ENVIRO-ECONOMIC ANALYSIS OF PHOSPHORUS NONPOINT POLLUTION

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Selected Paper, 2001 Annual Meeting of the American Agricultural Economics Association, August 5-8, 2001, Chicago IL.

Abstract

The state of Minnesota seeks to reduce phosphorus loading to the Minnesota River by 40% from current levels. The state agency charged with achieving this reduction has indicated each watershed should reduce its current phosphorus loading by 40%. We hypothesized that policies targeting specific practices or regions would have a smaller negative impact on farm income than policies requiring every nonpoint polluter to reduce its contribution by 40%.

Using a stylized version of one major watershed in the river basin as an example, we analyzed the cost-effectiveness of various nonpoint pollution reduction policies. We simulated current and alternative farming systems (designed to reduce phosphorus loading by changing tillage or fertilizer practices) in distinct regions within the watershed using a biophysical process model. For each system, estimates of phosphorus loading from biophysical simulation were combined with production cost and return estimates to create an enviro-economic model of the watershed. Additionally, risk premiums were estimated and included with cost estimates for each alternative system. We used a positive math-programming (PMP) version of the enviro-economic model to analyze nonpoint pollution reduction policies (pollution standard, phosphorus effluent tax, conventional tillage tax, and phosphorus fertilizer tax).

When regions and practices within the watershed could be targeted for achieving the pollution reduction standard, 13,500 fewer hectares (6% reduction from the baseline cropland level) were farmed. When the same standard was uniformly applied to all regions (not targeted), cropland decline by 40,500 hectares (20%). Under either scenario, cropland was removed from production, implying some producers may exit

farming. Cropland reductions resulted in farmers losing $2.8 million (5% reduction from the baseline income level) in income with targeting, while not targeting caused farm income to decline by $11.4 million (21%). This finding illustrates how difficulty it is to reduce nonpoint pollution if one does not focus on specific regions.

An effluent tax of $74 per kilogram of phosphorus reaching the river was needed to reduce phosphorus loading by 40% from current levels. With this tax rate, watershed farm income declined by $14 million (25% reduction from the baseline income level), $11 million of which were revenues from the effluent tax.

Neither the conventional tillage tax nor the phosphorus fertilizer tax achieved a 40% reduction in phosphorus loading. This finding illustrates the difficulty of reducing nonpoint pollution by focusing only on one practice.

Under a pollution-reduction standard, our results indicated it is more cost effective to reduce nonpoint pollution by targeting particular regions or practices in a watershed compared to not targeting. 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 will appreciably reduce phosphorus nonpoint pollution loading potential. Efforts to target those producers could minimize potential losses in farm income in the watersheds and the river basin.

Introduction

Despite decades of regulation and management of nonpoint source pollution, many water bodies remain in poor quality. This is due largely to nonpoint source pollution even though nonpoint sources are included in the Clean Water Act of 1972. Poor water quality is particularly evident in agricultural basins, such as the Minnesota River, with 92% of its land in agricultural use. One key source of pollution in the river is phosphorus. To improve water quality the state and federal governments set a goal of reducing the river's phosphorus load by 40% from 1980 levels (Frost and Schwanke 1992).

A range of alternative policies and practices could be used to reach this goal. Among others, practices include conservation tillage, lower fertilizer or manure application rates, and changes in fertilizer or manure application methods. Policies may include land retirement or restrictions in cropping practices by location, taxes or restrictions on fertilizer inputs, effluent taxes, or a subsidy for pollution reducing practices. The policies may be mandated in a uniform, nontargeted manner, or a targeted approach may be used. Each of these policies, and the associated change in production practices, will affect producer income and the local economy. Before settling on a particular policy or set of policies to reduce nonpoint pollution, policy makers need to know what impacts each might have on farm income or the local economy. To model these impacts requires an integrated approach that focuses on the differences in biophysical and socio-economic conditions within the watershed.

If the environmental problem results from nonpoint sources that are heterogeneous in nature, one needs to consider the spatial distribution of the pollutant within the landscape. Using an approach that integrates socio-economic elements and biophysical factors in a spatially heterogeneous manner, we can improve our understanding of the intended and unintended repercussions of policies for reducing agricultural nonpoint phosphorus pollution. By evaluating policies within such a framework, policy makers can rank policies by factors or metrics considered critical to society (such as environmental effects, agency budget impact, producer income, and local economic impacts).

The Minnesota River originates along the border between Minnesota and South Dakota and flows for 540 kilometers before joining the Mississippi River in Saint Paul, Minnesota. Consisting of 12 major watersheds, it drains approximately 44,000 square kilometers or 4 million hectares in Minnesota, Iowa, and South Dakota (Figure 1) (MPCA 1992, 1994). Agriculture within the river basin accounts for two-fifths of the state's corn production and over one-half of its soybean output. Considerable livestock production also occurs within the Minnesota River Basin. Over one-fifth of Minnesota's beef production, and two-fifths of its hog output occurs in the basin (MPCA 1994, p.1-11). Agriculture’s prevalence and a large human population within the basin help explain the poor water quality.

