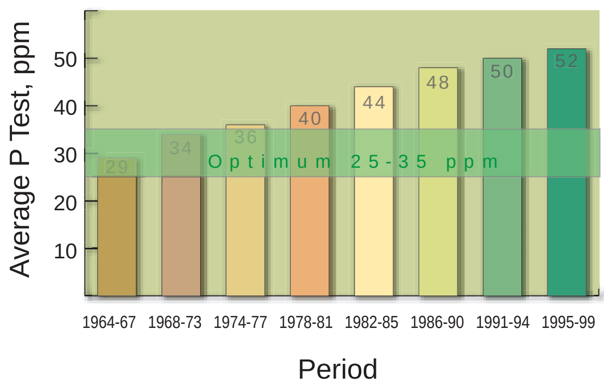
On many livestock operations, if dietary P supplementation could be reduced, the amount of P in manure and the amount of land required for spreading manure would also decrease. Research conducted in Wisconsin and elsewhere shows that avoiding excess P supplementation of dairy rations could substantially reduce the amount of P in manure without harming animal production (Satter and Wu, 1999). *See the Dietary Phosphorus Management section of this publication (page 22) for further discussion of Wisconsin research and management recommendations.*

Phosphorus Contributions from Agricultural and Urban Land Uses

Agriculture

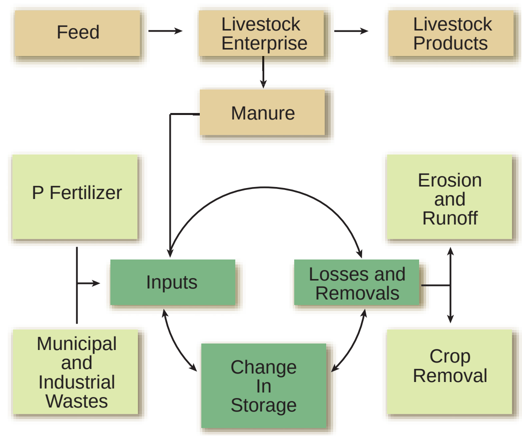
Agricultural land use has been identified by the United States Environmental Protection Agency as the major source of nutrients causing accelerated eutrophication in the nation's lakes and rivers (Parry, 1998; USEPA, 1996; USEPA, 1995). According to the EPA, agricultural runoff is the major source of stream and lake contamination that prevents attainment of legislatively mandated water quality goals (Parry, 1998, USEPA, 1988). The potential for P loss in agricultural runoff has increased with the land application of fertilizers and manure from livestock operations at levels greater than farm utilization (Edwards and Daniel, 1992; McFarland and Hauck, 1995; Sharpley et al., 1996b). The resulting imbalance of P on many operations has increased soil P to levels that are of environmental concern in some areas (Sharpley et al., 1996a).

Figure 7: Average soil test phosphorus in samples analyzed by Wisconsin soil testing laboratories from 1964-1999.



Source: Bundy and Sturgul, 2001.

Figure 8: Crop and soil phosphorus budget for Wisconsin.



Source: Bundy and Sturgul, 2001.

In Wisconsin, soil test P values – which reflect the amount of plant-available P in agricultural fields – have increased substantially over the past 25 years (**Fig. 7**). The average soil test P level (Bray P-1) of Wisconsin cropland fields exceeds the levels needed for optimum production of most crops. Average soil test P levels in Wisconsin have increased from an average of 29 ppm P in 1964-67 to 52 ppm P in 1995-99 (Combs and Peters, 2000). A level of 25-35 ppm is considered more than adequate for corn, soybean, and alfalfa on most of Wisconsin's soils (Kelling et al., 1998). These above optimum soil P levels have accumulated over time due to long-term P additions exceeding P removals in harvested portions of crops (Bundy and Sturgul, 2001). The increase of soil test P values over time parallels a national trend from livestock-producing states (Sharpley et al., 1999).

To further investigate the relationship between agriculture and P additions to the environment, a Wisconsin cropland P budget was developed by Bundy and Sturgul (2001) for several years between 1970 and 1995. The P budget considers the major inputs, losses, and removals of P from cropland (**Fig. 8**) in an attempt to better understand the sources and losses of P from Wisconsin cropland. Major components of the budget are inputs (manure and P fertilizers), P losses and removals (erosion, runoff, and crop uptake), and P storage in the soil. Soil P storage was calculated as the difference between inputs and losses/removals and provides an estimate of the average excess of P additions to Wisconsin cropland.

Phosphorus additions exceeded removals and losses throughout the time period investigated in the Wisconsin P budget exercise (**Table 6**). Soil P storage

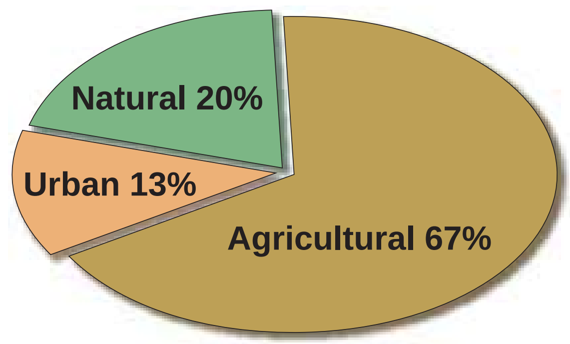
Table 6. Generalized phosphorus budget for Wisconsin cropland from 1970 - 1995.

Budget Component	Year						
	1970	1975	1980	1985	1991	1994	1995
	P, million lbs						
Additions:							
P in Manure	112	120	116	115	109	99	98
P in Fertilizer	102	114	137	136	98	116	96
Removals/Losses:							
Crop Removal	104	113	146	145	134	176	160
P in Runoff	2.9	3.1	3.2	3.1	2.8	3.1	3.0
Soil P Storage:	107	118	104	103	70	36	31

Source: Bundy and Sturgul, 2001.

(excess P) amounts applied to cropland ranged from a high of 118 million lbs of P in 1975 to 31 million lbs in 1995. The overall trend with time was a reduction in the amount of excess P additions as illustrated by the 74% reduction in 1995 values relative to 1975. While the decrease in excess P additions to cropland is encouraging, the amount of excess is still substantial. In 1995, excess P amounts were 31 million lbs of P – an amount equivalent to about 3.3 lb of P (or 7.5 lbs of P_2O_5) per cropland acre. Excess P is stored with a resulting enrichment of cropland soils as reflected by the build-up of soil test P values. Long-term changes in the state average soil test P values (Fig. 7**)** are consistent with the amounts of excess P applied to cropland during the same period according to the P budget calculations.

Figure 9: Sources of phosphorus to Tainter Lake, Wisconsin.



Source: Wisconsin Department of Natural Resource.

Urban

Although the majority of this publication deals with agricultural-P issues, it needs to be noted that P losses occur from other land uses as well. Runoff and erosion (nonpoint source pollution) from urban sources such as construction, lawns, streets, etc. can also be locally significant sources of P (Daniel and Keeney, 1978). Lathrop (1990) found urban contributions of total P to Madison, Wisconsin's Lake Mendota to be 12 to 50% of the P input from rural portions of the lake's watershed. Additionally, the Wisconsin Department of Natural Resources (Stevenson, 1995) estimates that organic wastes from industry and municipal sewage treatment plants in Wisconsin account for about six million pounds of land-applied P annually. However, the latter amount is very small relative to agricultural P contributions (see Table 6).

Water discharged directly into lakes and streams (point source pollution) from municipal and industrial wastewater treatment facilities is another source of P. Point-source pollution has been greatly reduced over the past decades due to strict regulation, management, and investment in capital improvements by industries and municipalities. The success in reducing point sources of pollution and the substantial costs involved with further reduction of point sources of P is focusing public attention on the reduction of nonpoint sources of pollution to further improve surface water quality.

Urban watersheds are few relative to agricultural watersheds in Wisconsin. Many of the state's watersheds contain both urban and agricultural areas, but the urban impact on surface water quality often pales in comparison to agricultural P contributions due to large differences in acreage of the two land uses (**Fig. 9**). As a consequence, the focus of water quality protection programs has been to reduce nonpoint source pollution from the largest overall land use affecting it – agriculture. It is not implied that urban sources of point and nonpoint pollution are not a concern. Local water quality impacts due to urban contributions within a watershed can be significant.

Phosphorus Terminology - Forms of Phosphorus and Their Significance

Discussions of the impact of P on surface water quality are complicated by a number of factors. The complex chemistry of P and the various reactions it may undergo affect the form and availability of P in both soil and water environments. In addition, ambiguity exists in the P research literature due to inconsistent nomenclature for the various fractions of P. A descriptive summary of P terminology follows:

- **Phosphorus (P)**

Elemental P is a naturally occurring, essential plant and animal nutrient. In plants, P is required for photosynthesis, respiration, seed production, root growth and other critical functions. In animals, P is critical for proper bone and muscle growth, metabolism, reproduction, and overall animal performance.

