



Effects of Swine Manure Applications on Soil Nutrient Levels and Phosphorus Loss Risk

**Results from a southwest Minnesota monitoring project and
the application of the Minnesota Phosphorus Index**

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Acknowledgements

The swine manure monitoring study depends on county funding and the cooperation of the pork producers who supply records and access to fields.

Concerns with Land Application of Swine Manure

Many areas in Minnesota have seen rapid and sweeping changes in swine production practices in the past decade (Elias Morse, 2001). Structural changes in the industry have resulted in numerous large swine finishing buildings with liquid manure stored in under-slat pits. The manure is periodically land applied, usually in the fall after soybeans and before corn in the typical corn-soybean rotation.

There are some concerns that nitrogen, phosphorus, and trace elements in the manure may build up in the soil to problematic levels. Nitrogen (N) losses to tile drainage systems and ground water are controlled primarily by setting application rates to match the N needs of the first crop following application. Appropriate application practices also account for season and temperature, soil type, potential carry-over N from previous years, and geology.

Phosphorus (P) loss to lakes and streams is associated with elevated soil P levels, direct P losses from manure, and especially with high erosion rates related to steep slopes, proximity to water body, and some tillage practices. Elevated soil P levels are often caused by a history of excessive manure application. The amount of N relative to P in manure is usually less than that required by most crops, including corn. Thus, when manure is applied at a rate estimated to meet N requirements, P may be applied in excess of the crop P requirements. This may be partially offset in the common corn-soybean rotation when manure is not applied during the soybean year and the soil phosphorus level is drawn down somewhat. The amount of P used and P availability are affected by soil, climate, and crop yield.

Manure contains several heavy metals and other elements. Some are micronutrients that are essential to plant growth. Compared to other

types of manure, swine and poultry manure have higher levels of copper (Cu) and zinc (Zn) because these nutrients are added to feed (Augenstein et al., 1994). Soil levels of Cu and Zn may build up after long term or heavy manure applications. Excessive levels of Cu and Zn can induce deficiencies of iron and other nutrients (Marschner, 1995; Tisdale et al., 1993).

Swine manure applications are unlikely to cause soil levels of Cu and Zn that are toxic to plants. The level of soil copper and zinc at which plants are affected is variable and depends on plant species, pH, organic matter, and levels of other metals and nutrients (Chaney, 1993). Borkert et al. (1998) identified critical soil levels of 10 ppm Cu (Mehlich-3) for corn, 43 ppm Zn for soybeans, and 185 ppm Zn for corn¹. Tucker et al. (2005) stated that critical toxic levels for plants that are not unusually sensitive are 60 ppm for Cu and 120 ppm for Zn (Mehlich-3). Some U.S. and Minnesota agricultural soils are above these levels (Holmgren et al., 1993; Linden et al., 1995). Levels of 1 to 3 ppm Cu and 4 to 8 ppm Zn on sites with long-term dairy manure applications were measured by Schmitt (1999).

The U.S. Environmental Protection Agency (USEPA) does not restrict biosolid applications based on Cu and Zn until the material has more than 1500 mg/kg of Cu or 2,800 mg/kg of Zn (USEPA, 1994). Swine manure is typically enriched to about 1,000 mg/kg for both Cu and Zn (Chaney, 1993). Cumulative application limits for a plot of land are 1,500 kg of Cu or 2,800 kg of Zn per acre (1,335 and 2,492 lbs/ac).

¹Original data from Borkert et al. were 17 mg Cu/dm³, 70 mg Zn/dm³, and 300 mg Zn/dm³. Conversions to ppm assumed soil bulk density of 1.4.

Accuracy in reaching targeted nutrient application levels with manure can be challenging because of

- variation in the forms and quantities of nutrients,
- challenges in calibrating equipment,
- use of equipment not designed for low-rate application,
- lack of sufficient acres to apply at appropriate rates, and
- practical constraints that compel producers to apply manure using less-than-optimal methods or timing.

Also, producers may try to ensure an adequate N supply by using an estimate of N availability that is lower than general recommendations, and thus will calculate higher manure rates.

Southwest Minnesota Monitoring Study

Description of the monitoring sites

Since 1998, a county water planning committee in southwest Minnesota has funded an ongoing on-farm monitoring project in cooperation with Bob Koehler (Extension Educator-Livestock Systems at the Southwest Research and Outreach Center). The objective is to study the potential for nutrient build-up in soils with swine manure applications to better understand the impact of the swine finishing operations typical of those built in the mid-1990s.

