Agricultural Phosphorus Nonpoint Source Pollution in the Minnesota River

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Abstract: Phosphorus loads from agronomically diverse practices were simulated using representative farms from a heterogenous watershed of the Minnesota River. Results from integrated bioeconomic analyses were used to test hypotheses about nontargeted and targeted nonpoint source phosphorus pollution abatement programs, with respect to net farm income and phosphorus loading.

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Introduction

An externality exists when the welfare of one agent (firm or household) depends directly on its activities as well as those of another agent. A negative externality is represented by a watershed in which the ecosystem, and recreational, commercial, and municipal uses of water are affected adversely by phosphorus loading, from agriculture for example. This instance of market failure may arise when no clear delineation of property rights for the resource (clean water) exists. Because producers have imperfect information about the impacts of their cropping practices on the river and its multiple uses, market failure inevitably occurs.

In response to societal concerns about specific environmental problems policy makers often propose policies or programs to address these concerns. To measure the impact on producer income and the local economy of any policy, as well as to evaluate its effectiveness at meeting its stated objectives within its budget constraint, an approach that integrates socio-economic, bio-physical, and environmental factors is needed. If the environmental problem results from nonpoint sources that are heterogeneous in nature, one should consider the spatial distribution of the pollutant within the landscape. Using an approach that integrates socio-economic elements and bio-physical factors in a spatially heterogeneous manner, we 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 Problem

The poor quality of the waters of the Minnesota River is one such societal, environmental concern. Sediments sully and phosphorus fouls the river, frequently resulting in a water body unfit for recreational, municipal, or commercial uses. These pollutants originate from many sources, including river and stream banks, construction sites, feedlots, septic systems, urban lawns, and agricultural fields.

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.*). 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 may be released from the soil particles into the water.

When phosphorus is released into water bodies (with adequate nitrogen available), the biological activity or productivity 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.*). 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.

Study Area

The Minnesota River originates along the border between Minnesota and South Dakota and flows for 335 miles before joining the Mississippi River in Saint Paul, Minnesota (MPCA, p.1-1). It drains an area of approximately 17,000 square miles in Minnesota, Iowa, and South Dakota. Agriculture within the river basin represents over 90 percent of land-based activities, and accounts for two-fifth's of the state's corn production and over one-half of its soybean output. Considerable livestock production occurs within the Minnesota River basin, too. Over one-fifth of Minnesota's beef production, and two-fifths of its hog output occurs in the basin (MPCA, p.1-11).

A major watershed of the Minnesota River, and the study area for this research, is the Le Sueur River watershed. Intensive production agricultural occurs in the Le Sueur River watershed, as demonstrated by almost all of the cropland (95%) being planted to either corn or soybeans. Like the Minnesota River basin, considerable livestock production occurs in the Le Sueur River watershed.

The nature and extent of the phosphorus problem is demonstrated by samples of phosphorus load taken over a 15-year period in St. Paul, Minnesota. These samples indicate 1,600 tons of Total Phosphorus flow from the Minnesota to the Mississippi each year (MWCC, p.141). The average concentration of Total Phosphorus in water samples over that period was 0.394 mg/L (MWCC, p.141) -- 20 to 40 times higher than concentrations required to accelerate eutrophication (Randall *et al.*).

The problem of phosphorus nonpoint pollution is spatially heterogeneous. Of the 22 major watershed in the Minnesota River basin, the three closest to its mouth account for two-thirds of the total phosphorus load of the river. For these three, the Le Sueur River watershed (with 9% of the surface area of the Minnesota River basin) contributes 17% of total phosphorus load; while the Blue Earth contributes 15% and the Lower Minnesota contributes 33% of the total phosphorus load (MWCC, p.141).

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). To reduce nonpoint pollution in the Minnesota River by 40 percent from pre-1980 levels, by 1996, was a goal established by the U.S. Environmental Protection Agency (EPA) and the Minnesota Pollution Control Agency (MPCA) (Frost). As this goal has not been attained, any efforts to achieve it necessarily will include programs to reduce the contribution of agriculture to the phosphorus pollution levels in the Minnesota River.