Terms Relevant to Water Quality

- **Dissolved P (DP) / Soluble P (SP)**

Phosphorus is carried in runoff in both the dissolved (DP) and particulate (PP) forms. Soluble or dissolved P is the form of P that is readily available for plant uptake in soil solution. It is also the form of P in runoff that can have an immediate impact on algae and aquatic vegetation growth (Sharpley et al., 1996; Nurnberg and Peters, 1984). Phosphorus that passes through a 0.45 micron (µm) filter as well as any P that is released from solids by certain chemical extractants is deemed DP (USEPA, 2000). The terms SP, DP, dissolved reactive phosphorus (DRP), soluble reactive phosphorus (SRP), dissolved molybdate reactive P (DMRP), and ortho-P are often used interchangeably.

Early P runoff monitoring studies often measured only SP – which provided only partial information on the impacts of P on water quality (Daniel et al., 1989). Additional P parameters are now recognized as being important as well.

- **Orthophosphate (Ortho-P)**

Ortho-phosphate is the form of P that is assimilated by plants, algae, and bacteria (Correll, 1998; Jarrell, 2000; Helmke et al., 2000). It is an inorganic form of P and is always in the soluble or dissolved form as $H_2PO_4^-$ and/or $HPO_4^=$. The abundance of each form depends on soil pH. Ortho-P is often used interchangeably with SP/DP.

- **Particulate P (PP)**

Phosphorus is carried in runoff in both the dissolved (DP) and particulate (PP) forms. Particulate P is bound to eroded sediment or organic matter contained in runoff. This form of P is also termed sediment-P. Particulate P is made up of particles that do not pass through a 0.45 um filter (USEPA, 2000). Particulate P is the dominant form of P reaching surface waters in agricultural watersheds and often represents a major reservoir of P to algae and aquatic vegetation within the bottom sediments of lakes and streams. Sharpley et al. (1992) state that 60-90% of P transported in runoff from cultivated land is in the PP form. Runoff from grass or forested land carries little sediment and is dominated by DP (Sharpley et al., 1994). Particulate P can be a long-term reservoir of P in lakes and streams (Carignan and Kalff, 1980). Although not immediately available, portions of PP can come into solution with time, especially as SP levels in lake waters are depleted (Fig. 2). Huettl et al. (1979) and Williams et al. (1980) estimate that 20-40% of PP is potentially bioavailable while Sharpley et al., (1992) found that the eventual bioavailability of PP can vary from 10 to 90% depending on the nature of the sediment and receiving lake.

- **Total P (TP)**

Total P (TP) is the total amount of P, both PP and SP, carried in runoff water. Many researchers (Vollenweider, 1976; Correll, 1998) believe that TP is the most important parameter to measure when trying to predict the response of lakes to P additions. Numerous models used by lake managers and researchers involve TP as a primary input (Correll, 1998). Total P is the parameter the Environmental Protection Agency is using to develop regional and water body-specific nutrient criteria for water quality protection programs (USEPA, 2000). Total P has been used throughout North America as a basis for setting state water quality criteria and in developing related models (NALMS, 1992). Researchers have also shown that TP concentrations in runoff can be readily related to watershed land use (Reckhow and Simpson, 1980; Walker, 1985), which makes it a key variable for addressing point and nonpoint source loads from watersheds (USEPA, 2000).

Bioavailable P (BAP)

Bioavailable P (BAP) includes virtually all the SP in runoff and an estimate of the portion of PP that can come into solution and be available to aquatic algae and plants. Amounts of BAP are determined through the correlation of standard chemical extractions of P with the amount of P taken up by a given plant or algae (a bioassay). Levels of BAP have been estimated to represent up to 98% of the P that can be utilized by algae (Williams et al., 1980). BAP measurements are a more accurate estimate of long-term P availability to aquatic plants and algae than SP measurements alone (Daniel, 1989).

Terms Relevant to Crops, Soils, and Fertilizers

Rock Phosphate

Rock phosphate is the original source of nearly all P fertilizer in the U.S. Rock phosphate alone is not an effective P source for most soils. It is treated with acid in the fertilizer manufacturing process and converted to soluble forms that can be taken up by plants (Schulte and Kelling, 1992).

Organic P

Organic P includes P derived from plant residues and microbes within the soil as well as stable compounds that have become part of the soil organic matter. A large portion of the P in animal manure is in an organic form and must be converted to plant-available forms via soil biological activity, a process known as mineralization (Fig. 1). Organic P acts more like a slow-release fertilizer than commercial inorganic fertilizers, which are initially more soluble and readily available to plants (Daniels et al., 1998).

Inorganic P

Inorganic P reserves in the soil include soluble fertilizers that are readily available to plants, slowly soluble phosphate compounds, and stable (insoluble) Fe and Al phosphate oxides (Sharpley and Beegle, 1999). Inorganic P that is taken up by plants is usually in the orthophosphate form (Rehm et al., 1997). Both inorganic and organic forms of P are important sources for plant growth, but their availabilities are controlled by soil characteristics and environmental conditions.

Soil Test P

Soil test P values are estimates of plant-available P contained in soil samples collected from fields, lawns, gardens, etc. These values are an index -

relative to crop demand - of the nutrient-supplying capacity of the soil. They are not a direct measure of total P or the total amount of plant-available P in the soil. Soil test P values are determined by chemical analysis at soil testing laboratories. Regional variation exists in the analytical procedures used to determine soil test P values. In Wisconsin, soil testing labs use the Bray P1 method to chemically extract and measure the amount of P from the soil sample (Kelling et al., 1998). It is assumed that the extractant is removing P from the soil at levels proportional to that which will be available to the crop during the growing season. Soil test P levels are expressed in parts per million (ppm). Soil test values are correlated with fertilizer response research trials for specific crops, soil types, and climatic regions to determine the economic optimum amount of P fertilizer to apply. Soil test results are assigned crop-specific interpretive values of either very low, low, optimum, high or excessively high. Optimum soil test levels and P fertilizer recommendations for common Wisconsin crops are shown in Tables 7 and 8.

Phosphate (P_2O_5)

Although soil test P levels are expressed in elemental form (ppm of P), P fertilizer application recommendations and fertilizer product analysis (or grade) are expressed on a phosphate (P-oxide) basis. There is no phosphate in commercial fertilizer. Expression of P in the oxide form originated from early agricultural chemistry research. Schulte and Walsh (1993) speculate that it would be simpler and less confusing to express P (and potassium) content of fertilizers on an elemental basis, but the oxide term has become so entrenched in the fertilizer industry that any change in terminology would be very difficult. Conversion factors for P include: 1 pound P = 2.29 pounds P_2O_5; 1 pound of P_2O_5 = 0.44 pound of P.

Interpretation of Phosphorus Research

■ Units of Measure of P: ppm and ppb

The terms parts per million (ppm) and parts per billion (ppb) are units of measure for P concentrations in soil, runoff, and water. In water measurements, ppm of P is the same as milligrams (mg) of P per liter (1,000 ml) of water and ppb of P is micrograms (µg) of P per liter of water. In soil, ppm P is mg of P per kilogram (1,000 grams) of dry soil and ppb is µg of P per kilogram of dry soil.

■ P Concentration and P Load

Research investigating P in runoff and its impacts on surface water quality has been reported in two manners: 1) Concentration and 2) Load. The concentration of P is the amount of P per unit volume of runoff and is expressed in terms like ppm or mg per liter. Phosphorus load is the amount of P carried in runoff. It is calculated by multiplying the runoff-P concentration by the total volume of runoff. Loads are often expressed as pounds, tons, grams, or kilograms per acre or hectare. In evaluating research literature dealing with P, it is important that the distinction between the two parameters is clearly understood. Phosphorus loading is the parameter of greatest concern when estimating the impacts of runoff-P on surface water quality (Daniel, 1989).

From a lake or stream standpoint, it is often more desirable to predict algal and aquatic vegetation productivity based on measures of the concentration of P in the water body. The techniques for measuring P concentrations in water are much easier than measurements of loadings from runoff into a water body (Correll, 1998). Total P concentrations are the most common form of P measured in lake studies (Correll,1998).

Total P or SP: Which Parameter is Most Important?

Historically in P and water quality research, it was assumed by many that PP inputs to lakes and streams had relatively little effect on algal growth and, consequently, SP was the form of P to monitor and control (Sonzgogni et al., 1982). A P research review by Correll (1998) concludes that this assumption is not valid and that TP should be the focus of P control programs and research activities. This opinion is based on studies that found trends in SP concentrations in lakes over time could only be explained by considering the dynamics of P released from both suspended PP and bottom sediment-PP (Edmond et al., 1981; Boyton and Kemp, 1985; Jordan et al., 1991). *Remember: TP is the sum of SP and PP.* When sediments are discharged into a lake, the PP in the suspended sediment equilibrates with the receiving water's SP. If the concentration of SP is low, P is released from the suspended sediment and vice versa (Correll, 1998). Once sediment has settled to the bottom of a lake, the release of P becomes more complex. Biological activity can gradually mineralize organic P and release SP. This SP may diffuse into the lake or it may become bound to the surfaces of lake bottom particles before it can reach the overlying water (Correll, 1998).