Manure and soil nutrient levels have been monitored in nine fields that receive biennial liquid swine manure applications originating from six deep-pitted, slatted-floor, swine-finishing barns and one slatted-floor nursery barn. Fields are in a corn-soybean crop rotation with manure injected every other year after soybean harvest. Seven sites have been sampled since the fall of 1998. Two sites were added in 1999 and one was dropped after 2004.

Study methods

Approximately one acre in each field is sampled annually in the fall just before harvest, with 16 probes comprising the sample. Samples are taken to a 7-inch depth. The sample areas are identified by the number of paces from a permanent landmark and samples follow a grid pattern also measured by paces. Soil is tested for soluble salts, pH, phosphorus, potassium, sulfur, zinc, iron, manganese, copper, boron, calcium, and magnesium.

Four sites (Fields 1, 4, 7, and 9) started with very high P levels. The high P levels are probably associated with a history of manure application but long term records are not available to confirm this. The remaining fields had very low or low soil test P levels in 1998.

Manure and nutrient application rates for each field site are shown in **Table 1**. Manure was tested for total N, ammonium N, P, and potassium (K). Before 2001, applications were made with a drag-hose technology typical for that time, which did not allow for low-rate applications. Thus, application rates were higher than commonly recommended, and were higher than rates applied since 2001 when applicators started using slurry tankers. Average rates with the drag hose were 6,050 gallons per acre, resulting in the application of 262 lbs/acre of estimated available N, and 188 lbs/acre of phosphate (P_2O_5). Application rates with the slurry tanker declined over the period and averaged 4,180 gallons per acre, resulting in the application of 189 lbs/acre of estimated available N, and 140 lbs/acre of P_2O_5 . Modifications to equipment, including the addition of flow controllers, will make rates just above 3000 gallons per acre possible beginning in 2006.

Manure nutrient tests were used to estimate daily nutrient production per pig.

Table 1: Manure application rates

Manure was injected with a drag hose from 1998 through 2000, and with a slurry tanker beginning in 2001.

Field	Year	Fall manure (gal/ac)	N - - - (lbs/1000 gal) - - -	P ₂ O ₅	K ₂ O	Avail. N ^a - - - - - (lbs/ac) - - - - -	P ₂ O ₅	K ₂ O
1	1999	5400	59.5	39.0	43.5	258	211	236
	2001	4200	54.0	41.0	39.0	181	172	164
	2003	4200	58.3	34.0	36.7	196	143	154
	2005	4000	61.5	31.0	40.5	197	124	162
2	1999	5400	59.5	39.0	43.5	258	211	236
	2001	4200	54.0	41.0	39.0	181	172	164
	2003	4200	58.3	34.0	36.7	196	143	154
	2005	4000	61.5	31.0	40.5	197	124	162
3	1999	5400	61.0	31.5	43.5	264	171	236
	2001	4200	71.5	59.0	43.5	240	248	183
	2003	4250	72.5	45.5	41.0	247	193	174
	2005	4000	51.0	32.5	31.0	163	130	124
4	1998	5400	56.0	22.0	33.0	242	119	178
	2000	4450	63.0	43.0	42.0	224	191	187
	2002	4200	52.0	34.5	34.5	176	146	146
	2004	4100	57.0	26.0	42.0	188	107	173
5	1998	5400	56.0	22.0	33.0	242	119	178
	2000	4450	63.0	43.0	42.0	224	191	187
	2002	4200	52.0	34.5	34.5	176	146	146
	2004	4100	57.0	26.0	42.0	188	107	173
6	2000	5700	76.5	49.5	46.5	348	281	264
	2002	4200	70.0	46.5	43.0	235	195	181
	2004	4200	64.5	34.0	40.0	218	144	169
7	1998	7500	49.5	25.5	28.5	297	191	214
	2000	8750	42.0	26.5	24.5	294	232	214
	2002	4200	43.0	24.0	27.5	145	101	116
	2004	4200	56.0	19.5	36.5	189	82	154
8	1999	7450	38.5	20.0	25.0	230	149	187
	2001	4200	37.5	26.0	31.0	126	109	130
	2003	4200	57.0	33.5	33.0	196	142	139
9	1999	7200	46.0	27.0	33.0	264	194	237
	2001	4200	52.0	34.5	30.0	175	145	126
	2003	4200	50.0	24.0	29.5	169	101	125
	2004	4250	45.0	27.0	33.0	153	115	140
Average		4836	56	33	37	215	157	174
Avg. (drag hose)		6045				262	188	213
Avg. (slurry tank)		4177				189	140	153

^a Available N is calculated as 80% of total N (Schmitt, 1999).

