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Effects on Farm Income and the Environment from Targeting Agricultural Best Management Practices (BMPs)

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ABSTRACT

To evaluate potential effects on net farm income and water quality from specific agricultural Best Management Practices (BMPs), estimates of phosphorus loading for current and alternative farming methods were combined with cost and return estimates to create a positive mathematical programming model of a major watershed. Targeting specific BMPs to susceptible regions was the most effective policy for improving water quality. This had smaller negative impacts on farm income than not targeting BMPs to reduce phosphorus effluent from agriculture.

OBJECTIVES

The objective of this research was to evaluate how targeted and nontargeted implementation of agricultural BMPs affected agricultural production, net farm income and agricultural phosphorus nonpoint loading in a watershed.

BACKGROUND

In appropriate quantities, phosphorus is beneficial, and indeed, critical to production agriculture, and thus society. However, at excessive levels in surface waters, phosphorus can become detrimental. Phosphorus is the principal contributor to eutrophic conditions in surface waters in Minnesota (MPCA 2000). Eutrophication from excess phosphorus is associated with nuisance algae blooms and reduced transparency that makes the water unsuitable for swimming and other recreational activities. The presence of, problems caused by, and solutions to excessive levels of phosphorus in the Minnesota River have been described in many studies and reports

(McCann; McCann and Easter; Taff and Senjem; Mathews, Homans, and Easter; Meyer and Schellhaass; Engstrom and Almendinger). These studies indicate phosphorus in the Minnesota River originates from both point and nonpoint sources. Point sources, such as wastewater treatment facilities, are significant sources of phosphorus to surface waters during periods of low precipitation and stream flow. Conversely, nonpoint sources such as runoff from farm fields can contribute significant amounts of phosphorus to surface waters during periods of high precipitation and stream flow (MPCA 2000).

Water samples from the Minnesota River help to illustrate the nature and extent of the phosphorus problem. These samples indicated an annual average of 1,600 tons of total phosphorus flow from the Minnesota River to the Mississippi River (MWCC, p.141). The average concentration of total phosphorus in water over that same period was 0.394 mg/L (MWCC, p.141) -- 20 to 40 times higher than concentrations associated with accelerated eutrophication (Randall *et al.*).

A goal established by the U.S. Environmental Protection Agency (EPA) and the Minnesota Pollution Control Agency (MPCA) was to reduce sediment and phosphorus pollution in the Minnesota River by 40 percent from pre-1980 levels (Frost and Schwanke). Frost and Schwanke and Mulla *et al*. indicated point source contributions (from wastewater treatment facilities) to the phosphorus load in the Minnesota River have been reduced considerably (50%) over the past three decades. Efforts have focused recently on reducing nonpoint contributions to the total load of sediments and phosphorus. As agriculture constitutes the predominant land use, it is viewed by many as a major contributor of nonpoint pollution in the Minnesota River basin. Frost and

Schwanke and Mulla *et al.* indicate that 53-77% of the phosphorus entering Lake Pepin immediately from the Minnesota River basin is from fertilizer, manure, soil erosion or other diffuse sources. Therefore, efforts to reduce total phosphorus load from nonpoint contributors in the river basin by 40% in general and in the Le Sueur Watershed (the study area) specifically, need to include agriculture. How the implementation of BMPs affects phosphorus pollution levels and net farm income in the watershed, relative to the estimated baseline levels are the issues addressed in this study.

DATA AND METHODS

Study Area: Le Sueur River Watershed

Because the scale of the Minnesota River basin is so large and hydrological modeling the entire river basin would have been problematic, the Le Sueur River watershed, a major watershed in the basin, was selected to examine the effects of targeted and nontargeted implementation of agricultural BMPs to control nonpoint phosphorus pollution. Located in south central Minnesota, this 285,000 hectare watershed is one of the twelve major watersheds of the Minnesota River Basin. The Le Sueur River is a major contributor of phosphorus load to the Minnesota River Basin (17%, MWCC). Like the Minnesota River Basin, intensive agricultural production occurs in this watershed with 95% of the cropland planted to corn and soybeans (USDA 1999). Over 80% of the surface area of the watershed is in some type of cropping system, with approximately 40% of the cropland under some type of conservation tillage system (USDA 1999; CTIC 1999). Considerable livestock production occurs in this watershed as it does in the Minnesota River basin.

