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NON-POINT SOURCE POLLUTION CONTROL IN A DIVERSE AGRICULTURAL SETTING: A BIOPHYSICAL SIMULATION APPROACH

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ABSTRACT: This paper examines economic incentives to offset non-point source pollution from agriculture. A biophysical simulator to estimate technical relationships is linked to linear programming models for representative farms in the Willamette Valley of Oregon. The results indicate site-specific conditions greatly influence policy effectiveness.

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Introduction

Rapid changes in the structure of U.S. agriculture since World War II, particularly agriculture's reliance on agricultural chemicals, have produced environmental effects causing growing public concern. In addition, renewed awareness of and demand for environmental amenities by the general public are changing attitudes towards the agricultural industry and its implicit property rights. This public concern is prompting a growing use of regulatory controls for pollution problems. However, development of control policies can be hindered by the complex nature of non-point source pollution. An evaluation of the farm-level consequences of such policies can provide insight into their effectiveness.

The objective of this paper is to assess the effectiveness of alternative regulatory policies aimed at reducing effluent from farmland in a diverse agricultural setting, the Willamette Valley of Oregon. This will be achieved by accounting for the technical and economic dimensions through linkage of a biophysical simulator with farm-level economic models.

Physical and economic dimensions of agricultural externalities

One of the primary national concerns about agricultural production methods is the effects of agricultural pollution on the quality of water and subsequent impacts on wildlife, human and animal health, water treatment costs, and recreational activities. These potential environmental damages arise from three processes: (1) soil erosion resulting in sediment deposited off the farm field, (2) fertilizer and pesticide runoff deposited directly in surface water courses, and (3) fertilizer, nutrients and pesticides percolating into groundwater. Referred to as *non-point sources (NPS)*, these processes result in the most common form of agricultural pollution. The significance lies in the fact that regulation, control, and containment is considerably more difficult to implement than with point-source pollution, for which the discharger and volumes are more easily identified and measured.

Research indicates that crops use only 50 to 70 percent of applied nitrogen fertilizer [Johnson, Keeny], with the remainder transported by erosion or runoff, leached, or chemically transformed and lost to the atmosphere. In the process of growing crops, loosened topsoil that has moved to a streambed imposes additional costs on other users of that water. Nutrients attached to that sediment and water-soluble chemicals in runoff, can also be deposited in waterways. This sediment and nutrients can harm fish and cause turbidity and excessive plant growth, reducing recreational opportunities. Human health may also be affected when surface or groundwater containing nitrates or pesticides is used for consumption [Miranowski, Crosson and Brubaker, Bower].

There is a socially optimal level of effluent from agricultural processes, but a number studies have suggested this level is exceeded in many locations, sometimes by great amounts (see Ribaudo; Clark, et al.). In a recent EPA report to Congress, 17 states (including Oregon) identified agriculture as a primary or major non-point source of pollution, and another 27 states identified it as a problem [National Research Council].

Agriculturalists are not accustomed to being perceived as a polluting industry and see water quality as mostly an information problem [Batie]. Many non-agriculturalists, however, see public policy and direct controls, or a redefinition of property rights, as the solution. Recent years have seen the implementation of such regulations: Arizona requires permits for all fertilizer applications; fertilizer use regulations have been imposed in Mississippi and Nebraska; and fertilizer taxes are now in effect in Iowa, Wisconsin, and Illinois [Ferguson, et al.].

The control of agricultural runoff is a bioeconomic problem affecting many interests. The problem facing policy makers is how to identify control strategies that do not significantly harm the industry. The environmental economics literature suggests four general approaches for correcting externalities (see Baumol and Oates, and Shortle and Dunn):

- Charges (or Pigouvian taxes), which involve a direct tax on the effluent causing the externality. It is an appropriate theoretical tool, but requires considerable information that may be difficult or impossible to find, such as full cost or damage functions, and is difficult to implement.
- Input taxes (such as for nitrogen fertilizer). They are easy to implement, but may not be very effective at reducing effluent if there is a high marginal value or inelastic demand for the input, or when crops have different utilization rates.