Monitoring results

Manure nutrients

Liquid manure nutrient data are shown in **Table 2** and **Table 3**. Nitrogen levels in the liquid manure ranged from 44 to 70 pounds per 1000 gallons when averaged by barn for the 7- to-8-year monitoring period. Ammonium-N was more than 80% of total N, which is higher than published values of 50% to 75% (Lorimor et al., 2004). Nearly 100% of ammonium-N and only about 30% of organic-N is available to crops

Table 2: Manure trace elements

	2006 manure test (dry weight)	Estimated annual application (lb/ac/yr) ^a
Calcium	35,000 mg/kg	32
Magnesium	19,000 mg/kg	17
Sodium	22,000 mg/kg	20
Sulfur	9,000 mg/kg	8.6
Copper	230 mg/kg	0.2
Iron	2,553 mg/kg	2.3
Manganese	574 mg/kg	0.5
Zinc	1,821 mg/kg	1.7

^a Assumes 4800 gallons per acre applied every other year and 2006 manure nutrient levels.

in the first year. Thus, with a high proportion of ammonium, the availability of total N in this manure is likely to be slightly higher than the University of Minnesota recommended estimate of 80%, which assumes average proportions of ammonium and organic-N (Schmitt, 1999). As application technology allows for lower manure rates to match crop N needs, it becomes more important to accurately estimate N availability.

P₂O₅ levels averaged 35 lbs per 1000 gallons of manure before phytase was added to diets and averaged 28 lbs per 1000 gallons after phytase was added starting in 2004. For all sites over all years the average annual application of P was 79 lbs P₂O₅/ac/yr. A lower rate in 2004 and 2005 of 58 lbs P₂O₅/ac/yr reflects the combination of declining manure application rates and lower P concentration in manure. These values are somewhat higher than the expected annual P removal rate of 51 lbs P₂O₅/ac, which assumes 190-bushel corn at 0.34 lbs P₂O₅ removed per bushel and 45-bushel soybeans at 0.82 lbs P₂O₅ removed per bushel (USDA). With the use of dietary phytase, P applications would equal crop removal if 3,500 gal/ac of manure were applied in alternate years. At this rate, estimated available N applications would be 160 lbs/ac.

Table 3: Manure test results

Average of two barns at each site for seven or eight years.

Site	Manure test per 1000 gallons						Rate per acre (applied alternate years)			
	Dry matter (%)	N (lbs)	Org.-N (lbs)	NH ₄ ⁺⁻ N (lbs)	P ₂ O ₅ (lbs)	K ₂ O (lbs)	Manure (1000 gals)	Avail. N ^a (lbs)	Total P ₂ O ₅ (lbs)	Annual excess P ^b (lbs P ₂ O ₅)
A	5.5	58	9.0	49	35	39	4.4	203	156	28
B	4.9	53	8.2	41	29	31	5.2	189	148	23
C	6.8	67	12.9	54	45	41	4.7	251	211	55
D	3.6	47	7.1	40	25	29	5.5	200	142	21
Mean	5.2	56	9.3	46	33	35	4.9	210	164	32
SD	1.3	8.1	2.7	6.3	8.3	5.5	0.5	29	33	17

^aAvailable N is assumed to be 80% of total N (Schmitt, 1999).

^bAssume 60 lbs P₂O₅ removed by corn crop and 41 lbs P₂O₅ removed by soybean crop.

Average copper and zinc content of the manure in 2006 was 230 mg Cu/kg and 1800 mg Zn/kg of manure (dry weight). Reported typical levels are 1,000 mg Cu/kg and 1,000 to 2,000 mg Zn/kg (Clemson University, 2006; Chaney, 1993). At 4,800 gallons of manure per acre, application rates would be 0.42 lbs Cu/ac and 3.3 lbs Zn/ac. These rates are far below EPA annual limits of 67 lbs Cu/ac and 125 lbs Zn/ac, and cumulative limits of 1,335 lbs Cu/ac and 2,492 lbs Zn/ac (USEPA, 1994).

Nutrient production by swine

Nutrient production per pig was estimated for each barn based on records of gallons pumped and average manure test values (Table 4).

Total P₂O₅ production was slightly lower than published values (Lorimor et al., 2004). The use of dietary phytase beginning in 2004 reduced P production per pig by 26%.