ADAPT Modeling

ADAPT is a field-scale water table management model that combines GLEAMS (Leonard *et al*.) and DRAINMOD (Skaggs). ADAPT can model crop fields that have tile drainage, a dominant feature of fields in the study area. Land cover, agricultural management practices (crops, rotation and tillage), slope and soil information were overlaid with Geographic Information System (GIS) to create data input files for the ADAPT model that reflected the spatial distribution of current production practices in the watershed. ADAPT has been calibrated to the data collected in several watersheds in Minnesota (Davis *et al*., Dalzell, Johansson, Westra *et al*.). Davis *et al*. calibrated and validated the ADAPT model for tile drainage and associated nitrate nitrogen losses using long-term monitoring data measured on three experimental plots in southern Minnesota. Dalzell used observed data from six gauged tributary watersheds of the Lower Minnesota River Watershed to calibrate ADAPT to local conditions (land cover, slope, tillage practices, soils information and weather data). This calibrated model was used to simulate monthly flow, sediment and nitrate nitrogen losses from ungauged watershed of the same watershed. Dalzell concluded the watershed methodology applied to ADAPT modeling was best suited for watershed dominated by agricultural activities. Johansson and Westra *et al.* used the ADAPT model calibrated to different watersheds to examine various biophysical and economic effects of policies to reduce nonpoint pollution in the Minnesota River Watershed. ADAPT has provided estimates of monthly stream flows using NRCS soils data, land use, and tillage information for a small agricultural watershed in Ohio (Gowda et al. 1999a).

Field-edge sediment losses and runoff were estimated for each current farming system using the ADAPT model. ADAPT provides edge-of-field estimates for nutrient and soil losses from the different systems, based on soil type, application rates and management techniques, and daily weather data. Weather data were rainfall, temperature, wind speed, relative humidity, and solar radiation. Simulation of all agricultural activities and land uses occurred over a 50-year period (1950 - 1999). Daily temperature and precipitation data were obtained from a weather station located in the watershed from the Historical Data Retrieval and Climate Summaries webpage maintained by the University of Minnesota, Department of Soil, Water and Climate.

Using a methodology described by Westra *et al*., we estimated the sediment delivered to the mouth of the stream with a modification of ADAPT developed by Gowda to aggregate field-edge estimates across each watershed. For this approach, the watershed was divided into sub-watersheds (termed Transformed Hydrological Response Units or THRUs; Gowda et al. 1999b), an ADAPT simulation was performed for each THRU, a hydrograph was developed for each sub-watershed, the hydrographs were combined, and then routed to the outlet of the watershed.

Estimates were developed for the baseline land use in 1999 and the BMP scenario by simulating different proportions of each land use or farming practice in each watershed. Producers or land managers were surveyed on the telephone to identify field locations, crop rotations or livestock systems, production practices, and tillage and nutrient practices. Land use in the watershed was assumed to correspond to that of the area-weighted average for the counties in which the watershed was located (Minnesota Land Use and Cover). Information on the crop acreage from the latest Census of

Agriculture (USDA 1999) was combined with the land use data to reflect the predominance and location of various production practices in the watershed. For each of the agricultural systems analyzed (cropping and livestock, traditional pastured and intensive grazing systems), specific hydrology and erosion information for the soils was obtained for the predominant STATSGO map units from the MUUF (Map Unit Use File) soils database for the corresponding soils in the watershed.