Because the scale of the basin is so large, we selected the Le Sueur River watershed in the river basin to examine the effects of targeting efforts to control nonpoint phosphorus pollution. The Le Sueur River is a major contributor of phosphorus load to the Minnesota River Basin (17%) (MWCC 1994). Like the river basin, the Le Sueur River watershed is dominated by agriculture. Unlike the Le Sueur and the Minnesota River Basin, urban development is prevalent in the Lower Minnesota

River watershed (which furnishes 32% of the phosphorus load to the basin). The topography of the Le Sueur is more diverse than that of the Blue Earth River watershed – another major contributor to the phosphorus load of the Minnesota River Basin (15%). Finally, data for the Le Sueur River watershed were available and physical model had been calibrated to this area. Therefore, with the watershed as an example, we demonstrate the benefits of targeting and illustrate how they may be extended to the larger basin.

The Problem: Phosphorus Pollution

In appropriate quantities, phosphorus not only is beneficial, it is critical to production agriculture, and by extension society. Phosphorus is essential for terrestrial and aquatic plant growth. When phosphorus is available in sufficient quantity for plant uptake, it stimulates early plant growth and root development, facilitates fruit and seed production, and accelerates plant maturity. As crops take up phosphorus in soil solution, the concentration of phosphorus in solution decreases. This causes phosphorus from the active phosphorus pool to be released into the soil solution to re-establish a chemical equilibrium. As the amount of phosphate in solution decreases the amount of phosphate absorbed by soil decreases (and vice versa) (Busman *et al.* 1997). This explains why soil particles serve potentially as either a source of or sink for phosphate to the surrounding water. When soils with high levels of phosphate (like most soils within the Minnesota River basin) erode into a water body with relatively low levels of phosphate, phosphates are released from the soil particles into the water.

When phosphorus is released into water bodies (with adequate nitrogen available), the biological activity of surface water increases (eutrophication). Accelerated or cultural eutrophication of surface waters, caused by nutrient inputs such as phosphorus, stimulates algal and rooted aquatic plant growth (Sharpley *et al.*1994). As these plants expire and decompose, oxygen levels in the water may decrease and produce deleterious conditions for other aquatic life. In addition to these negative ecosystem effects, cultural eutrophication impairs amenity and recreational uses (fishing, boating, swimming, among others), as well as industrial and municipal uses, which can have negative local and regional economic effects.

The Minnesota Pollution Control Agency (MPCA) documented frequent violations of federal or state standards for bacteria, phosphorus, turbidity, and dissolved oxygen at several monitoring stations in the Minnesota River Basin in a report entitled Minnesota River Assessment Project (MRAP) (MPCA 1994). MRAP suggested both nonpoint and point sources of pollution are responsible for degrading the river. Potential sources for these pollutants included feedlots, septic systems, wastewater treatment plants, stream and ditch erosion, and runoff or erosion from agricultural lands. During spring and summer especially, water quality in the Minnesota River can be severely impacted by nonpoint pollution.

The nature and extent of the phosphorus problem is demonstrated by water samples taken over a 15-year period in St. Paul, Minnesota. These samples indicate 1,450 metric tons of Total Phosphorus (TP) flow from the Minnesota to the Mississippi each year (MWCC 1994, p.141). The average concentration of Total Phosphorus (0.394 mg/L) in samples was sufficient to cause eutrophication (MWCC 1994).

The problem of phosphorus nonpoint pollution is spatially heterogeneous. Of the 12 major watershed in the Minnesota River basin, the three closest to its mouth account for two-thirds of the total phosphorus load. Though the Le Sueur River watershed constitutes only 9% of the surface area of the Minnesota River basin, it contributes 17% of total phosphorus load. The other nine watersheds in the basin drain three-fourths of the total basin, but generate only one-third of the total sediment and phosphorus loads.

Previous research of sediment and phosphorus in the Minnesota River Basin shows significant increases in both loads and yields going from the western to eastern portion of the basin (MPCA 1994). Three primary reasons for this increase are:

- **Mean annual precipitation** increases from 56 cm on the western side to 81 cm on the eastern side of the basin. Consequently, mean annual runoff increase from less than 5 cm on the western side to 20 cm eastern side of the basin.
- **Steeper landscape** combined with a wetter climate, results in soils being more erodible in the eastern part of the basin than in the western part.
- Large **population** centers are located on the eastern side of the basin. About 60% of the basin population resides in the six eastern-most counties of the 37 counties in the basin (http://www.soils.agri.umn.edu/research/mn-river/).