Soil phosphorus

Soil phosphorus levels varied substantially from year to year, rising an average of 5 ppm Olsen-P in the year after manure application and falling the following year. Over the nine-year study, the five fields that started with low P levels rose from about 6 ppm Olsen-P and appear to have stabilized at about 22 ppm (Fig. 1). Over nine years, soil test P levels in individual plots have not exceeded 36 ppm on any of the fields with initially low P. This declining rate of build-up

Figure 1: Soil test P (STP) and manure application rates

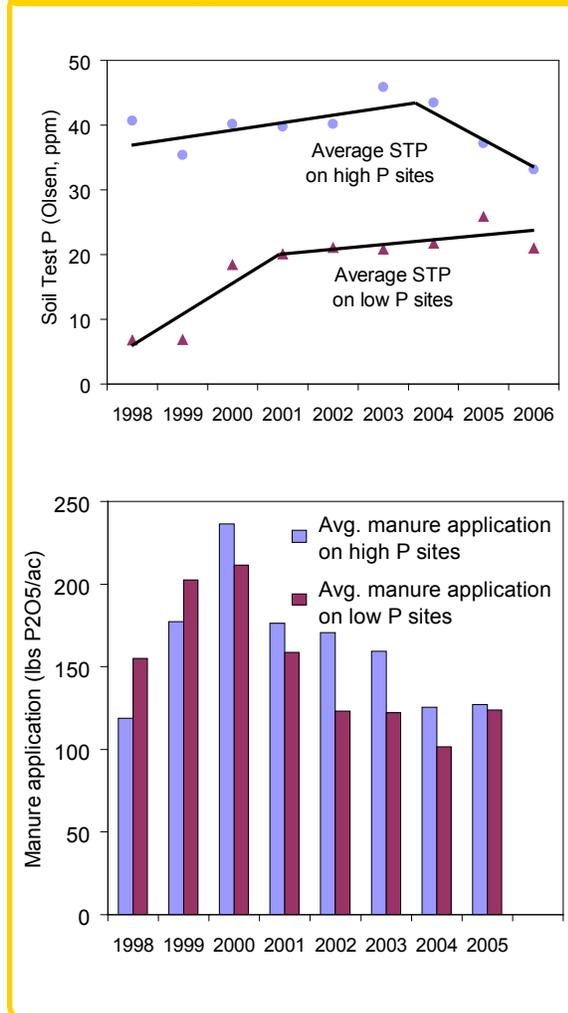


Table 4: Estimates of daily manure and nutrient production per animal^a

	Average over all barns	Published values ^b	Monitored sites compared to published values
Manure (gallons)	0.91	0.89	102%
Nitrogen hauled (pounds)	0.052	0.047	111%
Nitrogen excreted (pounds) ^c	0.065	0.059	111%
P ₂ O ₅ hauled (pounds)	0.031	0.036	86%
K ₂ O hauled (pounds)	0.032	0.033	97%

^a 2001-2005 data. Assumed 670,000 pig-days per 2000-head capacity site and average animal weight of 150 lbs.

^b From Lorimor et al., 2004, Table 7 for wet/dry feeders (annual production per pig space/365 days).

^c Assumed 20% of N is lost in storage.

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of soil test P could be explained by high tie-up of P by the calcareous soils or by the movement of P down through the soil below the sampling depth. Downward P movement is consistent with the observation that soil test P is less stratified in the sites with initially high soil test P, which are thought to have a history of manure application (**Fig. 2**). Manure applications increase the solubility and downward movement of P (von Wandruszka, 2006). The average soil test P increase for all sites was 1.2 ppm Olsen-P per year. The increase for fields with initially low soil test P was 2.0 ppm per year. Increases were higher during the first four years following higher manure application rates (**Table 5**).

Soil trace elements

Levels of trace elements have been variable from year to year but no trends have been apparent (**Table 6**).

Figure 2: Effect of depth on soil test phosphorus (STP), 2006

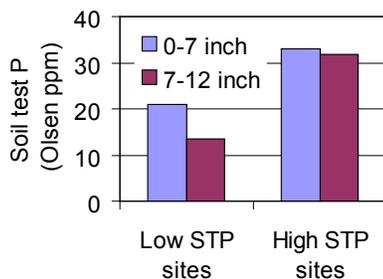


Table 5: Change in soil test P

	Manure rate	Change in soil test P	
		low P sites	high P sites
1998 to 2001	188 lbs P ₂ O ₅ /ac	5.1 ppm/yr	0.2 ppm/yr
2002 to 2006	140 lbs P ₂ O ₅ /ac	0.5 ppm/yr	-2.3 ppm/yr

Table 6: Soil properties (average over all sites and years)

pH	6.9
Soil organic matter	5.2%
Boron	1.3 ppm
Calcium	3,590 ppm
Copper	2.2 ppm
Iron	66 ppm
Magnesium	633 ppm
Manganese	17 ppm
Phosphorus (Olsen)	27 ppm
Potassium	199 ppm
Soluble salts (E.C.)	0.30 mmhos/cm
Sulfur (SO ₄ -S)	9.2 ppm
Zinc	3.1 ppm

Using the Minnesota Phosphorus Index to Analyze Swine Manure Applications

Description of the MN P Index

The Minnesota Phosphorus Index (MN P Index) is a tool designed to estimate the relative risk of P loss from farm fields (Lewandowski et al., 2006). It is a decision-support tool that allows users to evaluate management alternatives that may reduce this risk. The MN P Index is not intended to be used as a regulatory tool nor to estimate changes in surface water quality measurements. The MN P Index program, user guide, and technical guide are available on-line (<http://www.mnpi.umn.edu>).