Nutrient files were created from information gathered from the producer surveys. These files had information about all the field operations performed for that farming system by the farmer. Data about nutrient application rates and methods (including manure, where applicable), planting, all tillage operations, and harvesting were furnished for all crops by the producer and included in the input files.

For systems currently using conservation tillage, no change in tillage was simulated for the BMP scenario. However, for a system under conventional tillage, a change to conservation tillage was simulated. This typically entailed switching to a less aggressive tillage system. One or two fewer trips across the field occurred, or a less aggressive tillage implement was substituted for the most aggressive implement. For most systems, the same complement of equipment was used. All systems currently being practiced by producers were changed for the BMP scenario to reflect a reduction in phosphorus and nitrogen application rate. These changes reflected appropriate nutrient credits for the previous crops or manure applications (according to University of Minnesota Extension Service recommendations).

Enviro-Economic Modeling

To analyze the change in agricultural practices in the watershed, a positive mathematical programming (PMP) economic model was developed that was similar to regional agriculture sector models described by Howitt, McCarl, House, Faeth, and Hazell and Norton. The PMP approach was chosen over a linear programming (LP) model for several reasons. First, the PMP model, which does not use flexibility constraints, responds to changes with more flexibility than a linear model with flexibility constraints (Howitt). Flexibility constraints on alternative systems are hard to justify empirically, especially after a new policy is in place. Flexibility constraints that restrain the model to base-year levels of resource allocations inadvertently limit the set of possible resource allocations available to the model in subsequent policy shocks. They artificially restrict resource allocations to levels the modeler may perceive as appropriate. Consequently, flexibility constraints imposed to achieve a calibrated baseline may not be appropriate for policy scenarios and may distort conclusions drawn from such analysis.

The objective function of the linear economic model was to maximize net farm income in the watershed (Equation 1).

$$\text{Max } \Pi(t, m; f, s, e) =$$

$$\sum_e^E \sum_s^S \sum_f^F \left(\sum_c^C q_{cfse} p_c + GP_{fse} - \sum_n^N x_{nfse} w_n - FC_{fse} - RP_{fse}\right) a_{fse} \qquad (1)$$

This objective function was subject to the following set of constraints:

$$\sum_f^F a_{fse} \leq A_{fse}^* \bullet (1.025) \quad \forall f,s,e \qquad (2)$$

$$\sum_f^F a_{fse} \geq A_{fse}^* \bullet (0.975) \quad \forall f,s,e \qquad (3)$$

$$\sum_s^S \sum_f^F a_{fse} \leq \sum_f^F A_{fse}^* \quad \forall s,e \qquad (4)$$

$$\sum_e^E \sum_s^S \sum_f^F a_{fse} \geq \sum_s^S \sum_f^F A_{fse}^* \bullet (0.975) \quad \forall e \qquad (5)$$

$$a_{fse} \geq 0 \quad \forall f,s,e \qquad (6)$$

In these equations, for each activity: ***t*** is tillage system, ***m*** is nutrient (phosphorus) management, ***f*** is field within the soil association-water proximity combination, ***s*** is soil association, ***e*** is proximity to water within the soil association, a_{fse} is hectares of production activity, A_{fse}^{*} is hectares of production activity estimated to be present (from producer surveys), q_{cfse} is output ***c*** from each activity, c_p is phosphorus effluent, p_c is price of output ***c***, x_{nfse} is variable input ***n*** used for each activity, w_n is price of variable input ***n***, GP_{fse} is government payment for each activity, FC_{fse} is fixed costs for each activity, RP_{fse} is the risk premium for each activity (described in Westra, Easter and Olson 2002). In the objective function, for a given production system, total returns per hectare were $\sum_c^C q_{cfse}p_c$ and variable costs per hectare were $\sum_n^N x_{nfse}w_n$.

