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Farm-Level Response to Agricultural Effluent Control Strategies: The Case of the Willamette Valley

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This article examines economic incentives and other mechanisms 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 models are then optimized for profit maximization under alternative non-point pollution control policies. The results indicate that site-specific resource conditions and production possibilities greatly influence policy effectiveness and the cost of achieving pollution abatement. Nevertheless, some abatement is possible on all farms for relatively little cost.

Key words: BMPs, bioeconomic modeling, nitrogen effluent control, on-farm costs, water pollution.

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 (U.S. Environmental Protection Agency; Vigon). In addition, public awareness of and demand for environmental amenities are changing attitudes towards the agricultural industry and its implicit property rights (Batie). This change in attitudes is evidenced by the growing use of regulatory controls for pollution problems, and the coupling of federal agricultural support programs with land use and other restrictions on farm-level decisions.

As the societal debate on agricultural pollution moves toward implementation of specific control policies, it is important to understand how economic incentives and other farm-level mechanisms to offset pollution are likely to influence farmer behavior. An evaluation of the farm-level consequences of such policies can provide insight into the effectiveness of these policies and suggest whether the social goal of a sustainable food supply that meets environmental demands in rural areas is attainable.

The overall objective of this article is to assess farm-level responses to policies designed to control nitrogen, phosphorus, and soil sediment effluent from farmland, with particular application to the Willamette Valley of Oregon. Specifically, we examine the economic efficiency of selected pollution control policies in a diverse agricultural setting. The approach integrates a biophysical simulation model with farm-level economic models to capture both technical and economic dimensions of agricultural effluents.

The Willamette Valley offers an excellent case study for such research, given the highly diversified nature of agricultural production in the region and a range of soils and topographic conditions. The findings from this case study simulate the farm-level effects of agricultural effluent control policies under complex conditions; the results suggest the feasibility of control instruments in meeting effluent goals under such diversity.

Physical and Economic Dimensions of Agricultural Externalities

A primary concern about agricultural production methods is their effect on water quality and subsequent impacts on human and animal health, wildlife, water treatment costs, and recreational activities. Excessive

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nitrates (NO_3^-) in drinking water have been linked to methemoglobinemia disease (blue baby) in animals and infants (Bower). At high levels, nitrogen in water can be toxic to humans and animals, and nitrogen in ammonia can kill or injure fish (Miranowski; Crosson and Brubaker). Nitrogen and phosphorus also play a role in accelerating eutrophication[1] through the stimulation of aquatic plant growth, which can restrict navigation, reduce recreational values, produce undesirable tastes and odors in water supplies, and deplete dissolved oxygen. Pesticides reach surface water and groundwater in smaller proportions than nitrates, but their widespread use, persistence, and toxicity at low concentrations are of concern (National Research Council).

These potential environmental damages arise from four processes: (*a*) soil erosion resulting in sediment deposition off the field of origin; (*b*) fertilizer and pesticide runoff deposited directly in surface water courses; (*c*) fertilizer, nutrients, and pesticides percolating into groundwater; and (*d*) volatilization losses at the time of application. Referred to as non-point sources (NPS), these processes result in the most common form of agricultural pollution. The significance of NPS pollution from a management perspective is that regulation, control, and containment are more difficult to implement than with point-source pollution. A lack of data on the extent of pollution in rural areas and on the relationships between agricultural production methods and pollution levels hinders development of control strategies. However, increased research efforts, particularly with respect to nitrogen and phosphorus, are narrowing the information gap.

Research indicates that crops use only 50 to 70% of applied nitrogen fertilizer (Johnson; Keeny), with the remainder either transported by erosion or runoff, leached, or chemically transformed and lost to the atmosphere. Plant nutrient use in the U.S. nearly tripled from 1960 to 1981, with a substantial increase in total and per acre nitrogen fertilizer application. The amount of nutrients delivered to surface water and groundwater likely increased as well (Miranowski).

Off-site effects associated with soil erosion, and some rough damage estimates, are provided by Ribaudo, and Clark, Haverkamp, and Chapman. Despite a federal investment of $15 billion and "many billions of dollars" more by farmers, contemporary soil erosion rates are almost as severe as 50 years ago (Colacicco, Osborn, and Alt), due in part to agricultural production practices such as larger acreages of monocultures.

Agriculturalists, not accustomed to being perceived as a polluting industry, tend to 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. This has been manifested in the promulgation of various 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, Klausner, and Reid).

The problem facing policy makers is to identify control strategies that do not significantly harm the industry. What constitutes a Best Management Practice (BMP) may depend upon local circumstances, but particular tillage and management systems usually fit the criteria for such practices. These include reduced and no-tillage, low input or sustainable agriculture systems, and nitrogen management techniques. Some believe that the broad definition of BMPs prevents a clear and definitive analysis for policy (e.g., L. Christensen; Crutchfield, Ervin, and Brazee); a practice may be "best" in an engineering sense for minimizing loss of chemicals, but not in an economic sense. Traditional approaches to economic evaluation and selection of BMPs have relied on partial-budgeting approaches that compare costs of operation only, rather than incorporating perceived yield impacts (L. Christensen).