- Standards, defined as levels representing an "acceptable environment," are set subjectively on the basis of scientific evaluation. They may be a least cost method, but in general are only appropriate when the existing situation imposes a high level of social costs not correctable by other means.
- Controls, which involve a directive to decision makers about specific practices that must be used (such as no-tillage) or which are banned from use (such as certain pesticides). They are generally inexpensive to implement, but are effective only when enforcement is possible.

Regulations are targeted to affect management (through choice of crop rotations and mix, sources and application levels of nutrients, and pest control) and tillage practices (such as deep plow, minimum tillage or no-till) particularly through incorporation of Best Management Practices. However, the linkage between the theory and application of measures for control are complicated by the general nature of the pollutants, which are stochastic and cannot be monitored with reasonable accuracy or at reasonable cost. As a result, policy analysts increasingly rely on biophysical models which estimate or predict environmental flows and simulate agronomic processes. These models help to reduce uncertainty associated with developing policies for curtailing non-point source pollution [Shortle and Dunn].

Approach and procedures

The analysis of farm-level policies for the control of non-point source pollution proceeds in a general two-part simulation involving (1) a biophysical simulator to generate environmental and technical parameters, and (2) an economic optimization routine. Specifically, this simulation process consists of a series of steps:

1) identifying characteristic soils and crops;
2) building associated rotation-tillage practice-soil-slope combinations, which represent the options faced by farmers, for use in both the biophysical simulator and optimization model;
3) running computer simulations of these combinations for a sufficient length of time (25 years) to produce expected annual levels of crop and environmental outputs;
4) creating representative farms containing appropriate soils and crop rotation options for the associated biophysical simulator outputs;
5) selecting profit maximizing crop rotations for each farm; and
6) optimizing the linear programming models under constraints of imposed standards, charges, and taxes.

The EPIC (Erosion-Productivity Impact Calculator) biophysical simulator, developed by the Agricultural Research Service [Williams, et al.] generates the technical and environmental information required for this economic analysis. It is designed to simulate crop growth and nutrient flow under conditions considering climate and soil, and farming system characteristics. EPIC has been tested throughout the United States, and was used by the American Agricultural Economics Association Soil Conservation Policy Task Force [A.A.E.A.]. Among the outputs from EPIC are annual crop yields (averaged over the simulation period) and nutrient flow levels.

A separate linear program for each of the representative farms is modeled with GAMS [Brooke, et al.]. Farm-level data were used to generate crop budgets, and farm specific behavior (relating to rotations and tillage practice combinations) was used in forming both activities and constraints. Associated nutrient flow levels and yields from EPIC are incorporated as coefficients. Environmental restrictions and regulations are also imposed when conducting policy tests. Details of the simulation and farm models are provided in Taylor.

The output of each of the farm models is an optimal (profit maximizing) crop mix (including rotation and tillage practices), and an associated set of environmental outflows. The changes in profit, crop mix, and physical outputs recorded between the unrestricted (unregulated) farm and that farm under imposed policies provides a measure of policy effectiveness and cost.

The distinction between enterprise sets and crop rotation sets is a key component of the formulation. Enterprise sets are defined as the costs and operations associated with production of a single commodity. Rotation sets combine appropriate enterprises with soils and land slope, thereby incorporating the biological interactions of crop rotations into simulated crop yields and environmental outflows.

The empirical focus of this study is on the Willamette Valley of Oregon. The Willamette Valley represents an important diversified agricultural region in the Pacific Northwest. Important commodities include grass grown for seed, hay for cattle and dairy farms, and small grains; other crops include vegetables for processing, berries and horticultural products. Its climate consists of mild summers and cool winters with heavy precipitation. The winter precipitation is the most important climatic characteristic due to the high proportion of fall-seeded crops.