An additional concern with using SP as a sole water quality indicator is also described by Correll (1998). He cites lake studies where the SP concentrations of water have not correlated with periods of increasing eutrophication, but TP values have. One example is the Chesapeake Bay. During a period of increasing eutrophication in the 1970s, TP concentrations in the Bay increased over an eight-year period from 20-50 ppb to 150-200 ppb while SP ranged from 5-8 ppb and hardly changed at all over this period. If only the SP concentrations had been monitored over this time period, no change in water quality due to P additions would have been apparent. This study, along with others, indicated that while a relatively low concentration of SP is needed to stimulate algal growth, the turnover or recycling rate of the SP must be sufficient to maintain such concentrations. By measuring TP, a better estimate of the pool (or reservoir) of P that may become available to algae can be made. Monitoring SP alone is of little value if the goal is to judge the eutrophication potential of a water body (Correll, 1998). Correll concludes by stating "If one needs to assess the P status of a receiving water based only on P concentrations in the water column, it is better to measure TP (the sum of SP and PP) than to rely on SP concentrations."

Agricultural Management Practices for Phosphorus

Appropriate agricultural management practices for P vary widely with the various cropping, livestock, topographical, environmental and economic conditions found in Wisconsin. Runoff is usually generated from limited areas within a watershed. The size and impact of runoff from these areas varies rapidly in time as a function of storm intensity and duration and also due to conditions such as soil moisture, soil water storage capacity, topography, etc. These variations add to the challenges of predicting P movement on the landscape and the development of effective management practices for reducing P contributions to waters in agricultural watersheds. With such a variety of factors, it is impossible to issue blanket recommendations applicable to all Wisconsin farms. Agricultural management practices for protecting water quality must be tailored to the unique conditions of individual farming operations.

The overall goal of management practices to reduce P losses from agriculture should be to balance inputs of P to farms with outputs in crop and animal production. At the same time cropland needs to be managed to maintain soil P at adequate levels while minimizing runoff and sediment losses. A general summary of P management practices follows.

Soil Conservation

Cropland activities associated with agriculture can increase the potential for runoff and soil erosion. Consequences of cropland erosion include loss of fertile topsoil, accelerated eutrophication and sedimentation of surface waters, destruction of fish and wildlife habitat, and decreased recreational and aesthetic value of surface waters. The key to minimizing nutrient contributions to surface waters is to reduce the amount of runoff and eroded sediment reaching them. Numerous management practices for the control of runoff and soil erosion have been researched, developed, and implemented. Runoff and erosion control practices range from changes in agricultural land management (cover crops, diverse rotations, conservation tillage, contour farming, contour strip cropping, etc.) to the installation of structural devices (buffer strips, diversions, grade stabilization structures, grassed waterways, terraces, etc.)

Despite the proven effectiveness of soil conservation practices in reducing nutrient loadings to surface waters, their effect on groundwater quality is unknown. Practices that reduce surface runoff by increasing soil infiltration may, in turn, enhance the movement of soluble agricultural chemicals through the soil profile to groundwater (Crowder and Young, 1988). Trade-offs between reducing runoff and protecting groundwater quality may exist. If such is the case, decisions weighing the impact of one resource versus another will need to be made. Research on the effects of soil conservation management practices on groundwater quality is limited and often contradictory.

Soil Testing and Phosphorus Application Rates

Careful management of P in crop production systems is essential for preventing nutrient enrichment of surface waters. Contributions of P to surface waters have been shown to increase with increasing rates of applied P (Pote et al., 1996; Mueller et al., 1984; Romkens and Nelson, 1974). Fertilizer applications at rates higher than crop utilization are unwise from both an environmental and economic viewpoint. Using soil tests to determine crop P needs, setting realistic crop yield goals, and taking appropriate nutrient credits are techniques that can reduce environmental risk and increase economic benefits.

To avoid over-fertilization with P and other nutrients, fertilizer additions should be made according to soil test results. Regular and systematic soil testing is required for determining P application rates. The University of Wisconsin soil testing system (Kelling et al., 1998) recommends soil nutrient applications at levels which, in combination with nutrients supplied by the soil, result in the best economic return for growers. This reliance on both soil-supplied and supplemental nutrients reduces threats to water quality by avoiding excessive nutrient applications. At optimum soil test levels, the recommended P (and potassium) additions are approximately equal to anticipated crop removal and are needed to optimize economic return and maintain soil test levels in the optimum range. This approach adds extra emphasis on regular soil testing. When soil fertility levels are maintained in the optimum range, they have the potential to drop below economically optimum thresholds in only a few growing seasons. To prevent this, soil test levels need to be monitored closely to detect changes in status. It is recommended that soil tests be taken at least every three to four years and preferably every other year on sandy and other soils of low buffering capacity. Detailed information on soil test recommendations is available in the UW-Extension publication A2809, *Soil Test Recommendations for Field, Vegetable and Fruit Crops*.

Optimum P soil test levels for corn, alfalfa, and soybean production in Wisconsin are given in **Table 7**. Phosphorus fertilizer recommendations for

Table 7. Optimum soil test phosphorus levels for corn, alfalfa, soybean.

Crop	Subsoil*	Soil Test Category				
		Very Low	Low	Optimum	High	Excessively High
		Soil Test P, ppm				
Corn	A	<5	5-10	11-15	16-25	>25
	B & C	<10	10-15	16-20	21-30	>30
	D	<8	8-12	13-18	19-28	>28
	E & O	<12	12-22	23-32	33-42	>42
	X	<5	5-8	9-15	16-25	>25
Alfalfa	A	<10	10-15	16-23	24-32	>32
	B	<10	10-17	18-23	24-30	>30
	C	<12	12-17	18-25	26-35	>35
	D	<10	10-15	16-23	24-30	>30
	E & O	<18	18-25	26-37	38-55	>55
	X	<5	5-10	11-15	16-23	>23
Soybean	A, B, D	-	<6	6-10	11-20	>20
	C	-	<8	8-13	14-23	>23
	E & O	-	<10	10-15	16-25	>25
	X	-	<6	6-10	11-17	>17

*A list of subsoil fertility categories for each of the 699 soil series found in Wisconsin can be found in Kelling et al., 1998 (Univ. Wis. Extension publication A2809). A general definition of subsoil groups is: A=southern, formerly forested, medium and fine-textured soils; B=southern, formerly prairie, medium and fine-textured soils; C=eastern, red, medium and fine-textured soils; D=northern, medium and fine-textured soils; E=sandy soils; O=organic soils; X=high pH (alkaline) soils.

Source: Kelling et al., 1998.

corn, alfalfa and soybean are based on crop yield goal and soil test results as shown in **Table 8**.

Realistic Yield Goals

An important criteria in the recom-mendation of appropriate P application rates is the determination of realistic yield goals. Yield goal estimates that are too low will underestimate nutrient needs and could inhibit crop yield. Yield goal estimates that are too high will overestimate crop needs and result in soil nutrient levels beyond that needed by the crop, which may increase the likelihood for nutrient contributions to water resources. Yield goals must be realistic and achievable based on recent yield experience. Estimates should be based on field records and some cautious optimism. Yield goals 10 to 15% higher than a 3-to-5 year crop average yield from a field are suggested because annual yield variations due to factors other than nutrient application rates (primarily climatic factors) are often large (Kelling et al., 1998).

Starter Fertilizer

A minimal amount of starter fertilizer is recommended for corn planted in Wisconsin soils that are slow to warm in the spring. For corn grown on medium and fine-textured soils, a minimum application of 10 lb N, 20 lb P_2O_5, and 20 lb K_2O per acre is recommended as a starter at planting (Kelling et al., 1998). In most cornfields, all the recommended P_2O_5, and K_2O can be applied as starter fertilizers. On soils

Table 8. Phosphorus fertilizer recommendations for corn, alfalfa, soybean.

Crop	Yield Goal	Soil Test Level				
		Very Low	Low	Optimum	High	Excessively High
		Amount of P_2O_5 to Apply, lb/a				
Corn	91-110 bu	70-100*	60-80*	40	20	0
	111-130 bu	75-105*	65-85*	45	25	0
	131-150 bu	85-115*	75-95*	55	25	0
	151-170 bu	90-120*	80-100*	60	30	0
	171-190 bu	100-130*	90-110*	70	35	0
	191-210 bu	105-135*	95-115*	75	40	0
Alfalfa	2.6-3.5 ton	65-85**	55-75**	35	15	0
	3.6-4.5 ton	80-100**	70-90**	50	25	0
	4.6-5.5 ton	95-115**	85-105**	65	30	0
	5.6-6.5 ton	105-125**	95-115**	75	35	0
	6.6-7.5 ton	120-140**	110-130**	90	45	0
Soybean	26-35 bu	35	35	25	15	0
	36-45 bu	45	45	35	20	0
	46-55 bu	55	55	45	20	0
	56-65 bu	60	60	50	25	0
	66-75 bu	70	70	60	30	0
	76-85 bu	80	80	70	35	0

* Use higher values on sandy or organic soils.
** Use lower values on sandy soils.