The MN P Index model considers three pathways of P movement across the landscape (**Fig. 3**). The first is the transport of sediment-bound P associated with the eroded particles in rainfall runoff. The second is the transport of dissolved P by rainfall runoff. The third is

the transport of P by spring snowmelt. Losses from these three pathways are added, giving a total P index (unitless) for the given site. This index value represents the relative long-term average risk of P losses for a given site and set of management practices.

Inputs to the MN P Index include soil type, distance to surface water, crops, tillage systems, and manure and fertilizer P application amounts and methods. Erosion rates are an important input and are calculated by the P Index using the RUSLE2 erosion prediction model.

Analysis methods

The MN P Index (version 1.3) was used to estimate P loss risk from the monitoring sites (Table 7), and to determine what factors most affect P loss risk by testing P loss risk from a typical range of Minnesota hog farms (Table 8). The typical farms were examined by testing a base or average scenario. Alternative values for each input were then varied one at a time to determine the size of their independent effect on MN P Index results.

P Index results

Monitoring sites

Rotation average P loss risk estimates were low or very low for all of the monitoring sites (Table 7). This shows that swine manure can be applied in these landscapes in a manner that does not threaten water resources with excess P. Phosphorus loss risk was highest on sites 7 and 8 due to higher erosion because of steeper slopes and tillage oriented up-and-down the slope. Even when erosion does occur on these landscapes, sediment is often deposited before it reaches surface water because of the long distance between the field and the nearest ditch or stream, or because of ponding occurring around tile inlets.

The MN P Index estimates that soil test P will rise at a rate of about 1 ppm Olsen-P per year, so manure applications at this rate will have only small effects on soil test P and on long term P loss risk.

