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IDEAS & INNOVATIONS

A spreadsheet planning tool for assisting a state agency with cost-effective watershed scale surface water nitrogen planning

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The Minnesota Pollution Control Agency (MPCA) is developing a statewide nutrient reduction strategy and coordinating with other states to reduce nitrogen (N) and phosphorus (P) loads in the Mississippi River. Excess N in surface waters is of concern both because of toxicity to aquatic organisms locally and because many Minnesota watersheds feed into the Mississippi River and the Gulf of Mexico, where a 45% reduction in both N and P has been proposed (USEPA Science Advisory Board 2007). Minnesota's Nutrient Reduction Strategy identifies how the state intends to achieve its first 20% reduction in N leaving the state via the Mississippi River.

To provide a scientific foundation for the N reduction efforts needed in Minnesota, the MPCA worked with the University of Minnesota and US Geological Survey to characterize N loading in watersheds throughout Minnesota. Other states in the Mississippi River Watershed are engaging in similar efforts, including Iowa (Iowa Department of Agriculture and Land Stewardship et al. 2013). The University of Minnesota's role in the project included estimating nonpoint source N loads from different sources (agriculture, forestry, and urban) and pathways (runoff, drainage, and groundwater discharge); a literature review on N reduction effectiveness of various best management practices (BMPs); a survey of farmers and focus groups of water resource professionals; and development of a spreadsheet tool for estimating watershed N reductions to waters when combinations of BMPs are adopted (Davenport and Olson 2012; Fabrizzi and Mulla 2012; Lazarus et al. 2013; Mulla et al. 2102). These findings, along with other findings from the MPCA and US Geological Survey, were incorporated into a comprehensive report entitled "Nitrogen in Minnesota Surface Waters: Conditions, Sources, Trends and Reductions" (MPCA 2013). The survey and focus groups explored farmer perspectives on farming and water resources, examined the decision-making process associated with N use on farms, and identified drivers of and constraints to on-field and off-field N BMP adoption. The University of Minnesota–modeled N loads to surface waters (figure 1) represent existing conditions on which future nutrient reduction goals are based. Fifteen eight-digit hydrologic unit code (HUC8) watersheds each contribute more than 25 million kg (5.6 million lb) of N loadings, and these watersheds represent a majority of the N loads in Minnesota. The dominant land use in each of these 15 watersheds is agriculture.

Part of the study was to develop a spreadsheet-based watershed N planning tool that could be used to optimize selection of nine different agricultural BMPs for reducing the N load from the highest contributing sources and pathways in a watershed. The nine BMPs included

1. reducing the fertilizer N rate on corn (*Zea mays* L.) acres to a target N rate,
2. switching fall N applications to spring preplant,
3. switching fall N applications to sidedressing,
4. adding riparian buffers on suitable acres,
5. restoring wetlands on suitable acres,
6. installing controlled drainage on suitable acres,