Source: Kelling et al., 1998.

Table 9. Probability of corn yield response to starter fertilizer on excessively high testing soils for various hybrid maturities at latest recommended planting dates in several Wisconsin production zones.

Zone	Relative Maturity	Recommended Latest Planting Date	PDRM Value [1]	Probability of Economic Return(%)
Southern	105-110	May 5	230-235	37-43
	100-105	May 15	235-240	43-49
	95-100	May 25	240-245	49-56
South-central	105-110	May 8	228-233	35-41
	100-105	May 18	233-238	41-47
	95-100	May 28	238-243	47-53
North-central	105-110	May 11	226-231	32-38
	100-105	May 21	226-236	38-44
	95-100	May 31	226-236	38-44
Northern	105-110	May 8	219-224	23-30
	100-105	May 18	219-229	23-36
	95-100	May 28	220-230	25-37

[1] PDRM = planting date (Julian days) + hybrid relative maturity.

Source: Bundy and Andraski, 1997.

with test levels in the excessively high range, starter fertilizer applications in excess of 10 lb N, 20 lb P_2O_5, and 20 lb K_2O per acre should be avoided.

Corn yield responses to starter fertilizer additions do occur on soils that are excessively high in P and potassium (K). The probability of a yield response can be estimated using site-specific information about individual fields. Crop yield increases with starter additions to excessively high soils are much more likely if soil test K levels are less than 140 ppm and/or the combined effect of corn hybrid relative maturity (RM) and planting date result in an inadequate growth period for the crop to achieve its full yield potential (Bundy and Andraski, 1999). Specifically, responses are more likely with late planting dates and long-season RM hybrids. The probability of response to starter fertilizer on excessively high testing soils at a range of hybrid RM and planting dates is shown in **Table 9**.

Nutrient Crediting

In the determination of supplemental fertilizer application rates, it is critical that nutrient contributions from all sources are credited. Both economic and environmental benefits can result if the nutrient supplying capacity of all nutrient sources is correctly estimated. Economically, commercial fertilizer application rates can often be reduced or eliminated entirely when nutrient credits are accounted. Environmentally, the prevention of nutrient over-fertilization reduces potential threats to water quality. The use of appropriate nutrient credits is of particular importance in Wisconsin where manure applications to cropland, legume crop production, and the land application of organic wastes are common.

Manure can supply crop nutrients as effectively as commercial fertilizers in amounts that can meet the total N and P requirements of crops. To utilize manure efficiently, the nutrient content and the application rate need to be estimated. The most effective method of gauging the nutrient content of manure is to have samples analyzed by a commercial or university laboratory. Large farm-to-farm variation in nutrient content can occur due to manure storage, handling, livestock feed, or other farm management differences (Peters and Combs, 1998). In instances when laboratory analysis is not convenient or available, estimates of crop nutrients supplied by animal manures should be made. **Table 10** summarizes the University of Wisconsin estimates of first-year available nutrient values for various livestock manures. Manure application rates can be determined through the calibration of the manure spreading equipment.

Table 10. Estimated available nutrient content of solid and liquid manure from various livestock species.

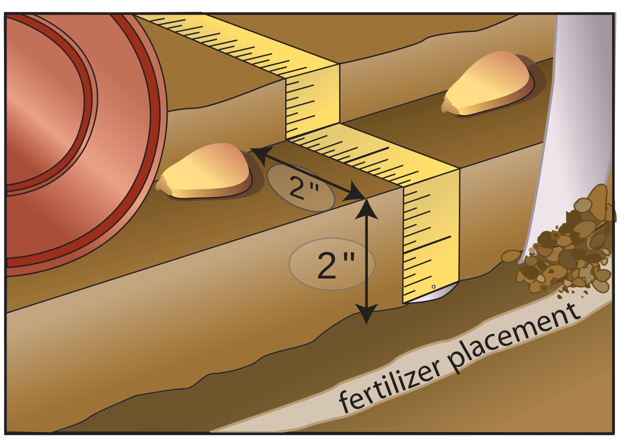
Livestock	Nitrogen (N) surface	Nitrogen (N) incorporated	Phosphate (P_2O_5)	Potash (K_2O)
	Solid			
	lbs/ton [1]			
Dairy	3	4	3	7
Beef	4	5	5	9
Swine	7	9	6	7
Chicken	20	24	30	24
Turkey	20	24	24	24
Livestock	Nitrogen (N) surface	Nitrogen (N) incorporated	Phosphate (P_2O_5)	Potash (K_2O)
	Liquid			
	lbs/1,000 gal [1]			
Dairy	7	10	5	16
Beef	5	7	5	16
Swine, indoor pit	25	33	25	24
Swine, outdoor pit	17	22	10	16
Swine, furrow[2]	13	16	14	18
Poultry	8	10	6	10

[1] Values rounded to the nearest whole pound.

[2] furrow/nursery indoor pit

Source: NPM Program, 2002.

Figure 10: Starter fertilizer in a 2x2 placement.



Source: Bundy et al., 1994.

Placement of Phosphorus Fertilizer

The placement of P-containing materials directly influences the amount of P transported to lakes and streams by runoff. When P fertilizer is broadcast on the soil surface and not incorporated, the concentration and loss of available-P in runoff water can rise sharply and have a greater potential impact on surface water quality than from soil surfaces where P was incorporated (Baker and Laflen, 1982; Timmons et al., 1973; Barisas et al., 1978; Mueller et al., 1984). Phosphorus is strongly bound to soil particles; however, adequate soil-P contact must occur to allow for adsorption. Incorporation by tillage or subsurface band placement of fertilizers is a very effective means of achieving this contact. To avoid enriching surface waters with soil nutrients, it is recommended that annual fertilizer applications for row crops such as corn be band-applied near the row as starter fertilizer at planting. Annual starter applications of P can usually supply all of the P required for corn. This practice reduces the chance for P enrichment of the soil surface and reduces P loads in runoff from cropland. Band fertilizer placement should be two inches to the side and two inches below the seed (**Fig. 10**) (Bundy, 1998a). Rates of application should be monitored closely if placement is closer to the seed. When large broadcast P fertilizer applications are needed to increase low soil P levels, these applications should always be followed by incorporation as soon as possible (Schulte and Bundy, 1988).

Manure Management

Manure applications to cropland provide nutrients essential for crop growth, add organic matter to soil, and improve soil structure, tilth, and water holding capacity. The major environmental concerns associated with manure applications are related to its potential for overloading soils with nutrients if manure applications exceed crop needs.

Manure Application Rates: Phosphorus vs. Nitrogen Strategies

When applying manure to cropland, one of two nutrient utilization strategies can be followed: 1) a nitrogen (N) strategy that applies manure at rates that meet the crop's need for N; and 2) a phosphorus strategy that applies manure at rates that meet the crop's need for P.

Phosphorus Strategy

If maximum nutrient efficiency is the goal, rates of manure application need to be based on the nutrient present at the highest level relative to crop needs. For corn, this nutrient would be P. Manure application rates that meet the P requirement of corn are typically in the range of 10-20 tons of dairy manure per acre. Additional N will need to be supplied from other nutrient sources (**Fig. 11**). A management strategy based on P dictates lower manure application rates but it is less likely to elevate soil test P values. It has the disadvantages of being inefficient with respect to labor, energy, time, and economics (Bosch et al., 1998). A P-based strategy for manure applications requires spreading manure on a much larger acreage than is required for a N-based manure application.

Nitrogen Strategy

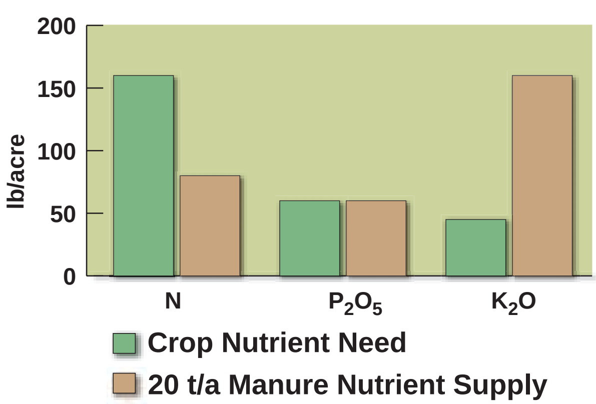
The most common strategy for utilizing manure is to determine a rate of application that will fulfill the crop's requirement for N. This strategy maximizes the rate of application but usually results in the addition of P and K in excess of the nutrient needs of the crop (**Fig. 12**). The N strategy is preferred if the amount of land available for application is limited because it allows for maximum application rates – in the range of 40-60 tons per acre for corn. However, following a nitrogen strategy for manure applications will lead to an accumulation of soil P with repeated applications. A N-based strategy is more time and labor efficient than a P-based strategy and is the preferred approach when the availability of suitable land for spreading is limited.