Because the valley is a region with no single crop- or farm-type dominant, five farm-types were defined to represent the major combinations of crops, soil types, and geographic subregion within the valley. These include two farms from the river bottom land, two from the broad terrace land, and one from the foothills. An important characteristic of these farms is the range of options available to farmers of the different types, and how they may respond to imposed inducements.

Five policy options are tested. These include: (1) a per-unit tax of levels on leached nitrates, surface runoff of organic nitrogen and nitrates, and both classes combined were used in this study; (2) a tax on nitrogen fertilizer, implemented as a tax of 50% and 100% to the cost of nitrogen; (3) per-acre standards of various levels, imposed by placing a maximum limit on per-acre runoff (or leachate); (4) a requirement for use of no-till drills on small grains and grass seed production; and (5) a ban on fertilizer use in autumn months, to reduce winter leachate.

Results of imposed pollution control options

Results of the simulation framework are presented here in two parts. The first provides a summary of results for the base case or current situation (unrestricted scenario) as computed by each of the representative farm models. The second set of results are generated from applying the various pollution control mechanisms through the biophysical simulation-LP models. Detailed results may be found in Taylor.

Base case analysis

Results of the representative farm models for the unrestricted case are summarized in this section. The solutions generated in each case reflect the most profitable crop mixes given the resources, soils, and production constraints facing each farm. Effluent (soil erosion, leachate, and runoff) is not considered in the decision, and remains unvalued.

The farms with well-drained soils in the bottomland and the terraces are profitable under intensive crop rotations, including vegetables, grass seed, and small grains. Nitrate leaching is considerable in the bottomland farms, averaging more than 16 pounds per acre over the crop mix. Surface runoff of nitrates and nitrogen and soil erosion, however, are not significant problems there. Effluent from the terrace farm consists of a moderate level of nitrate leaching (4.47 pounds per acre), reasonably high runoff of organic-N and nitrates (8.92 pounds per acre), and nearly two tons per acre of soil erosion. An essential difference between the farms is that the terrace farm encompasses four slope classes and increased runoff and erosion with steepness.

A different outcome applies to the poorly-drained farms of the bottomland and terraces because far fewer productive cropping options exist. The profit maximizing LP solutions for the representative farms are dominated by annual and perennial grass seeds. As a consequence, leaching of nitrates is less than 3.5 pounds per acre, but the surface losses exceed 10 pounds per acre.

The fifth representative farm (for the foothills) is not intensively tilled, but features highly profitable land uses, including Christmas trees and wheat-annual ryegrass. Perennial ryegrass for seed occupy the remaining acreage. As a consequence of the well-drained nature of the soils, considerable leaching of nitrates occurs and runoff is substantial, but erosion rates are generally low.

In summary, the base case of unrestricted farm production results in one farm facing groundwater problems, two facing surface runoff problems, and two having a mix of both. It is significant that the non-point pollution is not geographically isolated in the sense that both leaching and runoff affect river bottom, terrace, and foothill farms. Excessive erosion (above a sustaining level) occur on only a relatively few acres of two farms, and phosphorus runoff was minor in nearly all rotations. Figure 1 summarizes the relative severity of nitrogen-based effluent from the five farms.

Least-cost solutions

Pollution control options are gauged here according to their effectiveness for achieving abatement at least cost. An "efficiency frontier" of least-cost solutions are obtained by constraining each farm to effluent levels of a specified average per acre level. The efficiency frontier of one farm is shown in figure 2, which displays changes in profit associated with percentage of abatement. Table 1 contains the optimization results for the same farm.