There are significant agricultural and non-agricultural sources of pollution degrading water quality in the Minnesota River Basin. For example, it is estimated that municipal and industrial wastewater discharges account for about 10% of the loading during high flow years, and for about 65% of the total phosphorus loading in the Minnesota River during low flow years (MPCA 1994). Indirect measurements suggest non-agricultural sources of sediment and phosphorus such as stream bank erosion and construction sites account for about 25% of the river's total loading (http://www.soils.agri.umn.edu/research/mn-river/). This implies all agricultural sources may account for 10-65% of sediment and phosphorus loading in the river.

The U.S. Environmental Protection Agency (EPA), the Minnesota Pollution Control Agency (MPCA), and the Minnesota River Basin Joint Powers Board recommended that sediment and phosphorus pollution entering the Minnesota River be reduced by 40 percent from pre-1980 levels (Frost and Schwanke 1992). Efforts to achieve the goal necessarily will include programs to reduce the contribution of agriculture and other nonpoint sources of phosphorus pollution in the Minnesota River. However, the key question is how can nonpoint pollution reductions be achieved cost-effectively.

Study Area: Le Sueur River Watershed

A major watershed of the Minnesota River, and the study area for this paper, is the Le Sueur River watershed. Like the Minnesota River Basin, intensive agricultural production occurs in this watershed, as demonstrated by almost all of the cropland (95%) being planted to either corn or soybeans (USDC 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 (USDC 1999; CTIC 1999). Considerable livestock production occurs in this watershed as it does in the Minnesota River basin. Located in south central Minnesota, this watershed is one of the twelve major watersheds of the Minnesota River Basin (watershed #32 in Figure 1) and contains approximately 285,000 hectares.

Another method for delineating regions within a river basin is to use agroecoregions. The Minnesota River Basin has 13 unique agroecoregions that are distinguished primarily by differences in soil types and geologic parent material, slope steepness, internal drainage (natural and artificial), erosion potential and climatic factors that influence crop productivity. Agroecoregions are zones with unique soil, landscape, and climatic characteristics. These characteristics help define the types of crop and animal production that occur in that region. Each agroecoregion contains unique physiographic factors that influence the potential for production of nonpoint source pollution and the potential for adoption of farm management practices (http://www.soils.agri.umn.edu/research/mn-river/).

Each of the twelve major watersheds in the basin has from two to six agroecoregions. One must consider the variability in soils and landscapes within a watershed, as illustrated by agroecoregions, to understand the sources of nonpoint pollution and the potential for management practices to reduce phosphorus pollution. Of the two agroecoregions in the Le Sueur River watershed, the “less steep moraine” on the eastern side of the watershed, with steeper slopes, has much higher erosion potential than the relatively flat “wetter clays and silts” agroecoregion. This suggests that targeting efforts would need to begin in the steeper region first.

Method: Integrated Analysis

Analyses integrating bio-physical and economic policy models have included nitrates in groundwater or surface water (such as Mapp *et al.* 1994; Helfand and House 1995; Larson, Helfand and House 1996; Johnson, Adams, and Perry 1991; Wu, Mapp, and Bernardo 1996), pesticides in groundwater or surface water (such as Bouzaher and Shogren 1997; Bouzaher *et al.* 1992), sediments in surface water (such as Braden *et al.* 1989; Prato and Wu 1991), and combinations of these (such as Randhir and Lee 1997). When agricultural phosphorus pollution has been analyzed it has been an ancillary issue with sedimentation reduction analysis (such as Setia and Magleby 1987; Vatn *et al.* 1996, 1997) or the focus of pollution reduction from livestock, usually treated as a point source issue (Rorstad and Vatn 1996).

In the integrated analysis we conducted, we first focused on the two agroecoregions of the watershed. However, we found that neither the watershed nor the agroecoregions provided sufficient detail to make targeting conservation production practices in critical areas effective. Therefore, the two agroecoregions were disaggregated into six major soil associations (three for each agroecoregion) (Figure 2). Physical, chemical, and topological characteristics of the three predominant soils in each soil association were used in the biophysical simulation of all production practices included in the set of cropping activities. Each of the six soil associations in the watershed was divided into areas within 90 meters of water bodies ("close") and areas not within 90 meters of water ("distant"). Thus our analysis represented differences in soil erodibility and sediment and phosphorus delivery ratios to the water body.

Fourteen producers representative of typical production practices occurring in each soil association within the Le Sueur River watershed were surveyed. Because not every producer was present in each region, there were a total of only 98 possible farming practices in the twelve different regions (six soil associations divided into two sections – close to and distant from water). To represent current conditions in the watershed, we examined the 98 current production systems where they occurred.

