Watershed Phosphorus Reduction Planning Tool (PBMP.xlsm) for Comparing the Economics of Agricultural Practices to Reduce Watershed Phosphorus Loads

by

William F. Lazarus, David J. Mulla, David Wall, Jake Galzki and Jian Tang

September 29, 2015

Watershed Phosphorus Reduction Planning Tool (PBMP.xlsm) for Comparing the Economics of Practices to Reduce Watershed Phosphorus Loads

by

William F. Lazarus[1], David J. Mulla[2], David Wall[3], Jake Galzki[4], and Jian Tang[5],

Introduction

The Watershed Phosphorus Reduction Planning Tool (file name PBMP.xlsm) Excel spreadsheet was developed under a contract between the Minnesota Pollution Control Agency and the University of Minnesota, to be used as a tool for refining Minnesota's Nutrient Reduction Strategy and allowing that strategy to be incorporated into planning at the watershed level. The project purpose was to develop a framework for a watershed phosphorus planning aid that could be used to compare and optimize selection of "Best Management Practices" (BMPs) for reducing the phosphorus load from the highest contributing sources and pathways in a watershed. PBMP.xlsm is intended to serve as that framework. It compares the effectiveness and cost of potential BMPs that could be implemented to reduce the phosphorus load entering surface waters from cropland in a watershed.

This spreadsheet is intended for use by water resource planners evaluating how phosphorus loads in the watershed can be reduced to achieve water nutrient goals. Such resource planners would normally not be the crop producers who would actually be deciding whether or not to implement any of the practices listed. Another potential use for the spreadsheet might be to help decide the levels of subsidies or other incentives appropriate for producers who would be making such implementation decisions.

Loading the spreadsheet on your computer

The link to download the PBMP.xlsm spreadsheet is http://z.umn.edu/nbmpdoc. You will be prompted to enter your contact information.

Important note: PBMP.xlsm includes a number of macros and functions written in Excel's VBA programming language to help automate various calculations and to help navigate to different parts of the calculations, so clicking that button allows them to run. In order to run the PBMP.xlsm spreadsheet effectively, you will need to "enable macros" and have Excel Solver installed on your computer. If you were not prompted to "Enable Content" when you first open the spreadsheet, then you will need to change your "Macro Security" level to "Disable macros WITH notification.".Then, save the spreadsheet and open it again, and this time enable macros at the prompt.

To install Solver, first save and close the PBMP.xlsm spreadsheet. Then select File, Options, and Add-ins in Excel. If you don't see "Solver Add-in" under Active Application Add-ins, make sure "Excel Add-ins" is

[1] Professor, Department of Applied Economics, University of Minnesota
[2] Professor, Department of Soil, Water, and Climate, University of Minnesota
[3] Senior Hydrologist, Watershed Division, Minnesota Pollution Control Agency
[4] Fellow, Department of Soil, Water, and Climate, University of Minnesota
[5] Graduate Research Assistant, Department of Applied Economics, University of Minnesota

showing in the "Manage:" box at the bottom, and click "Go...". Then, check the box next to "Solver Add-in" in the list of Add-ins available. Finally, re-open the PBMP.xlsm spreadsheet.

Excel 2013 is the version we use with these spreadsheet. Excel 2010 and 2007 will probably work, but no guarantees. Earlier versions of Excel than 2007 will definitely NOT work. It has NOT been tested on an Apple Macintosh computer.

Geographic boundaries

The overall acreages considered in the model are acres of cropland (cultivated agricultural land). Two geographic units that are important for users to understand when using the spreadsheet are watersheds and agroecoregions. The spreadsheet calculates load reductions and associated costs for a watershed that the user selects. The spreadsheet contains data for 68 HUC8 watersheds and for Minnesota as a whole. It also contains data for the portions of the ten major river basins that at least partially exist in Minnesota as well as the part of the overall Mississippi River basin in Minnesota. The analysis can also be narrowed down to a specific HUC10 watershed that can be selected from those in a given HUC8 watershed. The soil, crop, and phosphorus loading data in the spreadsheet are initially calculated for each of 39 separate agroecoregions. Agroecoregions are units having relatively homogeneous climate, soil and landscapes, and land use/land cover. Agroecoregions (referred to simply as "regions" below) can be associated with a specific set of soil and water resource concerns, and with a specific set of management practices to minimize the impact of land use activities on soil and water resource quality. A watershed typically includes parts of several regions. When the user selects a watershed for analysis, the spreadsheet retrieves the acres of each agroecoregion in that particular watershed, along with the soil, crop, and phosphorus data for those regions. Three other agroecoregions contained in Minnesota are not included in this spreadsheet because they contain little cropland.

The model is based generally on a phosphorus index methodology as discussed in (Birr and Mulla 2001). A description of the phosphorus index and updates made to it for use in this model is included as an appendix to this documentation. The soil, crop, and phosphorus loading data were provided by David Mulla and his staff. The spreadsheet is continually being improved over time, so the results from the current version will be slightly different from what is shown in that chapter.

BMPs and Associated Assumptions

Assumptions underlying the calculations are described in Tables 1 and 2 below. The spreadsheet compares various individual practices and combinations of those practices against a baseline of current practices developed by Professor Mulla and his staff, many of which are discussed in (Mulla et al. 2012). The model is watershed-scale rather than farm-level. Ten practices considered in the model include:

1) Reducing the fertilizer P2O5 rate on six major acres to a target rate,
2) Switching fall application of P2O5 on corn & wheat to spring preplant/starter,
3) Use reduced tillage,
4) Adding riparian buffers,
5) Planting a perennial crop on marginal lands for corn and soybean.

6) Planting a rye cover crop on early harvest crops including corn silage, small grains, peas, sweet corn, sugar beets, and/or dry edible beans,
7) Installing controlled drainage,
8) Installing tile inlet riser pipes or sand filters, and
9) Injecting or incorporating manure.

Results are calculated in the model for each of the practices as if they are implemented individually, for all of the practices combined, and for selected subsets of the practices.

Key Assumptions

Table 1. Assumptions underlying the existing adoption percentages in column B and the suitable acre values shown in column C of the Main sheet. The “Existing Acres” include an estimate of the fraction of cultivated lands that are already using the BMP, if known. The “Suitable Acres” include the additional fraction of the cultivated acres in the watershed where the BMP could potentially be adopted in the future.

BMP	Existing Acres	Suitable Acres
Adopt BMP P2O5 rate – Select from three choices for the target rate: 1) 100% of the crop removal rate, 2) a user-entered percentage of the crop removal rate, and 3) U of MN recommendations based on the Bray soil test (STP).	Set to zero (shown as NA) because we don't know much of the six major crops currently receive the U of M recommended rate or the crop removal rate. We only have the average rate/acre by agroecoregion	Considers acres of the six major crops of corn, soybeans, wheat, potato, sugarbeet, and dry beans.
Fall corn&wheat fert to preplant/starter	Percent existing here represents all corn that is NOT fertilized in the fall in a given year (i.e. where the BMP of spring application is already being adopted)	Fall-fertilized corn, in a given year
Use reduced tillage	All cropland >2% slope that is already in reduced tillage. “Reduced tillage” is defined as operations that provide more than 30% residue cover.	Cropland >2% slope that was not in reduced tillage (at the time of the transect surveys)
Riparian buffers	Acreage of land with existing riparian buffers of perennial vegetation. Based on perennial vegetated lands within the specified distance from public waters, divided by all acres in the watershed or statewide	Acres currently cultivated within the specified distance to waters.
Perennial crop % of marginal corn&soy land	Based on 2007 CRP acres	Corn grain and soybean acres on marginal land (<60 Crop Productivity Index (CPI)).. Corn silage is not included here, so the percentage is slightly less than in the NBMP model

Table 1 (continued)

BMP	Existing Acres	Suitable Acres
Corn grain & soybean acres w/cereal rye cover crop	Currently used on a small fraction of the corn and soybean acres. Therefore assumed to be zero.	All acreages planted to either corn or soybean during a given year.
Short season crops planted to a rye cover crop	Because the acreage of cover crops is not currently well-tracked in Minnesota, existing acres are assumed to be zero.	Potentially all of corn silage, sugarbeets, small grains, sweet corn, peas, dry edible beans, adjusted by user-defined choices in the covercrop sheet.
Controlled drainage	Assumed to be zero currently.	Acreages assumed to be tiled (based on crop type, soils and slope) and of less than a given slope, set at 1% by default.
Alternative tile intakes	Based on user-entered percentages in the Inlets sheet, 25% default. The fraction of open tile inlets with existing riser pipes is multiplied by an estimated average of acres that drain toward the inlet. Acres suitable for inlets varies with slope.	Acreages assumed to be tiled (based on crop type, soils and slope) and where the average slope of the land nearby is greater than 2% and less than 10%, not in the Red River Valley, and not well drained. Acres suitable for inlets varies with slope. The number of inlets in the Anoka Sands and the Central Till regions were adjusted based on anecdotal information.
Inject or incorporate manure	Estimated acreage where liquid manure is injected, or solid manure is incorporated immediately in a given year	Estimated acreage of land receiving liquid manure that is not injected, or solid manure NOT incorporated immediately, in a given year

Calculations linking the BMPs to total pounds of P load leaving the cropland

The P load calculations are based on the P index concept (see the appendix or (Birr and Mulla 2001)). The P index is made up of source factors (soil test P, fertilizer P rate and method of application, and organic P (manure) rate and application) and transport factors (soil erosion, runoff, and acres near a watercourse). The BMPs included in this model correspond generally with that list of factors except that both reduced tillage and perennial crops affect the erosion factor, and two index components are added to Birr and Mulla's list for controlled drainage and alternative tile line inlets. The overall index value for a given agroecoregion is converted to pounds of P load per acre by dividing the index by a coefficient (default 50) and multiplying by the treated acres for a given BMP.

Birr and Mulla's index can be seen to be linear in those factors, which is convenient but did not provide reasonable results in our model. Consequently, we added several additional calculations that introduced nonlinearities into the calculations. One change was that cover crops, which were not considered by Birr and Mulla, are assumed to reduce the overall P load calculated from other factors by a percentage. The other change was to assume that reduced tillage, perennial crops on marginal cropland, and riparian buffers not only affect the erosion and riparian buffer index components but also the runoff, soil test P, fertilizer rate and method, and manure rate and method index components. The percentage impacts on those components are entered in the Main sheet, A47:D54.

The component index scores are drawn from lookup tables contained in the Parameters sheet. In general, each index component and BMP impact is calculated in a separate sheet. The individual index components are then summarized in the P_Index_Scores sheet for the current and BMP scenarios, and the differences, by region. Those results are then carried over to the P Export sheet, where each value is converted from metric to English units, and each unit of the index is converted to pounds of P2O5 per acre, using parameters from the Parameters sheet. Pounds per acre is then converted to region total pounds by multiplying by region acres (see rows 3-8). The acreages used varies by component:

Index component	Acres used to convert pounds/acre to pounds/region and pounds/watershed
erosion, controlled drainage, and inlets	corn and soybean acres
perennials and buffers	total region acres
soil test P and fertilizer rate	acres not already meeting the rate target, from rows 14 and 15 of the Fertilizer Rate sheet
Fertilizer method and manure method	Corn and wheat acres

The P Export sheet also contains the calculations of the reduction in exported P2O5 due to cover crop adoption.