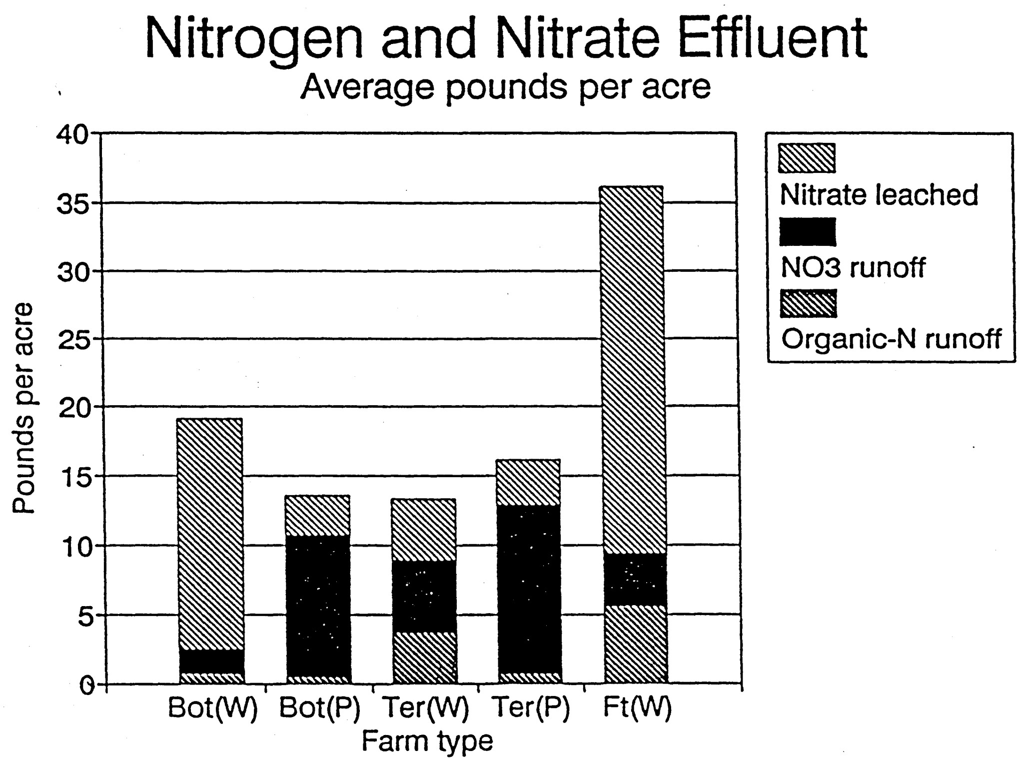

Figure 1. Nitrogen and nitrate effluent from Willamette Valley farms.

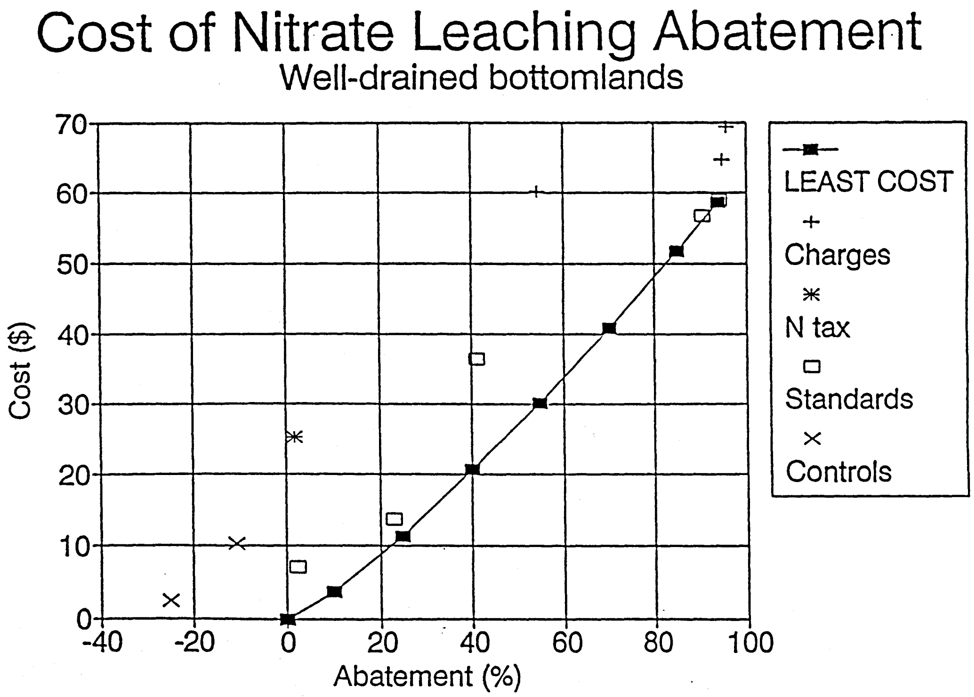

Figure 2. Cost of nitrate leaching abatement, well-drained bottomland farm.