The environmental economics literature (e.g., Baumol and Oates; Shortle and Dunn) suggests at least six general approaches for correcting such externalities. These include: charges (or Pigouvian taxes), which involve a direct tax on the effluent causing the externality; input taxes (such as for nitrogen fertilizer); standards, defined as levels representing an "acceptable environment"; controls, which involve a directive to decision makers about specific practices which must be used (such as no-tillage) or which are banned from use (such as certain pesticides); cost-share incentives, in which public agencies bear a portion of the use of pollution control measures; and transferable pollution permits, which may or may not be exchanged for bid prices.

In general, these various regulations are targeted to affect management (e.g., 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 by incorporation of BMPs. However, the linkage between the theory and application of measures for control is complicated by the nature of the pollutants. An inherent feature of non-point sources of pollution is that flows cannot be monitored with reasonable accuracy or at reasonable cost. Another is that non-point pollution is stochastic in nature, influenced strongly by weather processes. As a result, policy analysts increasingly rely on biophysical models which estimate or predict environmental flows and simulate agronomic processes. While such biophysical models will never be perfect substitutes for monitoring of actual flows, they can serve as important tools for analysis (Shortle and Dunn).

Related Literature

Policy and economic issues associated with agricultural non-point pollution are well documented. Park and Shabman examined local versus regional distributional constraints on quality improvements, and developed a benefits and compensation scheme for implementation. Sharp and Bromley focused on the coordination of institutions in implementing NPS control, finding that flexibility and adaptability by agencies is necessary to reconcile conflicting incentives. Griffin and Bromley evaluated versions of four strategies for control where (*a*) returns to farmers are known by planners and (*b*) runoff is observed without error. They concluded the approaches are equally efficient when specified properly. Saliba addressed the physical and economic relationships of irrigation and groundwater quality, and recommended policies for irrigation management to influence non-point effects. Shortle and Dunn identified and assessed the efficiency of four environmental control policies for NPS pollution, finding that properly specified management practice incentives generally outperform runoff standards, runoff incentives, and direct controls. Shortle and Miranowski demonstrated that improved efficiency in allocation of resources may be elusive because allocative efficiency is not necessarily unidirectional; that is, intervention may be counterproductive to pollution control.

Regulations focus primarily on the use of BMPs as a means of control. Segerson addressed the issue of the appropriateness and flexibility of BMPs as a pollution control measure, finding they do not always provide cost-minimizing abatement strategies. Stevens evaluated the fiscal impacts of imposed charges and input taxes on nitrogen and water, with input taxes determined to be more expensive than an effluent fee. Griffin used an optimal control model to assess the spatial and intertemporal effects of pollution on economic efficiency, finding that pollutant persistence alone invalidates the economic advantage of price-guided policies over regulatory policies. Lambert addressed the use of input taxes as a control policy for nitrogen leachate and its impact on distribution of farm net returns according to risk attitudes.

Empirical research on non-point pollution relies heavily on technical information generated by natural and physical scientists, information that is frequently difficult to obtain on a site-specific basis. Not surprisingly, then, the integration of models of biophysical systems with economic assessment techniques has been considered for at least the last decade. Jacobs and Timmons, Heimlich and Ogg, L. Christensen, Duttweiler and Nicholson, Setia and Magleby, and Crutchfield, Ervin, and Brazee are notable examples of research that features this bioeconomic integration.

Approach and Procedures

The approach used here to evaluate farm-level policies for the control of non-point source pollution from nutrients proceeds in a general two-part simulation involving (*a*) a biophysical simulator to generate environmental and technical parameters, which are then linked with (*b*) an economic optimization model of farm-level behavior (Taylor). Specifically, this simulation process consists of a series of steps: (*a*) identifying characteristic soils, land slopes, and crops in the region; (*b*) building activities of particular input levels (fertilizer applications, tillage practices, and machinery), which represent the options faced by farmers, for use in both the biophysical simulator and optimization model; (*c*) running computer simulations of these combinations for a sufficient length of time (25 years) to produce expected annual levels of crop and environmental outputs; (*d*) creating representative farms containing appropriate soils and crop rotation options for the associated biophysical simulator outputs; (*e*) selecting profit-maximizing crop rotations for each farm; and (*f*) optimizing the (linear programming) models under constraints of imposed standards, charges, and taxes.

The Erosion–Productivity Impact Calculator (EPIC) 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 varying conditions with respect to climate and soil ("environmental inputs"), and farming system characteristics. The physically-based components of EPIC include hydrology, weather simulation, erosion simulation, nutrient cycling, plant growth, tillage, and soil temperature. EPIC's yield response model is based on the principle of "yield plateaus," an assumption frequently used by soil scientists. The use of yield plateaus also is found in economic research of fertilization (e.g., Lanzer, Paris, and Williams). The plateau implies that overapplication of inputs (nutrients or water) does not translate into negative marginal products. Among outputs generated by EPIC are annual crop yields (averaged over the simulation period) and nutrient flow levels.