The Parameters sheet also contains a variety of parameters and conversion coefficients used in various places in the spreadsheet. It also contains the lookup tables used to calculate the P index component scores.

Crop Acres Receiving the BMP P2O5 Rate (see the STP sheet and the Fertilizer Rate sheet)

Six major crops are considered in the target rate calculations - corn, soybeans, wheat, potato, sugarbeet, and dry beans.   Similar to the NBMP model, we don't have data on the percentage of the acres already receiving the U of M recommended rates or the crop removal rates.

The user can select from three target fertilizer P[6] rates: 1) crop removal rates based on the crop yields (see the Parameters sheet, D22:D27), which will theoretically result in the soil test levels remaining constant over time, 2) a percentage of the crop removal rates, where using less than 100% should result in a slow decline in the STP over time, and 3) the U of M recommended rates, which likewise should result in declining STP over time on the acres where the STP is over 21. Manure P is subtracted from the crop removal or recommended rates to arrive at fertilizer P that is needed, if any.

The model contains estimates of the average Bray P soil test levels (STP) by agroecoregion from the U of M soil test lab. The average soil test values by region are from the U of MN soil test lab. To reflect field-to-field variability, each region's acres is split into equal proportions of high and low soil level fields. The low fields are assumed to have soil test levels 50% less than the region average, while the high fields are 50% over the region average. The suitable percentage is % that exceed a target soil test level. Given the region average soil test levels, the high half of every region is over the 21 target. The low half of every region is under the 21 target except for the Central Till region, where both the high half and the low half of the acres are over the target. For example, the average STP for the "wetter clays and silts" region is 31.2. The high half is assumed to be (31.2 * 150%) or 46.8. The low half is (31.2 * 50%) or 15.6. Since the low half of the acres have an STP of 15.6, which is less than 21, fertilizer P is recommended on those acres. The U of M recs are for NO fertilizer P on the high half of the acres, since 46.8 is over the 21 ppm cutoff.

The fertilizer P price per pound and most of the other economic parameters required for the cost calculations are in the Returns_Per_A sheet. The fertilizer P price is in cell C74 in that sheet. This sheet is called "Buffer costs" because buffers take land out of production, so a complete set of crop enterprise budgets is required to arrive at the crop net returns lost when that land is taken out. The same budgets are also used for the perennial crop BMP on cropland not in riparian areas.

Unlike the NBMP model, the target P rates in this are not based directly on crop yield fertilizer response functions, due to a lack of data and because P remains in the soil profile from year to year and makes yields more difficult to predict. Rather, the crop yields are not varied in this model and do not enter into the cost calculations except for the buffer and perennial crop BMPs where cropland is withdrawn.

[6] The measure of phosphorus actually used in the model is P2O5, but is written here as just P for brevity.

The U of M P recommendations are expressed in the model as formulas shown under the phosphate fertilizer guideline tables in (Kaiser et al. 2011). The general form of the formulas for corn, wheat, soybeans, and dry beans is:

$$P\ rate = (b_0 - b_1 * stp) * yield$$

Where P rate is the recommended P rate per acre, stp is the Bray soil test level, yield is the crop yield, and b_0 and b_1 are coefficients. There was no formula provided for sugarbeets, so the table was used to derive three discrete rates: 55 lb for STP less than or equal to 12; 35 lb for STP greater than 12 but less than or equal to 16, and 10 lb for STP greater than 16 but less than 21. There was also no formula for potatoes, so the potato rate is based on the average of the rates for the other five crops.

[For each BMP, we should describe how both the water quality improvement and economics are estimated, showing what is changed in the P index or otherwise calculated more directly]

<u>Shifting corn acres fertilized with P2O5 in the fall to spring preplant or starter applications</u>

The suitable percentage here is corn grain, corn silage, and wheat acres that are fertilized with MAP or DAP in the fall in a given year, from the 2010 fertilizer survey and based on the types of fertilizer applied (see the Fertilizer Method sheet for the data). Only considers corn or wheat acreages for a single year, instead of using all land where corn or wheat is grown in the rotation. Because soybeans are typically rotated with corn, the corn acreage during any one year is slightly more than half of the total corn/soybean acreage.

Rows 8-21 of the Fertilizer Method sheet show the percentages of the corn and wheat acres fertilized in the fall, spring preplant, and spring starter time periods as well as the percentages of corn and wheat that were not fertilized with P2O5. For the P index score, the fall-applied acres are given a score of 4. The spring preplant acres are assigned a 2 and the starter acres are assigned a 1. Acres not fertilized at all are assigned a 0. The region score is then a weighted average of those scores, weighted by the acreage in each category.

The BMP scenario data is shown in rows 40-52. If the target P rate in cell A9 of the Main sheet is set to "Apply U of MN recs," the adopting acres in the high soil test P corn and wheat soils, and the adopting acres with low soil test P in the Central Till region, are assumed to not be fertilized because the STP is over the 21 ppm cutoff. That change in the Fertilizer Rate sheet from being fertilized currently to not being fertilized in the BMP scenario has implications for the fertilizer method calculations because it would not be reasonable to penalize a given acre for applying fertilizer in the fall when that acre is not receiving any fertilizer at all. To avoid an unreasonable penalty on those newly unfertilized acres in the BMP scenario, they are shifted to the "None applied" row for calculating the region score in the BMP scenario.

Use reduced tillage (see the Erosion, Impl_select, Crop_codes, and Returns_Per_A sheets)

Reduced tillage is considered for corn, soybeans, and small grains on land with slopes greater than 2% that are not already using reduced tillage. The existing percentage is all cropland land that is already in reduced tillage is based on percentages developed for the Minnesota Nutrient Reduction Strategy (MPCA 2014) (see row 15 of the Erosion sheet). These percentages were estimated by Tetratech from transect surveys conducted in 2004 and 2007.

The Impl_select sheet contains the calculations for arriving at the machinery costs, crop residue impacts, and crop yield differences under an assumed current scenario and the reduced tillage BMP scenario. The PBMP tool assumes that reduced tillage is not used on slopes less than 2 percent, and no yield reduction is assumed on the slopes over 2 percent.

The machinery costs per acre for the current scenario and the reduced tillage BMP scenario are based on the tillage and planting machinery operations selected for corn and soybeans in columns A:I of the Impl_select sheet. The costs for individual implement types and sizes are drawn from the Machinery Cost Estimates extension publication database, which is duplicated in this sheet starting in M48.

Each machinery operation reduces the level of crop residue by multiplying the previous level by a percentage based on data provided by David Mulla. Winter weathering also reduces residues in a similar manner. Reduced tillage in and of itself reduces costs rather than increasing them in the default scenario. The tillage practices assumed for land going into corn are shown in rows 4:17 of Impl_select, while those for land going into soybeans are in rows 21:33. The current scenario practices are in columns A:D while the BMP scenario is in columns F:I.

The overall residue percentages remaining after the entered tillage practices under the current and BMP scenarios are shown in the boxes in D17, I17, D33, and I33. Those percentages are transferred over to rows 122:127 of the Erosion sheet, where the corn and soybean percentages are averaged for the current and the BMP scenarios. The BMP percentages are then divided by the current scenario percentages to arrive at the factors in row 128. The C_worst factors from row 9 are divided by those factors to arrive at C factors that are applied to the USLE to calculate erosion on the adopting acres.

In somewhat of a departure from the linearity assumption of the P index methodology, reduced tillage is thought to potentially reduce the impacts of high soil test P, fertilizer and manure rates, and fertilizer and manure application methods on P exports. The default assumption is that the P index scores for those pathways will be reduced by half as much as the reduction in the tillage score itself. The data entry cells to change that assumption are in the Main sheet, C50:C54.

Shift marginal corn grain and soybean acres to a perennial crop (see the Erosion sheet)

Calculations estimating the effects of converting marginal row crop lands into a perennial crop are in the Erosion sheet because land converted to a perennial crop is netted out of the cropland acres considered in the acres affected by the tillage system used on the food and feed crops. Only marginal cropland (crop productivity index less than 60) is considered for this practice. The marginal land acreages are from a data layer that isolates NLCD 2011 cultivated land with Crop Productivity Index values of less than 60 to identify marginal cropland that could be converted to perennial crops with a reduced economic cost as compared to converting prime cropland.

Similar to reduced tillage, a shift to a perennial crop in the buffer area or in the marginal corn and soybean acres elsewhere is thought to potentially reduce the impacts of runoff, high soil test P, fertilizer and manure rates, and fertilizer and manure application methods on P exports. By default the indices for all of these pathways are assumed to be reduced by the same percentage as the percent of the region shifted to buffers or a perennial crop, **except for the runoff pathway which is assumed to be reduced by half as much as that percentage shift**. The data entry cells to adjust those percentages are in the Main sheet, D49:D54.

[Is there a way to explain the P index approach for someone who does not already understand the intricacies of this index?]

<u>Riparian buffers (see the Buffer sheet and Returns Per A sheet)</u>

The existing and suitable acres in the P model can be toggled between two definitions: 1) only permanent streams and water bodies, and 2) both permanent and intermittent streams, as in the NBMP model. Users can select between these two choices in the Main sheet, cell F27. The permanent versions of the existing and total (existing plus suitable for future) data draw on rows 6 and 9 of the Buffer sheet. That data was calculated based on a 90m (300 ft) buffer width. The permanent plus intermittent version draws on rows 20 and 22, which are copied from the NBMP model and were calculated based on a 30m (100 ft) buffer width. Regardless of which definition is selected by the user, the actual buffer width lost to agriculture is adjusted to the width entered in cell C85 of the Returns_Per_A sheet, and is 50 feet by default. The width actually treated is assumed to be the width of the cropland that drains to the buffer and is treated, and so is independent of the actual width of the buffer that is lost to crop production. The treated width is based on Returns_Per_A cell C86, and is 100 feet by default. This user-specified treated width is adjusted by the stream power index adjustment factors shown in Buffer row 14, which ranges from 0.57 on the poorly drained BE till, to 1.32 on the Rochester plateau. Changing the treated width does not change the lost cropland width, which is in Returns_Per_A cell D85 and can be changed there.

The actual buffer acres lost to agriculture are shown in row 12 for the permanent (perennial waters) only definition, or in row 32 for the permanent plus intermittent version.

The Returns_Per_A sheet contains crop enterprise budgets that are used to arrive at returns to land/acre for seven major crops (corn grain, soybeans, wheat, barley, oats, sugar beets, potatoes, alfalfa, and other hay). Corn grain and soybean returns are calculated separately for marginal and nonmarginal land.