For surface water quality protection, it is recommended that for fields where manure cannot be incorporated, no more than 25 tons/acre of solid dairy manure or its equivalent based on P content be applied annually. In long term cropping situations that exclude manure incorporation (i.e. continuous no till corn) it is recommended that a cumulative total of not more than 25 tons/acre of solid dairy manure (or its equivalent in P content) be applied over a five year period unless previously applied manure has been incorporated (Madison et al., 1998).

Soil Test Phosphorus Limits for Manure Applications

In Wisconsin, a general recommendation exists for reducing manure applications and planting P demanding crops such as alfalfa when soil test levels for P reach **75 ppm.** At P soil test levels of **150 ppm**, manure and other sources of P should be discontinued until soil test levels decrease (Madison et al., 1998). More restrictive soil test P criteria are being considered in the proposed revision of the USDA-NRCS Nutrient Management Standard-590. Current drafts of the 590 Standard include P management recommendations at 50 and 100 ppm values (NRCS, 2002). Soil runoff and erosion control practices such as residue management, conservation tillage, contour farming and others are strongly recommended on soils with P levels in excess of crop needs.

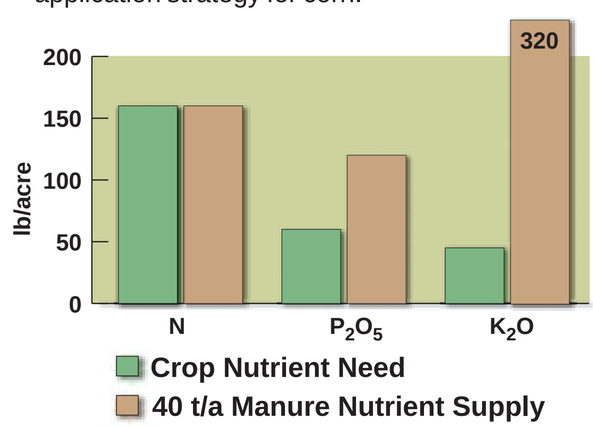
Figure 11. Phosphorus-based manure application strategy for corn.



Manure application strategy that meets the P needs of corn. Dairy manure applied at a 20 ton/acre rate. Notice the N application is less than the crop's need.

Source: Bundy, 1998b.

Figure 12. Nitrogen-based manure application strategy for corn.



Manure application strategy that meets the N needs of corn. Dairy manure applied at a 40 ton/acre rate. Notice the P applications in excess of crop need.

Source: Bundy, 1998b.

Manure Application Methods

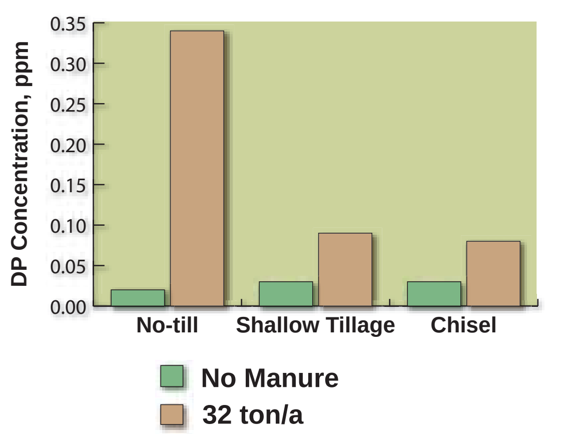
Previous Wisconsin research has shown that the incorporation of land-applied manure is very important for reducing dissolved P and bioavailable P concentrations and loads in runoff (Mueller et al., 1984, Daniel et al., 1989). To protect surface water quality from dissolved P additions, it is recommended that manure be incorporated within three days of application (Madison et al., 1998). Incorporation should reduce nutrient loss provided the tillage is sufficiently deep and does not accelerate soil loss. If a reduction in soil erosion protection appears likely from the incorporation of manure on sloping lands, a form of reduced tillage should be used. All incorporation or injection should follow the land contour when possible. When the incorporation or injection of manure is not practical, manure spreading should be directed to fields that have runoff control practices in place and which do not discharge unfiltered runoff to streams and lakes.

While incorporation of manure has been shown to reduce dissolved P (DP) losses, it has also been shown to increase the risk of total P (TP) losses through increased soil erosion. Recent Wisconsin findings (Bundy et al., 2001; Bundy and Andraski, 2001) suggest that the long-established management recommendation for incorporating manure may not minimize cropland P losses ***if*** TP reductions are the objective. Currently, the U.S. Environmental Protection Agency is developing nutrient criteria based on TP parameters (USEPA, 2000). The P runoff research by Bundy et al. was conducted on two sites in Wisconsin. At the south-central Wisconsin site (Arlington) the influence of three tillage systems - no-till, shallow tillage, and chisel plow – on P in runoff using simulated rainfall was investigated. Each tillage system was established with and without dairy manure applied at approximately 32 tons/acre. Manure was applied prior to tillage and corn planting. All plots received simulated rainfall in the spring and the fall.

> A reminder to the reader that the **concentration of P** is the amount of P per unit volume of runoff and **P load** is the amount of P carried in runoff. Phosphorus loading is the parameter of greatest concern when estimating the impacts of runoff-P on surface water quality.

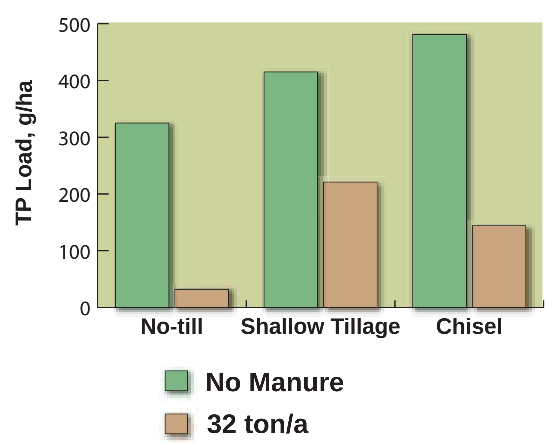
Similar to previous runoff studies conducted in Wisconsin (Mueller et al., 1984), results showed that incorporation of spring-applied manure significantly reduced DP concentrations in runoff (**Fig. 13**). However, contrary to previous findings, DP losses (or loads) were not significantly reduced with tillage. In the fall, runoff was analyzed for both DP and TP content. Results found that DP losses in September runoff among the tillage systems were not significantly different due to incorporation of manure. However, TP losses in September runoff showed a significant impact from manure applications. The TP load of runoff collected in September was five to eight times greater from plots where the manure was incorporated in the spring versus the no-till plots (**Fig. 14**). Figure 14 also indicates that the addition of manure in spring

Figure 13. Tillage and manure effects on dissolved phosphorus (DP) concentrations in spring runoff, Arlington, 1999.



Source: Bundy et al., 2001.

Figure 14. Tillage and manure effects on total phosphorus (TP) loads in fall runoff, Arlington, 1999.



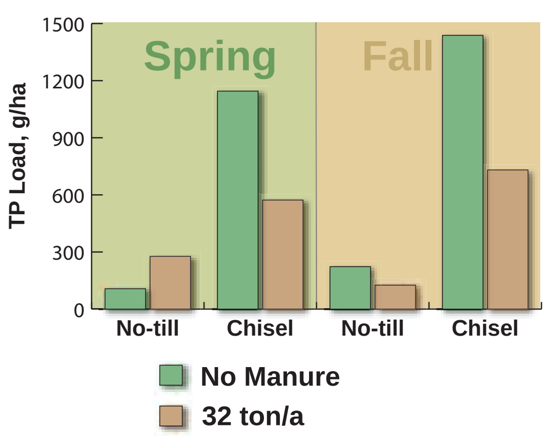
Source: Bundy et al., 2001.

resulted in significantly reduced TP losses in September runoff from each of the three tillage treatments.

Additional research investigating the influence of manure applications on P in runoff from no-till and chisel tillage treatments was conducted in southwestern Wisconsin (Lancaster) by Bundy and Andraski (2001). Similar to the Arlington study, each tillage system was established with and without dairy manure applied at 32 tons/acre. All plots received simulated rainfall in the spring and the fall. Analysis of the P content of runoff from each tillage system found that the incorporation of spring-applied manure significantly reduced DP concentration in runoff, but in agreement with the Arlington data had no effect on the DP load in either the spring or fall runoff events. Losses (or loads) of TP in runoff from plots where manure was incorporated with chisel plowing were found to be significantly higher than the no-till plots where manure was not incorporated in both the spring and fall runoff events (**Fig. 15**).