EPIC has been applied to a number of biophysical–economic linkage models. Recent examples include an evaluation of conservation compliance on Tennessee farms (Thompson et al.) and cropping strategy assessment in the Texas Trans-Pecos region (Ellis et al.).

A difficulty inherent in most off-the-shelf biophysical simulation models is that coefficients and processes must be calibrated to reflect local conditions. Such calibration is essential to model validation, as it ensures that results are applicable to the region of interest. Proper calibration of biophysical simulation models, such as EPIC, is complicated by a lack of data on nitrate leaching or runoff and soil erosion under regional conditions, a problem encountered in this study. EPIC parameters regarding nitrogen fate were not calibrated explicitly in this study; however, the results are consistent with ongoing physical science research in the Willamette Valley. Nevertheless, errors in estimation may exist.

EPIC results for the Willamette Valley were treated in the following manner. Simulation runs of typical operations (as determined by interviews with farmers) were made for wheat, corn, and grass seed for seven soils; yields and environmental outputs (erosion and nitrogen and nitrate flows) were then estimated. Soil scientists assessed the model's performance based on their knowledge of nutrient fate in the region. For most soils, the performance of the nutrient model was consistent with limited empirical information, but crop yield estimates were 10 to 25% low. In the case of one important soil type, simulated yields were too low and leachate higher than expected; results were noted as probable "overestimates" of actual leachate. For a second, less important soil, estimated erosion was deemed excessive by the soil scientists, and the soil was eliminated from the analysis.

Estimated yields from the 25-year simulations were indexed to crop yields that would be expected from each soil, and served as base yields. Then, yields generated under alternative scenarios (changed tillage, fertilizer levels, or rotations) were computed relative to the base yields. While such an indexing of estimated yields may impose a source of error, the primary intent in using the biophysical simulator is to estimate changes in environmental outputs under alternative control strategies, not absolute levels.

A separate linear program for each of the representative farms is modeled with the General Algebraic Modeling System (GAMS) (Brooke, Kendrick, and Meeraus) using input from the EPIC simulator. Specifically, environmental outputs (nutrient flow levels and erosion) and crop yields from EPIC are incorporated as technical coefficients. Farm-level data are used to generate crop budgets, and farm-specific behavior (relating to rotations and tillage practice combinations) is used in forming both activities and constraints. Environmental restrictions and regulations are then imposed on the farm-level models to test the efficacy of various regulatory policies.

The output of the representative farm models is an optimal (profit-maximizing) crop mix (including rotation and tillage practices) and an associated set of environmental outflows under alternative pollution control strategies. The changes in profit, crop mix, and physical outputs between the unrestricted (unregulated) farm in the base case and that farm under imposed policies provide a measure of policy effectiveness and farm-level cost (reduced profit).

Conceptually, the LP model is identical for all representative farms. A maximum profit plan is given by solving a problem with the following components.

Maximize

$$\text{(1)}\quad PRICE_i Y_i \qquad - EXPEND_s X_s \qquad - TAX_f Q_f$$

subject to:

$$
\begin{array}{llllllll}
(2) & -Y_i & +YIELD_{ik}Z_k & & & & = 0 & \text{for all } i \\
(3) & & ACRES_{rk}Z_k & & & & \leq S_r & \text{for all } r \\
(4) & & ENT_{jk}Z_k & -L_j & & & = 0 & \text{for all } j \\
(5) & & ENVOUT_{fk}Z_k & & & -Q_f & = 0 & \text{for all } f \\
(6) & & & INP_{sj}L_j & -X_s & & = 0 & \text{for all } s \\
(7) & & & MACH_{utj}L_j & & & \leq T_{ut} & \text{for } u,\ t \\
 & & & & Y_i,\ Z_k,\ L_j,\ X_s,\ Q_f \geq 0 & & &
\end{array}
$$

The activities are Y_i, the quantity produced of crop i; X_s, units of input s; Z_k, acres of rotation set k; L_j, acres of enterprise activity j; and Q_f, units of environmental output f. The coefficients include $PRICE_i$, price of crop i; $EXPEND_s$, per unit cost of input s; $YIELD_{ik}$, yield of crop i in rotation k; $ACRES_{rk}$, acres of soil r in rotation k; ENT_{jk}, acres of enterprise activity j in rotation k; $ENVOUT_{fk}$, units of environmental output f in rotation k; INP_{sj}, units of input s for enterprise activity j; and $MACH_{utj}$, hours of machine u at time t of the crop year for enterprise j. Resource limits are S_r, acre limit of soil r; and T_{ut}, hour limit for machine u at time t of the crop year.

The objective function [equation (1)] is maximized, generating total revenue minus expenditure for inputs. The first constraint [equation (2)] links products (crops sold) with yields associated with various rotation and management combinations. The second constraint [equation (3)] is an acreage limitation, based on soil types for respective farms. Equation (4) links enterprise activities to rotations. The fourth constraint [equation (5)] accounts for environmental outputs, such as nitrate percolation and erosion, generated by crop rotations, measured as the total for the farm. Equation (6) compiles input costs of enterprise activities. The final constraint limits machinery usage by enterprise to hours available in various time periods. (An option for machinery rental was considered, but was never binding.)