Cover crops (see the Covercrop sheet)

Cover crops can be considered following corn, soybeans, and the short season crops of corn silage, sugar beets, peas, sweet corn, potatoes, dry edible beans, wheat, barley, and oats. Cereal rye is the cover crop species assumed by default. The adoption rates in the main screen are split into one cell for corn grain and soybeans, and a second cell for the other crops. They are separated because it is assumed that the short season crops can be seeded with ground equipment that would have a high success rate (90% is assumed) while the corn and soybeans may need to be seeded by air into the standing crop in September to give it enough time to germinate, and that has a much lower success rate (20% is assumed by default). In the Covercrop sheet, the corn and soybean acres can be treated differently within the corn/soybean category. For example, the cover crops following corn could be seeded by air while that following soybeans could be seeded with ground equipment. Sugar beets can be treated differently from the other crops. Within the group of other short season crops, wheat, barley, oats, and peas can be included or excluded separately by entering percentages in F6:F8.

The corn/soybeans cover crop adoption rate entered in the Main sheet can be applied to either both corn and soybeans, or just to corn or just to soybeans,, by changing the 100% in row 5 of the Covercrop sheet to zero or some other percentage. Likewise, the cover crops assumed for the short-season crops can be allocated to all or only part of these crops by changing the percentages in E5:F8. The germination success rate can be changed in cells B23:F23 of the Covercrop sheet.

The cover crop phosphorus reduction efficiencies of 50% are based on the estimate in Table 6 of the Iowa Nutrient Reduction Strategy document (Iowa Department of Agriculture and Land Stewardship et al. 2013). The cover crop effectiveness after sugar beets is reduced to 25% because the cover crop is assumed to be seeded in the early spring rather than in the fall as for the other crops.

Controlled drainage (see the C-Drain sheet)

Suitable acres for controlled drainage is based on slopes of less than 1% by default, but the maximum can be varied to less than 2% or up to 4%. The estimates are from the likely tile drained land layer (poorly drained soils, and 2009 CDL corn, soybeans, wheat, or sugarbeets).

The costs for controlled drainage in the model are the total of the annualized installation costs and periodic gate replacement costs, plus a maintenance cost. Those cost calculations are done in the Cost Data sheet.

Alternative tile inlets (see the Inlets sheet)

Suitable acres for alternative tile inlets include steeper slopes than for controlled drainage – an average slope of the land nearby is greater than 2% and less than 10%, cultivated, not in the Red River Valley, and not well drained. The number of inlets in the Anoka Sands and the Central Till regions were adjusted based on anecdotal information. The density of inlets is much less on the steeper slopes than on the flatter land. The suitable acres in each agroecoregion were calculated based on an assumption of

30 hectares per inlet for 0% slopes and 1 hectare per inlet for 10% slopes, and a linear interpolation between, based on LiDAR analysis of flow accumulations (Ginting et al. 2000)g. Then a portion of the Central Till and Anoka sand plains regions was removed due to well drained soils that are not generally suitable for inlets. By default 25% of the risers in each region are assumed to already be treated (row 11). This assumption can be changed in row 11. Only the acres considered suitable for inlets are included in the P export calculations, not all acres. The percent of the cropland in the watershed that drains into open tile inlets without riser pipes are considered suitable, and are shown in Inlets row 16.

The costs for alternative tile inlets in the model are the total of the annualized installation costs plus a maintenance cost. Those cost calculations are done in the Cost Data sheet.

Inject or incorporate manure (see the Manure Method sheet)

The P index component calculation for the liquid manure method for the current scenario starts by assigning factors for five methods each for liquid manure and for solid manure, as follows:

P index interpretation per region (liquid)	
None Applied (0)	0
Injected (1)	1
Incorporated Immediately before crop (2)	2
Incorporated >3 months or Surface Applied <3 months before crop (4)	4
Surface applied >3 months before crop (8)	8
Total applied by any method	

The factors for solid manure are the same except that injection is not a choice. Percentages of the liquid manure applied by each method in each region are multiplied by these liquid manure factors to arrive at a weighted average, and the same calculation was performed for the solid manure. The final score for this component is the sum of those two weighted averages.

For the BMP scenario, the liquid manure percentages with factors of 2, 4, or 8 were reduced by multiplying them times 1 minus the adoption rate, and add the difference to the percentages injected, which was assigned a factor of 1. For solid manure, the percentages with factors of 4 or 8 were again reduced by multiplying by one minus the adoption rate, with the difference added to the percentage incorporated immediately before the crop, which was assigned a factor of 2.

The data entry cells and cost calculations for the different manure methods start in row 98. There are two sources for the liquid manure application cost increase due to a switch from broadcast to injection or incorporation. The 2013 Wisconsin Custom Rate Guide lists rates/gallon for surface application and injection (USDA National Agricultural Statistics Service 2014). However, the drawback of that source is that the injection rates are broken out for tanker and dragline systems, while the surface application rate does not state whether it is for tanker or dragline systems. The average surface rate is \$0.011/gallon. The tanker injection average is \$0.012/gallon while the dragline injection average is \$0.011/gallon, the same as the surface application rate.

The other source is a 2012 on-farm comparison of surface application and injection in Idaho (Chen et al. 2014). The data from that article for the different application methods are in columns D-H. I calculated the cost difference between surface and injection using their tank results only, since they compared surface and injection only for the tank applicator. I show their costs for the drag line injection system, but there is no drag line surface application scenario for me to compare that to. Another difficulty I found with that study is that their stated applicator widths and speeds, and their application rates/minute for the tank systems appear to work out to rates of 5,363-6,629 gallons/acre while they state in the text that the rate was 20,000 gallons/acre. I had to estimate the percentage of total time spent actually applying vs. travelling from the storage from their stated acres/hour and the width and speed of the applicator. It appeared that the applicator spent 24% of the time actually applying. I would need to reduce their stated applicator speeds from 7 or 8 miles/hour to between 2 and 3 miles/hour to get the per-acre rate up to 20,000 gallons. That would raise the percentage of time actually applying up to around 66-76%. The cost difference between surface and injection is \$0.00137/gallon at their stated speeds, or \$0.00103/gallon at a slower 2.5 mile/hour speed that would give their stated 20,000-gallon/acre rate.

The default cost difference between surface and injection is set at \$0.001/gallon based on those two sources. The cost of incorporating the solid manure is based on a separate tillage operation which can be selected in A104 from the same list of operations used in the reduced tillage scenarios, which are found in the Impl_Select sheet, from (HOWLEY 2015). The default incorporation tool is a field cultivator.

The cost difference to incorporate solid manure is based on the liquid manure cost difference and assuming a default liquid application rate of 8,000 gallons/acre in B100, since neither source contained such a comparison for solid manure.

<u>Avoided fertilizer N cost related to the increased manure N availability with injection or incorporation</u>

Injecting or incorporating manure is expected to increase the first-year availability of the nitrogen it contains. Availability factors (percentages) are from Table 2 of MPCA's guidance document for NPDES-permitted feedlots (Minnesota Pollution Control Agency 2010). The injection factor is based on the midpoint of the factors for sweep and knife injection. The factor for immediate incorporation is based on the midpoint of the "less than 12 hours" and the "12-96 hours" factors.

This calculation draws on the regional total manure N amounts by region and the species breakdown from the NBMP spreadsheet. See rows 28:54 and 74:86. The availability percentage lookup table and the fertilizer N price data entry is in A176:E187.

<u>Sheets not directly related to an individual BMP</u>

<u>Watersheds sheet</u>

This contains the cropland acreages by region and watershed. It contains acres of marginal land and suitable buffer acres. It also contains acres of the major crops in each region.

Watacresall sheet (hidden)

The tool originally contained acres of cropland, forest, grasslands, and developed urban land. The measure of acres was changed to just cropland in late 2014. This sheet contains the original acres by way of an archive, in case we ever need to go back to that data.

Scenarios sheet (hidden)

This is carryover from the N tool, where the user had a way to save and then retrieve the data for a given set of scenarios. That feature has not been updated recently in the N tool, so it probably doesn't save certain data that was added recently, and that feature has not been added here yet.

How to use the Tool

Note: Copies of the key graphs and tables are included below, but they are only examples. Obviously, the nature of a spreadsheet planning tool is that the results will vary based on data entered and selections made by the user, so readers are cautioned to not assign any particular importance to the results shown here.

Using the model involves three steps. The first step is to select a watershed, enter hypothetical adoption rates for each BMP, and compare the effectiveness and cost of the individual BMPs. The second step is to compare suites of the BMPs that would attain any given reduction in the P load at minimum cost. The third step is to "drill down" to the details and assumptions behind the models of effectiveness and costs of any particular BMP and make any adjustments to reflect your particular situation.

The main screen is shown in Figure 1 below. Row 7 contains a dropdown list of the watersheds that you can select from and the acreage of the watershed currently selected. Below that box is a list of the BMPs that are modeled. Input cells are formatted in yellow. Calculated cells are in white. The spreadsheet is password-protected to help avoid inadvertent changes to the calculation formulas.

The statewide total data is shown. The data includes crop acreages, yields, and other information for ten different crops: corn grain and silage, soybeans, the small grains of spring wheat, barley, and oats, sugar beets and potatoes, and alfalfa and other hay. Total crop acres and average P fertilization rates are also included for sweet corn, peas, and dry edible beans because the impact of cover crops on P loads are calculated for those crops, but the other information is not included for those three short-season crops.

	A	B	C	D	E	F
7	Watershed Statewide				19.647	million acres of
8	Pathway	% existing	% suitable	% adoption	% treated	acres treated (thousands)
	Apply U of MN recs					
9	Target P2O5 rate	45.36%	43.57%	80%	34.85%	6,848
10	Fall corn&wheat fert to preplant/starter	29.45%	10.19%	50%	5.10%	1,001
11	Use reduced tillage	20.42%	36.70%	40%	14.68%	2,884
12	Riparian buffers, 50 ft wide	13.94%	3.30%	25%	0.82%	162
13	Perennial crop % of marginal corn&soy land	0.00%	8.36%	30%	2.51%	493
14	Corn grain & soybean acres w/cereal rye cover crop	0.00%	74.80%	10%	7.48%	1,470
15	Short season crops planted to a rye cover crop	0.00%	14.13%	50%	7.06%	1,388
16	Controlled drainage	0.00%	10.16%	20%	2.03%	399
17	Alternative tile intakes	1.73%	5.20%	80%	4.16%	2,247
18	Inject or incorp manure	6.55%	1.43%	50%	0.71%	140
19	Total for all BMPs			Load default data	Recalcu	
20	Weather Scenario:	Average weather				
21						
22	Cropland P load reduction with these adoption rates:		15.6%			
23	Treatment cost before fertilizer cost savings		$196.21	million/year		
24	P and N fertilizer cost savings		-$172.36			
25	Net BMP treatment cost		$23.85	million/year		

Figure 1. Main Screen of PBMP.xlsm Spreadsheet

After selecting a watershed, the next step is to specify how much of each BMP you think is reasonable or that you wish to consider for implementation in the watershed. For example, if you (as the resource planner) think that a particular BMP is likely to be adopted widely by producers farming in the watershed, enter a high percentage rate. Enter a lower rate for other BMPs that you think would be unpopular because of cost or whatever reason. You enter the percent adoption rates in column D. Column C shows a measure of suitable acreage associated with each BMP that is based on GIS watershed analyses and an assessment of watershed acreage for which that BMP can realistically be adopted, as a percentage of total watershed acreage. The adoption rates in column D represent a percentage of that maximum suitable acreage.