The differences in TP losses in runoff among the various tillage treatments were due to crop residue cover reducing erosion by reducing the sediment concentration in runoff and also by increasing water infiltration. The addition of manure to each tillage treatment served as an erosion-reducing mulch that was effective in reducing sediment losses even further (**Table 11**). Both the Arlington and the Lancaster studies found the majority of the TP load was sediment- or particulate-bound phosphorus (PP) - - up to 97% of the TP in the fall runoff at Arlington was PP. Dissolved P (DP) is a very small component of the TP loss from these cropping systems. Earlier

Figure 15. Tillage and manure effects on total phosphorus (TP) loads in spring and fall runoff, Lancaster, 2000.



Source: Bundy and Andraski, 2001.

Table 11. Effect of tillage and manure on sediment load in runoff at Lancaster, WI, Sept. 2000.

	Tillage	
Manure Application	Chisel Plow	No-till
(tons/acre)	(sediment load, kg/ha)	
0	4,493	467
32	1,779	127

Source: Bundy and Andraski, 2001.

work by Mueller et al. (1984) also found lower sediment losses and generally lower TP losses in runoff where manure was applied.

The research summarized in this section shows greater TP losses in runoff from fields where manure has been incorporated rather than surface-applied. These findings suggest that the incorporation of manure can have opposite effects on TP and DP losses in runoff, and these effects may be dependent on the time of runoff events. Unincorporated manure applications tend to reduce TP losses by lowering soil erosion but increase DP losses. Incorporating manure with tillage may lower DP losses but tends to increase TP losses. The fact that commonly recommended management practices may have opposite effects on TP and DP losses indicates a need to identify the forms of P in runoff from agriculture that will have the greatest environmental impact and design specific management recommendations to minimize these losses (Bundy et al., 2001).

Manure Application Timing

Manure application timing is an important management practice for minimizing P contributions to surface waters. Manure should not be spread on sloping lands any time a runoff-producing event is likely. Unfortunately, runoff-producing events are impossible to predict and the elimination of manure applications to sloping lands is seldom a practical option for landowners. The period of major concern is the late fall, winter, and early spring months. Manure applied on frozen ground has an increased likelihood for contributing nutrients to surface waters due to spring thaws and rains causing runoff.

If winter applications of manure must be made, the risk should be minimized to the greatest extent possible. Manure applications to frozen soils should be limited to slopes of less than 6%. Preferably these soils are cornstalk covered, roughly tilled, or protected from up-slope runoff (Madison et al., 1998).

If applications of manure to frozen soils with slopes of 6 to 12% must be made, conservation measures need to be in place in order to protect surface waters. Grassed waterways must be well established and maintained. Terraces should be in place, if appropriate, or fields contoured and strip-cropped with alternate strips in sod. If fields are farmed on the contour, they should be protected with an adequate residue cover from the previous year's crop (Madison et al., 1998).

Manure should not be applied to frozen soils on slopes greater than 12% (Madison et al., 1998).

Site Considerations for Manure Applications

The main site characteristics affecting nutrient contributions to surface waters are those that affect soil runoff and erosion. These include slope, soil erodibility and infiltration characteristics, rainfall, cropping system, and the presence of soil conservation practices. Site related management practices dealing specifically with manure placement to protect surface water include:

Do not apply manure within a 10-year floodplain or within 1,000 feet of lakes or 300 feet of streams unless incorporation follows as soon as possible - no later than 72 hours after application. Do not apply manure to frozen soils in these areas. The setback allows for buffer strips to slow runoff velocity and deposit nutrient and sediment loads. Do not apply manure to the soils associated with these land areas when they are saturated (Madison et al., 1998).

Do not apply manure to grassed waterways, terrace channels, open surface drains or other areas where surface flow may concentrate (Madison et al., 1998).

Buffer Strips

Maintaining or establishing strips of close-growing vegetation adjacent to water bodies is a practice that can reduce the sediment and nutrient content of runoff waters reaching them (Daniels and Gilliam, 1996). The velocity of runoff is reduced when passing through a buffer strip as is its capacity for transporting sediment and nutrients. Sediment is deposited and runoff infiltrates or passes through the buffer strip with a substantially reduced nutrient load.

The width of an effective buffer strip varies with land slope, type of vegetative cover, watershed area, etc (Schmitt et al., 1999). Buffer strip dimensions need to be specifically designed for given field and cropping conditions. Although proven effective in improving surface water quality, buffer strips may potentially have an adverse effect on groundwater quality. Increased infiltration in an area of sediment deposition may promote the leaching of soluble contaminants such as nitrate (Crowder and Young, 1988). The extent to which this may occur needs to be investigated and evaluated against the benefits to surface water quality.

Dietary Phosphorus Management

The need exists for more integrated approaches to improve nutrient management on Wisconsin's livestock farms. One area that has shown potential for helping balance farm P inputs with outputs from livestock operations is the manipulation of dietary P intake. Feed inputs, such as protein and mineral supplements are often major contributing factors to on-farm surpluses of P (Sharpley et al., 1999). The goal of dietary P management is to avoid overfeeding P and, in turn, avoid the subsequent enrichment of livestock manure with P. Phosphorus in land-applied manure is one of the major sources contributing to soil P accumulation in Wisconsin, and there is research showing that the amount of P in manure can be substantially reduced by avoiding excess P supplementation of dairy rations (Ternouth, 1989; Morse et al., 1992; Khorasani et al., 1997; Metcalf et al., 1996). Phosphorus excretion in manure is directly related to the level of P intake (Table 5). Overuse of dietary P supplements significantly increases the land required for application of manure - ***if*** P-based manure spreading restrictions are in place. It also accelerates the build-up of soil test P levels of fields. On many livestock operations, if P supplementation could be reduced to the recommended concentrations needed for animal production, the amount of P in manure and the amount of land required for spreading would also decrease. Both feed costs and the amount of manure-P that has to be land-applied can often be reduced.

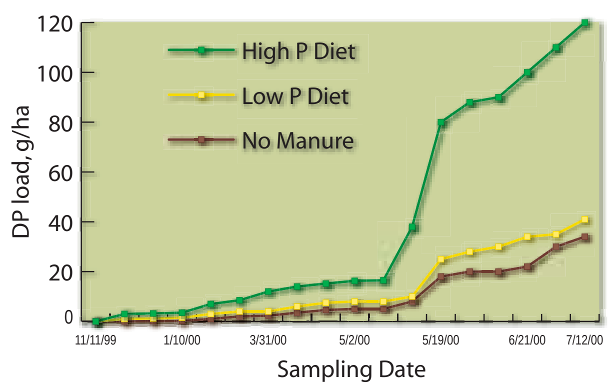
The U.S. National Research Council (NRC, 2001) recommends that the typical dairy cow diet contain between 0.32 and 0.38% P, depending on milk production (**Table 12**). To minimize perceived risks of P deficiency, many dairy herds are fed dietary P at levels that exceed NRC recommendations. The common practice of overfeeding P to animals – particularly dairy cattle - stems from a widely held belief that high P diets improve animal reproductive performance. While it is true that P deficiencies can lower the reproductive fertility of dairy cattle, a review of published research trials by Shaver (1995) showed little indication that feeding excess P enhances animal fertility. Most studies show that problems in dairy cows don't begin to show up until dietary P levels fall below 0.3% (Wu et al., 2001, 2000). Dietary P levels commonly observed on dairy farms are between 0.5 and 0.6% for high producing herds (Howard and Shaver, 1992; Keuning et al., 1999). Such levels of dietary P are excessive and can be substantially reduced without sacrificing milk production or quality (Satter and Wu, 1999).

A recent Wisconsin study illustrates the potential effects of excessive dietary P on runoff losses of P (Ebeling et al., 2002). Dairy cattle were fed two diets: one diet contained no supplemental P and the second contained supplemental P in the form of monosodium phosphate. These diets resulted in feed P concentrations of 0.32 and 0.48%, respectively, and produced manures with P concentrations of 0.48 and 1.28% P, respectively. Both manures were surface applied at 25 ton/acre rates on silt loam soils covered with corn residue at a southern Wisconsin site. Simulated rainfall was applied to the plots in June and October and runoff was collected and analyzed for P content. Natural runoff from the same plots was collected from November through May and analyzed for P as well.

Results from the study indicate that when manures from dairy cows fed different concentrations of P are land-applied at the same rates, the high P diet manure will release more P in runoff than the low P diet manure (**Table 13**). In June, dissolved P (DP) concentrations in runoff from the high P diet plots were almost ten times higher (2.84 vs. 0.30 ppm P) than runoff from the low P diet plots. Phosphorus concentrations in October runoff and November to May natural runoff (**Fig. 16**) were lower, but trends were the same as for the June runoff. In October the same comparisons showed that at equivalent manure application rates, DP concentrations from the high P diet fields were almost four times higher (0.89 vs. 0.21 ppm P) than the low P diet treatments. Losses (or loads) of DP from the various diets followed trends similar to the DP concentrations for all of the

The P terminology used in the dietary-P study is DP rather than TP due to the fact that parameters influencing TP losses – such as tillage, residue cover, slope, etc. were kept constant in this runoff study. The only variables were dietary-P intake and manure-P content. The impact of dietary-P on runoff-P is best expressed in terms of DP.