The linkage between activities and crop rotation sets is a key component of this formulation. Activities are defined as the particular input levels, costs, and operations associated with production of a single commodity. For example, an activity might be winter wheat, produced using conservation tillage, with 140 pounds of applied nitrogen. A number of activities are defined for each enterprise to provide a reasonable variety of points on the production function. Rotations (such as wheat following corn and wheat following grass seed) combine appropriate enterprise activities with soils and land slope, thereby reflecting the biophysical interactions associated with crop rotations in the simulated crop yields and environmental outflows.

Study Area

The empirical focus of this study is on the Willamette Valley of Oregon, an important diversified agricultural region in the Pacific Northwest. Commodities produced include grass grown for seed, hay, small grains, vegetables for processing, berries, and horticultural products. The climate consists of mild summers and cool winters with heavy precipitation. Winter precipitation is an important climatic characteristic due to the high proportion of fall seeded crops.

Studies of agricultural externalities in the Willamette Valley indicate "frequent contamination" of surface water and groundwater (Oregon Department of Environmental Quality). Nationally, the Willamette River Basin ranks in the highest category of phosphorus, inorganic nitrogen, and total nitrogen levels (Omernik). Soil erosion is not considered a general problem, despite the high annual rainfall (N. Christensen). A few cultivated foothill areas, however, are subject to moderate to severe erosion. The Willamette Valley also contains nearly 80% of the state's population, increasing the potential damage from agricultural externalities.

Because the region has no dominant crop or farm type, five farm types are defined to represent the major combinations of crops, soil types, and geographic subregions within the valley. These include two farms representing river bottomland, two for the broad terrace lands, and one for the foothills (table 1). An important characteristic of these farms is the wide range of crop, soil, and cultural practice options available to farmers; this characteristic is likely to affect the efficiency of imposed regulations.

Five policy options are tested. These include: (*a*) a per unit tax on leached nitrates and runoff of organic nitrogen and nitrates, as well as combinations of each, implemented by including in the objective function a positive tax ($TAX_f Q_f$) on relevant environmental outflows; (*b*) a tax on nitrogen fertilizer, implemented as a tax equal to 50% and 100% of the cost of nitrogen; (*c*) per acre effluent standards of various levels, imposed by placing a maximum limit constraint on per acre runoff (or leachate) as $Q_f \leq LIMIT_f$; (*d*) a requirement for use of no-till drills on small grains and grass seed production; and (*e*) a ban of fall fertilizer applications to reduce winter leachate.

Results of Pollution Control Options

Results of the simulation framework are presented in two parts. The first provides a summary of results (including environmental outputs) for the base case or current situation (unrestricted scenario) as computed by each of the representative farm models. The second set of results is generated by imposing the various pollution control mechanisms on the biophysical simulation–LP models.

Base Case Analysis

Results of the representative farm models for the unrestricted case are presented in this section, and in table 2. The solutions generated represent the most profitable crop mixes given the resources, soils, and production constraints facing each farm. The magnitude of effluent (soil erosion, leachate, and runoff) is not considered in the choice of crop mixes, and remains unvalued.

Bottomland and terrace farms with well-drained soils are profitable under intensive crop rotations, including vegetables, grass seed, and small grains, with winter cover crops. Simulated nitrate leaching in the bottomland farms averages more than 16 pounds per acre over the crop mix. Runoff of nitrates and nitrogen and soil erosion, however, are low relative to the farms with poorly-drained soils. Compared

Table 1. Generalized Description of Five Representative Farms for the Willamette Valley

Farm Type	Characteristics
(1) Well-drained bottomland	
Acreage	450 acres, 1% slope
Main Crop	Vegetables
Location	Central valley
Soil	Sandy loam
(2) Poorly-drained bottomland	
Acreage	200 acres, 1% slope
Main Crop	Grass seed and pasture/hay
Location	North valley
Soil	Clay
(3) Well-drained terrace land	
Acreage	500 acres, with 373 acres 1% slope, 80 acres 6% slope, 32 acres 10% slope, and 15 acres 15% slope
Main Crop	Wheat, vegetables
Location	Central valley
Soil	Loam
(4) Poorly-drained terrace land	
Acreage	1,000 acres, 1% slope
Main Crop	Grass seed
Location	Southern valley
Soil	Clay
(5) Well-drained foothills	
Acreage	400 acres, with 193 acres 5% slope, 128 acres 10% slope, and 79 acres 15% slope
Main Crop	Pasture
Location	All valley foothill areas
Soil	Sandy loam

