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Metamodelling phosphorus best management practices for policy use: a frontier approach

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Abstract

This article presents a modelling system for synthesising heterogeneous productivity and nutrient loading potentials inherent in agricultural cropland for policy use. Phosphorus abatement cost functions for cropland farmers in a southeastern Minnesota watershed are metamodelled using frontier analysis. These functions are used to evaluate policies aimed at reducing nonpoint phosphorus discharges into the Minnesota River. Results indicate an efficiently targeted policy to reduce phosphorus discharge by 40% would cost US\$ 167,700 or 844 per farm.

JEL classification: Q15; Q25; Q28

Keywords: Nonpoint source pollution; Phosphorus; Abatement costs

1. Introduction

The Minnesota River Basin has been identified as one of the top 20 American Rivers seriously threatened by pollution (American Rivers, 2000). This classification is mainly due to eutrophication resulting from high levels of nutrient inputs. Water quality monitoring data show extremely high quantities of phosphorus entering the Minnesota River from point and nonpoint sources (Minnesota Pollution Control Agency—MPCA, 1998). Consequently, the Minnesota Pollution Control Agency has adopted the ambitious goal of reducing biochemical oxygen demanding substances by 40%. To achieve this goal, phosphorus discharge by agricultural, nonpoint sources (NPSs) must be reduced by more than 40% (MPCA, 2000).

Traditionally, policymakers have addressed agricultural NPS pollution using voluntary conservation programs designed to encourage agricultural producers to adopt alternative (or ‘best’) management practices (BMPs). These are typically cost-share programs, which pay farmers directly to adopt pollution-

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mitigating practices (Heimlich and Claassen, 1998). For example, the Conservation Reserve Program (CRP) essentially pays farmers to cease cropping activities on environmentally sensitive lands (Ribaudo et al., 1994). Policymakers have also employed uniform reduction policies and/or required management standards, such as new US Environmental Protection Agency (EPA) regulations for the land application of manure from animal feeding operations (EPA, 2002). In addition, many advocate the use of market mechanisms to control NPS pollution (Ribaudo et al., 1999), as evidenced by more than 37 effluent trading and offset programs for US water pollution (Environomics, 1999). Moreover, the EPA has recently promoted water quality trading for pollutants such as phosphorous to help address the Total Maximum Daily Load standards (TMDLs) for impaired US surface waters (EPA, 2001, 2003).

However, changing program criteria and fluctuating levels of funding make it difficult for policymakers to estimate what level of pollution mitigation will result from voluntary NPS conservation programs. Under a policy of required management standards, edge-of-field abatement may be uniform, but the cost of achieving those reductions may not be. Lastly, to design cost-effective market-based policies, detailed cost and benefit information for heterogeneous nonpoint sources is needed. Therefore, given the wide range of options available to policymakers, measures linking pollution abatement to the cost of achieving that abatement are essential for informed decisions. Such measures are facilitated through the use of metamodels, defined by Wu and Babcock (1999) as "... a statistical response function that approximates outcomes of a complex simulation model".

In this paper we illustrate a metamodel for integrating complex biophysical and economic analysis to allow greater flexibility in policy analysis, both from the cost-side and from the abatement-side. This methodology can be used by policymakers to compare heterogeneous parameters such as aggregate abatement levels and compliance costs when designing abatement policies. Section 2 describes how the metamodel linking costs and abatement levels for phosphorus is constructed and estimated. In Section 3 we apply this methodology to a tributary sub-watershed of the Minnesota River. To illustrate the functionality of this approach in Section 4, we evaluate four possible policies that might be chosen by a regulator to achieve the desired water quality goal: a 40% reduction in aggregate NPS phosphorus discharges. These policies are representative of those currently used in the United States to address water quality impairments: uniform reduction policies (such as nontradable quotas), land retirement policies (such as the CRP), and market-based polices (such as tradable quotas). Section 5 concludes the paper.

2. Metamodelling for policy use

Many environmental protection agencies have begun to adopt a geographical approach known as "Watershed Protection Approach" (WPA), acknowledging that water quality problems can be best solved at the watershed level (EPA, 1998). This approach is also reflected in the 'vulnerable zones' designation of European cropland with high nitrate loading potentials. However, it is costly to intensively survey all the farms in a watershed or to conduct field trials for the many possible combinations of management practices on different soil plots in order to successfully implement WPA. For these reasons, field-scale simulation models, which account for variability in land cover, soil, tillage, and drainage practices, have been increasingly used to enhance the efficiency of WPA (e.g., Fleming and Adams, 1997; Faeth, 2000). The appropriateness of simulation modelling to predict water quality changes for policy use has been questioned (Dosi and Moretto, 1993). However, as noted, such models are preferred when the costs of acquiring information about actual nutrient loads are prohibitively high as in the case of nonpoint source pollution.