Integrated Analysis

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

In the integrated analysis I conducted, I disaggregated the Le Sueur River watershed into six major soil associations (from two agroecoregions). 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. Thus differences in soil erodibility and sediment and phosphorus delivery ratios to the waterbody were captured in the analysis.

Producers representative of typical production practices occurring in each of the soil associations within the Le Sueur River watershed were surveyed. I used this information to construct representative practices that were simulated in ADAPT (a bio-physical model that combines GLEAMS and DRAINMOD). Simulation with ADAPT provided nutrient output by practices and locations. Because producers identified field locations, as well as their production practices, I could represent tillage and nutrient practices (and associated nutrient effluent) spatially within the watershed.

To analyze policies I developed a mathematical programming model of production activities, by tillage practice (conventional and conservation), nutrient management (actual and recommended rates of phosphorus), and location in the Le Sueur River watershed. Assuming risk-neutral producers, the social planner's objective is to maximize net farm income for the watershed (equation 0), subject to several constraints. Net farm income is a function of net returns from crop production, variable and fixed costs of production, as well as government payments received from other farm programs. The acreage constraint (equation 1) was applied at the soil association level. Equation 2 constrained total phosphorus at the watershed (agroecoregion) or soil association level, depending on the policy examined. For a nontargeted or uniform reduction of phosphorus, the constraint was active at the soil association level. For example, if the social planner (state agency responsible for pollution reduction in the Minnesota River) wished to reduce phosphorus pollution by 40% uniformly across the basin or watershed, then each soil association had to reduce its baseline phosphorus load by 40%. Therefore, the constraint was active at each soil association. If the policy was more flexible and allowed for a 40% reduction within the basin or watershed, then "hot spots" can be targeted and the constraint would be applied at the watershed level only. With this model formulation, I can evaluate the economic efficiency of a regulated reduction in agricultural phosphorus pollution administered in two different manners.

(0) $\text{Max } \pi(t,n,; f,s,e) = \Sigma_e^E \Sigma_s^{Se} \Sigma_f^{Fs} (\Sigma_c^C y_{cfse}p_c - \Sigma_n^N x_{nfse}w_n - FC_{fse} + GP_{fse})a_{fse}$

subject to:

(1) $\Sigma_f^{Fs} a_{fse} \leq A_s^*$ $\forall$ s,e

(2) $\Sigma_f^{Fs} y_{cfse}a_{fse} \leq (1 - b)Y_c^*$ c = phosphorus; $\forall$ s,e

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

where for each activity:

$t \in T$ tillage system

$n \in N$ nutrient management system

$e \in E$ agroecoregion

$s \in S$ soil association within agroecoregion

$f \in F$ field or farm within soil association

a_{fse} area in activity (t,n) fse

y_{cfse} output (yield and effluent) c from activity fse

p_c price of output c (negative if effluent tax)

x_{nfse} variable input n used for activity fse

w_n price of variable input n

FC_{fse} fixed costs for activity fse

GP_{fse} government payment for activity fse

b reduction in phosphorus load (0 <= b <= 0.4)

Results and Conclusions

Policy makers in Minnesota, as well as state environmental agency personnel have a goal of reducing phosphorus and sediment load by 40% of present levels. In my analysis of the Le Sueur River watershed, I assumed that the estimated portion of current (baseline) phosphorus load attributable to agriculture would be reduced by 40%. As there is considerable disagreement about how much phosphorus load is attributable to agriculture (30-70% in the Minnesota River basin as a whole), not to mention how much is derived from crops or livestock, I assumed 50% of total phosphorus load from nonpoint sources was agriculture's contribution to the problem.