Column E shows the percentage of the watershed would be treated based on the suitable acres and adoption rate entered. The percent load reduction that the combination of BMPs entered will provide is shown in C22, with the costs below it.

Click the "Recalculate" button after making any changes in the data entry cells. Most changes will be fully incorporated with one recalculation, but a few may require two clicks to fully recalculate.

The graph starting at cell I22 shows the effectiveness and cost of the BMPs for the watershed and the adoption rate you have chosen (see Figure 2). The red bars show effectiveness, which are keyed to the left vertical axis. Effectiveness is shown as a percent of the p load reduced in the watershed surface waters due to that BMP, in the absence of any of the other BMPs. (Suites or combinations of the BMPs are evaluated in step 2 of the analysis as discussed below.) The blue line shows cost/lb of P removed, which relates to the right vertical axis. Both the effectiveness and cost will change with the adoption rate you enter. The graph shows that for the Statewide watershed and at the adoption rates entered, reducing fertilizer P rates on corn and switching to spring preplant or starter application provide significant P reductions at relatively low cost, while cover crops are relatively expensive for the reductions attained.

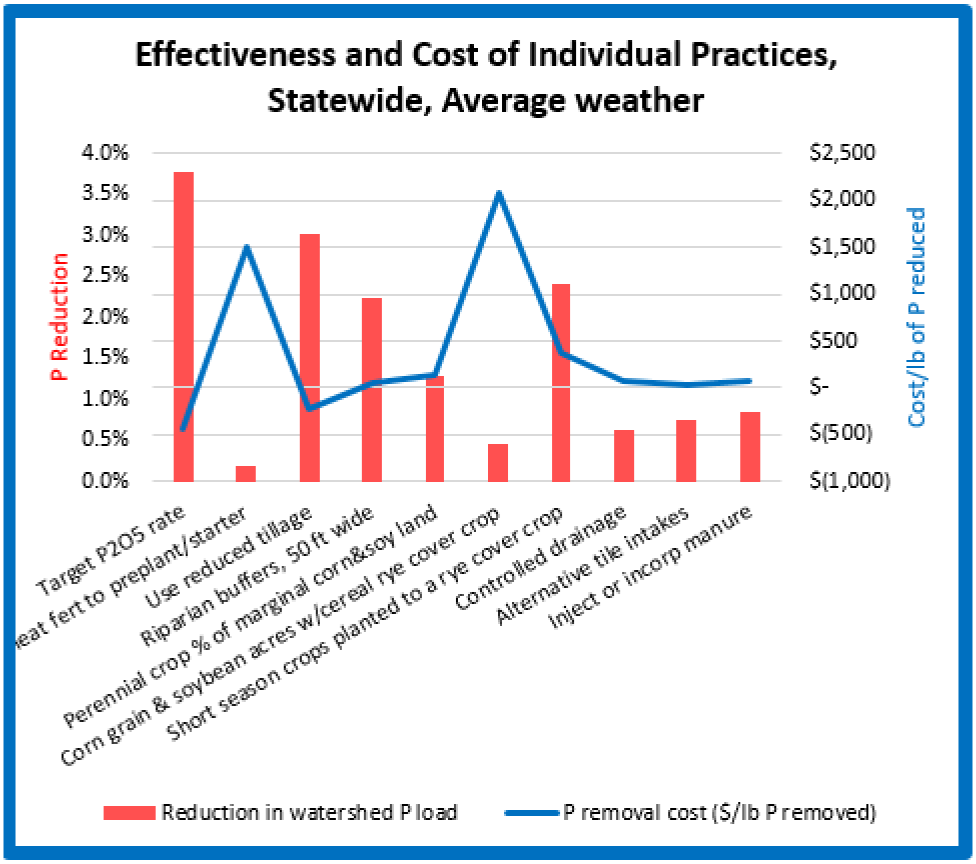


Figure 2. Graph Comparing the Effectiveness and Cost of Individual BMPs, Showing Results for the overall state. Effectiveness is shown as percentage reductions while cost is per pound of reduced P load.

Figure 3 is a model output graph which shows the P reductions and cost/acres TREATED, as opposed to acres of WATERSHED shown in Figure 3. The columns in the graphs and table can be sorted in a number of different ways. Here they are sorted by effectiveness per acre of watershed.

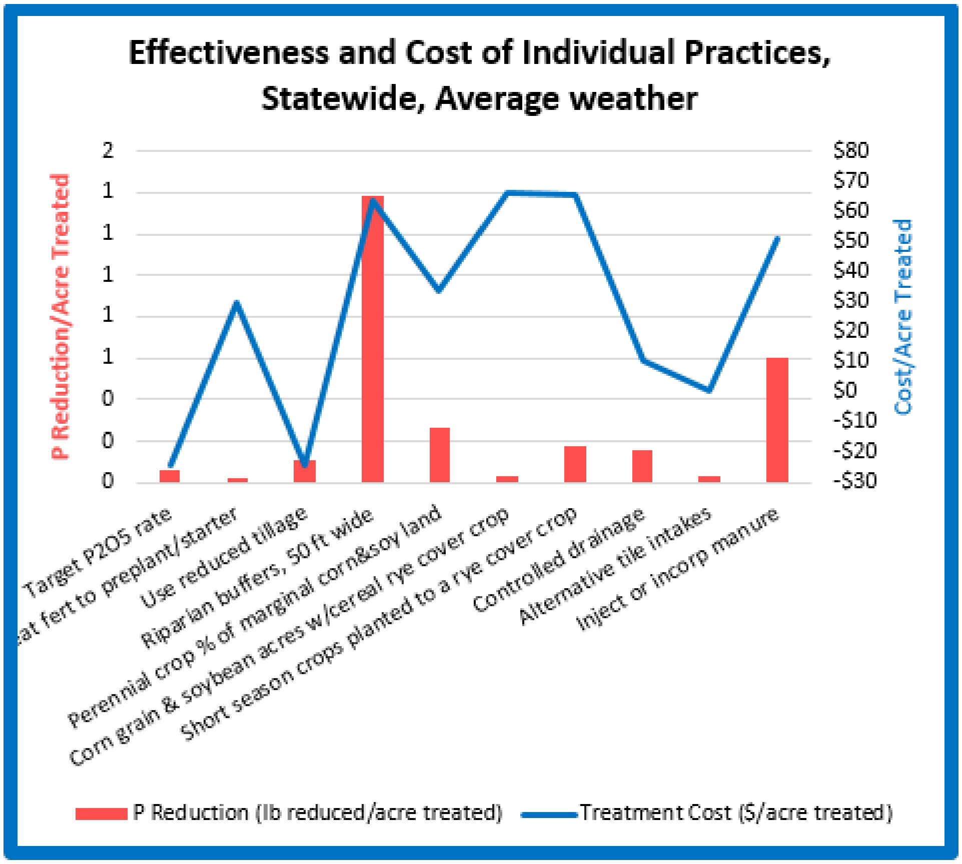


Figure 3. Graph Comparing the Effectiveness and Cost of Individual BMPs, Showing Results for the overall state. Effectiveness is shown as pounds reduced per acre while cost is per acre treated.

Table 2 shows the numbers which correspond to the graph in Figures 2 and 3. Table 3. Note that only a percentage of marginal land is assumed to be available for planting to a perennial crop. A negative number in a cost column means that the BMP will result in a cost savings rather than a cost increase.

Table 2. Comparison of the cost and effectiveness of the individual BMPs when adopted at the rates shown in Figure 1, in an average weather year, sorted by BMP category.

	Total P reduction, (000 lb)	Reduction in watershed P load	Total treatment cost ($ 000)	Treatment Cost ($/acre treated)	P Reduction (lb reduced/acre treated)	Treatment Cost ($/acre of watershed)	P removal cost ($/lb P removed)	Percentage of watershed treated
Target P rate	379	3.8%	$(164,895)	$(24.08)	0.055	$(8.39)	$(434.61)	34.9%
Fall corn fert to preplant/starter	20	0.2%	$29,590	$29.56	0.020	$1.51	$ 1,511.83	5.1%
Use reduced tillage	304	3.0%	$(69,565)	$(24.12)	0.105	$(3.54)	$(228.80)	14.7%
Riparian buffers	224	2.2%	$10,274	$63.43	1.385	$0.52	$ 45.78	0.8%
Perennial crop % of marginal corn&soy	130	1.3%	$16,603	$33.70	0.263	$0.85	$128.19	2.5%
Cover crop on corn&soy	47	0.5%	$97,602	$66.42	0.032	$4.97	$ 2,088.80	7.5%
Cover crop on short season cr	244	2.4%	$91,437	$65.88	0.175	$4.65	$375.49	7.1%
Control Drainage	64	0.6%	$4,137	$10.37	0.161	$0.21	$ 64.49	2.0%
Alternative tile intakes	75	0.7%	$1,567	$ 0.70	0.033	$0.08	$ 20.84	11.4%
Inject or incorp manure	85	0.8%	$ 7,102	$50.69	0.605	$0.36	$ 83.79	0.7%
Total, all BMPs	1,492	14.9%	$28,539					