Figure 3: The Minnesota Phosphorus Index Model

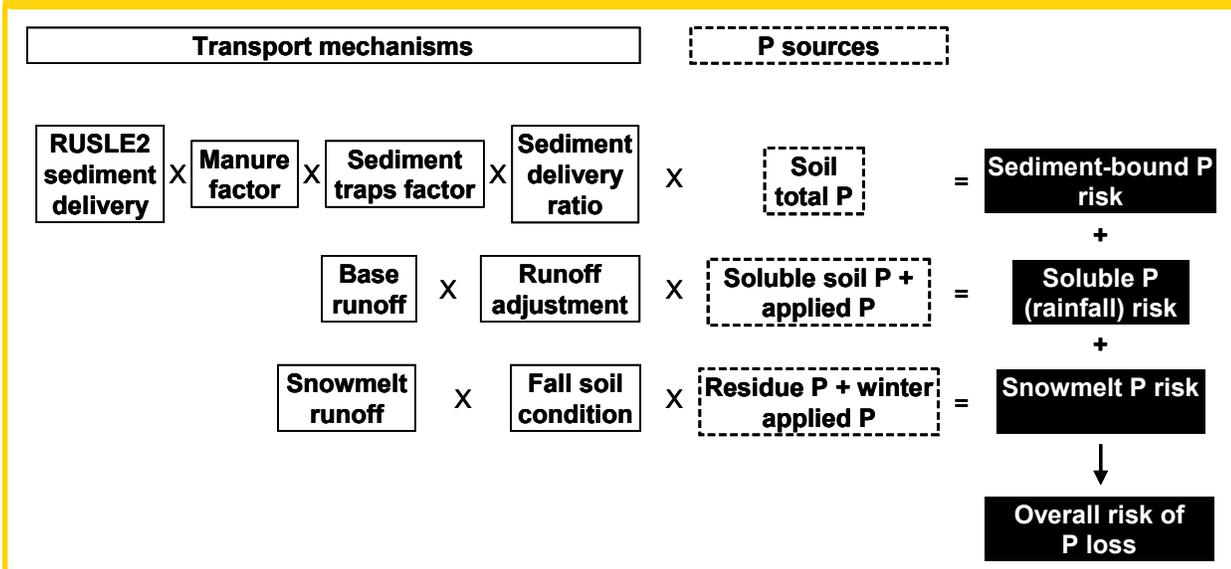


Table 7: MN P Index inputs and results for monitoring sites

	Average for the 9 sites *	Minimum	Maximum
INPUTS			
Drainage	Subsurface drainage tile with open surface inlets, 42% of field drains to inlets	15%	80%
Soil type	Webster cl, Clarion I, Nicollet cl	coarser soils on site 1	
Slope	3%	1%	6%
Initial soil test P	21 ppm Olsen	6 ppm Olsen	55 ppm Olsen
P buffer category	Fine textured soils	Sites 3, 7, and 8 were calcareous	Site 1 was coarse textured
OM	5.3%	4.9%	6.3%
Tillage orientation	Cross slope		Site 8 was up-and-down slope
Distance to water	5,955 ft	2,640 ft	10,560 ft
Cropping system	Alternating years of corn (175 bu) and soybeans (45 bu) Fall chisel plow, spring field cultivate No P fertilizer or fall anyhdrous N 5% to 20% residue cover after planting corn; greater than 20% after planting soybeans.		
Manure	Alternate years, fall injected after soybeans 157 lbs P ₂ O ₅ /ac	82 lbs P ₂ O ₅ /ac	281 lbs P ₂ O ₅ /ac
RESULTS			
Sediment del. (RUSLE2)	1.2 t/a/y	0.4 t/a/y	2.5 t/a/y
Total P Index	0.8	0.6	1.1
Particulate P pathway	0.2	0.1	0.4
Soluble P pathway	0.5	0.4	0.6
Snowmelt pathway	0.1	0	0.1

*Sites 1-7: 1998 to 2005. Sites 8-9: 1999 to 2005.

Effects of individual variables on P loss risk

P loss risk estimates for scenarios where only one variable is changed at a time show the sensitivity of the P loss risk to each variable.

Soil type

P loss risk was somewhat elevated on the Collinwood soil because of its lower hydraulic conductivity. Hydraulic conductivity is a measure of how readily water moves through the soil. Lower hydraulic conductivity means lower infiltration into the soil and higher runoff and P loss over the surface. Soluble P loss risk in the years when manure was applied was double that of the other soils with more typical hydraulic conductivity.

Soil type can also affect erosion rates, but had little effect in these scenarios. Slope gradient and length and management factors were more important in determining erosion rates.

Soil test P

Soil test P affects the risk of sediment-bound P losses and the risk of soluble P loss.

Sediment-bound P loss risk doubled between the low and high P soils (5 ppm Olsen-P vs. 150 ppm Olsen-P) in the test scenarios. Because of the low erosion rates, a doubling of risk is inconsequential in these scenarios but would be important where erosion rates are high or on land near waterways.

Soluble P loss risk (relative P Index value) attributable to soil solution was near zero for

Table 8: MN P Index inputs for testing typical hog farm scenarios

Input category	Base scenario values	Alternative values
Time period	2 years	20 years
Sediment traps	none	
Inlets	Surface, contributing area = 50%	
Tillage orientation	Cross slope	Up/down slope
Distance to water	300 ft	(With no inlets) 10 ft, 25 ft, 300 ft, 1000 ft, and 2000 ft
Initial soil test	20 ppm Olsen 5% OM	5 ppm Olsen 150 ppm Olsen
Soil type	102b Clarion l	33B Barnes loam (9% slope) 86 Canisteo cl (calcareous) 96a Collinwood sic 141a Egeland sl
Slope	2%, 100 ft	9%
Crops	Soybeans (45 bu), Corn (175 bu)	
Tillage	After both crops: Fall chisel Spring field cultivate	After soybeans: Fall disk/Spring field cultivator Fall strip till, Spring no tillage Fall no tillage, Spring field cultivator Fall chisel, spring field cultivator
Manure application	Injected in fall before corn	Winter before corn
Manure rate	175 lbs P ₂ O ₅ /ac	90 lbs P ₂ O ₅ /ac, and 300 lbs P ₂ O ₅ /ac
Residue cover	>20%, 5-20%	

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the low soil test P soil and 0.5 for the high soil test P soil. For comparison, soluble P loss risk attributable to partially incorporated manure adds another 2 index units. In other words, although high soil test P soils have high soluble P losses, direct P losses from manure can be more important.

Long term phosphorus buildup

The soil test P of some soils will increase more than that of other soils in response to the same amount of added manure. For example, the coarse Egeland soil has a lower buffering capacity than the calcareous Canisteo soil and thus will have a higher soil test P after 20 years of manure applications (**Fig. 4**). The buildup of soil P is especially important where erosion rates are high or on land near surface water².

Calcareous soils are common in southwest Minnesota. Calcium precipitates with P making it unavailable to plants and unavailable to be dissolved and lost in runoff. However, P bound to sediments can be carried to surface water by erosion. Once in stream and lake beds, the P may eventually become available to aquatic organisms and lead to eutrophication. For this reason, the MN P Index considers total soil P – not just crop available P – when estimating the risk of sediment-bound P loss.