To compare the effects, on phosphorus load and net farm income, of uniform and flexible reduction of phosphorus nonpoint pollution from agriculture I constrained the economic policy model at one of two scales as described above. Examining the physical effects first, it can be seen in Table 1 that administering a regulated reduction in phosphorus in either manner (flexible or uniform) resulted in the same level of total phosphorus load from agriculture in the watershed. When the policy was implemented in a uniform manner, *each soil association* within the watershed reduced load by 40%. However, with flexible implementation (40% reduction in phosphorus load at the *watershed* scale), phosphorus load reductions varied by soil association; from 25% reduction in MN079 to 100% reduction (to 0 pounds phosphorus) in MN163. Thus, we see how implementation affects phosphorus load and the production activities causing that load by location.

The physical analysis indicates that certain regions (soil associations) of the watershed contribute disproportionately more phosphorus than do other areas. This corresponds well with observed phenomena and common sense. Every watershed has "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 soil association MN163, phosphorus load from drainage is highest because for these heavy soils to be cropped, they are tile drained. On the other hand, steeply-sloped soils in MN087 have the highest phosphorus load from sedimentation and run-off.

Looking at Table 2, we appreciate how this physical relationship affects the net farm income of the watershed. When the mandated 40% reduction in phosphorus load is implemented in a uniform manner, net farm income for the watershed declines to $65.9 million. This is 4% less than the net farm income for the watershed when the mandated reduction occurs in a flexible manner ($68.5 million).

Examining Table 2 one observes that to reduce agricultural phosphorus load by 40%, some cropland (15-20%) would come out of production, depending on how the regulation is implemented. A less severe regulated reduction in phosphorus (20%), if implemented flexibly, would reduce producer income by less than 5% ($2.2 million), and keep all cropland in production.

Flexible implementation of a pollution standard is more efficient than uniform (nontargeted) implementation. If society wishes to reduce nonpoint pollution, allowing flexible implementation (or targeting) of the policy will achieve the goal more efficiently.

Table 1. Effects of implementing a program in two different manners on agricultural phosphorus load, by percentage reduction in baseline load and soil association.

Uniform Phosphorus Reduction

	0%	**10%**	**20%**	**30%**	**40%**
MN087	71,028	63,927	56,824	49,721	42,618
MN160	21,680	19,517	17,348	15,180	13,011
MN457	38,593	34,736	30,876	27,017	23,157
MN079	22,709	20,439	18,168	15,897	13,626
MN163	30,338	27,306	24,272	21,238	18,204
MN454	51,031	45,936	40,832	35,728	30,624
Watershed	235,380	211,860	188,320	164,780	141,240

Flexible Phosphorus Reduction

	0%	**10%**	**20%**	**30%**	**40%**
MN087	71,028	67,061	66,949	41,411	50,815
MN160	21,680	18,366	15,190	17,835	15,190
MN457	38,593	32,979	25,495	25,495	25,495
MN079	22,709	22,710	17,785	17,099	17,099
MN163	30,338	30,338	30,338	30,338	-
MN454	51,031	40,761	32,879	32,879	32,879
Watershed	235,380	212,215	188,636	165,056	141,477

Table 2. Effects of implementing a program in two different manners on net farm income, cropland, and agricultural phosphorus load, by percentage reduction in baseline load.

Uniform Phosphorus Reduction

Phosphorus Reduction	Net Farm Income (Dollars)	Total Cropland (Acres)	Conservation Cropland (Acres)	Total Phosphorus (Pounds)
0%	82,840,096	704,542	289,022	235,380
10%	81,184,602	696,213	411,639	211,860
20%	78,898,128	686,633	624,811	188,636
30%	74,191,215	645,920	645,920	164,780
40%	65,949,743	572,644	572,644	141,240

Flexible Phosphorus Reduction

Phosphorus Reduction	Net Farm Income (Dollars)	Total Cropland (Acres)	Conservation Cropland (Acres)	Total Phosphorus (Pounds)
0%	82,840,096	704,542	298,833	235,380
10%	82,205,443	704,542	410,620	212,215
20%	80,644,468	704,542	690,812	188,636
30%	74,747,749	647,549	647,549	165,056
40%	68,519,095	596,855	596,855	141,477

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