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THE BIOECONOMICS OF REGULATING NITRATES IN GROUNDWATER FROM AGRICULTURAL PRODUCTION THROUGH TAXES, QUANTITY RESTRICTIONS, AND POLLUTION PERMITS

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ABSTRACT*

Agricultural production in the United States, through its intensive use of nitrogen fertilizer, has contributed to nitrate accumulation in groundwater. Concern over this contamination has led to increased public interest in schemes designed to reduce nitrate leachate from agricultural lands. This research compares the costs of alternative regulatory policies in an area of the Corn Belt with those for an area of the Northeast.

The bioeconomic models of agricultural production and nitrate leaching are used to compare alternative policy instruments. They include soil-specific leaching and productivity characteristics, variables for management response, the dynamic nature of nitrogen movement through the soil, and the stochastic influence of precipitation on both net farm revenue and nitrate leaching. The models include state variables for nitrogen levels in the crop root zone and control variables for nitrogen fertilizer application and crop rotations. Nitrate leaching is restricted using a chance constraint, thus in some sense minimizing the probability of worst-case leaching scenarios.

Six alternative regulatory policies are compared empirically in two specific regions: Boone County in Iowa and Genesee and Wyoming Counties in New York. The policies, which are designed to reduce expected annual leachate by 10% and 25% in each region, include a tax on nitrogen fertilizer, quantity restrictions on both fertilizer and leachate, and three forms of leachate permits. The three permit schemes are permits sold by a regulatory agency at a fixed price, permits auctioned by a regulatory agency, and tradable permits initially allocated at no cost to farmers with the initial distribution based on historic leachate levels.

The empirical analysis shows that costs of achieving a regional reduction in leachate are greater in Iowa than in New York. Within a region, the net cost of reducing regional leachate (the net cost being the cost to farmers less any public revenues generated) is the least under the three permit schemes, although the costs of other policies are generally not substantially greater. The ranking of the net costs of these other policies differs by region and by the percent reduction in leachate. While net costs are the least under all three permit schemes, two of the three schemes result in substantial transfers of money from the farming community to the public treasury. In addition, a case is made for using a tradable permit scheme in targeted areas in and around major groundwater sources that are highly susceptible to contamination.

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The Bioeconomics of Regulating Nitrates in Groundwater from Agricultural Production Through Taxes, Quantity Restrictions, and Pollution Permits

INTRODUCTION

Both the increasing public awareness of the extent of surface and groundwater pollution and the associated human health hazards have elevated concerns over the quality of our nation's water supply. Point sources of water contamination, such as industrial dumping of wastes or the leaching of chemicals from abandoned waste disposal sites, are easy to identify and are frequently reported in the press. Less is known about the extent to which non-point sources of contamination exacerbate the problem. While national studies (Nielson and Lee, 1987; Kellog *et al.*, 1992) suggest that non-point agricultural sources contribute to the seriousness of the nation's groundwater problems (particularly in the Midwest, southeastern coastal plains, and western irrigated farming areas), there remains substantial disagreement as to how widespread the chemical contamination is and the extent to which it is due to the agricultural industry. Even if contamination is concentrated in a small proportion of the groundwater supplies or in shallow or regional aquifers, the potential groundwater contamination from agriculture cannot be ignored since it is estimated that over 50 million people in the United States obtain drinking water from groundwater sources (Neilson and Lee, 1987).[1]

In placing this relatively recent concern over groundwater contamination in proper perspective, it is important to remember that prior to World War II, production agriculture was much less dependent on chemical inputs than it is today. Pest and weed problems were eradicated by crop rotations; additional nutrients came primarily from manure and legume crops. While these practices are still used widely, chemical use has increased dramatically. According to Osteen *et al.* (1989), insecticides are used on approximately 35% of corn acreage nationally while herbicides are used on 90% of the corn and soybean acreage. Chemical fertilization, especially with nitrogen, is standard for most non-legume field crops.

The trend toward chemical-intensive agriculture began with the invention of synthetic organic pesticides, inexpensive technology for producing nitrogen fertilizer, and the

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[1] Independent estimates by the U.S. Geological Survey (1988) suggest that over half of the drinking water consumed in the United States is from groundwater sources.

development of new crop varieties responsive to fertilizer. Through declining production costs of chemical inputs and rising relative prices of other agricultural inputs, farmers faced strong incentives to substitute chemicals for other inputs. Government policy also contributed to the chemical intensification of agriculture through implementing farm programs designed to sustain agricultural prices and providing public research aimed predominantly at intensification.

Because of these trends in agricultural production, some believe that farmers are largely responsible for the health threat posed by groundwater contamination. Yet agricultural producers are often at greater risk than consumers. According to the Scientific Advisory Committee of the Environmental Protection Agency (EPA), worker exposure to toxic chemicals ranks among its higher risk problems (EPA, 1992). Due to this risk, increased government regulation, and higher chemical prices, the factors affecting farmers' use of chemicals are more complex than in years past. For example, farmers have implemented alternative management strategies, such as reduced tillage systems and integrated pest management systems, and practiced conservation measures, such as terraced slopes with seeded waterways and filter strips along water channels, to diminish the amount of pollutants entering the water supply.

Groundwater Policies and Programs

In response to concerns over the environment by both consumer and producer groups, many national and state environmental policies are being developed to address these issues (Fox *et al.*, 1991). For example, 44 states have groundwater protection strategies (EPA, 1992), some of which go beyond the national regulations embodied in the "Clean Water" and "Safe Drinking Water" Acts of 1972 and 1974 and their subsequent amendments.