Table 2. Results of Unrestricted Solution for Each Representative Farm

	Valley Location				
	Bottom	Bottom	Terrace	Terrace	Foothills
Range of Slope	1%	1%	1–15%	1%	5–15%
Farm Acreage	450	200	500	1,000	400
Drainage Condition	Excellent	Poor	Good	Poor	Excellent
Crop Rotation:					
Corn/beans	167			26	
Corn/beans (85% fertilizer applied)			201		
Corn/beans/wheat (w/cover crop)	89				
Perennial ryegrass seed	90	40	100	200	
Perennial ryegrass seed (no fall N)					80
Tall fescue seed	54	24	60	34	
Annual ryegrass seed (no-till)		136		740	
Wheat/annual ryegrass seed (no-till)			139		180
Wheat (no-till)	50				
Christmas trees					140
Effluent Per Acre:					
Soil erosion (tons)	0.30	0.07	1.85	0.14	1.10
Organic N lost to sediment (lbs.)	0.75	0.53	3.77	0.72	5.65
NO_3 lost to runoff (lbs.)	1.86	10.27	5.15	12.23	3.81
NO_3 leached beyond root zone (lbs.)	16.64	2.92	4.47	3.31	26.79
Phosphorus lost to runoff (lbs.)	0.61	0.89	0.83	0.91	0.00

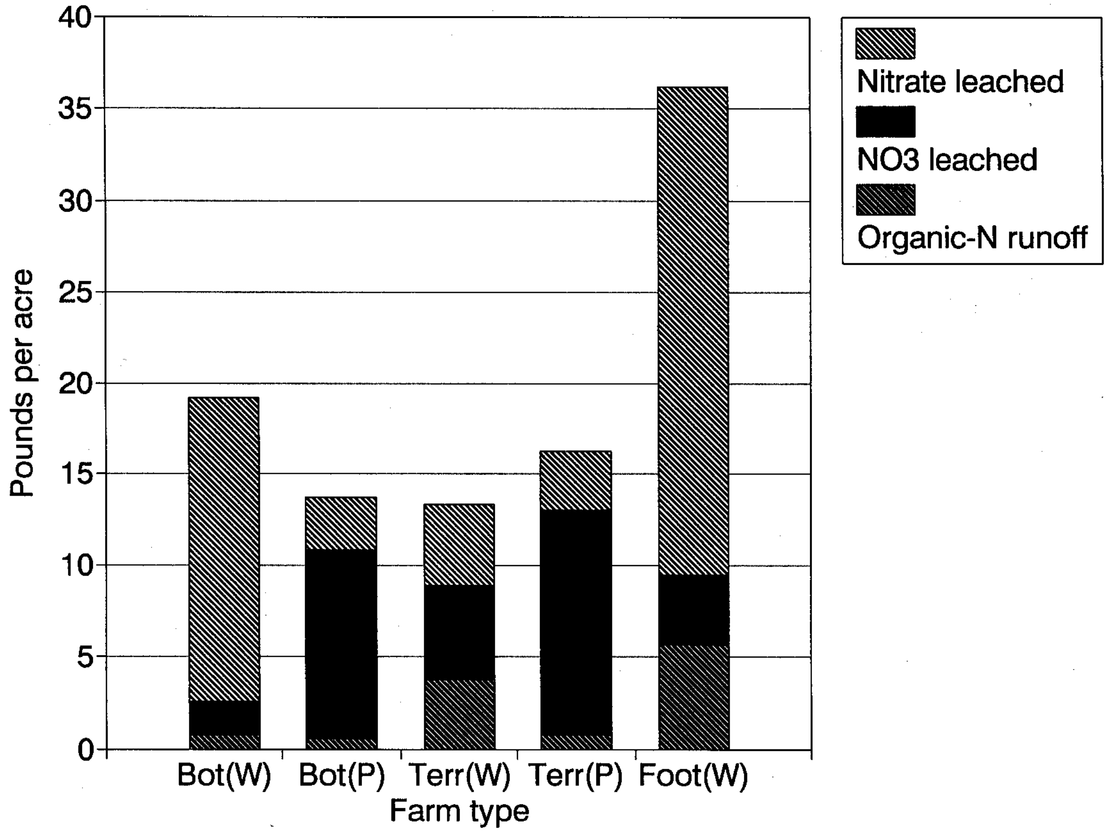

Figure 1. Nitrogen and nitrate effluent from Willamette Valley farms

with other farms, 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 fewer cropping options exist. The profit-maximizing solutions for the representative farms are dominated by annual and perennial grass seeds. As a consequence, simulated leaching of nitrates is less than 3.5 pounds per acre, but losses exceed 10 pounds per acre.

The fifth representative farm (for the foothills) features highly profitable land uses, primarily Christmas trees and wheat–annual ryegrass. Perennial ryegrass for seed occupies the remaining acreage. As a consequence of the well-drained nature of the soils, considerably higher leaching of nitrates occurs and runoff is also greater than for the other farms, but erosion rates are generally low.