Recent approaches in evaluating agricultural nutrient reductions reflect these trends and have included different biophysical (Gowda et al., 1998; Dalzell et al., 1999) and economic (Govindasamy and Cochran, 1995; Parker, 2000) applications. Several authors have promoted 'metamodelling' as a means to synthesise these detailed biophysical and economic analyses in a policy-relevant framework. Metamodelling, not to be confused with 'meta-analysis' or 'metaregression analysis',[4] is an econometric

[4] Metaregression analysis is used to statistically synthesise the results of previous research efforts (e.g., Rosenberger and Loomis, 2000).

methodology designed to integrate simulation data with behavioural assumptions in order to predict responses to policy. Wu and Babcock (1999) metamodelled nitrogen loading in the Central United States. Simulations from EPIC, a biophysical soils model, form the basis of their econometric estimations of the response (of farm profit) to policy-relevant control variables (e.g., cropping system, residue management, etc.). Antle et al. (1999, 2001) and Antle and Capalbo (2001) have formalised a metamodelling approach to estimate the costs of carbon sequestration policies applied to dryland grain production in the northwestern United States. They note that, "the use of linked disciplinary simulation models to evaluate complex natural and human systems is becoming the standard methodology for analysis of many leading environmental issues".

2.1. Biophysical model

To simulate abatement levels and crop yields resulting from alternative phosphorus BMPs, we use the agricultural drainage and pesticide transport (ADAPT) model. This field-scale, water table management model was developed as an extension of GLEAMS (Leonard et al., 1987) to incorporate subsurface drainage, subsurface irrigation and deep seepage algorithms, useful for the tile-drained soils of the Midwestern United States. Furthermore, ADAPT estimates of nutrient loads and crop yields have been calibrated for several watersheds in the Minnesota River Basin (Dalzell et al., 1999; Johansson, 2000; Westra, 2001).[5] Nonspatial input data for ADAPT simulations include variable management practices (crop choice, residue management, fertiliser application rates and method of application) and climatological data (precipitation, temperature, solar radiation and wind velocity).

We use the watershed modelling approach developed by Gowda et al. (1998) to predict nutrient loading. This approach first identifies hydrologic response clusters for the region using geographically-referenced data layers, which include land uses, slopes, distances to water channels, tillage practices, and soil types. These clusters are then aggregated into identifying transformed hydrologic response units (THRUs). THRUs can be thought of as representative farm units on a per hectare basis. These farms can be used with ADAPT to simulate the phosphorus-loading effects of different BMPs. The BMPs chosen include reduced fertiliser treatments, incorporated and broadcast fertiliser treatments, cropping choices reflective of the region, and residue management practices. All of these practices have well-documented potentials to limit phosphorus runoff into area waters (e.g., Rehm et al., 1998).

2.2. Economic model

To model the adoption of phosphorus BMPs in response to water quality regulations, we estimate phosphorus abatement cost functions for each farm. This function maps the cost-minimising choice of abatement effort for each soil map unit necessary to achieve any desired abatement level, where abatement level represents the reduction in kilograms of phosphorus discharges from historical levels. This framework follows Montgomery (1972) examination of cost functions under regulation. Similar to Yiridoe and Weersink (1998), the abatement effort to achieve the required level of phosphorus reduction can be described by abatement effort on the extensive and intensive margins. Extensive margin practices include such things as crop selection, whereas intensive margin practices include residue management, fertiliser application rates, and fertiliser application methods.

More formally, we consider the problem of phosphorus pollution caused by perfectly competitive and risk-neutral agricultural producers. Expected agricultural production is a function of the chosen extensive and intensive practices as well as inherent topographic and soil qualities. Production per hectare for the ith farm can be expressed as: $y_i = y_i(r_i, z_i)$, where y_i is the agricultural output per hectare, r_i represents the farming practices on the extensive margin, and z_i the farming practices on the intensive margin. Given competitive input prices, the variable cost of production is $vc_i = vc_i(r_i, z_i)$. Expected profit per hectare in the absence of phosphorus abatement given competitive output prices (P) and choice of extensive and intensive management practices is $\pi_i(r_i^*, z_i^*) = Py_i(r_i^*, z_i^*) - vc_i(r_i^*, z_i^*)$.