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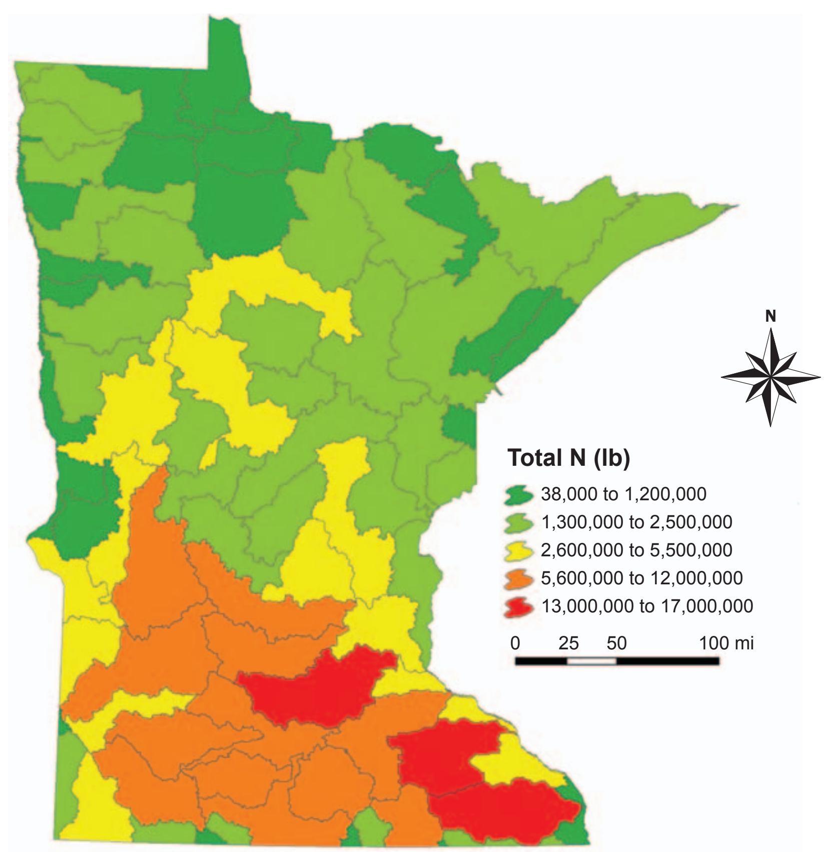
Figure 1

Modeled estimates of nitrogen (N) load by eight-digit hydrologic unit code watershed, based on a nonpoint source assessment of nitrogen sources. The 15 red- and orange-coded watersheds contribute a majority of N losses to surface waters for the state of Minnesota.



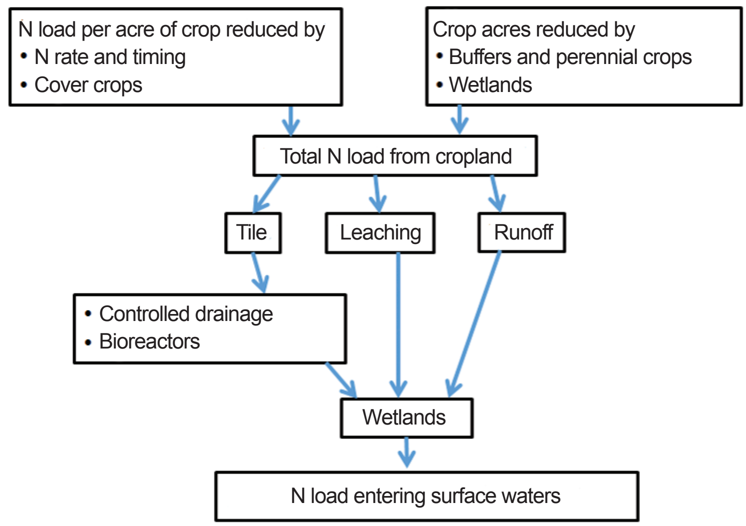
7. installing tile line bioreactors on suitable acres,
8. planting a rye (*Secale cereal* L.) cover crop on corn grain and soybean (*Glycine max* [L.] Merr.) acres, and
9. planting a perennial crop on marginal land corn and soybean acres.

This paper discusses that spreadsheet, referred to here as the Watershed Nitrogen Reduction Planning Tool, or NBMP. The tool is available for downloading at http://z.umn.edu/nbmpdoc.

The relationships between the BMPs in the model are illustrated in figure 2. The individual BMP loading reductions and costs per pound of N reduction are not additive, in general. For example, controlled drainage costs a fixed amount per acre to install and maintain and reduces the tile line N by a fixed percentage. The percentage reduction times the original N load gives the load reduction. The cost per pound of N reduced with controlled drainage is calculated by dividing the controlled drainage cost per acre by its N reduction. If the N load per acre of corn is reduced by optimizing the N fertilizer rate and timing, it also reduces the tile line N load available for reduction by the controlled drainage BMP. Therefore, the same percentage reduction would translate into fewer pounds of N reduced, translating in turn into a higher cost per pound of reduction. Similarly, riparian buffers and perennial crops reduce the watershed-wide impacts of optimizing the corn fertilizer N rate and timing BMP and the cover crop BMP because those BMPs reduce the acres of corn and soybeans that are available to be impacted by the fertilizer and cover crop BMPs.