In summary, the base case of unrestricted farm production suggests one farm with potential groundwater problems, two with potential runoff problems, and two having a mix of both. It is significant that the various forms of non-point pollution are not isolated geographically, in that both leaching and runoff occur on bottom, terrace, and foothill farms. Excessive erosion (above a sustaining level) occurs on two farms; 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

In evaluating specific control options for the various farms and pollutants, it is instructive to measure those options against some benchmark. Pollution control options are gauged here according to their effectiveness in achieving abatement at "least cost." The first step in providing such a comparison is to establish an "efficiency frontier" for each farm generated with LP solutions over a range of pollution

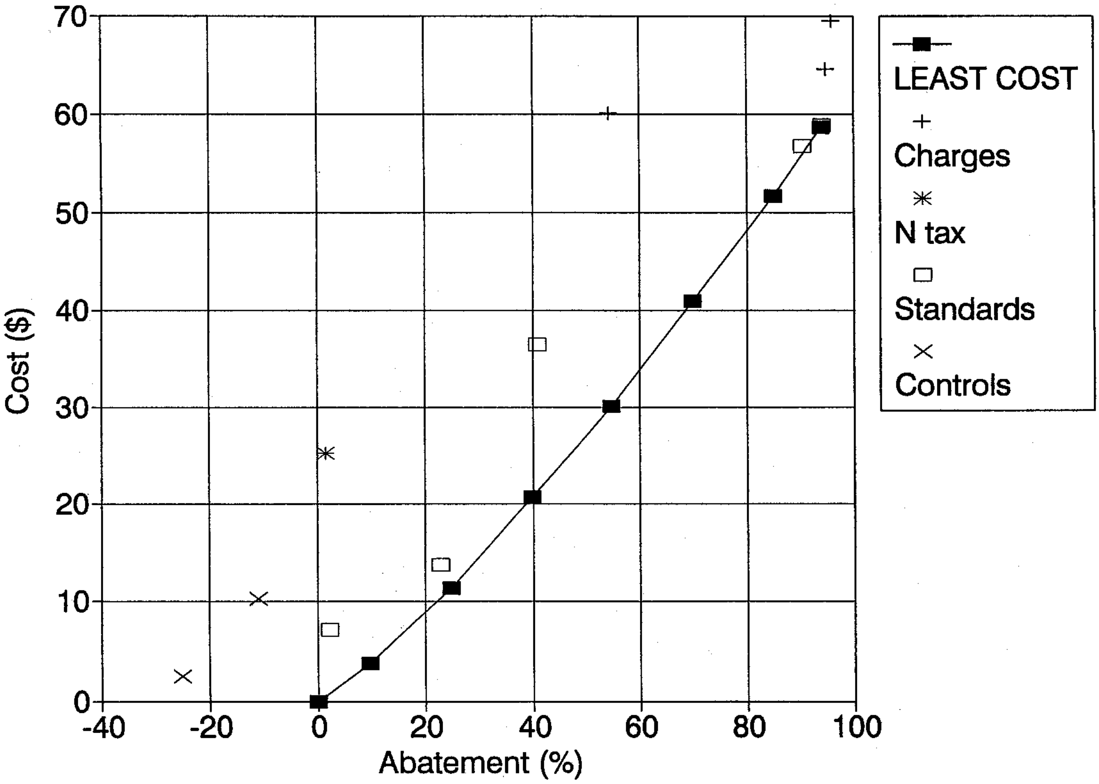

Figure 2. Cost of nitrate leaching abatement, well-drained bottomland farm

abatement levels. These frontiers of least-cost solutions are obtained by constraining each farm to effluent levels of a specified average per acre level. The efficiency frontiers of two farms are shown in figures 2 and 3, which display changes in profit associated with percentage of abatement. The LP results which determine an efficiency frontier and applied control measures for the bottomland farm (figure 2) are displayed in table 3.

The targeted pollutant varies by farm. 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 cultivated crops 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. An important difference between these farms and those farms with better soil quality is that reduction in profit is roughly double for a given 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 reduction in one environmental residual (leaching, runoff, or erosion) often increases 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, there is no single optimal solution path,[2] so the analysis focuses on controlling runoff and leaching in tandem at increasingly restrictive levels. In general, the optimal patterns involve more intensive vegetable rotations and longer rotations of perennial crops. Abatement is more difficult on this farm, 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, whereas the per acre costs on other farms are $27 to $60.

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 4. In general, a slight change in operations or application rates of nitrogen is sufficient to attain 5% to 24% abatement, depending