To allow for changes in production practices under various policies, we examined 270 alternative cropping systems. These alternative systems consisted of changes in tillage (conventional to conservation, for producers currently using conventional tillage), reduction in phosphorus fertilizer application rate (from a producer's current rate to 16.8 kilograms per hectare at planting of corn), change in phosphorus application method (from broadcast only to broadcast and incorporate, for producers currently broadcasting phosphorus in the fall), and combinations of these. Any associated changes in costs resulting from changes in tillage, phosphorus application rates and application methods were incorporated into the estimates of respective system's production costs. Likewise, any changes in crop yields from changing the production system were incorporated into the returns for each system.

We used producer management information to construct representative practices that were simulated using ADAPT (Agricultural Drainage And Pesticide Transport) (Desmond and Ward 1996). ADAPT is a field scale water table management model that combines GLEAMS (Leonard, Knisel, and Still 1987) and DRAINMOD (Chung, Ward, and Shalk 1992). This model was selected primarily for two reasons. First, ADAPT is able to model crop fields that have artificial drainage – a dominant feature of fields in this watershed. Second, ADAPT had been calibrated to the data collected at the University of Minnesota Experiment Station located in this watershed (Davis 1998). Therefore, ADAPT was used to simulate how variations in crop management practices and locations within the watershed affected sediment and nutrient output. We also used ADAPT to estimate how crop yields changed if producers switched to conservation tillage practices. Estimated yield reductions (1%) from switching to conservation tillage obtained from ADAPT simulation conformed well to observed data from Minnesota (Randall *et al*. 1996). Because producers identified field locations, as well as their production practices, we represented tillage and nutrient practices (and associated sediment and nutrient effluent) spatially in the watershed.

We estimated production costs from information producers provided in our farmer survey and from the local South Central Farm Business Management Association for the pertinent crops (corn and soybeans) (Jackson 1999). We calculated production costs for alternative systems based on changes in production (equipment use and fertilizer input levels) appropriate to the systems analyzed.

Our estimates of production costs for the alternative systems indicated that for most producers these systems were marginally less costly than their current cropping system. For example, producers switching to conservation tillage from conventional tillage generally could reduce production costs by $0.5-1.5 per hectare. This was consistent with estimates of cost of converting to conservation tillage in other parts of Minnesota (Olson and Senjem 1996). Additional cost reductions (with no yield reduction) occurred for systems using phosphorus application rates that were consistent with University of Minnesota Extension Service recommendations. As a result, many alternative systems were more profitable than systems currently being used by the producer.

By not selecting a more profitable choice, producers are demonstrating some risk aversion. A risk-averse person is one who values a certain income more than an equal amount of income that involves risk or uncertainty. Producers who are risk-averse would be willing to pay a risk premium to avoid situations that may have uncertainty (such as changes in farming systems). We used a method described by Olson and Eidman (1992) to estimate risk aversion coefficient (λ) for each of the 270 alternative management decisions producers faced in reducing phosphorus load. These included: change to conservation tillage, change to reduced fertilizer rate, change to reduced fertilizer rate combined with a change to conservation tillage, change in fertilizer application method, and change in fertilizer application method combined with a change to conservation tillage. First we estimated the certainty equivalent of the 98 current practices using:

$$y_{CE} = E[y] - (\lambda/2) \bullet (\sigma^2_y) \qquad (1)$$

where y_{CE} is the certainty equivalent of net returns of a system and $E[y]$ is the expected value of net returns for that system (essentially our estimate of net returns). For all current systems, we assumed the Pratt-Arrow absolute risk aversion coefficient (λ) is 0.0001 per dollar. This value was within a range of estimates for producers (Olson and Eidman 1992). Using information on variation in yields, from 50 years of physical simulation with ADAPT, we determined the variation of net returns for each system (σ^2_y). With this information we calculated a certainty equivalent of net returns for each current system.

Given this certainty equivalent we estimated for each current system and estimates of net returns and variations of net returns for each alternative system, we solved equation (1) again for a risk aversion coefficient (λ^*) for each of the 270 alternative systems in the watershed. From all soil associations on which a producer farmed, we selected the maximum risk aversion coefficient (λ^*_{max}) for each decision each producer faced. We used the maximum risk aversion coefficients (λ^*_{max}) for each production decision for each producer to estimate a certainty equivalent (y^*_{CE}) for each alternative system. Then we estimated the risk premium associated with each production decision as the difference between certainty equivalent of net returns for the current system and the certainty equivalent of net returns for the alternative system ($y_{CE} - y^*_{CE}$). Risk premiums were incorporated into the estimates of production costs and returns for each system.