Expected phosphorus discharge per hectare is given by: $e_i = e_i(r_i, z_i)$, where e_i is the discharge rate per

[5] Complete details of the model, and studies with the model, are presented by Chung et al. (1992), and Ward et al. (1993).

hectare as a function of extensive and intensive management practices. Given historic levels of phosphorus discharge, $\bar{e}_i$, expected abatement per hectare is: $a_i = a_i(r_i, z_i)$, where $a_i(r_i, z_i) \equiv \bar{e}_i - e_i(r_i, z_i)$. When phosphorus discharge are restricted to some level, $\hat{e}_i$ the farm's restricted profit function is $\pi_i(\hat{r}_i, \hat{z}_i)$, where $\hat{r}_i$ and $\hat{z}_i$ represent cost-minimising choices of extensive margin and intensive margin abatement efforts given the phosphorus discharge constraint, $e_i(\hat{r}_i, \hat{z}_i) \leq \hat{e}_i$. Average abatement costs per hectare under phosphorus reductions are the difference between the unrestricted and restricted profit functions: $C_i(\hat{a}_i) = \pi_i(r_i^*, z_i^*) - \pi_i(\hat{r}_i, \hat{z}_i)$, where abatement levels per hectare meet or exceed the target reductions in phosphorus, $\hat{a}_i \geq \bar{e}_i - e_i(\hat{r}_i, \hat{z}_i)$. The abatement cost function is then, $C_i(a_i(r_i, z_i))$. We expect convex abatement costs: $\partial C_i(a_i(r_i, z_i))/\partial a_i > 0$ and $\partial^2 C_i(a_i(r_i, z_i))/\partial a_i^2 > 0$.[6]

2.3. Metamodel

There are a number of ways to estimate abatement cost functions for agricultural nonpoint pollution. Earlier integrations of biophysical and economic analyses have typically estimated production functions based on field experiments using OLS estimation techniques. Given an environmental constraint, method of control (e.g., input or output taxes), and relevant exogenous prices, the production function is optimised using a mathematical programming routine to predict constrained profit-maximising choices of technology and input levels (e.g., Fleming, 1995; Morgan, 1999; Antle et al., 1999). This same methodology is applicable to the dual, cost-minimisation problem given an environmental constraint and will result in the same levels and costs of abatement for a given policy.

We first use ordinary least squares when mapping abatement costs to abatement levels to identify the appropriate functional form, assuming that if two abatement practices with different abatement levels are achievable then a linear combination of those two practices is also achievable (Just and Zilberman, 1988). While OLS estimation will minimise the squared deviation of observations from the fit of the abatement cost function, it may be biased upwards due to redundant combinations of intensive and extensive abatement efforts in the simulation exercise. These redundancies may arise from topographical features and may not be consistent with cost-minimising behaviour. Therefore, we use frontier analysis to estimate the actual cost function (Battese, 1992; Coelli, 1995). The convex frontier will represent the cost-minimising shell of all best management practices.

This methodology is unique to the literature of integrated biophysical and economic analysis, however, Coelli (1995) note that estimating the influence of pollution controls for feedlots would be a policy application lending itself well to stochastic frontier analysis. We argue that frontier analysis is also appropriate and justified when using simulated data to model biophysical and economic processes due to simulation redundancies noted above. Precedent is found in a recent study of sediment abatement in Indiana, in which Randhir et al. (2000) employ data envelope analysis (DEA) to characterise the costs of reducing sediment loads on agricultural cropland. DEA provides an envelope describing the convex set of abatement choices available to farmers, but is generally not continuous and therefore, would not facilitate easy derivation of marginal cost values. In our case, frontier analysis provides continuous abatement cost functions, which can then be used to compare producer marginal costs of abatement, critical when designing cost-effective policy.

The frontier regression model used in our analysis is the classical linear regression model with a non-normal, asymmetric disturbance (Aigner et al., 1977; Green, 1997). Given our economic model, the formulation of the abatement cost estimation for the ith THRU is

$$C_{ij}(a_{ij}(r_{ij}, z_{ij}); r_i^*, z_i^*) = f_i(a_{ij}(r_{ij}, z_{ij}); \beta_i) + v_{ij} + |u_{ij}| \quad (1)$$

where j subscripts the various best management practices, $f(\cdot)$ is the convex abatement cost function, $v_{ij} \sim N[0, \sigma_v^2]$ is associated with random factors (e.g., measurement errors), and $u_{ij} \sim N[0, \sigma_u^2]$ establishes cost-minimising behaviour. Estimates of β (denoted as $\hat{\beta}$) are either the maximum-likelihood estimators or the corrected OLS (COLS) estimators, where the intercept estimator is the OLS estimator plus the largest

[6] This is consistent with previous assumptions of convex abatement costs (Leiby and Rubin, 2001; McKitrick, 1999; Kling and Rubin, 1997).