To reflect current distribution of cropping activities, the objective function (1) was subject to the following set of constraints. In equation 2, land was constrained at the field level within each region or subwatershed (soil association-water proximity combination) to no more than 102.5% of observed levels. Land was constrained, with equation 3, at the field level within each region to no less than 97.5% of observed levels. Equation 4 constrained the total cropland used in each region to no more than 100.0% of the total land available for cultivation in each region. Land in conservation tillage was constrained, with equation 5, by proximity to water proximity, to no less than 97.5% of observed levels for that portion of the watershed. Due to the disparate sources of data in the analysis, an error margin of 2.5% allowed for a feasible solution to the model. Equation 6 constrained all activities to non-negative levels. However,

during the initial solution to the linear version of the economic model, only the systems currently being used by surveyed producers were allowed non-zero values.

After the linear economic model was solved with this set of constraints, the calibration stage of the analysis began. First, optimal levels of the baseline activities were observed and recorded. Next, levels for the alternative (non-baseline BMP) activities were set at one-half hectare each. Because producers were not using alternative systems, the current area for each of these systems was zero. However, non-zero starting values were needed for model to solve. Therefore, each alternative system had a starting value of one-half hectare. The estimated land area from linear model solution and one-half hectare for each alternative system defined A_{fse}^{**}. These land area estimates were used in the calibration portion of the analysis. During calibration, the objective function was the same (1) but subject to constraints:

$$a_{fse} \leq A_{fse}^{**} + 0.001 \quad \forall f,s,e \qquad (7)$$

$$a_{fse} \geq A_{fse}^{**} - 0.001 \quad \forall f,s,e \qquad (8)$$

$$\sum_{f}^{F} a_{fse} \leq A_{fse}^{*} \quad \forall f,s,e \qquad (9)$$

In equation 7, land for each current and alternative system was constrained to no more than 0.001 unit area more than levels determined in the linear model or by assignment described above. Land for each activity with negative net returns was constrained, with equation 8, to no less than 0.001unit area less than levels determined in the linear model or by assignment described above. Though it may not seem economically rational, there actually were farmers who did not maximize net revenues on each hectare of their farm. For equation 9, cropland was constrained at the field level within each region to no more than 100.0% of cropland limits in that area.

In the calibration formulation observed average output is assumed to be:

$$q_{cfse} = \beta_{cfse} - \delta_{cfse} a_{fse} \qquad (10)$$

In equation 10, β_{cfse} is the intercept and δ_{cfse} is the slope for the marginal yield function of crop ***c*** (corn and soybeans). With average crop yields assumed for the linear and calibration stages, this implies δ_{cfse} must equal zero. Dual values γ_{fse} from constraint (7) of the calibration model were used to estimate unobserved intercept and slope coefficients, for both crops (corn and soybeans):

$$\delta^{**}_{cfse} = (\gamma_{fse} 0.5)/(p_c A_{fse}^{**}) \qquad (11)$$

$$\beta^{**}_{cfse} = q_{cfse} + \delta_{cfse} A_{fse}^{**} \qquad (12)$$

Substituting equations 11 and 12 into 10, these values are included in a new primal nonlinear model:

$$Max\ \Pi(t, m; f, s, e) = \sum_e^E \sum_s^S \sum_f^F (\sum_c^C (\beta^{**}_{cfse} - \delta^{**}_{cfse}) a_{fse} p_c$$

$$+ GP_{fse} - \sum_n^N x_{nfse} w_n - FC_{fse} - RP_{fse}) a_{fse} \qquad (13)$$

The nonlinear model was only subject to cropland constraint 9. Solution values for each cropping activity are the same with either the primal nonlinear, calibration or linear models.

To analyze the effects of targeted and nontargeted agriculture BMPs, equation 13 was subjected to constraints:

$$\sum_f^F a_{fse} \leq A_{fse}^* \ \forall f,s,e \qquad (14)$$

$$\sum_s^S \sum_f^F a_{fse} \leq \sum_f^F A_{fse}^* \ \forall s,e \qquad (15)$$

$$\sum_f^F y_{cfse} a_{fse} \leq (1 - b) Y_{Cp}^* \ \forall f,s,e \qquad (16)$$

In these equations, c_p is phosphorus effluent per unit area; ***b*** is the bound for phosphorus load reduction (0 to 0.4, indicating 0 to 40% reductions in phosphorus load).