To analyze policies we developed a positive mathematical programming (PMP) model (Howitt 1995). With a PMP approach, initially a linear program model is defined that constrains cropping activities to levels currently observed at the field scale. In the next (calibration) step of this method, the marginal values on the appropriate land constraints from the baseline, linear model are used to create a nonlinear production function for the crops in each system. Essentially, the marginal values of binding land constraints (set at currently observed levels for each system) are used to adjust crop yields for all cropping systems. The new intercept and slope coefficients for the crop yield function created from this process reflect diminishing marginal productivity of cropland for corn or soybeans. These adjustments to the crop yields allow the model to solve exactly to the baseline levels of cropland for each system, *without the cropland constraints for each system*. With land constraints present only for each region, as opposed to each field, the model can select the combination of cropping activities in response to the policy modeled. Compared to a linear programming model, the PMP model can respond in a more realistic or smooth manner to shocks from changes in policy (Howitt 1995).

To analyze potential policies for reducing nonpoint phosphorus pollution, we used a PMP model that had as its objective maximizing net farm income in the watershed:

$$Max\ \Pi(t, m; f, s, e) = \sum_{e}^{E} \sum_{s}^{Se} \sum_{f}^{Fs} \Big(\sum_{c}^{C} (\beta^{**}_{cfse} - \delta^{**}_{cfse}) a_{fse}\, p_c + GP_{fse}$$

$$- \sum_{n}^{N} x_{nfse} w_n \alpha_{Np} - FC_{fse} - RP_{fse} - c_p \phi_{Cp} \Big) a_{fse} \qquad (2)$$

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

$$\sum_{f}^{Fs} a_{fse} \leq A_{fse}^{*} \ \forall f,s,e \qquad (3)$$

$$\sum_{s}^{Se} \sum_{f}^{Fs} a_{fse} \leq \sum_{f}^{Fs} A_{fse}^{*} \ \forall s,e \qquad (4)$$

$$\sum_{f}^{Fs} y_{cfse} a_{fse} \leq (1 - b) Y_{Cp}^{*} \ \forall f,s,e \qquad (5)$$

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

In these equations, for each activity: t is tillage system, m is nutrient management (reduced phosphorus application rates or change in application method), f is field within the soil association-water proximity combination, s is soil association, e is proximity to water within the soil association, β_{cfse} is the intercept and δ_{cfse} is the slope for the marginal yield function of crop c (corn and soybeans), a_{fse} is area of production activity, A_{fse}^{*} is area of production activity estimated to be present, 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. In the objective function, for a given production system, total returns per unit area were $\sum_{c}^{C} q_{cfse} p_c$ and variable costs were $\sum_{n}^{N} x_{nfse} w_n$; c_p is phosphorus effluent per unit area;

ϕ_{Cp} is per unit tax on phosphorus effluent; α_{Np} is per unit tax on purchased synthetic phosphorus fertilizer (P_2O_5); t_{tfse} is per unit area tax (negative subsidy) for conventional tillage. Equation 3 constrained land at the field level within each soil association-proximity to water combination (*n=98*), and was effective under a uniform reduction standard. Equation 4 was effective under a targeted implementation of the pollution standard; allowing more flexibility in achieving the desired reductions. In constraint 5, b is the bound for phosphorus load reduction (0 to 0.4). Equation 6 constrained all activities to non-negative levels.

In our analysis, we assumed the estimated portion of current phosphorus load attributable to agriculture would be reduced by 40%. There is disagreement about how much phosphorus load is attributable to agriculture (30-65% in the Minnesota River basin), not to mention how much comes from crops versus livestock. Our estimated baseline phosphorus load levels (from current cropping practices in the watershed) constituted approximately 35% of the estimated total phosphorus load for the watershed. Keep in mind the results reported pertain only to crop agriculture's portion of the load.

Results

In this study an integrated, enviro-economic model was developed to estimate the impacts of alternative policies for reducing phosphorus loading to the mouth of the Le Sueur River Watershed in the Minnesota River Basin by 40% from an established baseline. The policies examined included a pollution reduction standard for agricultural nonpoint phosphorus loss (either targeted or not targeted to specific practices and regions in the watershed), a tax on each pound of phosphorus delivered to the Le Sueur River, a tax on the use of phosphorus fertilizer in crop production, and a tax on each acre of cropland using conventional tillage practices.

The results from the analysis of specific pollution reduction standards (implemented in a targeted or nontargeted manner) underscored the benefits of targeting. Though the same reduction in phosphorus load was obtained with the “command and control” approaches (i.e., 40%), a pollution reduction standard that is targeted to regions or practices resulted in a significant net savings of private costs. With a targeted reduction standard, net farm income declined by approximately $3 million annually from the baseline of $53 million (Table1). In contrast, net farm income fell by $11.5 million annually with the nontargeted pollution reduction standard. Therefore, a net savings of $8.5 million annually could be achieved in the watershed ($11.5 million in loss from nontargeted minus $3 million in losses with targeting) if a pollution standard was targeted to regions or cropping systems within the watershed. These results allowed for the rejection of the null hypothesis that the nontargeted standard was no worse than the targeted standard in terms of abatement and net farm income. That is, the targeted reduction standard is better than the nontargeted reduction standard.