Table 1. Least-cost solutions and measures to induce change in groundwater percolation of nitrates (Well-drained bottomland farm).

Policy	Per-acre profit ($)	Per-acre profit Change	NO3-Leach/Acre (lbs)	NO3-Leach/Acre Change
LEAST COST SOLUTIONS*:				
Unrestricted	147.33	--	16.6	--
Ave. NO3 Leached < 15 lb.	143.57	- 3.76	15.0	- 9.9%
Ave. NO3 Leached < 12.5 lb.	135.99	-11.33	12.5	-24.9%
Ave. NO3 Leached < 10 lb.	126.62	-20.70	10.0	-39.9%
Ave. NO3 Leached < 7.5 lb.	117.21	-30.12	7.5	-54.9%
Ave. NO3 Leached < 5 lb.	106.41	-40.92	5.0	-70.0%
Ave. NO3 Leached < 2.5 lb.	95.61	-51.72	2.5	-85.0%
Ave. NO3 Leached < 1 lb.	88.65	-58.68	1.0	-94.0%
CHARGES ON LEACHATE:				
$ 4 / lb. Leached	87.23	-60.10	7.6	-54.5%
$ 6 / lb. Leached	82.75	-64.58	0.9	-94.8%
$ 12/ lb. Leached	77.93	-69.40	0.7	-95.9%
NITROGEN TAX:				
+ 50% tax on N fertilizer	122.05	-25.28	16.4	- 1.7%
PER-ACRE STANDARDS:				
Leached NO3 < 30 lb./ac.	140.18	- 7.15	16.3	- 2.3%
Leached NO3 < 20 lb./ac.	133.56	-13.77	12.8	-23.0%
Leached NO3 < 15 lb./ac.	110.85	-36.47	9.8	-41.1%
Leached NO3 < 10 lb./ac.	90.60	-56.73	1.6	-90.5%
Leached NO3 < 6 lb./ac.	88.48	-58.85	0.8	-94.2%
CONTROLS:				
Required no-tillage	144.87	- 2.46	20.8	+25.0%
Fall fertilizer ban	137.03	-10.30	18.5	+10.8%

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* Least-cost solution for average leachate per acre.

The target of pollution control varies by farm according to pollutant source. The well-drained bottomland farm requires reduced nitrate leaching and, as expected, the least-cost crop mixes change with respect to abatement level. In general, such restrictions result in shifts away from monocropping to greater use of intensive rotations and to reduced nitrogen applications. Leachate control on the foothill farm causes shifts from cultivation to Christmas trees, then to rangeland.

When runoff control is applied to the two poorly-drained farms, the least-cost solution reflects lower nitrogen inputs on grass seed and, eventually, shifts to irrigated hay. But an important difference in these farms from the better soil-quality farms is that the reduction in profit is roughly double for that abatement level. Crop mix and management options are more limited on the poorly-drained farms, and abatement control more expensive.

The well-drained terrace farm is in many ways the most difficult to target for effluent reduction because improvement in one environmental residual (leaching, runoff, or erosion) often adversely affects another unless multiple instruments are used. At the same time it presents the widest choice of production options of any farm. Because of multiple pollution problems the analysis employed here focused on controlling runoff and leaching in tandem at increasingly restrictive levels. In general, the optimal patterns tended to involve more intensive vegetable rotations and longer rotations of perennial crops. One important note is that overall abatement is more difficult on this farm than on the others, due in part to the multiple effluent problem. For example, to achieve a 50% reduction in total effluent entails a $90 per acre decline in profit.