Figure 16. Cumulative dissolved phosphorus (DP) load in natural runoff from manures differing in P content.



Source: Ebeling et al., 2002.

Table 12. Dairy cattle feed recommendations of the National Research Council.

Milk Production Level	Dietary P Level
(lbs/day)	(%)
55	0.32
77	0.35
99	0.36
120	0.38

Source: NRC, 2001.

Table 13. Dairy dietary-P intake effects on dissolved P (DP) losses from manured fields.

Runoff Event	Dietary-P Intake	Runoff-DP Concentration	Runoff-DP Load
	(%)	(ppm)	(g/ha)
June	0.32	0.30	7
	0.48	2.84	79
October	0.32	0.21	10
	0.48	0.89	37

Source: Ebeling et al., 2002.

runoff events. These results show that excess P in dairy diets increases the potential for P loss in runoff from land-applied manure.

In addition to the water quality concerns associated with P-enriched manure, supplementation of the diet of dairy cattle with excess P can dramatically increase the land requirement for manure application - ***if*** a producer is required to meet P-based manure application criteria. One P-based strategy proposed for Wisconsin is a restriction on manure application rates to equal crop P removal rates. In a Wisconsin farm scenario described by Powell et al. (2001), approximately 1.8 acres of a mixed alfalfa, soybean, corn grain and silage cropping system is required to utilize the manure-P excreted from each lactating cow fed at 0.38% P (**Table 14**). Raising dietary P from 0.38 to 0.48% increases the cropland area needed per cow by 44%. The trend continues with increasing dietary P levels. The substantial range in Table 14 values of 1.6 to 2.9 acres per cow to meet a P-based manure application strategy reflects the large impact dietary P levels can have on land requirements for manure spreading.

Dietary P supplementation can profoundly affect soil test P levels as well. For example in the farming system described by Powell et al. (2001), if a producer has 1.8 acres of cropland available for spreading per cow (Table 14), land application of manure from cows fed a diet providing no excess of P (0.38% P) would be sufficient to meet crop needs. Additionally, soil test P values would not rise. However, at the 1.8 acres per cow ratio, any amount of supplemental P in excess of the cow requirement would result in manure-P that when applied to cropland would increase soil test P levels - as illustrated in **Table 15**.

Research is progressing on techniques for reducing the P content of animal feed and to enhance P utilization in animals while maintaining animal health and production. Recent studies have shown that typical dietary P levels fed on dairy farms can be reduced by 25-30% - leading to an even greater percentage reduction in manure-P – without sacrificing milk production or quality (Van Horn, 1998; Satter and Wu, 1999). Feeding high P diets cannot be justified solely on the basis of improved reproductive performance (Shaver, 1995). Farms that produce manure-P in excess of crop P requirements may eventually need to consider changing feed and fertilizer practices, seek additional land for manure application, export manure off-farm, and/or reduce animal numbers if they are to balance P inputs with outputs. Powell et al. (2002) point out that on Wisconsin farms where manure P exceeds crop P requirements, the single management practice of feeding at NRC dietary P recommendations would reduce the number of farms and amount of land with an excess P balance by approximately two-thirds.

The positive environmental consequences of feeding P at recommended levels have to be weighed against the price, convenience, and availability advantages of protein and mineral feed supplements. Elevated levels of dietary intake-P are often contained in affordable, common protein feed supple-

Table 14. Land needed for applying manure from dairy cattle fed various dietary P levels.

Dietary P Level	Acres Needed For Manure Spreading[1]	Increase in Acres Needed For Manure Spreading
(% P)	(acres/cow)	(%)
0.35	1.6	-
0.38	1.8	13
0.48	2.4	57
0.55	2.9	87

[1] Assumes an alfalfa, soybean, corn grain and silage cropping system.

Source: Powell et al., 2001.

Table 15. Example of potential changes in soil test P levels due to applying manure from dairy cattle fed various dietary P levels.

Dietary P Level	Manure-P in Excess of Crop Demand[1]	Change in Soil Test P
(%)	(lb/acre/year)	(ppm P/acre/year)
0.35	-3.0	-0.4
0.38	-0.1	0
0.48	10.4	1.3
0.55	17.6	2.2

[1] Assumes a stocking density of 1 cow per 1.8 acres and a crop P removal of 27 lb P/acre from an alfalfa, soybean, corn grain and silage cropping system.

Source: Powell et al., 2001.

Table 16. Protein and phosphorus content of some common feeds.

Feed	Protein	Nitrogen	Phosphorus	N:P Ratio
	- - - - - - - - - - - - % of dry matter	- - - - - - - - - - - - - - -		
Bloodmeal	95.5	15.3	0.30	51.0
Soybean meal (48% CP)	49.9	8.0	0.70	11.4
Brewer's grains	29.2	4.7	0.67	7.0
Cottonseed	23.5	3.8	0.60	6.3
Corn distillers grains	29.7	4.8	0.83	5.8
Corn gluten feed	23.8	3.8	1.00	3.8
Wheat midds	18.5	3.0	1.02	2.9
Wheat bran	17.3	2.8	1.18	2.4
Meat and bone meal	54.2	8.7	4.73	1.8

Source: NRC, 2001.

ments fed on Wisconsin farms (**Table 16**). Most dairy producers purchase protein and mineral supplements based on availability and cost. Protein supplements commonly used in dairy rations often contain a significant concentration of P as well. For livestock operations needing to pay attention to soil P criteria, protein supplement choices may have to be altered to those containing lower P contents.

Low Phytate Corn and Phytase in Livestock Diets

Additional P management options being explored involve plant and livestock genetic manipulation for more effective manure-P management from monogastric animals (nonruminants such as swine and poultry). All these techniques attempt to reduce the P content in manure of monogastric animals by improving the efficiency with which the animal extracts P from feed. These options increase P uptake by the animal from feed grains and reduce the amount of P that bypasses the animal via the manure. Increasing animal uptake of P can allow manure application rates to continue or even be increased due to the slower build-up of soil P because of the reduced P content of the manure.

Reducing the phytate level of feed grains by use of low-phytate, high available-phosphate (HAP) varieties is one strategy. In corn and most feed grain plants, P is stored in the phytate form that is largely unavailable to non-ruminant livestock. As a consequence, swine and poultry feed is routinely supplemented with P, usually di-calcium phosphate. The unutilized phytate-P from the plant is excreted by the animals resulting in manure that is enriched in P content (Doerge, 1999). Plant breeders and geneticists have been working on the development of low-phytate grain hybrids that will store P in the available phosphate form rather than as phytate (Raboy et al., 1994). Corn has been the crop most extensively developed. Phosphorus availability to animals has been shown to increase when low-phytate corn is consumed. Generally, P availability to monogastrics from low-phytate corn is about two to three times higher than from normal corn (Ertl et al., 1998). The use of low-phytate manure has the potential for environmental benefits when manure rates are based on either a N- or a P-based strategy. A study of swine manure by Zublena et al. (1993) found that when manure application rates were based on the N requirement of the crop, the use of low-phytate manure reduced applied P by 30% over standard manures. When manure rates were restricted to meet only the P removal of the harvested crop, the use of low phytate manure allowed for a 44% increase in the application rate. Low phytate manure could be spread on 30% fewer acres than the same amount of standard manure. Currently, the challenge to plant breeders is to incorporate the low-phytate trait into commercial hybrids with other desirable agronomic traits (Doerge, 1999).

Another option for reducing the P content of manure from monogastric livestock is the use of commercially produced enzymes as a feed supplement (Kornegay, 1996). Phytase enzymes are capable of releasing phytate-P from plants into animal-available forms. Phytase enzymes occur naturally in some microorganisms, plants, and animals such as ruminants (cattle). Mongastric animals lack phytase and can only poorly utilize the P reserves in many grains (Doerge, 1999). By adding phytase enzymes to nonruminant animal feed, the efficiency of P uptake during digestion can be increased (Kornegay, 1996). These studies showed an associated reduction in the P content of the manure of monogastrics of 25-30%. In another study (Baxter et al., 1998) where both phytase additives were combined with low-phytate corn, a reduction in P excretion of 60% was recorded. While the phytase enzyme has been shown to decrease the need for mineral P additions, the economics of its use as a routine feed additive require evaluation (Daniel et al., 1998).