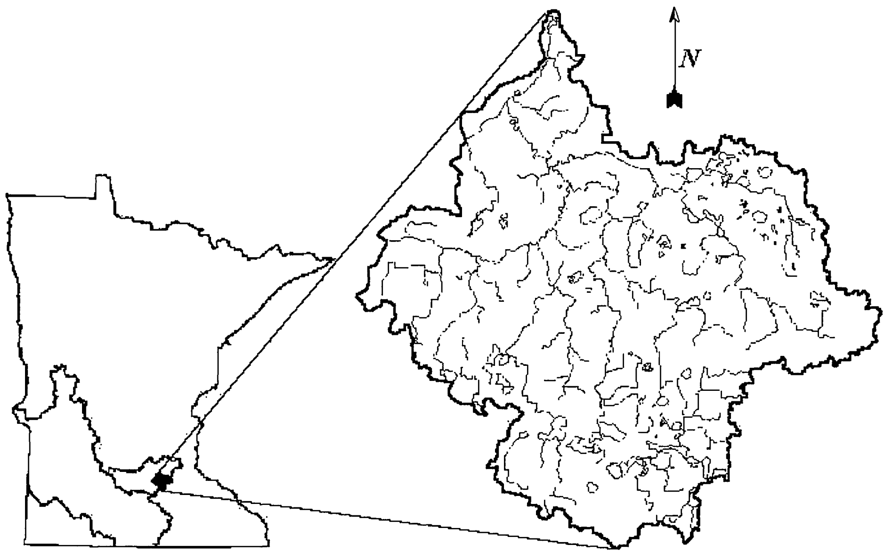

Fig. 1. Sand Creek watershed, Minnesota (65,000 ha).

residual necessary to encompass all the observations within the convex set of abatement choices (Battese, 1992).

Despite the advantages of combining heterogeneous biophysical and economic information in this manner, this methodology does rely on several assumptions and constraints. Because the abatement cost and level observations for the representative farms are simulated, acceptance of the ADAPT model and the underlying economic information (crop yields, variable costs and competitive prices) are necessary for meaningful results and analysis of the metamodel. Because biophysical simulations of agricultural practices require detailed topographical and climate data, the applicability of this methodology to larger watersheds or basins may be limited by data and computing capacity requirements.[7] Stochastic frontier estimation is also based on distributional assumptions regarding the random effect variables, which is a main criticism of this technique (Coelli, 1995). Furthermore, the use of frontier analysis to estimate the abatement cost frontier requires the assumption of cost-minimising, risk-neutral farmers with complete knowledge of abatement efforts, weather expectations and soil typology. This assumption is required for a parsimonious presentation of the main thrust of this article and is not expected to alter significantly the results presented herein.[8]

3. Sand Creek watershed

We utilise data from the Sand Creek watershed, a tributary watershed of the Minnesota River, to estimate the relevant abatement cost functions and to develop welfare comparisons. Sand Creek is located within the Lower Minnesota River Basin, the last sub-basin of the Minnesota River before its confluence with the Mississippi near Minneapolis and St. Paul, MN (Fig. 1). This region was chosen for several reasons. The Minnesota River drains roughly 4.4 million ha of agricultural cropland from Minnesota, Iowa, and South Dakota. It is a major source of sediment, nitrogen, and phosphorus to the Mississippi River and to the Gulf of Mexico. The Lower Minnesota Watershed is the largest contributor of phosphorus to the Minnesota River, discharging as much as 864 Mt of phosphorus in a year (MPCA, 1998). Sand Creek is one of the eight

[7] However, given sufficient resources, the application of metamodels to larger areas is possible (e.g., Wu and Babcock, 1999).

[8] The relaxation of this assumption to include uncertain and asymmetric information is an important issue for further analysis (Kaplan et al., 2003; Johansson, 2002).

Table 1
Descriptive statistics and abatement cost functions for representative Sand Creek farms

Farm unit[a]	Hectares	Baseline revenue (US$ ha^{-1})	Baseline discharge (kg/ha)[b]	Maximum abatement on the intensive margin (kg/ha)	Cost function[c], $C(a_i) = \beta_i(a_i)^2$
MN079a	23,882	839.51	0.38	0.22	$269.01a^2$
MN080a	4,724	856.47	0.46	0.26	$454.86a^2$
MN081a	3,430	770.15	0.46	0.26	$172.84a^2$
MN163a	3,359	855.37	0.29	0.17	$690.99a^2$
MN165a	1,022	775.37	1.36	1.15	$29.26a^2$
MN169a	580	441.04	1.32	1.07	$-5.30a^2$
MN171a	205	933.82	0.54	0.26	$306.71a^2$
MN178a	222	660.87	0.32	0.17	$1169.10a^2$
MN196a	14,145	909.29	0.53	0.31	$259.52a^2$
MN079b	3,731	839.51	1.00	0.57	$39.79a^2$
MN080b	731	856.47	1.19	0.68	$67.29a^2$
MN081b	555	770.15	1.19	0.68	$25.57a^2$
MN163b	780	855.37	0.77	0.44	$102.22a^2$
MN165b	202	775.37	3.54	2.98	$4.33a^2$
MN169b	148	441.04	3.43	2.78	$-0.78a^2$
MN171b	13	933.82	1.40	0.67	$45.37a^2$
MN178b	30	660.87	0.82	0.45	$172.94a^2$
MN196b	2,293	909.29	1.39	0.81	$38.39a^2$
Aggregate	60,052	850.10	0.57	0.34	

[a] Farm a refers to representative farms further than 100 m from a hydrologic pathway; farm b refers to representative farms closer than 100 m to a hydrologic pathway.