Figure 2

Relationships between the best management practices (BMPs) in the model, indicating that the individual BMP reductions and costs per pound of nitrogen (N) reduced are not additive, in general.



HOW THE WATERSHED NITROGEN REDUCTION PLANNING TOOL COMPARES TO OTHER MODELS

Process-based models such as the Soil and Water Assessment Tool and the Agricultural Policy/Environmental eXtender are available to evaluate tradeoffs between environmental quality and production efficiency of farms or small watersheds (Texas A&M University 2013a; Texas A&M University 2013b). Williams et al. (2012) review four other research-oriented models that have been used to optimize BMP placement in Illinois, Arkansas, Virginia, and the Mississippi Delta. As they point out, the methods and conclusions from these models are useful, but the models themselves would be difficult to use in an iterative planning process with state and local stakeholders as envisioned to meet the new N reduction goals and milestones.

A number of decision tools already exist, but they do not include several important BMPs that address N, such as tile line bioreactors and fertilizer application timing, and do not include data for Minnesota. Some decision tools that are similar in some respects to NBMP include the Soil-Erosion Economic Decision Support Tool for land management in Nebraska, which focuses on crop rotations, irrigation, and tillage practices (Mamo et al. 2009), and the web-based Chesapeake Assessment Scenario Tool, which is very comprehensive but is specific to the Chesapeake Bay Watershed (Devereux and Rigelman no date). The Kansas Watershed Manager allows the user to enter any BMP for consideration, but one drawback is that it does not help the user to arrive at the effectiveness of a given BMP in reducing erosion or N or P losses or to estimate watershed-scale impacts (Williams et al. 2012). The Watershed Restoration using Spatio-Temporal Optimization of Resources tool optimizes over multiple perspectives and goals but does not consider some BMPs that are important for Minnesota (Babbar-Sebens and Mukhopadhyay 2013). The decision to develop our own spreadsheet allowed us to include a number of BMPs not addressed in existing models and to build in a database of acreage suitable for each BMP in each watershed, as discussed below. It also allowed incorporation of recent research results on BMP effectiveness and cost. Another difference was that NBMP considers 216 different combinations of the 9 BMPs rather than the 5 that the Watershed Manager allows, which is important because no single BMP appears likely to yield N load reductions of anywhere near the 45% Environmental Protection Agency target, and most of the BMPs considered here can be implemented in combinations.

NBMP is similar to the Watershed Planner in that both are Microsoft Excel spreadsheets that analyze HUC8-scale watersheds. Both allow the user to select BMP adoption rates that are in some sense socially acceptable to the user. Some differences between NBMP and the Watershed Planner are that NBMP includes calculations of cost and effectiveness for some N-related BMPs that are apparently not calculated in the other spreadsheet. Two BMPs that are addressed in both spreadsheets are riparian buffers and wetland restoration. The Watershed Planner uses the Excel Solver optimization add-in to optimize the set of BMPs. NBMP can also optimize using Solver, but compares the combinations graphically in an "efficient frontier" as discussed below.