In summary, least-cost solution results for each farm indicate that some abatement of pollution is possible on all farms for relatively little cost. This point is demonstrated in table 2. In general, a slight change in operations or application rates of nitrogen is sufficient to attain 5% to 24% abatement, depending upon the pollutant and the farm type. Even this modest abatement level is more expensive for the more poorly drained land.

Table 1. Cost per acre of attaining nitrogen and nitrate abatement for five representative farms, Willamette Valley.

FARM	COST PER ACRE[1] ($)	ABATEMENT (%)	TARGET	COST PER LB.[2] ($)
Well-drained bottomland	$ 3.76	9.9%	Ground	$2.29 / lb.
Poorly-drained bottomland	1.83	4.7%	Surface	6.10 / lb.
Well-drained terraces	0.35	14.5%	Both	0.18 / lb.
Poorly-drained terraces	8.07	17.5%	Surface	3.57 / lb.
Well-drained foothills	11.67	24.1%	Both	1.33 / lb.

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[1] Cost measured as reduced profit.

[2] Reduced farm profit divided by change in nitrogen effluent.

Applied control measures

Five control policy options are tested, including direct charges on effluent, input taxes, per-acre standards on effluent, a directive to use no-till drills on small grains and grass for seed, and a ban on fall fertilizer applications. In this section the solutions for these applied policies are presented.

Charges. A tax on groundwater leachate for the well-drained bottomland and foothill farms induce "nitrogen-conserving" behavior with a corresponding change in crop mix. These changes come at some cost to farmers, both in terms of lower absolute profit associated with the new set of crops, and in the tax charge on remaining leachate. But, importantly, the crop mix that results from the charge is consistent with the least-cost solutions.

On poorly-drained soils, however, charges on runoff are ineffective. Only at high charge levels is significant abatement achieved (with a corresponding crop mix change), and then at high cost. The dichotomy of choices (profitable grass seeds versus less-profitable hay / pasture) is evident in the LP response to the charges.

Charges are also ineffective on the well-drained soils of the terrace farm at reducing runoff and leaching, except at the expense of the other. When administered on both leaching and runoff combined, a high tax charge is absorbed by farmers because of they lack available adjustments.

Standards. When per-acre standards are imposed on the well-drained bottomland farm, the cost to farmers of achieving levels of abatement corresponding to least-cost solutions is higher, particularly in the mid-range of abatement (for example, at 40% in figure 2). The resulting crop mixes are also considerably different from the least-cost solutions. In general, the solutions to achieve per-acre standards contain crops which are nearly uniform in leachate, tending to have levels close to the specified standard for all acres. This contrasts with the least-cost solution sets, which contain rotations that are high in leachate as well as some that are low. The difference in profit is the additional efficiency loss from the standards. At the highest abatement levels (95%), the profits and rotation mixes are similar, reflecting the limited range of choices at that level of control. A similar situation takes place on the foothill farm.

On the poorly drained soils restrictive per-acre standards on runoff are able to induce an intermediate abatement level (50%) unattainable by charges (figure 3), but again, the crop mix is considerably different than the comparable least-cost solution mix. An unusual blend of rotations, some with only 50% nitrogen applied and others having full nitrogen, is the result.

A multiple-target set of standards (for example, on surface runoff and erosion) applied to the well-drained terrace farm will provide cost-effective (that is, at least-cost) control in a limited range of overall abatement levels. However, it does not result in least-cost solutions in most cases.

Input tax. Input taxes of 50% and 100% of the price of nitrogen fertilizer are tested. The input tax reduces N applications on all farms, but at these tax levels overall abatement was relatively small. This is a reflection of the high marginal value of nitrogen for most crops. Differences in effectiveness between farms reflects, in part, the differences in utilization rates of nitrogen between crops.