[b] Discharge levels refer to in-stream loadings.

[c] Abatement cost functions are estimated over the intensive management margin. In certain instances, the estimation indicates that constrained profit exceeds the unconstrained profit. These negative abatement costs are often accompanied by the adoption of conservation tillage regimes (CTIC, 2001), but revert to the expected convex form when extensive management practices are required to achieve high levels of abatement.

tributaries of the Lower Minnesota. It drains approximately 65,000 ha and contributes approximately 11% of the Lower Minnesota phosphorus load (MPCA, 1998).

Sand Creek soils data used for the ADAPT simulations were developed from the STATSGO (State Soil Geographic) soil database (USDA–NRCS, 1998). Soil characteristics include: the number and depths of the soil horizons; the percentage of clay, silt and organic content in each horizon; vertical and horizontal hydraulic conductivity; porosity, wilting point, water and phosphorus content in the soil horizons at different matric suction and upflux levels (Dalzell et al., 1999). In this manner Sand Creek can be divided into nine basic farming areas corresponding to soil type (MN079, MN080, MN081, MN163, MN165, MN169, MN171, MN178, and MN196). These areas are differentiated spatially according to their distance to a water transport channel to identify representative farms (i.e., MN (a) and MN (b)). A distance of approximately 100 m to any perennial stream, intermittent stream or drainage ditch was chosen as a representative buffer distance (Sharpley et al., 1999). Table 1 presents summary statistics for these 18 representative farms.

To achieve varying degrees of phosphorus abatement depending on the type and level of regulatory policy imposed, each farm can choose between extensive and intensive abatement practices: crop rotations, fertiliser application rates, the manner by which that fertiliser is applied, and residue management tillage practices for this region. The predominant farming practice in the region is a corn–soybean rotation with conventional tillage and high rates of broadcast fertiliser. This baseline is used to normalise costs and abatement for the other management choices representative of southeastern Minnesota[9] (Table 2). These

[9] Tillage, fertiliser and cropping values are chosen to represent bounds on current practices in the region (University of Minnesota, 1995–1999; Rehm et al., 1998).

Table 2
Range of best management practices simulated for phosphorus abatement in the Sand Creek basin using the agricultural drainage and pesticide transport model

Simulation number	Crop rotation[a]	Tillage[b]	Method of application[c]	Fertiliser rates[d]	Abatement cost[e] (US$ ha^{-1})	Abatement level[e] (kg/ha)
0	CS	CVN	B	H	0.00	0.00
1	CS	CVN	B	M	19.53	0.11
2	CS	CVN	B	L	51.34	0.17
3	CS	CVN	I	H	6.06	0.14
4	CS	CVN	I	M	31.08	0.15
5	CS	CVN	I	L	48.93	0.17
6	CS	CSV	B	H	8.51	0.19
7	CS	CSV	B	M	26.30	0.26
8	CS	CSV	B	L	56.27	0.34
9	CS	CSV	I	H	14.57	0.32
10	CS	CSV	I	M	38.02	0.32
11	CS	CSV	I	L	54.06	0.34
12	P	N/A	N/A	N/A	715.40	0.40
13	CCC	CSV	B	H	54.11	−0.01
14	None	N/A	N/A	N/A	850.10	0.57

[a] Rotations—CS: corn–soybean; P: pasture; CCC: continuous corn.
[b] Tillage—CVN: conventional (fall mouldboard plow + spring disk harrow + spring planter); CSV: conservation (fall chisel plow + spring planter).
[c] Method of application—I: incorporated (fall application at 7.5 cm); B: broadcast (fall application).
[d] Application rate—H: high (180 kg/ha N + 50 kg/ha P for corn − 20 kg/ha P for soybeans); M: medium (140 kg/ha N + 20 kg/ha P for corn − 10 kg/ha P for soybeans); L: low (80 kg/ha N for corn).
[e] Abatement costs and abatement levels refer to an area-weighted average of in-stream abatement costs and loadings across all farm types. Negative abatement levels indicate that a movement from the baseline farming practice results in increased phosphorus loadings.

practices were simulated using ADAPT with 50 years of historic, regional climate data to estimate average yield and phosphorus loads for the 18 representative farms in the Sand Creek. The climate data needed for the ADAPT simulations consisted of daily precipitation and temperature observations for this region from 1947 to 1996 (NCDC, 2000). Each farm then has 700 (14 practices by 50 years) annual observations to estimate average yield and phosphorus loads across management regimes. Changes in variable costs and average values of the prices of corn, soybeans, pasture and CRP rental rates for this region were developed using University of Minnesota Extension reports (University of Minnesota, 1995–1999) and Minnesota Agricultural Statistics Bulletins (Minnesota Agricultural Statistics Service, 1992–1999).