Prioritization of Phosphorus Management Areas

Agricultural and environmental programs relative to P and water quality protection are being developed both nationally and by the state of Wisconsin. The Natural Resources Conservation Service (NRCS) is formulating policy that emphasizes P, as well as N, application rates in nutrient management plans (NRCS, 1999). A P-based approach to nutrient management planning may be required when manure is applied under various field conditions. It is imperative that practical, yet reasonably accurate site assessment tools be used for identification of areas where P-based planning needs to occur. Researchers have observed that it is common for limited areas to contribute the majority of P leaving a landscape (Gburek and Sharpley, 1998). Pionke et al., (1997) report that less than 10% of the area within agricultural watersheds they have studied is responsible for the majority - 90% - of the P exported in the runoff. Given such conclusions, it is imperative that management practices be prioritized for areas prone to losing P. Several approaches for identifying fields where a P-based nutrient management strategy should be implemented have been identified. These include: 1) Soil test P levels; 2) Soil-specific P threshold levels; 3) P index ratings (NRCS, 1999).

Soil Test Phosphorus Levels

Numerous studies (Bundy et al., 2000; Pote et al., 1996; Sharpley, 1996) have found a correlation between the P carried in runoff and the soil test P content at the soil surface (**Table 17**). In theory as soil P content increases, the potential for P transport in runoff increases. However, the use of soil test P levels as a sole parameter for assessing a field's risk for P loss may be limited for the following reasons: 1) Soil P testing techniques utilize methods of analysis developed to estimate plant availability of P – not algal or aquatic plant availability; 2) The majority of research has only investigated the relation of SP to soil test P levels - SP represents only a fraction of the P entering an aquatic system which can eventually become available (Daniel et al., 1998).

Soil Test Phosphorus Thresholds

The concept of using soil-specific P threshold levels as an inventory tool to identify areas where P-based nutrient management strategies need to be applied has been proposed. Soil P threshold values

Table 17. Soil test P effects on dissolved phosphorus (DP) concentration and load in runoff from no-till corn, Arlington, WI, 1998.

	Soil depth (in.)		Runoff	
Soil Test P Level	0-1	0-6	DP Concentration	DP Load
			(ppm)	(g/ha)
Low	8	3	0.02	3
Medium	10	6	0.02	4
High	39	33	0.15	17
Excessively High	62	51	0.12	15

Source: Bundy et al., 2000.

are soil-specific soil test P levels at which research has shown runoff losses of P to be environmentally significant (NRCS, 1999). The identification of threshold soil test P levels that can be used as a predictive tool for judging the potential for P loss in runoff has been difficult and controversial. Problems include:

1) There is no direct correlation between soil test values calibrated for crop response with soil test values causing nutrient pollution. If soil tests are to be interpreted as predictors of pollution, calibrations of soil test P with losses of P in runoff will be necessary (Beegle et al., 1998).

2) The amount of research investigating such correlations is very limited. There is an inadequate database in most regions to define the relationship between soil test P and P loss in erosion and runoff (Beegle et al., 1998). The research needed for proper identification of threshold values for all the soil types, landscape positions, cropping patterns, etc. may be overwhelming.

Phosphorus Index

A better method for assessing the susceptibility of a landscape to contribute P to surface waters would be a technique that integrates soil test results with other site-specific factors. For nutrient additions to surface water to occur there must be both a **source** of nutrients and a mechanism for **transport** of nutrients to water. Sources of P can include fields with high levels of soil test P, manure or fertilizer applications. Transport of P occurs through runoff, erosion, and, occasionally, leaching. A key concept to effectively managing P losses is to focus on landscape areas where source and transport factors coincide (**Fig. 17**) By identification of such critical areas for P loss to water bodies, appropriate management practices can be imposed on these sites while allowing flexibility in fertilizer and manure management in non-critical areas of the landscape (Beegle, 1999).

The P index concept (Lemunyon and Gilbert, 1993) is an example of an assessment tool that considers both P source and P transport criteria when ranking the susceptibility of a landscape. Research by Sharpley (1995) has shown a relationship between the P index and total P loss from a watershed. This work has also identified some limitations of the P index. A P index has been developed for use in Wisconsin and work continues to improve the model. The latest information on the Wisconsin P index can be found at the following website:

http:// wpindex.soils.wisc.edu

Figure 17. Critical phosphorus source and transport area indentification.

Conclusion

The previous pages provide a brief summary of agricultural management practices available to Wisconsin crop and livestock producers for reducing the impact of P on water quality while protecting farm profitability. Selection of appropriate P management practices for individual farms needs to be tailored to the specific conditions existing at a site. However, an overall goal of any agricultural operation should be to balance inputs of P (fertilizer, feed, etc.) with outputs (crop and animal products) and to manage fields in ways that retain soil nutrient resources (Sharpley, et al., 1999).

The implementation of management practices to reduce soil P levels will require time to show effect. Soil test P levels change slowly regardless of whether they are building or lowering. **Table 18** tracks the reduction in soil test P over the course of a 6-year crop rotation commonly found in Wisconsin. In this example, the field has an average soil test P value of 75 ppm at the beginning of the rotation - an excessively high value relative to most grain and forage crops needs. Over the course of this six year rotation in which no additions of any form of P are applied, soil test P is reduced by 18 ppm resulting in a soil test P value of 57 ppm. A value that is still excessively high! Table 18 illustrates the fact that it can take several years to draw-down (or build-up) soil test P values.

Management practices for minimizing P contributions to lakes and streams will be most effective if they are applied to fields that have greatest potential for P delivery. Not all agricultural fields are an equal threat to water quality as most P that reaches surface water originates from a small portion of a landscape during a few rainfall events. These high risk areas need to be accurately identified and then prioritized for management practices that will minimize P loss.

Table 18. Phosphorus removal over a six-year crop rotation.

Corn @150 bu/a removes 55 lb P_2O_5/a/yr x 2 years	=	110 lb P_2O_5
Oats @ 100 bu/a removes 25 lb P_2O_5/a/yr x 1 year	=	25 lb P_2O_5
Alfalfa @ 5 tons/a removes 65 lb P_2O_5/a/yr x 3 years	=	195 lb P_2O_5
Removal of P_2O_5 over 6-year rotation [1]	**=**	**330 lbs P_2O_5**
Change in soil test P (330 lb P_2O_5 / 18 lb P_2O_5) [2]	**=**	**18 ppm P**
Soil test P after the 6-year rotation (75 ppm P – 18 ppm P)	**=**	**57 ppm P (**still excessively high**)**

[1] *Source: Kelling et al., 1998.*

[2] *Soil P buffering capacity is the amount of nutrient (oxide basis) required to change the soil test P level (elemental basis) by 1 ppm. The P buffering capacity for most of Wisconsin's soils is 18 - meaning that 18 lbs/acre of phosphate (P_2O_5) must be either added or removed from the soil to change the soil test P value by 1 ppm (Kelling et al., 1998).*

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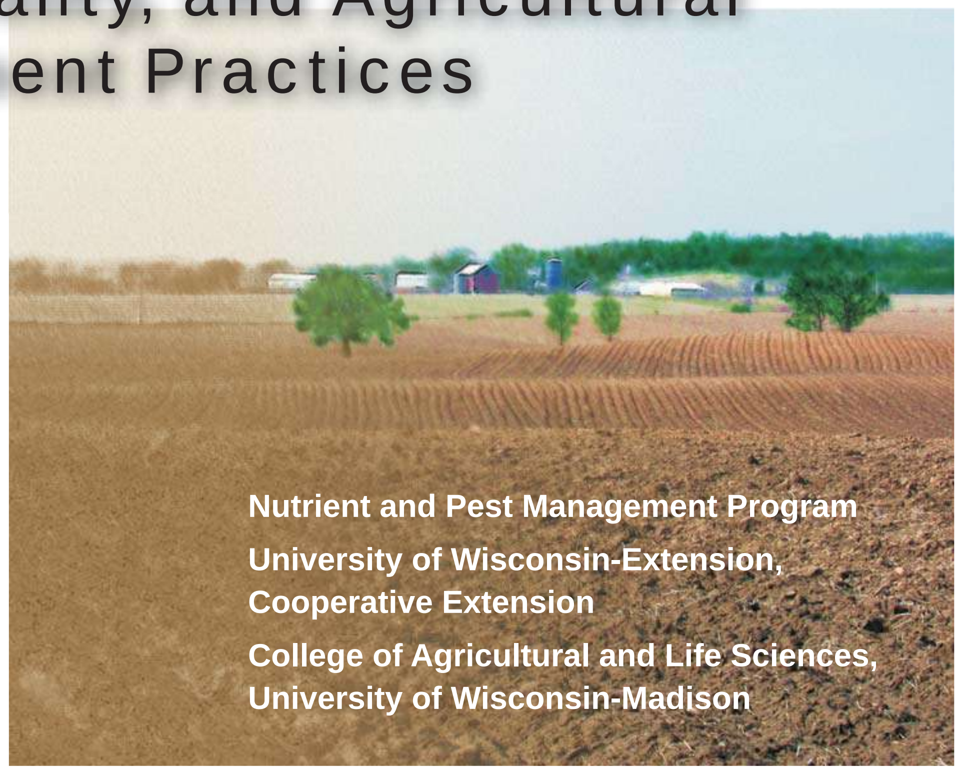
An Overview of Phosphorus, Water Quality, and Agricultural Management Practices



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