No-till directive. Use of conservation tillage (particularly no-till) has been credited with effective erosion control with little effect on crop yield. However, no-till has been linked to higher levels of nitrate leaching [Crosson and Brubaker]. Simulations of the EPIC model are consistent with this finding and, as a result, the three farms with groundwater leachate problems actually had solutions with higher leachate than the base. The directive had no effect on solutions for the two poorly-drained farms, as use of no-till was already most profitable.

Fall fertilizer ban. A ban on fall applications of nitrogen has a negative effect (by increasing overall leachate) on the highly-productive bottomland farm, and less so on the well-drained terrace farm. On both farms production moves away from fall seeded crops in favor of (higher polluting) vegetable crops where such a ban would not be applicable. Increased runoff is also experienced on the poorly-drained bottomland farm, where a complete shift takes place to annual ryegrass production, away from a portion in perennial ryegrasses, because the annual experiences a lesser yield decline. A slight reduction in runoff is noted on the poorly-drained terrace farm under the policy, although it is above the least-cost frontier.

The only case in which a ban is effective is on the foothill farm, in which all enterprises involve fall fertilization. By inducing shifts from annual cultivation to perennial crops, considerable control of leaching, erosion, and runoff is achieved.

Effectiveness of pollution control measures

The results from the five representative farms suggest that the effectiveness of each pollution control measure varies among farms. Important factors which influence this effectiveness include the range of production and cropping options available to farmers, and their relative profitability.

As was demonstrated, nutrient effluent from the representative farms differs both in volume and receiving waters (surface, ground water, or both). This indicates that a single policy, aimed at one type of pollutant and targeted on all farms in the valley, will not substantially reduce overall agricultural effluent, and may actually exacerbate other pollution problems. Therefore, abatement policies should address pollutants by soil quality (e.g., drainage potential), by farm type (such as vegetable farms for groundwater leachate), or by geographic location.

Because relatively small changes in practices can achieve some abatement, and these changes occur at least cost, they should be the first to be considered for voluntary or mandatory adoption. They would involve practices which could be considered "Best Management": decreasing nitrogen applications on at least a portion of the farm acreage, moving tillage-intensive crops to lower slopes, or lengthening vegetable crop rotations to include small grains and winter cover crops.

On well-drained farmlands (particularly where many production options exist), effluent charges could be implemented to achieve abatement at least cost, if monitoring were feasible. Though specific abatement levels may be difficult to target, charges still remain more efficient than per-acre standards.

The poorly-drained grass seed farms pose definite abatement difficulties, because of the lack of production alternatives. It must be considered whether the benefits from clean water attributed to reductions in effluent from grass seed farms outweigh the on-farm cost of achieving it.

A least-cost method of achieving various abatement levels may involve farmers shifting to the practices and rotations indicated by the least-cost "efficiency frontier" for each farm type. While farmers would absorb the costs through a loss in profit (assuming there are no supply-induced effects on crop prices), voluntary adoption would cost society less than any of the regulatory measures because of the associated implementation and monitoring costs.

Conclusions

It is clear that non-point source pollution policies will require some recognition of site-specific characteristics in order to effectively address the problems. No single policy is optimal across all farm types. Even within a region of similar climate and soil conditions, the effectiveness of control policies in general and BMPs in particular can vary. Aside from issues of implementation costs and monitoring difficulty associated with charges and standards, a less complex approach (such as permits) may bear consideration.

These analyses, for a highly-diversified agricultural region under a high winter rainfall regime, also suggest that some nitrate leachate and runoff reductions can be accomplished with little loss in profits. This conclusion is applicable to farms of differing size, geographic location, slope, and soil types. Although abatement is more expensive for poorer quality soils, relatively minor changes in tillage management or nitrogen application rates can reduce effluent.

Finally, this study demonstrates the importance of modeling biophysical processes in evaluation of environmental policies, particularly those for non-point source pollution. While the requirements of such modeling efforts can be complex, this integrated approach provides an important link between the biological and physical aspects of the problem and producer behavior with respect to agricultural production.

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