The nonlinear nature of costs as a function of abatement is readily apparent. For example, moving from a corn–soybean rotation, conservation tillage and low rates of incorporated fertiliser to a pasture regime nets an average of 0.06 kg/ha in abatement and costs on average US$ 661.34 ha^{-1}. A similar level of abatement (0.07 kg/ha) can be gained by moving from a corn–soybean conservation tillage regime with high rates of broadcast fertiliser to one with medium rates of broadcast fertiliser at only a fraction of the cost (US$ 17.79 ha^{-1}). By comparing various quadratic fits using stepwise OLS regressions, the functional form of the abatement cost functions having the largest F-statistics across soil the majority of soil map units was $C(a_i) = \beta_i(a_i)^2$.

However, as mentioned, some of the parameters chosen for the simulations are redundant given specific farm characteristics. A movement from simulation 5 to simulation 6 results in an average increase in abatement by 0.02 kg/ha, but simulation 6 actually costs US$ 48 ha^{-1} less. This result indicates that simulation 5 is redundant for some soils (i.e., not representative of potential farm choices), and therefore OLS estimates of the abatement cost function will be inflated. To correct for potential redundancies in modelling parameter choices, we estimate the cost

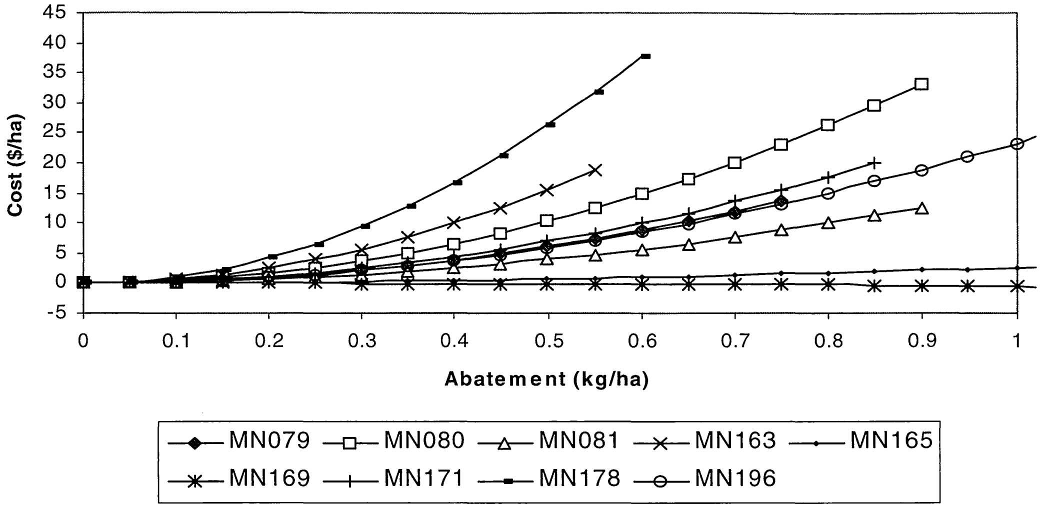

Fig. 2. Estimated edge-of-field, abatement cost functions for Sand Creek farms. The endpoints of the functions represent the maximum achievable abatement on the intensive margin (note that for MN165 and MN169 the endpoints will be 3.82 and 3.52 kg/ha, respectively).

functions using a stochastic frontier estimator with half-normal errors (Green, 1998). The heterogeneity in edge-of-field abatement for the nine soil types is illustrated in a plot of abatement costs and abatement levels (Fig. 2). Only the fit of the soil type MN169 (representative farms MN169a and MN169b) to the simple quadratic functional form is poor. This is a soil with low crop productivity and high-loading potential (Table 1), accounting for only 2.4% of Sand Creek phosphorus discharge. On these soils it is possible for farmers to increase profit by adopting abatement practices on the intensive margin.