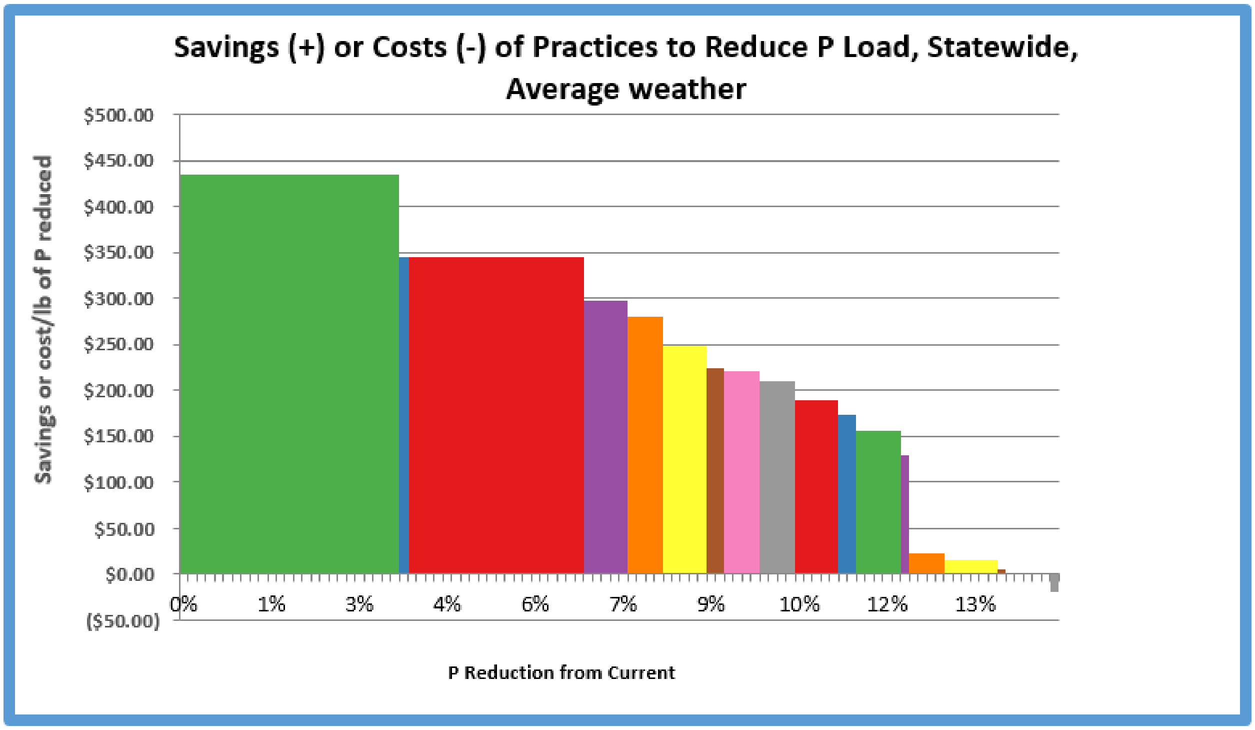
Scroll down to row 77 for step 2 of the analysis, as shown in Figures 4 and 5 below. The spreadsheet looks at 256 different combinations or suites of the 12 BMPs, and selects only those combinations that are “efficient” in providing greater P reductions than any other combinations that cost the same amount or less. These “Frontier scenarios” are displayed in the graph starting at E77, sorted from low to high “Cost/lb of P reduced”. The bars of the graph shown in Figure 4 are color-coded to the legend below it. For example, the first green bar shows the result of reducing the corn P fertilizer rate to a target rate on 80% of the corn acreage. The horizontal axis shows that just that one BMP would reduce the P load by around 3-4%, which matches what the top table and graph showed (Table 2 and Figure 2). The green bar goes up rather than down, showing that reducing the P rate would actually save money rather than costing money. As we move right on the graph to suites that cost more, we have weeded out any suites that don’t reduce the P load by more than the cheaper suites on the left. Adding saturated buffers to the P rate reduction would reduce loading a bit more. Replacing the saturated buffers with a shift to spring preplant P on 2.1% along with the reduced rate would reduce the P load by over 13%. The legend below the graph shows the order at which other BMPs would enter the mix. The additional BMPs cost money, but the fertilizer rate reduction saves enough money to offset the additional cost until around a 17% load reduction.

There are too many combinations of the ten practices to calculate results for all of them, so the combinations that are omitted are: 1) cover crops after corn or soybeans are combined with cover crops after short-season crops when combining with any other practices, and 2) controlled drainage is combined with alternative tile inlets when combining with any other practices.

With the adoption rates entered in the main screen, the far right bar shows that the greatest attainable load reduction is around 15%. This is attained by implementing all ten BMPs.

The suites of BMPs are mutually exclusive, so that the interpretation of any individual bar is that that suite would be used in the entire watershed, replacing the suites illustrated by the bars to the left of that bar. The vertical axis in Figure 6 shows the cost or cost savings per pound of P load reduced. The cost/acre for the different suites can also be displayed by clicking a button. Also, if the user desires to focus only on the suites that provide the greatest reductions, a minimum percentage for inclusion can be entered in D67.

These results assume an average weather year. The loading can also be calculated by the model for an unusually wet year or a dry year.



Key to graph colors by BMP (left to right, the numbers are percent of the watershed, from above)

Target P rate 35%
Target P rate 35%,Preplant/starter 5.1%
Target P rate 35%,Use reduced tillage 15%
Target P rate 35%, Inj & inc manure 0.7%,Use reduced tillage 15%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Use reduced tillage 15%
Target P rate 35%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Use reduced tillage 15%,Perennial crop 2.5%
Target P rate 35%, Inj & inc manure 0.7%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%, Inj & inc manure 0.7%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%, Inj & inc manure 0.7%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%, Inj & inc manure 0.7%,Preplant/starter 5.1%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Cover crop cs7.5%Cover crop ss 7.1%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%, Inj & inc manure 0.7%,Cover crop cs7.5%Cover crop ss 7.1%,Use reduced tillage 15%,Riparian buffers 0.8%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%,Cover crop cs7.5%Cover crop ss 7.1%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%
Target P rate 35%,Control Drainage2.0%Tile intakes4.2%, Inj & inc manure 0.7%,Cover crop cs7.5%Cover crop ss 7.1%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%
Target P rate 35%,Control Drainage 2.0%,Tile intakes 4.2%, Inj & inc manure 0.7%,Preplant/starter 5.1%,Cover crop cs 7.5%,Cover crop ss 7.1%,Use reduced tillage 15%,Riparian buffers 0.8%,Perennial crop 2.5%

Figure 4. Graph Comparing the Effectiveness (lb P Reduced from Surface Waters) and Cost of Individual BMPs Per Acre Treated, Showing Results for the overall state.

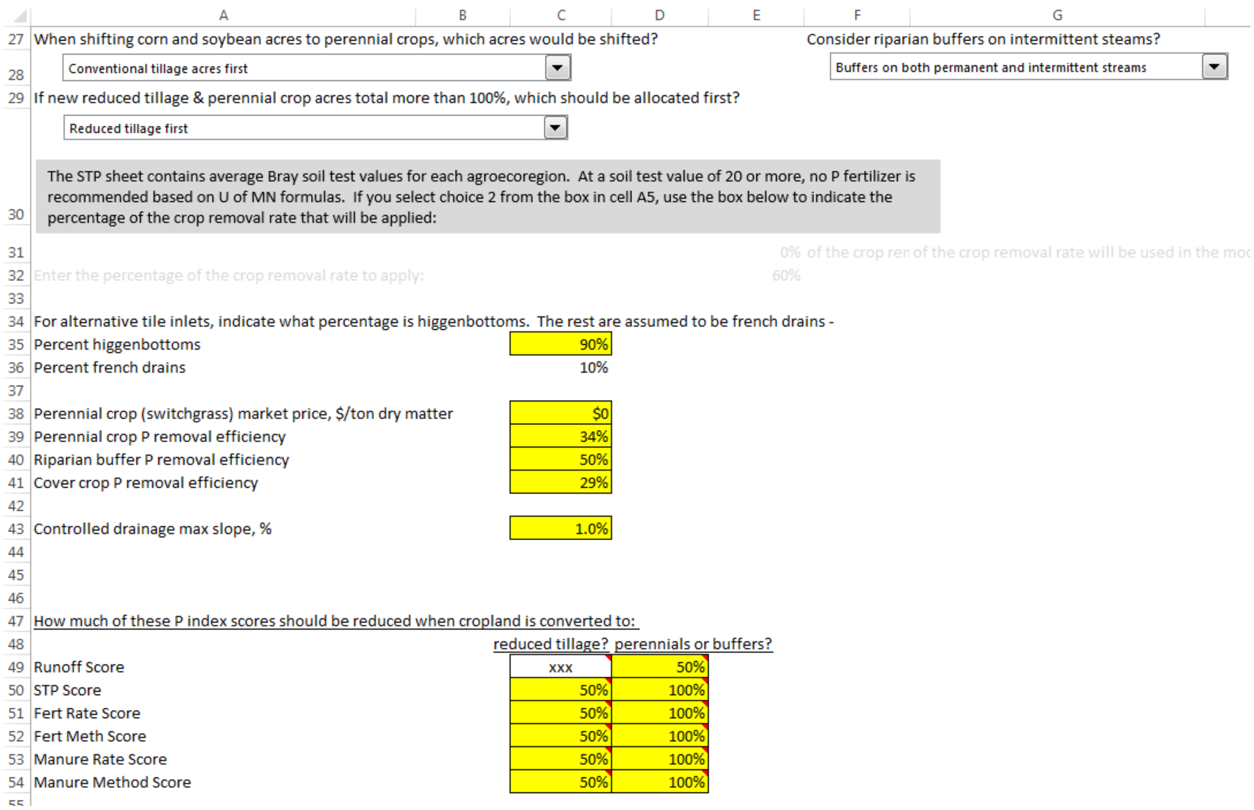


Figure 5. Screen Showing Cells to View or Change a Few Key Assumptions

References

Birr, A. S. and D. J. Mulla (2001). "Evaluation of the Phosphorus Index in Watersheds at the Regional Scale." Journal of Environmental Quality **30**(6): 2018-2025.

Chen, L., C. W. Gray, H. Neibling, S. K. R. Yadanaparthi, M. Chahine and M. E. d. H. Marti (2014). "On-Farm Comparison of Two Dairy Manure Application Methods in Terms Of Ammonia and Odor Emissions And Costs." Applied Engineering in Agriculture **30**(5): 805-813.

Ginting, D., J. F. Montcrief and S. C. Gupta (2000). "Runoff, solids, and contaminant losses into surface tile inlets draining lacustrine depressions." Journal of Environmental Quality **29**: 551-560.

HOWLEY, P. (2015). "THE HAPPY FARMER:THE EFFECT OF NONPECUNIARY BENEFITS ON BEHAVIOR." American Journal of Agricultural Economics Advance Access.

Iowa Department of Agriculture and Land Stewardship, Iowa Department of Natural Resources and Iowa State University (2013). Iowa Nutrient Reduction Strategy: A Science and Technology-Based Framework to Assess and Reduce Nutrients to Iowa Waters and the Gulf of Mexico. http://www.nutrientstrategy.iastate.edu/documents.

Kaiser, D. E., J. A. Lamb and R. Eliason (2011). Fertilizer Guidelines for Agronomic Crops in Minnesota, BU-06240-S. http://www.extension.umn.edu/agriculture/nutrient%2Dmanagement/nutrient%2Dlime%2Dguidelines/fertilizer%2Drecommendations%2Dfor%2Dagronomic%2Dcrops%2Din%2Dminnesota/docs/BU-6240S-PUB.pdf.

Minnesota Pollution Control Agency (2010). Manure Management Plans for NPDES Permitted Feedlots Guidance, wq-f8-47. http://www.pca.state.mn.us/index.php/view-document.html?gid=3462.