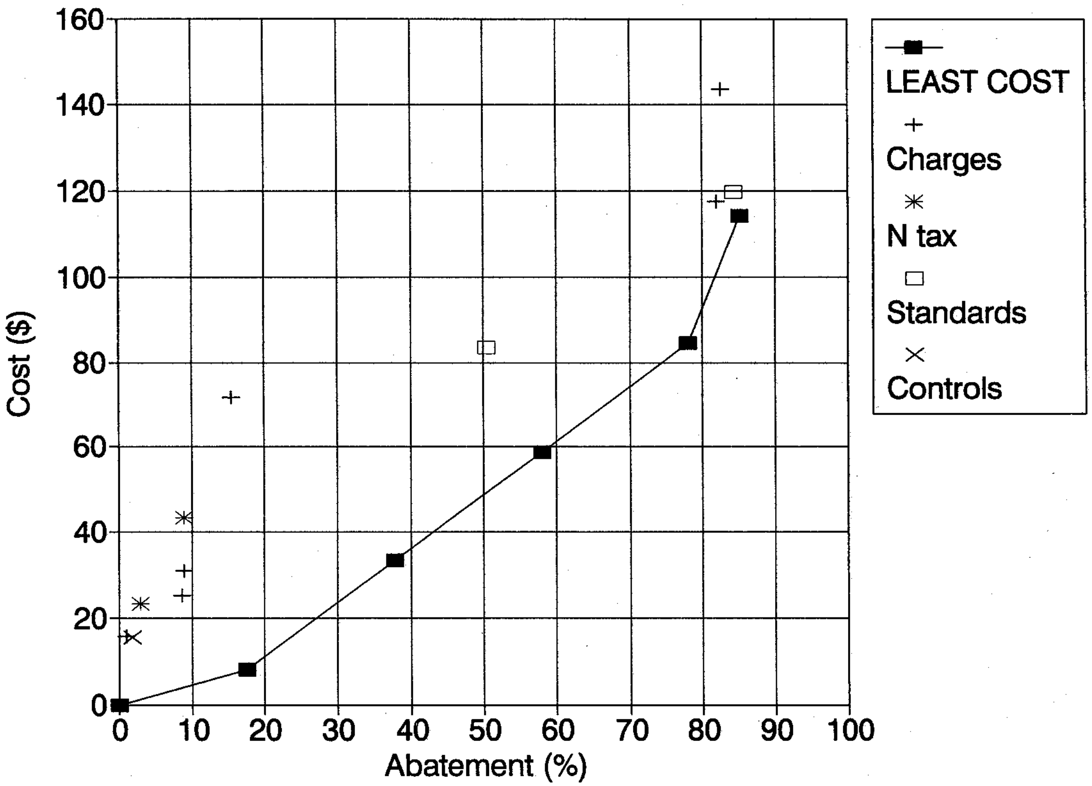

Figure 3. Cost of organic nitrogen and nitrate runoff abatement, poorly-drained terrace farm

on the pollutant and the farm type. Even this modest abatement level is more expensive for the more poorly drained land.

Applied Control Measures

Five specific control policy options are tested, including direct charges (taxes) on effluent, input taxes, per acre standards on effluent, required use of no-till drills on small grains and grass for seed, and a ban on fall fertilizer applications. The solutions for these applied policies are compared with the least-cost solutions presented above.

Charges. A tax on groundwater leachate for the well-drained bottomland and foothill farms induces "nitrogen-conserving" behavior reflected in changes 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. In fact, the difference in profit that results between the charge and the least-cost solution (for a particular abatement level) is just equal to the tax charge for the remaining effluent. (This result is consistent with qualitative analysis of such pollution charges.) 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 seed versus less-profitable hay/pasture) is evident in the LP response to the charges. Pigouvian taxes are also ineffective at reducing runoff and leaching on the terrace farm's well-drained soils. When administered on both leaching and runoff simultaneously, a high tax charge is absorbed because of a lack of available adjustments on the part of the farmer.

Standards. When per acre standards are imposed on the well-drained bottomland farm, the cost to farmers of such standards is higher than corresponding least-cost solutions, particularly in the mid-range of abatement (for example, at 40% in fig. 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 solutions, which contain rotations that are high in leachate as well as some that are

Table 3. Least-Cost Solutions and Measures to Induce Change in Groundwater Percolation of Nitrates (Well-Drained Bottomland Farm)

Rank and Policy	Per Acre Profit ($)	Per Acre Profit % Change	NO_3-Leachate/Acre (lbs.)	NO_3-Leachate/Acre % Change
Optimal Solutions:*				
Unrestricted	147.33	—	16.6	—
Average NO_3 leached < 15 lbs.	143.57	−2.6	15.0	−9.9
Average NO_3 leached < 12.5 lbs.	135.99	−7.7	12.5	−24.9
Average NO_3 leached < 10 lbs.	126.62	−14.1	10.0	−39.9
Average NO_3 leached < 7.5 lbs.	117.21	−20.4	7.5	−54.9
Average NO_3 leached < 5 lbs.	106.41	−27.8	5.0	−70.0
Average NO_3 leached < 2.5 lbs.	95.61	−35.1	2.5	−85.0
Average NO_3 leached < 1 lb.	88.65	−39.8	1.0	−94.0
Charges on Leachate:				
$4 per lb. of NO_3 leached	87.23	−40.8	7.6	−54.5
$6 per lb. of NO_3 leached	82.75	−43.8	0.9	−94.8
$12 per lb. of NO_3 leached	77.93	−47.1	0.7	−95.9
Nitrogen Tax:				
+50% tax on N fertilizer	122.05	−17.2	16.4	−1.7
Per Acre Standards:				
Leached NO_3 < 30 lbs. per acre	140.18	−4.9	16.3	−2.3
Leached NO_3 < 20 lbs. per acre	133.56	−9.4	12.8	−23.0
Leached NO_3 < 15 lbs. per acre	110.85	−24.8	9.8	−41.1
Leached NO_3 < 10 lbs. per acre	90.60	−38.5	1.6	−90.5
Leached NO_3 < 6 lbs. per acre	88.48	−39.9	0.8	−94.2
Controls:				
Required use of no-till drills	144.87	−1.7	20.8	+25.0
Fall fertilizer ban	137.03	−7.0	18.5	+10.8

* Least-cost solution for average leachate per acre.