Note that the proposed MPCA policy and those being considered in this paper focus on in-stream levels of phosphorus, and not simply edge-of-field values. Therefore, before using the frontier estimates for policy use, the abatement cost functions are calibrated using appropriate sediment delivery ratios. Sediment delivery ratios (SDRs) describe the percentage of edge-of-field phosphorus discharge that arrives at the watershed outlet via water-born transport pathways (surface water, tile-drainage system or drainage ditch). Because a farm that is relatively close to a stream or water channel will discharge a higher

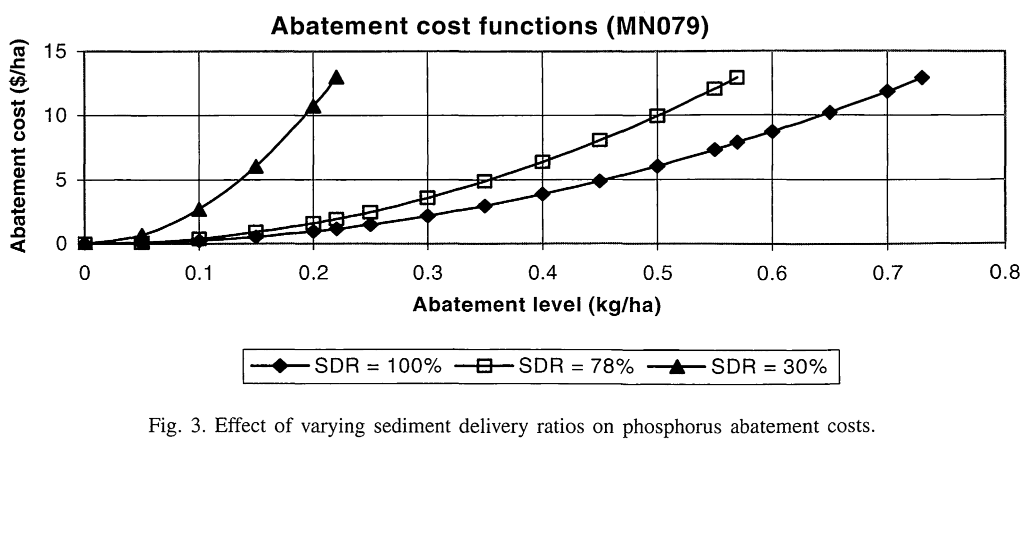

Fig. 3. Effect of varying sediment delivery ratios on phosphorus abatement costs.

Table 3
Total cost (TC) and average cost (AC) for representative farm abatement of phosphorus in the Sand Creek basin under four policy scenarios[a]

Farm unit	Uniform		Highest loads		Lowest productivity		Efficient	
	TC ($)	AC (US$/kg)	TC ($)	AC (US$/kg)	TC ($)	AC (US$/kg)	TC ($)	AC (US$/kg)
MN079a	150,788	41.21	0	0	936,144	226.32	95,394	32.76
MN080a	72,352	83.47	0	0	0	0	11,159	32.72
MN081a	19,776	31.57	0	0	294,980	186.96	21,323	32.75
MN163a	32,204	81.39	0	0	0	0	5,223	32.85
MN165a	8,889	15.95	87,892	63.24	87,892	63.24	37,528	32.75
MN169a	−856	−2.80	49,880	65.15	49,880	65.15	−3,520	−5.67
MN171a	2,905	65.87	17,630	159.26	0	0	721	32.77
MN178a	4,169	148.10	0	0	19,092	268.75	204	34.00
MN196a	167,483	55.43	162,042	162.26	0	0	58,231	32.66
MN079b	23,555	15.85	320,866	86.00	320,866	86.00	47,503	22.49
MN080b	11,196	32.10	62,866	72.27	0	0	11,669	32.78
MN081b	3,202	12.14	47,730	72.27	47,730	72.27	6,517	17.29
MN163b	7,482	31.30	67,080	111.69	0	0	8,200	32.80
MN165b	1,758	6.14	17,372	24.29	17,372	24.29	7,754	12.88
MN169b	−218	−1.08	12,728	25.07	12,728	25.07	-900	−2.18
MN171b	187	25.33	1,118	61.43	0	0	276	30.67
MN178b	553	56.96	2,580	104.88	2,580	104.88	184	30.67
MN196b	27,147	21.32	197,198	61.87	0	0	57,400	30.98
Total	532,572		1,046,982		1,789,264		364,865	

[a] Policy scenarios are explained in the text.

percentage of its edge-of-field phosphorus load than one further away, SDRs will significantly impact the costs and level of phosphorus abatement.

ADAPT simulations for Sand Creek's phosphorus discharge are calibrated to observed water quality (Johansson, 2000). Cropland within the 100 m buffer (approximately 13% of the region) is estimated to have a SDR of 78%, while the remaining cropland (87% of the region) has a SDR of 30%.[10] An illustration of the effect of an SDR on abatement costs for MN079 is shown in Fig. 3. The maximum abatement achievable on the intensive margin for MN079a is approximately 0.22 kg/ha. It can be seen that the cost per hectare for this level of abatement would be approximately US$ 14 ha^{-1} for croplands in MN079a and US$ 2 ha^{-1} for MN079b. In essence, the effect of a smaller SDR is to shift the abatement curves upward (i.e., it is more costly to reduce a given level of phosphorus as the SDR decreases). The calibrated cost estimate for in-stream abatement are reported in Table 1.