Distance to water

P loss risk of a field 300 feet from water was half the risk of the same field 10 feet from water. Risk of P loss from a field 2,000 feet from water was two-thirds that of a field 300 feet from water. These differences would be important where erosion rates are elevated.

Manure rate and method

Manure application rate can be the most important determinant of overall P loss risk because surface-applied manure is vulnerable to direct losses of dissolved P that can be much

greater than dissolved P from soil. In the test scenarios, the application rate was increased by 70% from 175 to 300 lbs P₂O₅/ac. The overall risk of P loss was dominated by this change, increasing by 60% during the manure application year and by 50% over the two year rotation. In contrast, if manure is injected, almost none is left exposed to runoff and even high manure application rates will have little short-term effect on P loss risk. Over the long term, high application rates, regardless of application method, will increase P loss risk by increasing soil test P.

Tillage

Reducing tillage and tilling across a slope reduces erosion rates and thus P loss risk. However, most of these scenarios already had low erosion rates because of the small slope gradients. Therefore, tillage had much more effect on snowmelt losses than on sediment P losses.

Winter manure application

Liquid hog manure is rarely applied in the winter but other types of manure may be winter applied. Because of relatively low snowmelt rates in southwestern Minnesota, winter applications have acceptable P loss risk in this scenario, except when there is no fall tillage or tillage runs up and down the slope. Up-and-down slope tillage in the fall before winter manure application increases P loss during spring snowmelt by one-third to one-half compared to cross-slope tillage (**Fig. 5**). P loss risk is substantially higher if the same cropping system is applied in southeast Minnesota where average rainfall runoff is about 33% higher and snowmelt runoff is 75% higher (**Fig. 6**).

²Sharpley et al. (1999) defined “near” as within 200 feet of a waterway.

Figure 4: Effect of buffering capacity on estimated change in soil test P

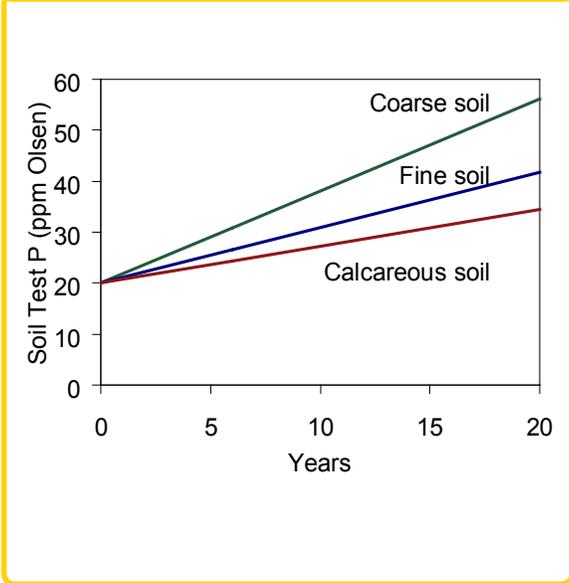


Figure 5: Effect of tillage orientation on snowmelt P loss risk after winter manure application