MODELING NITROGEN FLOWS AND BEST MANAGEMENT PRACTICES IN THE WATERSHED NITROGEN REDUCTION PLANNING TOOL MODEL

Modeling of N sources and pathways is described in a companion paper (Mulla et al. 2013). Two geographic units that are important for users to understand when using the spreadsheet are watersheds and agroecoregions; a single watershed encompasses several agroecoregions. Agroecoregions are units having relatively homogeneous climate, soil, landscapes, and land use/land cover. The spreadsheet analyzes a watershed that the user selects. However, the N loadings and crop economic calculations are first estimated by agroecoregion before aggregating results at the watershed scale. Specifically, major factors that vary across agroecoregions include crop mix and yields; current fertilizer application rates; soil organic matter; N deposition rates; dominant soil types, drainage and hydrology classes; percentage tile drained, denitrification rates; leaching rates; groundwater loss factors; and various runoff factors. The summary results of the model are organized by watershed rather than agroecoregion, however, under the assumption that watersheds are the main areas of interest to users. The spreadsheet includes area data on the agricultural HUC8 watersheds in Minnesota and also has options for aggregating the watersheds to major river basins and statewide scales. When the user selects a watershed for analysis, results are retrieved as an area-weighted average of the agroecoregions making up that watershed. There are 39 agroecoregions in the state. A given agroecoregion may fall into more than one watershed.

The N loadings from each agroecoregion are calculated based on a meta-analysis of research data for each pathway (Mulla et al. 2013) in three categories: runoff, drainage tile discharge, and leaching and subsequent groundwater discharge to surface waters from cropland. Nitrogen loading amounts consider effects of denitrification for the groundwater discharge pathway, but they do not consider denitrification losses that

Figure 3

Model form for entering adoption rates for the nine best management practices (BMPs) in a given watershed.

50.297 million acres in watershed or state

Watershed: Statewide	% suitable	% adoption	% treated	% treated, combined
Corn grain & silage acres receiving the target N rate	15.5%	90%	13.9%	13.9%
Fall N applications switched to spring, % of fall-app. acres	6.2%	45%	2.8%	2.8%
Fall N switch to split spring/sidedressing, % of fall acres	6.2%	45%	2.8%	2.8%
Riparian buffers	3.4%	70%	2.4%	2.4%
Restored wetlands	3.2%	50%	1.6%	1.6%
Tile line bioreactors	2.7%	20%	0.5%	0.5%
Controlled drainage	2.7%	50%	1.3%	1.3%
Corn &soybean acres planted w/cereal rye cover crop	29.6%	10%	3.0%	2.7%
Perennial crop % of corn & soybean area: marginal only	3.4%	10%	0.3%	0.2%

Weather scenario: Average weather - all of preplant N is available 1

For wet spring scenario 2, fertilizer & manure N lost 30%

N load reduction with these adoption rates: 21.1% of all nonpoint source load
23.5% of cultivated ag land source load

Total treatment cost: $311.81 million/year

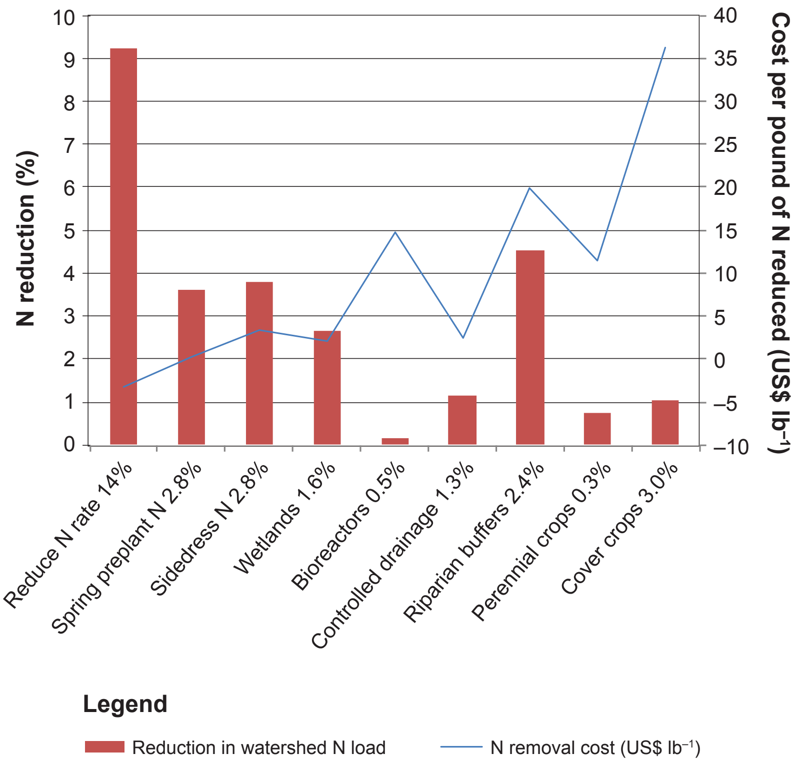
occur in surface waters after receiving runoff, groundwater discharge, and tile drainage. The BMPs affect only loading from cropland, but loading from forests and impervious urban and suburban land is also included in the total N loadings. The loadings are calculated for three weather scenarios: an average year (50th percentile) and wet and dry years (10th and 90th percentiles). Total N loadings to surface waters in an average climate year with existing farm management practices are 115 million kg (254 million lb), with 72% of this loading from cropland areas of Minnesota. These loadings agree closely with results of river water quality monitoring data collected by MPCA.