Mulla, D. J., D. Wall, J. Galzki, K. Fabrizzi and K.-I. Kim. (2012). Nonpoint Source Nitrogen Loading, Sources and Pathways for Minnesota Surface Waters. Report submitted to the Minnesota Pollution Control Agency as part of a comprehensive report on nitrogen in Minnesota Surface Waters. Department of Soil, Water & Climate, University of Minnesota.

USDA National Agricultural Statistics Service (2014). Wisconsin Custom Rate Guide 2013. http://wood.uwex.edu/files/2014/04/custom_rates_2013.pdf.

APPENDIX

An Updated Regional Phosphorus Index

ABSTRACT

Excess nutrients from agricultural runoff lead to surface water contamination issues, one of the largest being eutrophication of lakes and rivers caused by Phosphorus (P). There is potential to reduce agricultural P losses and mitigate these effects with properly sited best management practices (BMPs). In this study, a P Index originally developed by the USDA (Lemunyon and Gilbert, 1992) was evaluated and updated in order to prioritize Minnesota watersheds for BMP implementation. The index utilizes readily available spatial data within a Geographic Information System (GIS) that are related to the source and transport factors of P. Tile drainage P considerations were added as transport factors to the P index. Categorical P Index values were also interpolated in order to create continuous regional values to better analyze small effects of BMP implementation. A strong relationship (r^2=0.85) between multiyear monitoring data and the P Index was found in agricultural watersheds throughout Minnesota. Results of this study confirm that the P Index can be effectively used to identify P loss risks at regional scales. Furthermore, this tool can be used to prioritize watersheds and evaluate potential effects of BMPs by predicting regional P loss reductions.

INTRODUCTION

Excessive concentrations of P are the most common cause of eutrophication in freshwater ecosystems (Vollenweider, 1971; Schindler, 1977; Correll, 1998), which reduce both the ecological and aesthetic value of many rivers and lakes. Point sources have largely been identified and regulated, thus nonpoint sources of P such as agricultural runoff are the largest contributors to this eutrophication. A balance between environmental and economic values must be considered in agricultural systems; Sharpley et al. (1994) have suggested targeting source areas with indices to rank vulnerability of P loss in different regions and maximize efficiency of conservation measures. The USDA developed a P index tool that evaluates a number of P source factors such as fertilizer rate and soil test P along with transport factors such as erosion and runoff to estimate P loss risk (Lemunyon and Gilbert, 1993). Field scale studies demonstrate that the P index can be used to prioritize sites based on P loss risk (Stevens et al, 1993); a strong relationship between P index values and P losses based on long term monitoring data has also been demonstrated (Sharpley, 1995). The original P Index has been established as a successful field-scale tool, while a modified P index has been found to be an effective tool in identifying agricultural risk on a regional scale (Birr and Mulla, 2001). This regional P index is being re-evaluated for the development of a BMP cost-analysis tool to better analyze Minnesota's nutrient reduction strategy, which has been highlighted by the Environmental Protection Agency (EPA) as a leading strategy with both nutrient reduction targets and timelines (EPA, 2014).

MATERIALS AND METHODS

In this study, the modified regional P index of Birr and Mulla (2001) was re-evaluated in Minnesota. Transport and source data were calculated based on agroecoregions in Minnesota, regions identified to have similar climatic and geomorphological characteristics (Hatch et al, 2001). These 39 regions in Minnesota vary from 30,000 ha to 2,000,000 ha in size. Where appropriate, agroecoregions were used to calculate P index values due to their homogeneity relating to P sources and transport pathways; data available at county scales were weighted to agroecoregions as noted below. These data were then translated from agroecoregions to eight-digit hydrologic units, or major watersheds, for data analysis purposes.

Transport Factors

Soil Erosion and Runoff

Soil erosion potential was calculated based on the Universal Soil Loss Equation (USLE) as outlined by Wischmeier and Smith (1978). Adoption rates for conservation tillage were obtained to update C factors for this analysis (MRBDC, 2007). Average annual runoff values were derived from monitored discharge data at 327 stations throughout Minnesota measured from 1951 to 1985 (Lorenz et al., 1997). Monitored annual discharge is divided by the drainage area defined for the monitoring station to obtain an average annual runoff value, and these values were interpolated across the state. P index ratings were also derived for a wet and dry year scenario; runoff values for wet and dry years corresponded to the 90^{th} and 10^{th} percentile of runoff monitoring data respectfully. Rainfall erosivity was varied while calculating soil erosion potential for wet and dry years based on the same criteria. Detailed methodology for soil erosion and runoff is outlined in Birr and Mulla (2001).

Agricultural land within 90 m of a Stream

The percentage of cultivated and pastureland within 90 m of drainage ditches and perennial streams was determined for each agroecoregion using the National Land Cover Database and 24k stream data from the Minnesota DNR (Jin et al., 2013; MN DNR, 2001). This 90 m distance reflects a setback standard for manure application created by the Minnesota Pollution Control Agency (MPCA) for controlling nonpoint source pollutant loads from agricultural land. Regions with a larger proportion of agricultural land within a 90 m setback of streams and ditches are more vulnerable to transport organic and inorganic P soil amendments. Riparian buffers were considered in this transport pathway; buffer adoption rates were acquired for twelve-digit hydrologic units for the southern half of Minnesota (EWG, 2014), and data were available for eight-digit hydrologic units statewide (MPCA, 2014). P removal efficiencies vary in the literature (Mankin, 2007; Hoffman, et al., 2009); however, buffer efficiency was assumed to be 50%. Agricultural land within the 90 m setback were reduced by half where riparian buffers have been adopted, assuming this proportion of the risk has been mitigated by riparian buffers. Finally, regional averages of 30 m Stream Power Index (SPI) values were used to adjust this transport pathway. SPI isolates areas on the landscape with high slopes and flow accumulations, which has been demonstrated to identify potential erosion risks (Galzki et al., 2011). The ratio of regional SPI averages compared to the statewide average was used as an adjustment factor to weight riskier landscapes with higher P index results.

Tile Drainage

The effects of artificial tile drainage were not directly accounted for in the previous version of this modified P index. In this study we identified two tile drainage related transport pathways that contribute agricultural P to surface waters. The first represents the presence of subsurface drainage. Drainage was estimated to exist in Minnesota on cultivated lands with slopes of less than 4%. The Red River Valley was excluded from this estimation due to the extensive ditching that occurs in the region. Well drained soils were also excluded from the drainage estimation. The second drainage pathway represents the presence of open tile inlets in the region. Field surveys conducted in Minnesota identified the location of 2,300 tile inlets in Southern Minnesota (Schottler, 2014). Surveys were conducted on 130 hectare field plots, and the elevation range within the plot was found to be correlated with the density of inlets surveyed. In general, more relief in a survey plot translated into a smaller density of tile inlets. This relationship was used to estimate inlet densities across all tile drained lands in the state. Small numbers of inlets were also found on lands with steeper than 4% slopes, the majority being under 10% slopes. Inlet locations were then estimated to occur in lands with up to 10% slopes, albeit at smaller densities than steeper regions.

Source Factors

Soil Test Phosphorus

Mean soil test P levels represented a 5 year county level database consisting of 22,421 Bray-1 extractable P (Brown, 1998) samples analyzed by the University of Minnesota's soil testing laboratory. Soil test P varies across field scales, and spatial distribution of samples within each county are unknown; however, the county level database represents the best available data to represent regional Soil test P trends in the state. These county level data were area-weighted to agroecoregions, and later translated to major watersheds for analysis. Detailed soil test P levels from a 2,000 ha watershed were used to estimate the fraction of P test levels that were less than 21 ppm Bray-1 values in order to represent within field variability.

Inorganic Fertilizer

In order to determine the spatial distribution of inorganic P fertilizer, the Crop Data Layer (CDL) was utilized to isolate common crops with inorganic P amendments (NASS, 2013). Multi-year, surveyed fertilizer application rates were combined with percent of cultivated area fertilized to determine a representative rate for wheat, corn, and soybeans in Minnesota (USDA ERS, 2012). University of Minnesota recommended fertilizer rates were used for potatoes, sugar beets, and dry beans (University of Minnesota Extension, 2011). Regional fertilizer totals were then inflated to match fertilizer sales data (MDA, 2011). Fertilizer application methods were determined using the Minnesota Department of

Agriculture's Nutrient Management Survey results (MDA, 2014). Methods of application and timing for fertilizer on corn and wheat crops were weighted to match the proportion of each crop in the state.

Organic Fertilizer

Manure rates on agricultural lands were determined using a statewide feedlot database acquired from the Minnesota Pollution Control Agency. Manure production per animal was based on American Society of Agricultural and Biological Engineers' manure production standards (ASABE, 2010) and supplemented with Midwest Plan Service manure characteristics (Lorimor et al., 2004). Manure generated at feedlot sites was allocated to cultivated lands in the region to determine a representative regional average rate. Manure application methods were determined using the Nutrient Management Survey results (MDA, 2014). Liquid and solid manure proportions were estimated in each region by animal size and type as well as the size of the operation. According to G. Schwint, MPCA feedlot program Senior Engineer, manure was assumed to be solid with the following exclusions: 5% beef cattle manure; all manure from adult dairy livestock and 20% of heifer and calf manure for operations with 100 head or more; and all swine manure (personal communication, June 13, 2014).

Updated Regional Phosphorus Index

This study is based on a regional P index modified by Birr and Mulla (2001) and originally based on the P index developed by Lemunyon and Gilbert (1993). An 8 by 5 matrix of transport and source factors along with rating values was supplemented with the additional transport factors of tile drainage and tile inlets. The resulting 10 by 5 matrix (Table 1) is used to determine a value for each site characteristic, which is then multiplied by the weighting factor of the site characteristic and summed to determine the P index value rating for an individual region.

Field scale water quality monitoring data were used to determine weighting factors for the updated site characteristics; Mulla et al (2004) determined a 50:1 ratio when converting P index values to kg/ha of P export. P yields were assumed to be 0.18 kg/ha for areas that are tile drained (Wall source) and tile inlets were assumed to contribute 0.1 kg/ha under the highest densities of approximately 1 inlet every 40 ha (Ginting et al., 2000). The P loss potential was then determined by the proportion of a region under tile drainage or the density of tile inlets present.

Site Characteristic (weight)	Phosphorus loss potential (value)				
	Very low (0)	Low (1)	Medium (2)	High (4)	Very High (8)
<u>Transport Factors</u>					
Soil Erosion (1.5) §	0	1-5	6-14	15-21	>21
Runoff (0.5) ¥	0-8	9-13	14-16	17-21	>21
Percentage of Cropland within 90 m of a watercourse (1.5)	0-1.2	1.3-3	3.1-4.2	4.3-6.2	>6.2
Percentage of Tile Drainage (1.0)	0-10	11-20	21-40	41-80	>81
Density of Tile Inlets (0.6) **	<0.3	0.31-0.62	0.63-1.2	1.3-2.5	<2.5
<u>Source Factors</u>					
Soil Test P (0.75) ‡	0-19	20-26	27-31	32-39	>39
Fertilizer P application rate (1.0)*	0-7	8-13	14-19	20-24	>24
Fertilizer P application method (0.5)	None applied	Placed with planter deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface-applied <3 mo before crop	Surface-applied >3 mo before crop
Organic P source application rate (0.5)*	0-2	3-6	7-8	9-11	>11
Organic P source application method (1.0)	None applied	Placed with planter deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface-applied <3 mo before crop	Surface-applied >3 mo before crop

§ Units for soil erosion are Mg/ha

¥ Units for runoff are cm.