For a nontargeted implementation of BMPs to reduce phosphorus, constraint 14 was effective at the field level (at each of the 98 fields – combinations of soil associations and proximity to water). For example, if the state agency responsible for pollution reduction wanted to reduce phosphorus pollution by 40% uniformly across the watershed, then each field would have to reduce its baseline phosphorus load by 40% with the available BMPs. On the other hand, targeting the policy allowed for more flexibility in achieving the desired reductions (equation 15). Reducing phosphorus pollution by 40% at the watershed level allowed BMPs to be targeted to "hot spots" in the watershed. Thus, with this model the cost-effectiveness of a targeted or nontargeted implementation of BMPs for reducing agricultural phosphorus pollution could be evaluated.

RESULTS

The results from the analysis underscored the benefits of targeting agricultural BMPs. Though the same reduction in phosphorus load was obtained with either a targeted or nontargeted implementation of BMPs (i.e., 40%), BMPs targeted to specific regions of a watershed resulted in a significantly lower losses of production for producers. Soybean production fell by 5% from baseline with the targeted implementation of BMPs to reduce phosphorus loading by 40% (Table 1). To achieve the same reduction in phosphorus loading (40%), when BMPs are not targeted in a watershed, soybean production fell by 19% from baseline levels. Similar reductions in corn production occurred under the targeted (5% decline in corn output) and nontargeted (20% decline) implementation of BMPs (Table 1).

Land was removed from production under both scenarios as a way to achieve the desired reduction in phosphorus loading (40%). With BMPs targeted to regions of the watershed, less than 2% of cropland was removed from production. On the other hand, when BMPs were not targeted but phosphorus loading had to be reduced by 40% from baseline levels, almost 20% of cropland in the watershed was idled (Table 1).

With targeted BMPs, net farm income declined by approximately $3 million annually from the baseline of $53 million (Table 1). In contrast, net farm income fell by $11.5 million annually when BMPs were not targeted in a watershed to help reduce phosphorus loss. Therefore, a net savings of $8.5 million annually could be achieved in the watershed if BMPs were targeted to the appropriate regions within the watershed.

DISCUSSION

This research demonstrated how an integrated enviro-economic model could be used to capture the heterogeneity of agricultural systems and regional differences in soils in a watershed. As the diversity of agricultural systems in a watershed increases, the importance of representing the heterogeneity in an integrated manner increases. Along these lines, future research efforts examining potential ways of reducing nonpoint pollution from agriculture should include both cropping and livestock systems.

The results from the current analysis indicate that significant cost-savings can be achieved in reducing nonpoint pollution by targeting BMPs to specific regions of a watershed. Specifically, producers farming on cropland susceptible to erosion in close proximity to water who switch from conventional tillage to conservation tillage and reduce phosphorus fertilization levels to those recommended by the state extension

service may appreciably reduce phosphorus nonpoint pollution loading potential. Extension and outreach efforts to reduce nonpoint phosphorus contributions to waterbodies from agriculture could be more effective, and cost-efficient, if targeted to such practices in such regions within the watershed. Efforts to target BMPs could reduce potential costs to producers and society by millions of dollars annually, in this watershed alone.

Table 1. Annual Effects of Phosphorus Reduction Strategies in the Le Sueur Watershed

	Net Farm Income $	Phosphorus Load kilograms	Cropland hectares	Corn Production metric tons	Soybean Production metric tons
Baseline	53,019,489	51,729	221,569	1,016,785	366,251
Targeted BMPs	50,183,275	31,038	208,063	956,827	346,219
Nontargeted BMPs	41,637,221	31,038	178,547	816,630	297,138

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