The audience for the model is state and watershed resource managers, not farm operators. Adoption of a BMP is a farm-level decision, however, so the results depend heavily on making reasonable assumptions about attitudes of farm operators in the watershed toward the BMPs. The default adoption rates provided with NBMP are based in part on personal interviews conducted with 30 agricultural producers along with 2 focus groups of water resource professionals in 2 Minnesota watersheds (Davenport and Olson 2012). The model lends itself to being used in several different ways. Most importantly, the user can enter a set of adoption rates that are deemed to be likely or that would be achievable with some sort of planning process or incentive program. Adoption rates are limited to the area that is suitable for implementation of a BMP within a particular watershed based on soil, landscape, and farm management characteristics in the watershed. For example, the user-specified adoption rates shown in yellow in figure 3 are based on assuming that the N fertilizer rate could be reduced to the extension-recommended rate on most of the corn acres, thereby saving on fertilizer expenses in an average year, whereas adoption of cover crops is limited to 10% of the suitable area (following short-season crops) because of Minnesota's dry and cold fall weather. Adoption of controlled drainage is generally unpopular with Minnesota farmers and might only be adopted on 5% of suitable acres because of the time required to adjust the control structures. It was felt that a split preplant and sidedressed fertilizer application might be preferable to applying it all before planting, so the preplant practice is set at 10%, while 25% for the split application would be achievable. The selection of adoption rates for each BMP is flexible, according to the user's preference. The model is also designed to allow Excel's Solver optimization module to solve for a set of adoption rates that would achieve either (1) a given load reduction at minimum cost or (2) a maximum load reduction subject to a given maximum cost. More details on the criteria for suitability and other assumptions underlying the model are described by Lazarus et al. (2013).

The main results of the model are displayed as comparisons of cost versus effectiveness in reducing the N loading in the selected watershed. These results are displayed in two forms: (1) by individual BMP and (2) for selected combinations of the BMPs. The individual BMP infor-

Figure 4

Graph comparing nitrogen (N) reduction effectiveness and cost of individual best management practices (BMPs). The percentages next to the BMP descriptions are percentages of the state or watershed treated.



mation is displayed in two graphs and a table. One graph, shown in figure 4, compares the percentage N load reductions and costs per pound of N reduced. Another graph (not shown) compares pounds reduced per treated acre and cost per treated acre, while the table shows the same information along with watershed totals for each measure.

The first bar in figure 4 shows that reducing the N fertilizer rates from current averages (as found in the survey described in Bierman et al. [2011]) to profit-maximizing rates recommended by the University of Minnesota on 90% of corn acres or 14% of the watershed overall would provide the greatest N load reduction. The blue line shows that this BMP would also save money rather than costing money because reduced fertilizer purchases exceed yield losses. Improved crediting of manure N is included with the N rate reduction. The current scenario assumes that 70% to 90% of manure N is credited against fertilizer requirements, depending on animal species. The N rate reduction BMP assumes that 100% of the manure N is credited, and that change accounts for around one-third of the nearly 9% N load reduction shown. Riparian buffers are adopted on 70% of suitable acres in this scenario, and they provide the next highest reduction but at a higher cost since productive land is taken out of corn and soybean production for that BMP.