**Units for tile inlet density are inlets/km^2

‡ Soil test P is Bray-1 extractable P and units are mg P/kg

* Units for P application are kg P/ha

Index Value Interpolation

Previous versions of this P index employed discrete categorical index values. This P index has been updated in part to evaluate BMPs and their impact on P yields. If discrete categorical values are used to determine P index values, small changes in a given factor can yield large P index changes if that factor is near the categorical threshold. This causes inaccuracies during BMP analysis. To mitigate such errors, continuous values were interpolated for each factor in the index based on a linear interpolation of each category. Thus resulting index values reported are continuous, and small changes in a given factor yield appropriate P index changes.

RESULTS AND DISCUSSION

Water Quality Monitoring

Minnesota has extensive P monitoring data for several watersheds in the state from 2007-2011. To compare P index modeling data to these monitoring data, 18 major watersheds were chosen that met the following requirements: the watershed must have a minimum of 3 average climatic years of P monitoring data, agriculture must be the primary landuse in the watershed, and finally the watershed must be in a headwater position meaning there are no upstream hydrologic connections contributing P sourced from other watersheds. To further bolster comparisons of monitoring data, P yields monitored for each watershed were multiplied by the proportion of agricultural sources based on SPARROW modeling (Robertson and Saad, 2011). Not all factors affecting P source and transport could be accounted for such as streambank slumping and P cycling in lakes. However, by isolating appropriate watersheds and their agriculturally sourced total P from monitoring data, a robust dataset has been created to compare with P index modeling results.

Site Characteristics

Transport factors vary widely across the state (Figure 1). The highest values for soil erosion were found in the steep southeast part of the state as expected; however, most of the southern half of the state is in the “very high” category for erosion. Monitored runoff rates were generally found to be less in the western portion of the state and increased while moving east. Percentage of agriculture within 90 m of a watercourse was highest in both the heavily ditched areas in northwest Minnesota, and the south central portion of the state where a large portion of the state’s fertile soils are located. Both percentage of tile drainage and tile inlet density were highest in the south central and southwestern portions of the state where soils are fertile and slopes are flat.

As for source factors, soil test P levels are generally high for the entire state. Based on agronomic P requirements, three-fourths of the state are in the very high category where further P applications do not generate increases in crop yield (Rehm et al., 1994). Average fertilizer rates are high in the southern and western half of the state where agriculture is predominant; rates are only low in the northeast portion of the state where forest is the major landuse. A representative fertilizer method score was assigned to each region based on an MDA nutrient management assessment; higher scores represent riskier methods for P loss. The west and southwest portion of the state experience the highest risk for fertilizer methods. As for inorganic fertilizer amendments, rates are highest in the southeast and north central regions where animal numbers are higher in proportion to cultivated acres. Farmer surveys reflect riskier methods of manure application in these areas as well, although statewide methods are uniformly high across the state.

Phosphorus Index

P index ratings ranged from 7 to 31 statewide for major watersheds, and the average rating was 22. A high soil erosion potential was the most common cause of higher P index ratings; nearly half of all watersheds were listed as very high for soil erosion potential. The next most common contributor to high scores was agricultural land within a 90 m buffer of streams and ditches. Almost half of the P index ratings statewide can be attributed to the aforementioned categories. The rest is divided amongst the remaining eight factors, although drainage influences and fertilizer application methods had the smallest impact on total scores (Figure 2).

P Index vs. Monitoring Data

When translating P index ratings to P export coefficients, a 50:1 conversion factor was used (Mulla et al., 2004). The statewide average rating of 22 translates into an average P export of 0.44 kg/ha for agricultural areas. P export coefficients for watersheds ranged from 0.14 kg/ha to a maximum of 0.62 kg/ha. Of the 18 selected watersheds for comparison, a strong correlation (r^2 = 0.85) was observed between monitoring and P index modeled loads (Figure 3). However, the P index tended to underestimate P losses in portions of the Red River of the North. On a statewide basis, the P index model tended to over-estimate loads, as total modeled loads were 47% higher than the sum of monitoring loads (Figure 4). P index estimates represent edge of field agricultural P contributions, and don’t account for P losses beyond the edge of field. Although watersheds with a high amount of lakes were excluded from comparison, it is uncertain how much P cycling in surface waters reduced monitored P loads in remaining watersheds. Further study is needed to quantify this relationship to assess the accuracy of the conversion factor on the regional scale.

Baseline P Loadings

The updated P index model predicts baseline P loadings just over 12 million pounds statewide. Two-thirds of these modeled loads are predicted to come from transport factors, the largest being soil erosion risk which is predicted to contribute nearly 3.5 million pounds of total P. The percentage of cropland within a 90 m setback of streams is predicted to be the next largest contributor of P; predicted loads from this transport risk total nearly 2.5 million pounds. Tile drainage and runoff risks translate into another 2 million pounds of predicted loading. As for source factors, these are predicted to contribute 4 million pounds, or one-third of the total statewide load. These are divided somewhat evenly between manure method, fertilizer rate, and soil test P at nearly one million pounds predicted for each factor. Fertilizer method and manure rate combine to total another million pounds of P.

Figure 1. P Index source and transport risk factors and total P Index score by major watershed.

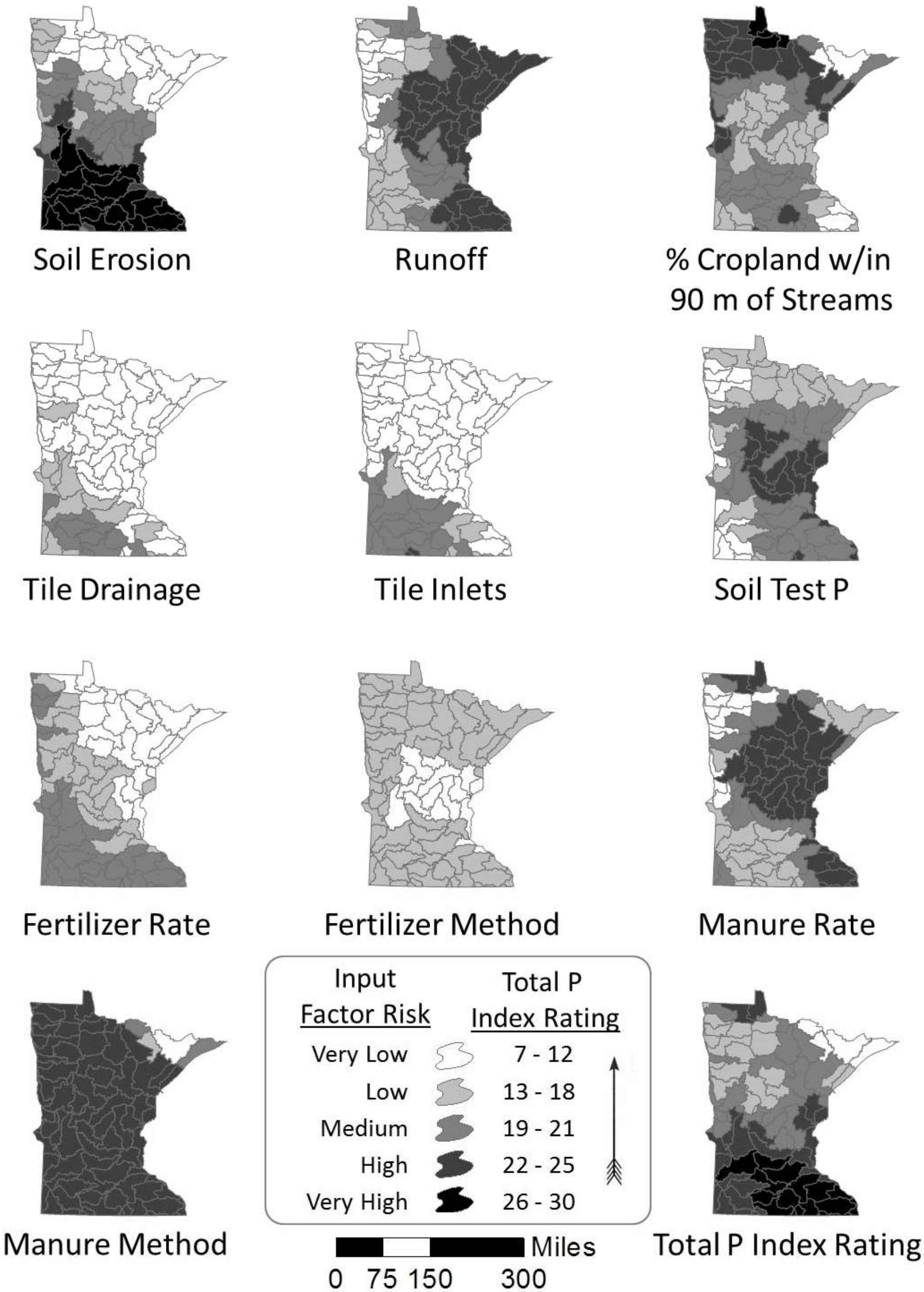


Figure 2. Modeled baseline P contribution from source and transport pathways

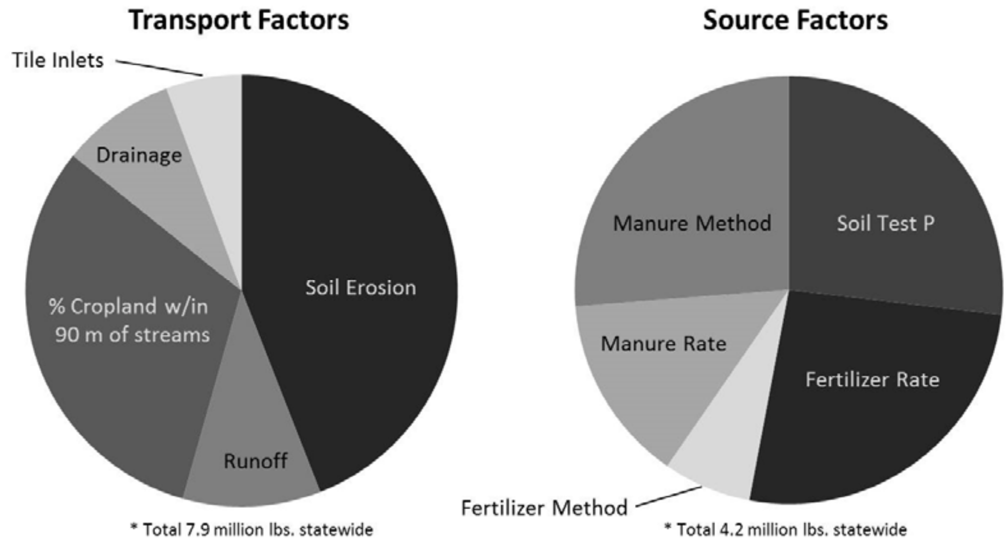


Figure 3. Linear regression of water quality monitoring loads vs. P Index based loads.