Results from the effluent tax analysis were similar to those from the targeted pollution reduction standard (from which the tax rates were derived). The effluent tax effectively targeted the least-cost producers of pollution abatement. However, to reduce phosphorus nonpoint pollution from agriculture by 40% from baseline levels, an effluent tax of $74 per kilogram of phosphorus delivered to water was required. The effluent tax at this rate generated approximately $14 million in tax revenue. Conversely, net farm income declined by $14 million with this effluent tax in this watershed alone. Given the potential political difficulty of enacting such a program, combined with the difficulty of implementing it, an effluent tax would not likely be approved by policymakers. Nonetheless, evaluating such a policy assisted in identifying the least-cost sources for reducing pollution in a region.

With an annual conservation tillage tax rate of $14 per hectare, only a 30% reduction in phosphorus loading was achieved. Under this policy, essentially all land was under conservation tillage so no further abatement could be achieved with higher tillage tax rates.

Likewise, with the phosphorus input tax, as the tax rate increased, systems with the lowest application rate (15 kilograms per hectare on corn only) were brought into production. As the rate approached and exceeded 900%, there were no options for reducing phosphorus because all systems were using that lowest application rate.

In addition to reducing net farm income, the different tax policies reduced phosphorus applications and crop production. Though phosphorus loading declined by 24% with a 900% phosphorus input tax, total annual application of phosphorus declined by 4.25 million kilograms. Assuming phosphorus fertilizer costs $0.60 per kilogram, locally fertilizer sales would decline by $2.5 million. In contrast, with the input tax rate at 25% phosphorus sales would fall by 0.3 million kilograms ($0.2 million annually). However, phosphorus loading with a 25% tax would be reduced by only 2% from baseline levels for the watershed.

Phosphorus use declined hardly at all with a $2 per hectare conventional tillage tax. With the tillage tax rate at $14 per hectare, phosphorus use declined by 0.5 million kilograms per year. Fertilizer sales would decline by $0.3 million annually with such a large tillage tax, assuming $0.60 per kilogram of phosphorus. Clearly the fertilizer tax would affect adversely the local fertilizer businesses more than a tillage tax.

Under a phosphorus input tax of 25%, crop production declined very little (4,300 metric tons of corn and 3,500 metric tons of soybeans annually). With the 900% input tax, corn production decreased by 50,000 metric tons per year, while soybean production declined by 22,000 metric tons annually. In addition to reducing producer income, such reductions in production would affect adversely the grain elevators in the local communities. Thus the negative impact on the local business community would be less with lower input tax. However, the lower the input tax the lower the reduction in phosphorus loading.

The conventional tillage tax had less of an impact on production than did the phosphorus input tax. With the tillage tax at $2 per hectare, annual corn production declined by 6,000 metric tons and soybean output per year fell by less than 2,000 metric tons. Under the steeper tax rate of $14 per hectare, output decline was slightly more severe. Corn production declined by 23,000 metric tons and soybean output declined by 6,500 metric tons. Nonetheless, the most severe tillage tax rate ($14 per hectare) had less of a detrimental effect on the local business community than the most sever phosphorus input tax.

Of the tax policies analyzed, only the effluent tax achieved the goal of reducing phosphorus loading from agriculture by 40% from baseline levels. However, this was only achieved at a very high tax rate - $74 per kilogram. Taxing conventional tillage or phosphorus as an input could not achieve the 40% reduction goal, even at very high tax rates. As the tax rate increased above the levels indicated, net farm income declined but phosphorus loading did not.

Summary and Conclusions

In this study we used an integrated model to estimate the impacts of reducing phosphorus loading to the Minnesota River by 40% from 1980 levels. Using a biophysical process model, we simulated a set of cropping practices representative of the range currently observed in this watershed. Additionally, we simulated alternatives to current practices that could potentially reduce phosphorus loading potential. Estimates of phosphorus load from the simulations of current and alternative production practices were combined with production cost and return estimates in an economic model of the watershed.

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 phosphorus nonpoint pollution from agriculture should include both cropping and livestock systems.

The physical analysis indicates that certain regions of the watershed contribute disproportionately more phosphorus than do other areas. This corresponds well with observed phenomena and conforms to intuition about the nature of nonpoint source pollution in a heterogeneous environment. Most watersheds have “hot spots” that contribute more of the nonpoint pollutant than others. These may be due to physical properties of the soil, location of the field being farmed, the production practices occurring on that soil, or the presence of artificial drainage. In the instance of the heavy soils in soil association MN163, which are tile drained, phosphorus loss from tile drains was highest. On the other hand, steeply sloped soils in MN087 had the highest phosphorus loss from run-off.