Figure 5 shows the estimated statewide impact of implementing all nine BMPs on suitable acres at the adoption rates shown in figure 3. The fertilizer rate reduction and the switch from fall to spring or split application are grouped into the "Fertilizer optimized" category and would result in a cost saving. The "Tile drainage BMPs" category includes controlled drainage and tile line bioreactors, along with wetland restoration. Those BMPs would cost US$11 million y^{-1}. The "Vegetation changes" category includes cover crops, riparian buffers, and perennial crops on marginal cropland and would cost US$312 million y^{-1}. This latter category, then, is much more costly than the first two categories, due to its impact on corn and soybean acres shifted to the buffers and perennial crops. This comparison can then lead to discussion of policy questions, including the following:

1. Is the load reduction provided by the improved fertilizer management and perhaps the tile drainage BMPs enough to meet environmental goals, or are the more costly vegetation changes also required?
2. What can be accomplished by increasing the adoption rates of the cheaper BMPs versus adopting the more costly ones at low rates at least?
3. If improved fertilizer management saves money, why aren't producers already doing it?

These results depend, of course, on many factors, not the least of which are the default US$197 Mg^{-1} (US$5.00 bu^{-1}) corn price and US$459 Mg^{-1} (US$12.50 bu^{-1}) soybean price in the model, and are somewhat different in wet and dry years.

Another way the results are displayed is in a graph of effectiveness versus cost for only those combinations of BMPs that are more efficient in providing greater N reductions than any other combinations that cost the same amount or less (figure 6). The full suite of nine BMPs would achieve a 20% load reduction at the adoption rates shown in the legend and would cost an average of US$14.92 kg^{-1} (US$6.77 lb^{-1}) of reduction. Effectiveness is shown on the horizontal axis and is measured here as a percentage N reduction in the watershed. Cost per pound of N reduced is shown on the vertical axis. In the example shown, the green bar shows that reducing the corn N fertilizer rate where it exceeds recommended rates on 90% of the state's corn acreage would reduce N loading by 9% and actually saves US$7.43 kg^{-1} (US$3.37 lb^{-1}) of reduced N loading rather than costing money, so the cost bar extends down rather than up. The blue bar shows that switching from fall to spring preplant N application along with the rate reduction would achieve an 11% reduction. The timing switch would cost money but not enough to offset the fertilizer cost savings. The fertilizer cost savings would actually cover a load reduction of 13% that could be achieved by applying the corn N fertilizer in a split preplant/sidedressed application, restoring wetlands, and adopting controlled drain-

Figure 5

Summary of the estimated nitrogen (N) loading reductions and annual costs of implementing the best management practices (BMPs) statewide at the adoption rates shown in figure 3.