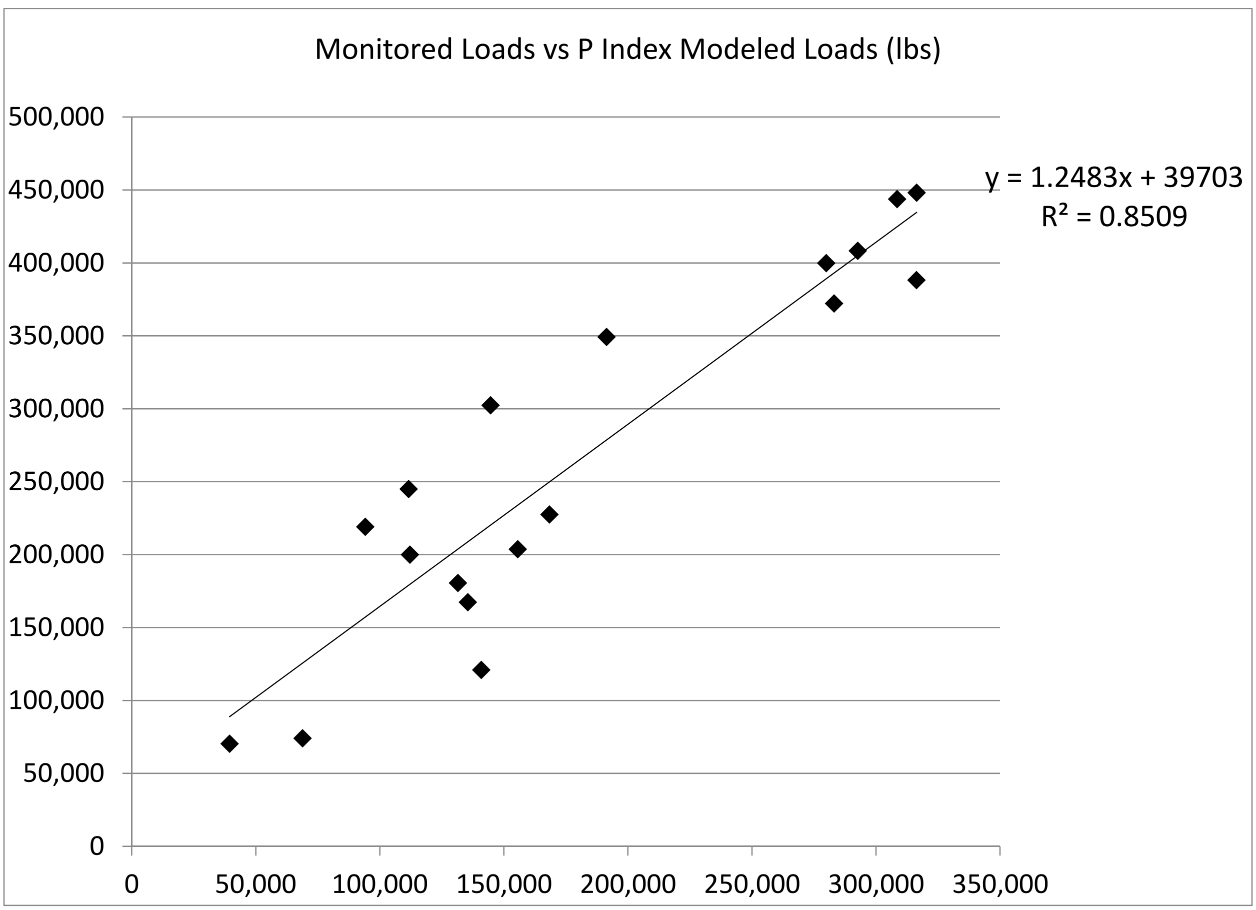
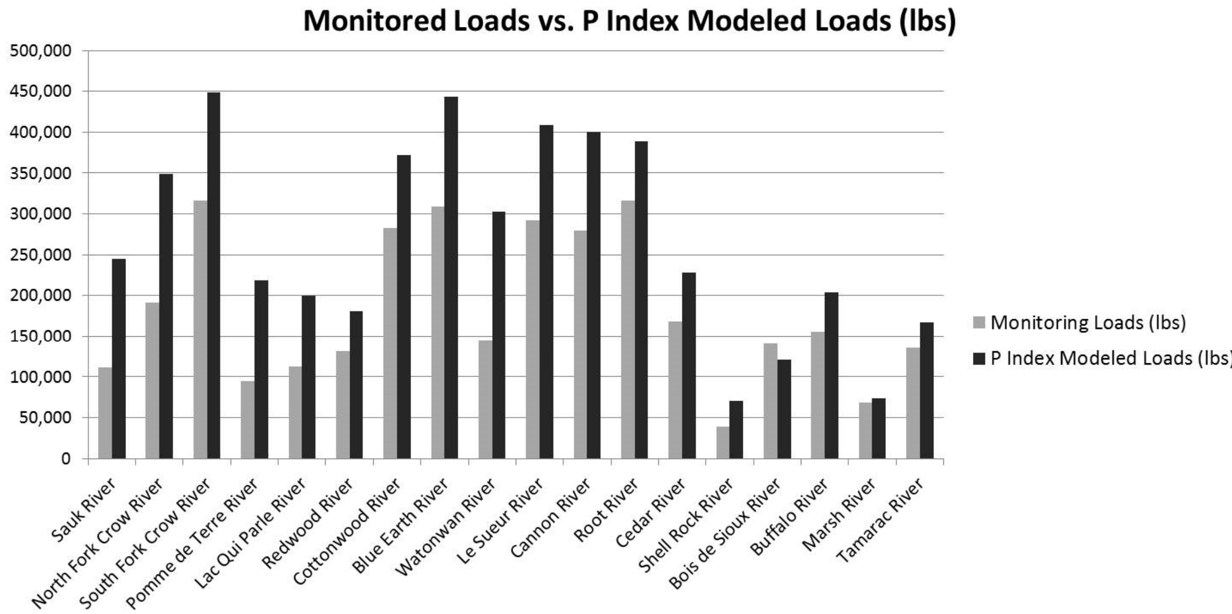


Figure 4. Water quality monitoring loads vs. P Index based loads for selected watersheds in Minnesota.



ASABE (American Society of Agricultural and Biological Engineers). 2010. Manure Production and Characteristics. https://elibrary.asabe.org/azdez.asp?JID=2&AID=32018&CID=s2000&T=2

Brown, J.R. 1998. Recommended chemical soil test procedures for the north central region. North Central Regional Res. Publ. no. 221 (Revised). SB 1001. Missouri Agric. Exp. Stn., Columbia.

Correll, D.L. 1998. The Role of Phosphorus in the eutrophication of receiving waters: a review. Journal of Environmental Quality 27(2): 261-266.

EWG (Environmental Working Group). 2014. Broken stream banks: failure to maintain buffer zones worsens farm pollution. http://www.ewg.org/research/broken-stream-banks.

Ginting, D., J.F. Montcrief, and S.C. Gupta. 2000. Runoff, solids, and contaminant losses into surface tile inlets draining lacustrine depressions. Journal of Environmental Quality 29:551-560.

Hoffman, C.C., C. Kjaergaard, J. Uusi-Kämppä, H.C. Bruun Hansen, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: review of their efficiency. Journal of Environmental Quality 38(5): 1942-1955.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment, 132: 159 – 175.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. Journal of Production Agriculture 6:483-486.

Lorenz, D.L. G.H. Carlson, and C.A. Sanocki. 1997. Techniques for estimating peak flow on small streams in Minnesota. Water-Resour. Investigations Rep. 97-4249. U.S. Geol. Survey, Denver, CO.

Lorimor, J., W. Powers, and A. Sutton. 2004. Manure Characteristics: Manure Management Systems Series. Midwest Plan Service. 18:1 (2nd ed.).

Mankin K.R., D.M. Ngandu, C.J. Barden, S.L. Hutchinson, and W.A. Geyer. 2007. Grass-shrub riparian buffer removal of sediment, phosphorus, and nitrogen from simulated runoff. Journal of the American Water Resources Association 43 (5): 1108-1116.

MDA (Minnesota Department of Agriculture). 2014. Fertilizer and Manure selection and management practices associated with Minnesota's 2010 corn and wheat production. http://www.mda.state.mn.us/protecting/cleanwaterfund/gwdwprotection/~/media/Files/protecting/cwf/2010cornnitromgmt.pdf

MN DNR (Minnesota Department of Natural Resources). 2001. DNR 24k Streams data layer. http://deli.dnr.state.mn.us/metadata/strm_baseln3.html#distinfo

MPCA (Minnesota Pollution Control Agency). 2014. The Minnesota Nutrient Reduction Strategy. Appendix A: Statewide Buffer Analysis. http://www.pca.state.mn.us/index.php/view-document.html?gid=20213.

MRBDC (Minnesota River Basin Data Center). 2007. Minnesota Tillage Transect Survey Data Center. http://mrbdc.mnsu.edu/minnesota-tillage-transect-survey-data-center#minnesota

Mulla, D. J., P. H. Gowda, G. Wilson, and H. Runke. 2004. Estimating phosphorus losses from agricultural lands for MPCA's detailed assessment of phosphorus sources to Minnesota watersheds. A report to the Minnesota state legislature. MPCA. St. Paul, MN. http://www.pca.state.mn.us/index.php/view-document.html?gid=3977.

NASS (National Agricultural Statistics Service). 2013. Cropland Data Layer grid. http://www.nass.usda.gov/research/Cropland/Release/index.htm

Robertson, D.M. and D.A. Saad. 2011. Nutrient inputs to the Laurentian Great Lakes by source and watershed estimated using SPARROW watershed models. Journal of the American Water Resources Association 47(5): 1011-1033.

Schindler, D.W. 1977. Evolution of phosphorus limitations in lakes. Science 195:260-262.

Schottler, S. P., J. Ulrich, P. Belmont, R. Moore, J.W. Lauer, D.R. Engstrom, and J.E. Almendinger. 2014. Twentieth century agricultural drainage creates more erosive rivers. Hydrologic Processes. 28: 1951–1961.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: issues and options.

USDA, ERS (United States Department of Agriculture, Economic Research Service). 2012. Fertilizer use and price. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#.VEZ24hYxikN

University of Minnesota Extension. 2011. Fertilizer guidelines for agronomic crops in Minnesota. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#.VEZ24hYxikN

Vollenweider, Richard. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organization for Economic Cooperation and Development. Technical Report DAS/CSI/68.27. Paris, France.