One could imagine losses in farm income as “takings” of property or production rights the farmers enjoy currently. A producer creates an externality by producing nonpoint source phosphorus pollution from current agricultural practices. However, the current practices examined in this research were not illegal. Therefore, if the government must compensate the farmers, one could consider the “takings” as the difference in watershed net farm income from the baseline to one of the two pollution reduction standards modeled. In the case of the targeted implementation, the annual compensation would be approximately $3 million, while the nontargeted case would require $11.5 million in annual compensation. Thus in this watershed the annual savings in reduced compensation costs for targeting would approach $8.5 million. Because the watershed accounts for 17% of the phosphorus load and only 9% of land in the river basin, annual savings for the entire river basin might approach $50 million using these model results.

Reducing agricultural phosphorus load by 40% can have a major impact on cropland, production and net farm income, depending on how the regulation is implemented. A less severe regulated reduction in phosphorus (30%), if targeted, would reduce producer income by only 2.5% (less than $1.5 million), and keep most cropland in production (96.5%). Thus, a less stringent standard (30% reduction), implemented in a flexible manner may achieve an acceptable level of phosphorus pollution reduction in the watershed or the Minnesota River Basin with minimal reduction in farm income.

The analysis with the tillage tax and the fertilizer tax shed some light on a case presented in the agricultural pollution debate. Under the situations examined with the economic model, neither a tillage tax nor a fertilizer tax achieved the reduction in phosphorus desired. Therefore, efforts to get producers to convert to conservation tillage practices *and* reduce the application rates of phosphorus to recommended levels will have to be in locations where these are appropriate and potentially effective at reducing phosphorus loading.

Our results from this integrated model indicate that significant cost savings were achieved in reducing nonpoint pollution by targeting particular practices or 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 will appreciably reduce phosphorus nonpoint pollution loading potential. Efforts to target those producers could reduce potential costs to producers and society by millions of dollars annually, in this watershed alone.