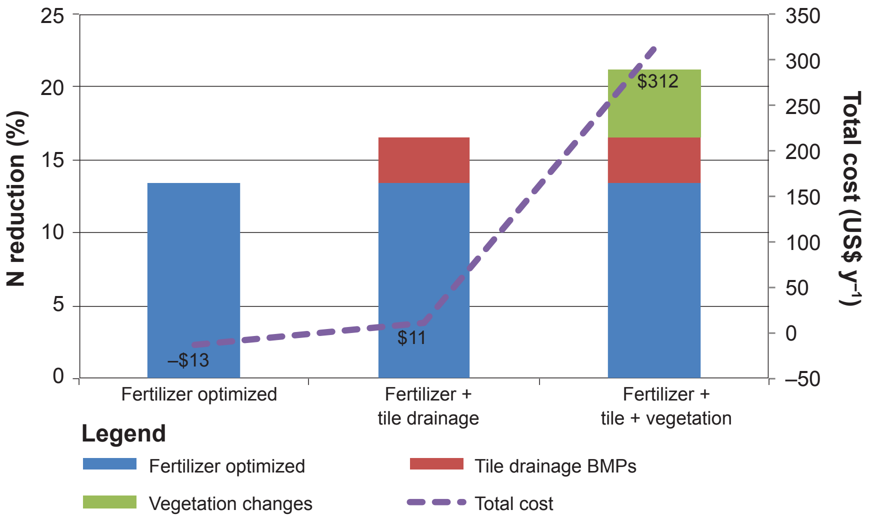
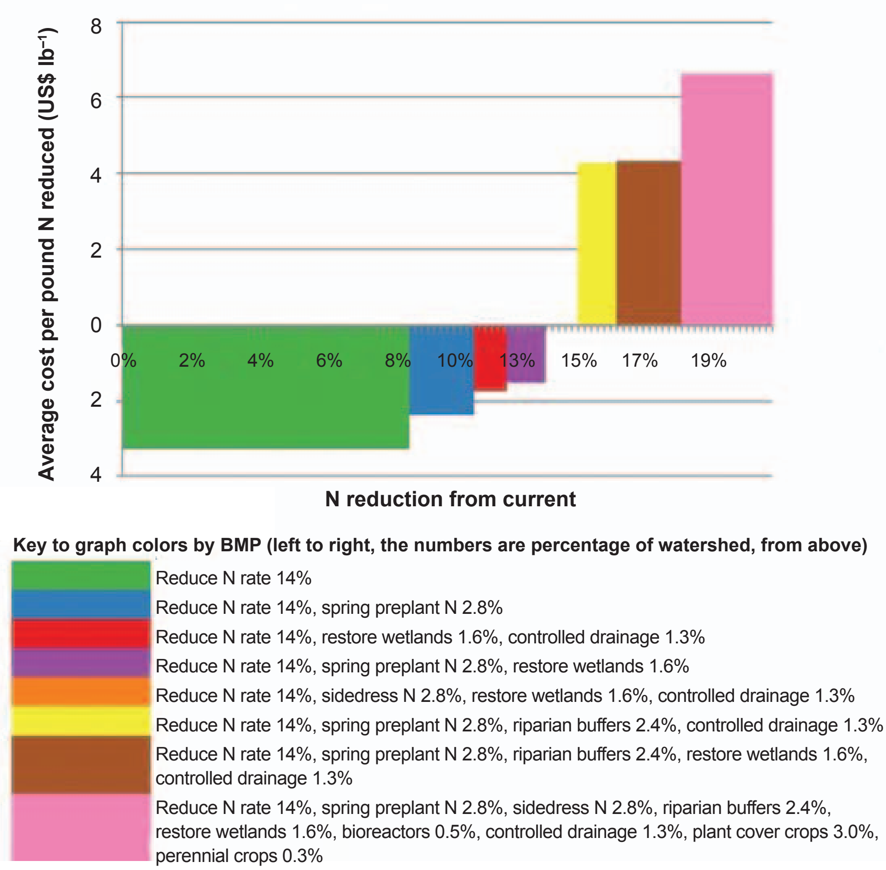


Figure 6

Graph of "efficient frontier" best management practice (BMP) combinations that achieve different load reductions at minimum cost for an average year.



age at the adoption rates shown in figure 2. This arrangement of the results can lead to discussions about how much load reduction is enough to meet environmental goals and what tradeoffs are economically and politically tolerable between reductions and costs.

Figure 6 only displays the efficient BMP combinations. However, in order to identify those combinations, 216 total combinations were evaluated. Three combinations are omitted to keep the total number small enough to calculate:

1. Timing changes from fall to either spring preplant application or a split preplant/sidedressed application were considered in separate scenarios but not together.
2. Bioreactors were not considered in the same scenario with controlled drainage.
3. Wetland restoration was not considered in the same scenario with a switch to a perennial energy crop on the corn and soybean acres.