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 to the least-cost solutions, reflecting the declining range of choices as increasingly stringent controls are imposed. A similar situation takes place on the foothill farm. On poorly-drained soils, per acre standards on runoff are able to induce an intermediate abatement level (50%) unattainable by charges (fig. 3), but again, the crop mix is considerably different than the comparable least-cost solution. 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 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.

Table 4. Cost Per Acre of Attaining Nitrogen and Nitrate Abatement for Five Representative Farms, Willamette Valley

Farm	Target	Abatement (%)	Cost per Acre[a] ($)	Cost per Lb.[b] ($)
Well-drained bottomland	Ground	9.9	3.76	2.29
Poorly-drained bottomland	Surface	4.7	1.83	6.10
Well-drained terraces	Both	14.5	0.35	0.18
Poorly-drained terraces	Surface	17.5	8.07	3.57
Well-drained foothills	Both	24.1	11.67	1.33

[a] Cost measured as reduced profit.
[b] Reduced farm profit divided by change in nitrogen effluent.

Input tax. Input taxes of 50% and 100% of the price of nitrogen fertilizer reduce nitrogen applications on all farms. However, overall abatement is relatively small, reflecting the highly inelastic demand for nitrogen for most crops. Differences in effectiveness between farms reflect, 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 for Willamette Valley conditions are consistent with this finding. In fact, the three farms with groundwater leachate problems actually produce 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 actually increases overall leachate on the highly-productive bottomland and well-drained terrace farms. 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 also is experienced on the poorly-drained bottomland farm, where annual ryegrass replaces all perennial grasses, because annual grasses experience a smaller yield penalty. The only case in which a ban is effective is on the foothill farm, where 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

In the environmental and agricultural situation modeled here, effectiveness of each pollution control instrument varies across farms. Important factors which influence this effectiveness include the range of production and cropping options and their relative profitability, as well as soil and topographic features.

Pollution taxes result in crop mixes similar or identical to the least-cost solutions on the better-drained soils. While it is not possible to target a specific abatement level with taxes, they are effective here with respect to nitrogen. However, taxes on effluent are relatively ineffective on more poorly-drained soils; instead, crop mixes remain similar to the unrestricted case, and the tax is merely absorbed. In particular, very high charge levels (e.g., $12/pound) may be necessary to achieve significant abatement when applied on poorly-drained soils.

Per acre standards result in crop mixes very different from the least-cost crop mixes. The result is that all acres tend to be more uniformly polluting under standards, rather than a mix of higher and lower polluting rotations found in the optimal solution cases. Where a charge and standard provide the same level of abatement, the charge (net of taxes) will provide abatement at least cost to society. However, such a policy places the bulk of the financial cost of control on farmers. In some cases, standards and charges result in the same crop mix, but the mix that results from imposed charges is always consistent with the least-cost solution.

Direct controls are of limited value in the Willamette Valley. A "fall fertilizer ban" results in a crop mix comparable to least-cost solutions only on the foothill farm. However, a ban increases pollution on the better-drained soils, as it induces shifts away from fall seeded crops and towards (higher polluting) vegetable production. A requirement to use no-till on small grains and grass seeds also is not applicable due to its tendencies to increase groundwater leaching of nitrates. No-till is effective at controlling erosion, but that is not a significant problem in the Willamette Valley.

Nutrient effluent from the representative farms differs both in volume and receiving waters (surface water, groundwater, or both). This indicates that a single policy, aimed at one type of pollutant and targeted on all farms, will not substantially reduce overall 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 among the first strategies to be considered. 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.

A least-cost method of achieving various abatement levels involves 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 command-and-control measures which require additional implementation and monitoring costs. However, farmers would not be expected to change practices unless they perceive greater welfare from maintaining autonomous choice than from an imposed command-and-control measure, although the outcome would be the same.

Conclusions

It is clear that non-point source pollution policies require recognition of site-specific characteristics to address the problem effectively. No single policy is optimal across all farm types. Even within a region of similar climate, 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 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 on poorly-drained 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 the evaluation of environmental policies, particularly those for non-point source pollution. While the data requirements of biophysical modeling can be great, this integrated approach provides a link between the biological and physical aspects of the problem and producer behavior with respect to agricultural production. The increasing availability and flexibility of biophysical simulators, such as the one used here, will enhance the ability of economists to perform non-point pollution analyses.

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Notes

[1] Eutrophication is a process involving nutrient enrichment of lakes and reservoirs, the resultant growth of plant life, and subsequent decline in dissolved oxygen.

[2] Optimal control methods are required to find the least-cost path in order to account for the interactive effects of the pollutants.

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