[10] There are many ways to calculate this ratio depending on the relevant delivery timeframe and topographical features that are being examined. Previous estimates for this region range from 10 to 100% (Senjem, 1997; Faeth, 2000; MPCA, 2000).

4. Results

Given the regulator's goal of reducing nonpoint phosphorus contributions in Sand Creek by 40%, we compare four different policies for achieving this goal. One policy requires all agricultural producers in the Sand Creek watershed to reduce in-stream phosphorus discharge by 40% (uniform). Two policies retire land from production based on one of two criteria: retire those lands having the highest loading potential for retirement first (highest loads) or retire those lands with the lowest agricultural productivity first (lowest productivity). These two policies are similar to the CRP and pay the farmer average CRP contract prices for this region on a per hectare basis. Lastly one policy targets heterogeneous abatement levels of each representative farm to achieve the environmental goal at least cost (efficient).

The resulting total costs and cost per kilogram of in-stream phosphorus abatement are shown in Table 3.

Achieving a 40% level of uniform phosphorus reductions would cost US$ 532,572 or 1233 for the typical 139 ha farm in southeastern Minnesota. This is approximately US$ 9 ha^{-1} or the equivalent of 6.3% of expected 1999 farm profits for a typical corn–soybean operation.[11] In contrast, the cost of achieving this goal using efficient levels of abatement would be 31.5% lower (US$ 364,865 for the watershed and US$ 843 for the typical 139 ha farm in southeastern Minnesota). The US$ 6 ha^{-1} abatement cost faced by farmers under this policy are equivalent to 4% of expected 1999 farm profits for a typical corn–soybean operation. The two CRP-like programs that achieve phosphorus abatement through land retirement are three times more expensive than the optimal policy.[12] It is not surprising that land retirement is not the most efficient way to achieve nonpoint abatement given convex abatement costs (Ribaudo et al., 1994). However, comparing the basis for retiring land (i.e., highest loading potential versus lowest productivity) illustrates that given a large budget for land retirement, there are efficiencies (in excess of 40%) to be gained from targeting the payments to high-loading soils.[13]

5. Conclusions

The use of multi-disciplinary approaches to evaluate conventional economic issues, such as nonpoint pollution, is an important innovation for policymakers concerned with efficient regulatory policies. This observation is especially true today given the possibility of the EPA issuing 40,000 new TMDLs for US water resources (EPA, 2001). These approaches are facilitated by the use of metamodels, defined by Wu and Babcock (1999) as "... a statistical response function that approximates outcomes of a complex simulation model". This paper combines simulated abatement data from a biophysical soils model with an econometric frontier model of cost-minimising behaviour. The estimations represent the convex shell of cost-minimising abatement practices available to the farmer. These cost functions are essential for comparing the costs to cropland farmers of different water quality goals and for calculating the aggregate costs resulting from the targeting policy used by policymakers to achieve those goals.

It should be noted that the metamodelling approach in this paper is limited in several regards. Metamodelling management practices for representative farms requires extensive computing and data resources, which may be limiting at scales larger than the watershed level. However, these resources are less than those required to collect farm-level data across similar areas. Furthermore, the simulation of crop and farm responses to management and policy changes require plausible biophysical and economic models. While these models are continuously being improved and calibrated to different regions, they are nevertheless subject to criticism when applied to policies such as the TMDL framework (Dosi and Moretto, 1993). Despite these drawbacks, policymakers require a means of evaluating the link between costs and environmental effectiveness when considering such policies. This metamodelling framework provides such a means in the absence of detailed farm-level cost and benefit observations.

In this study, data from the Sand Creek watershed were used to model abatement cost functions for phosphorus BMPs. Results confirm that heterogeneous productivity and loading potentials inherent in soil typology can significantly affect policy decisions even for relatively small geographic areas. The average cost per kilogram to reduce phosphorus discharge by 40% using a uniform (nontargeted) reduction policy is US$ 39.10 and would cost the typical 139 ha farm approximately US$ 9 ha^{-1}. The average cost per kilogram under an optimally targeted policy is US$ 26.80 and would cost the typical 139 ha farm only US$ 6 ha^{-1}. The two land retirement policies resulted in much higher aggregate costs, but illustrate the importance of targeting high-loading soils before targeting low-productivity soils.

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[11] Reported to be approximately US$ 19,578 over labour and management costs (University of Minnesota, 1995–1999).

[12] The average CRP rental rates are based on average Scott County, MN, rates for 1998 (Taff, 2002).

[13] Actually, these two polices provide the bounds for a phosphorus-based land retirement program. Hence, the cost-effective comparisons are most likely overstated due to improvements in targeting using the environmental benefits index (EBI; Ribaudo et al., 2001).

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