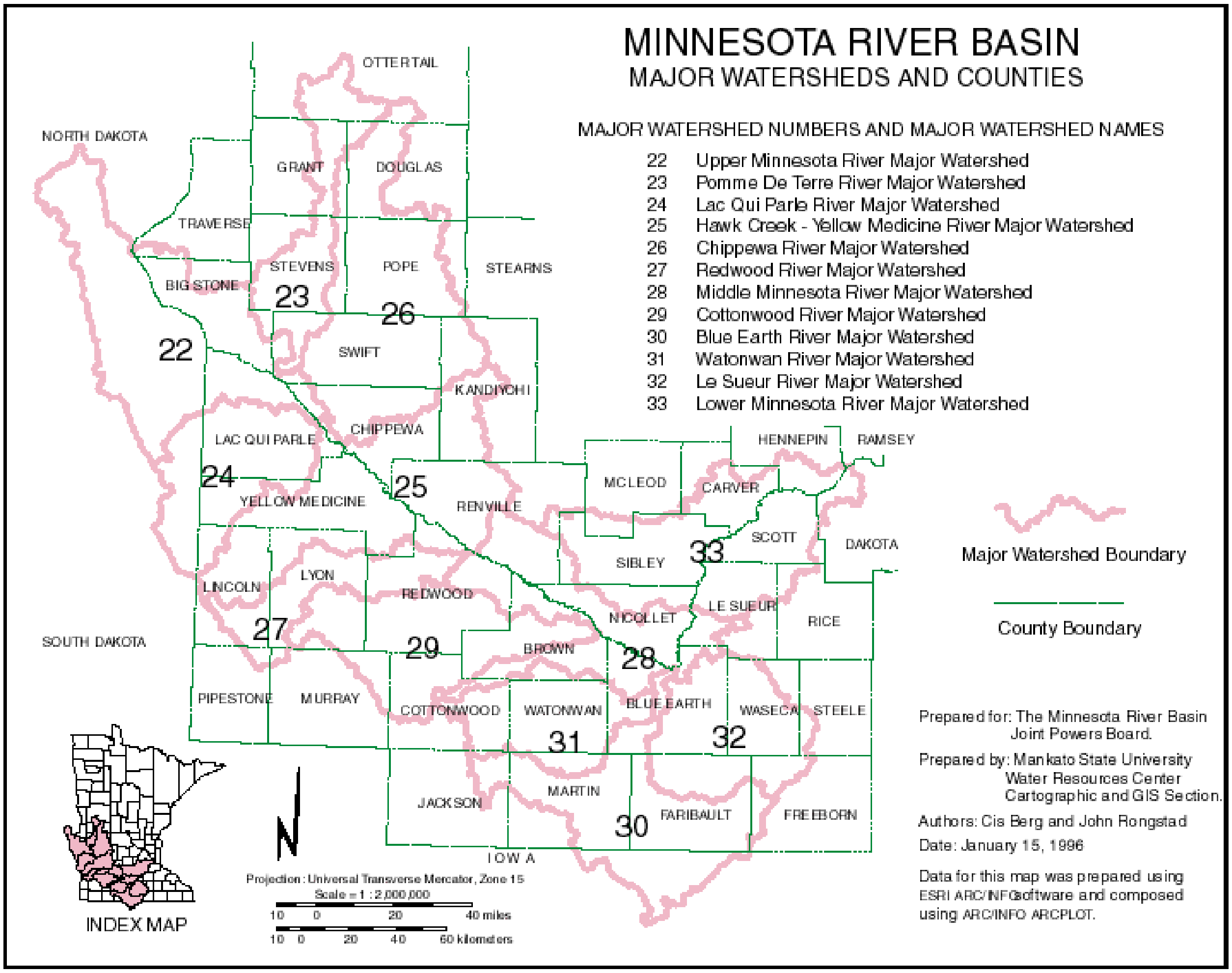

Figure 1. Minnesota River Basin. Source: (http://mrbdc.mankato.msus.edu/map811.html).

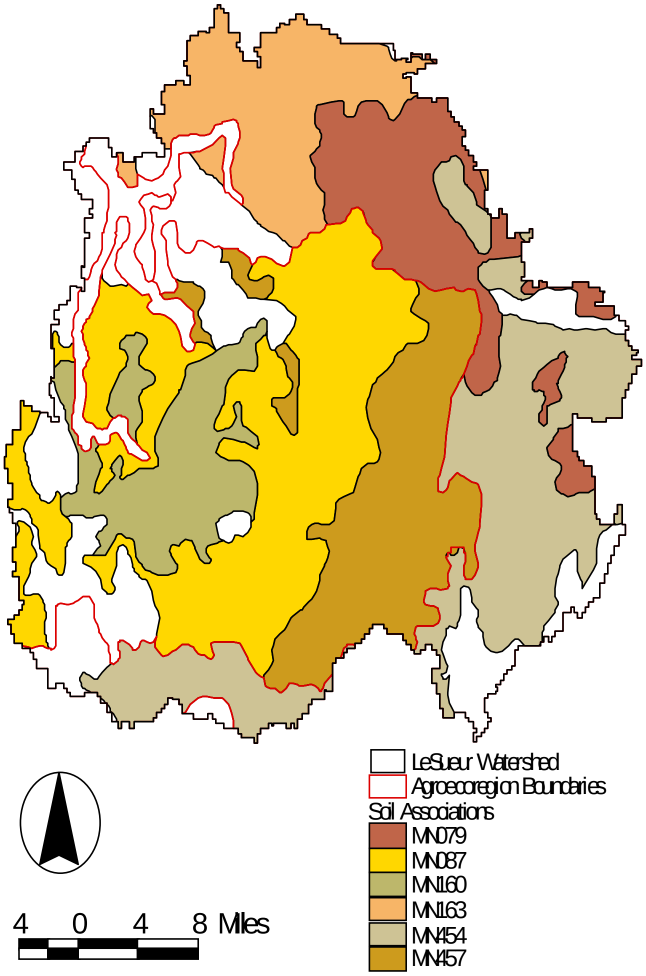

Figure 2. Map of the Le Sueur River Watershed and its Six Soil Associations.

Table 1. Annual Effects on Agricultural Producers and Production in the Le Sueur Watershed of Potential Policies for Reducing Nonpoint Phosphorus Pollution

	Net Farm Income ~~($)~~	**Phosphorus Load ~~(kgs)~~**	**~~(reduction)~~**	**Cropland ~~(hectares)~~**	**Phosphorus Applications ~~(kgs)~~**	**Corn Production ~~(metric tons)~~**	**Soybean Production ~~(metric tons)~~**
Baseline	53,019,489	51,729	0%	221,569	6,279,565	1,016,785	366,251
~~Pollution Reduction Standard~~							
Targeted	50,183,275	31,038	40%	208,063	5,368,442	956,827	346,219
Nontargeted	41,637,221	31,038	40%	178,547	4,574,354	816,630	297,138
~~Phosphorus Effluent Tax~~							
$74 per kilogram delivered	39,108,253	31,043	40%	208,069	5,368,800	956,856	346,229
$9 per kilogram delivered	50,861,036	46,458	10%	219,935	6,137,816	1,010,131	364,061
~~Phosphorus Input Tax~~							
900%	35,299,172	39,275	24%	207,419	2,026,137	946,878	344,526
25%	52,089,232	50,865	2%	220,407	5,961,924	1,012,412	364,748
~~Conventional Tillage Tax~~							
$14 per hectare	48,633,682	36,216	30%	218,419	5,732,086	993,823	359,746
$2 per hectare	51,809,288	47,230	9%	220,384	6,241,259	1,010,743	364,375

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