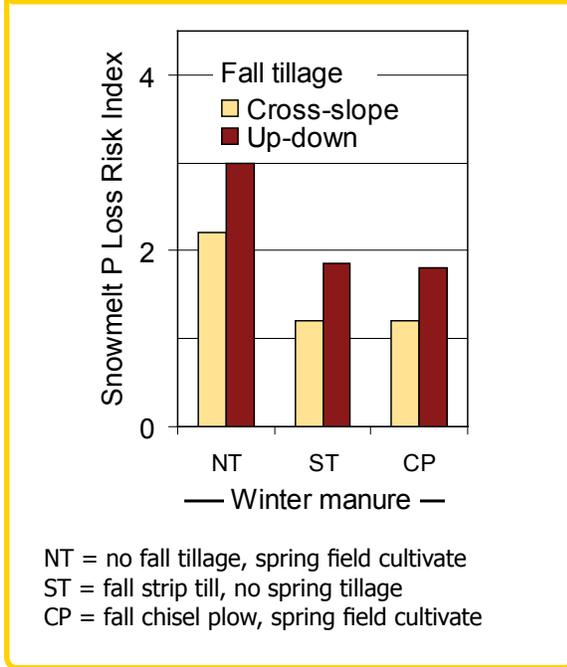
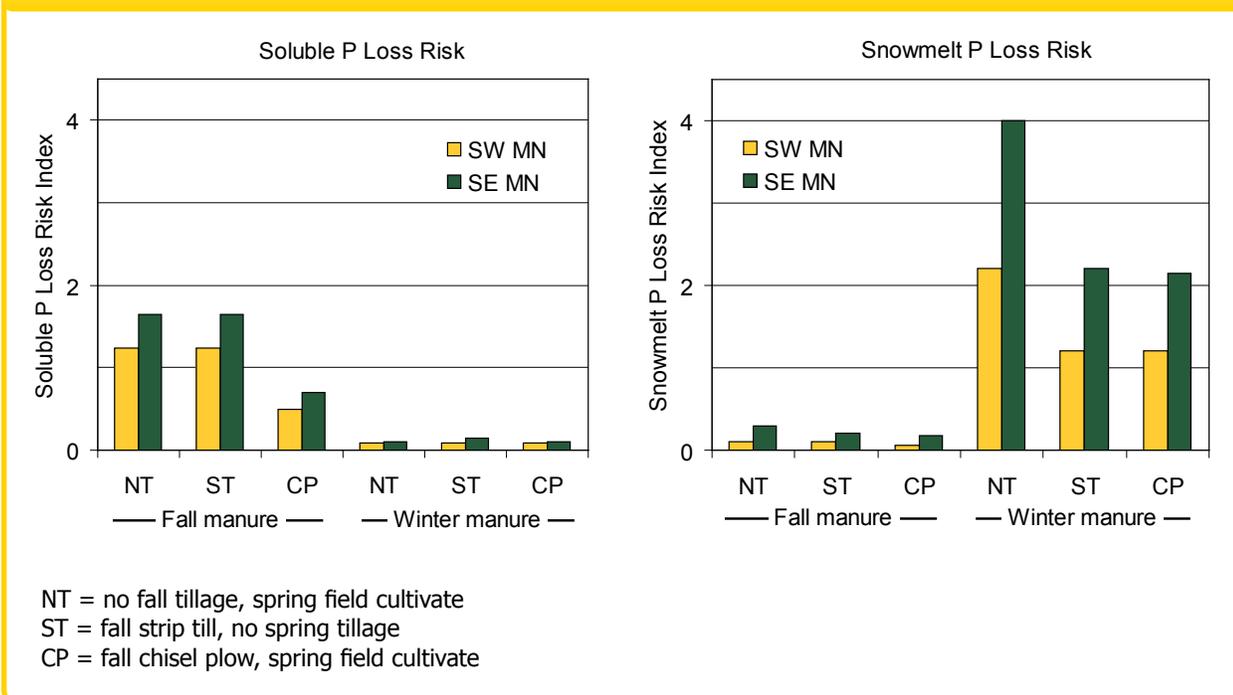


Figure 6: Effect of climate, and timing and incorporation of manure on P Index



Summary

Monitoring sites observations

- Soil test P did not increase linearly. Soil test P in fields originally testing low for P increased significantly after the first few manure applications and then increased only slowly from subsequent applications. Soil test P in fields originally testing high for P increased only slowly from manure applications.
- Per pig nutrient production estimated from manure test and gallons produced was similar to daily production estimates from MWPS (Lorimor et al., 2004).
- The proportion of ammonium to organic N was higher than typical values, making the total N slightly more available in the first year than commonly estimated.
- Manure application rates have trended downward over the observation period because of improvements in and adoption of manure application technology including the use of a tanker in place of a drag hose and improved controller equipment.
- With lower application rates (3,500 gallons/acre) and the use of dietary phytase, manure P application will not exceed two-year crop removal estimates for P.
- Trace mineral levels in the soil have not changed significantly over the observation period.

Phosphorus Index observations

- Based on the MN P Index, the monitoring sites pose minimal risk of P delivery to the nearest water bodies.
- P loss risk from swine manure applications primarily depends on the rate and method of application. P loss risk can be minimized by controlling erosion, avoiding winter manure applications, limiting rates for any single manure application to the equivalent of about 200 lbs P_2O_5 /ac, and limiting total applications over several years to amounts that prevent buildup of excessive soil P. The limit on single application rates will be lower if manure is not incorporated and in places with higher runoff, such as on soils with poor infiltration or in higher-rainfall regions of the state.
- Soil test P increases are moderate at N-based manure application rates.
- Soil test P levels depend on soil type. The elevated calcium carbonate levels in many soils of southwest Minnesota tend to buffer soil against soil test P increases. Although less available to plants, the P is still in the soil and can be carried via erosion to surface water.
- The MN P Index is useful for assessing the relative risk of P loss associated with animal agriculture in Minnesota. The Minnesota Phosphorus Index allows users to examine the effect of multiple P loss risk factors to estimate site-specific risk.

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