Some BMPs are complementary, such as reducing the N fertilizer rate and changing the timing from fall to spring. Other BMPs are competitive, such as converting cropland to riparian buffers and restoring the same cropland to a wetland pool. In other cases, the same acreage could be treated by more than one BMP, but the first BMP would likely reduce the N load enough that the second BMP would not be cost effective. This might be the case, for example, where corn land could be converted to a perennial crop and also have its runoff treated by a restored wetland nearby. The adoption rate for each BMP can be varied by the user from 0% to 100%, so even competitive BMPs can be considered in the same scenario as long as the adoption rates do not total more than 100%. In the "all-of-the-above" scenario and a few of the other scenarios, if the user does enter adoption rates totaling more than 100% for two or more competitive BMPs, formulas in the spreadsheet reduce the adoption rate of the more costly BMP down to a level where the adoption rates total 100%.

IMPACTS OF WEATHER SCENARIOS ON THE MODEL RESULTS

The N loading can be calculated by the model for an unusually wet year or a dry year, in addition to the scenario for an average climatic year. The weather scenario selected in the model affects the loading calculations via changes in tile line and runoff volumes. Agricultural producers tend to raise concerns about high N fertilizer losses from the crop root region in a wet year, which would reduce yield. The reduction in N load resulting from the various BMPs will vary due to different water volumes in dry and wet years. The amount of N loss in a wet year takes into account the impact of a given N loss rate on the corn yield estimated via the yield response function.

Selecting the wet year scenario brings up a choice or assumptions regarding whether the wet weather is assumed to occur late enough in the year to cause losses in the sidedressed N or just the preplant N, and whether the sidedressed rate is increased to make up for the losses in preplant N. The split preplant-and-sidedress BMP should be amenable to recent recommendations to apply fertilizer N applications in multiple applications and add more N at sidedressing time in a wet year with greater-than-expected losses from earlier applications (Betts 2013). A loss of 30% of the corn N fertilizer would reduce yields enough to more than offset the fertilizer cost savings so that the rate reduction is no longer the lowest-cost BMP. Restoring wetlands is now lowest, at US$2.78 kg^{-1} (US$1.26 lb^{-1}). Reducing the rate alone is not on the efficient frontier, but reducing the rate along with adding controlled drainage and restoring wetlands would cost US$9.02 kg^{-1} (US$4.09 lb^{-1}) in a wet year. This scenario assumes that 45% of the fall-applied corn acres are switched to the split application and receive enough extra sidedressed N to make up for the 30% loss of the preplant-applied N. The rest of the fall-applied acres and the acres currently spring-applied are assumed to experience the 30% loss. All nine BMPs together would cost US$17.33 kg^{-1} (US$7.86 lb^{-1}) in the wet year scenario, compared to US$14.92 kg^{-1} (US$6.77 lb^{-1}) in an average year.

USE OF THE WATERSHED NITROGEN REDUCTION PLANNING TOOL IN DEVELOPMENT OF MINNESOTA'S NITROGEN REDUCTION STRATEGY

The NBMP tool was used in several ways during the development of Minnesota's Nutrient Reduction Strategy. A 20% N reduction milestone was chosen for the Mississippi River after using the NBMP tool to estimate N reductions to waters under various BMP adoption scenarios. Once the milestone N reduction goal was set, the NBMP tool was used to consider the acres of each BMP adoption that would be needed to achieve the milestone reductions. By running various BMP scenarios with the NBMP, it was observed that attaining N load reductions greater than 25% will be very costly and will require large changes in agricultural management that at present are unacceptable to producers. In the future, water resource planners will be able to use the NBMP tool to develop action plans for BMP adoption in individual HUC8 watersheds. The NBMP tool, along with local expertise and experience, will enable planners to develop the most achievable and cost-effective approach for reducing watershed N loads.

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