The "Clean Water" Act's initial, major objective was to provide a safe surface water supply, although some provisions were made for protecting groundwater supplies. One such provision required states to submit annual reports (now biennial) on water quality, including groundwater quality, to the EPA Administrator. Section 208 required the EPA to develop information on the nature and extent of non-point sources of water pollution, including groundwater. Although the act included these provisions for groundwater protection, no safety standards for specific contaminants were identified.

On the other hand, the Safe Drinking Water Act (SDWA) directly addressed safety standards for contaminants in drinking water. Accordingly, it has become the predominant act for regulating contaminants in groundwater. Under the SDWA, the EPA was required to set non-enforceable maximum contaminant level (MCL) goals for groundwater contaminants such that if they were attained, no adverse effect on human health would arise. Enforceable maximum contaminant levels were then set as close to the MCL goals as feasible, with feasibility determined by the availability, performance, and cost of treatment technologies.

Other groundwater legislation includes the Resource Conservation and Recovery Act (RCRA) of 1976, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). RCRA's main objective was to establish cleanup and management standards to prevent contaminant release into aquifers from municipal solid and hazardous waste. CERCLA, or Superfund, enacted cleanup legislation for inactive waste disposal sites. FIFRA protects groundwater by controlling pesticide use through registration and certification procedures.

In supporting these specific legislative initiatives, several groundwater protection programs have also been implemented by government agencies and have contributed to improving groundwater quality. The Groundwater Protection Strategy developed in 1984 and the Groundwater Task Force established in 1989 sought to better integrate source specific control and cleanup programs into a more comprehensive policy at the state and national levels. The National Pesticide Survey was conducted in the mid-1980's in order to determine the extent of pesticide and nitrate contamination in public and private drinking water wells. Both President Bush's Water Quality Initiative in his 1990 budget proposal and the Pesticides in Groundwater Strategy adopted in 1991 sought to determine the extent of groundwater pollution resulting from agricultural practices and to provide farmers with the knowledge and technical means to voluntarily address environmental concerns. The Food, Agriculture, Conservation and Trade Act of 1990 (1990 Farm Bill), contains substantial provisions for protecting water quality. Within the bill, the Conservation Reserve Program, the Wetland Reserve Program, the Water Quality Incentives Program, and other measures seek to improve water quality. Dates, sites, and amounts of certain pesticides must now be recorded by chemical applicators. Some states have adopted taxes on nitrogen fertilizer in an effort to obtain monetary resources for future groundwater clean-up of nitrate contamination (Wise and Johnson, 1991).

Although our knowledge of the physical and economic dimensions of water pollution continues to expand rapidly (Fox *et al.*, 1991; Osteen *et al.*, 1981; McCarl, 1981), a number of significant obstacles remain to successful implementation of policies to deal with groundwater contamination, all of which require additional research. In order to calculate the socially optimal level of environmental quality, one needs to know the value of environmental quality and the costs of reducing agricultural chemical usage. Techniques do exist for valuing the environment (e.g., Randall, 1987) and have been implemented empirically, (e.g. Jordan and

Elnagheeb, 1993; Poe, 1993; Poe and Bishop, 1992; Sun *et al.*, 1992; Sun, 1990; Edwards, 1988; and Malone and Barrows, 1990), but it is difficult to value an environmental improvement for large regions by generalizing results from the small area studies. In addition, it is difficult to determine the extent and sources of pollution. Even the most complex biophysical transport models have difficulty predicting contamination levels, and they require detailed data. Determining the source of pollution is equally complex.

These difficulties imply that regulating groundwater quality would be costly and administratively problematic. As an alternative, policy makers have pursued policies regulating agricultural inputs associated with groundwater contamination, but these policies are not without their problems, and their effectiveness has not yet been substantiated. Taxing or restricting the amount of input purchased may not control the intensity with which chemicals are used on cropland. This underscores the importance of research to establish relationships between application of fertilizer and other agricultural chemicals and their appearance in ground or surface water across major soil groups. It is also important to understand more about production alternatives in response to higher chemical prices and regulation.

Focus of the Study

Although there is concern for contamination from numerous agricultural chemicals and fertilizers, the focus of this study is on the most widespread among agricultural pollutants in groundwater, water soluble nitrates (Nielsen and Lee, 1987). In 1990, 37 of 42 states and territories reporting stated that nitrates were their most frequently observed groundwater contaminant (EPA, 1992). Within the United States, modern varieties of crops such as corn, grain sorghum, and wheat require large amounts of nitrogen in order to stimulate plant growth and yields. Some of this nitrogen is made available from crop residues, the application of animal waste, or, perhaps most importantly today, the application of commercial nitrogen fertilizer. Since not all nitrogen available in the soil is utilized by the plants, residual nitrogen can remain in the soil and carry over for use in crop production the following year; some can leach below the crop root zone and later accumulate in underground aquifers; or some can accumulate in surface water as a result of soil erosion.

As stated above, three regions of the United States are particularly susceptible to nitrate contamination in groundwater. The Corn Belt is highly susceptible to such pollution (Kellog *et al.*, 1992) because it produces more than 70% of the nation's corn and soybeans (*Agricultural Statistics 1992*). Despite potential problems in large concentrated areas like the Corn Belt, localized regions elsewhere are susceptible to contamination as well.

Economic research related to nitrate contamination of surface and groundwater dates back to the early 1970's. Few studies of nitrate accumulation in surface or groundwater have attempted to examine the impact of regulation on a national scale. Most studies have involved regional or representative linear programming models that examine the effects of limiting nitrogen use through taxation or regulation on production patterns, farm profitability, and on social welfare, as measured by the sum of consumers' and producers' surplus less the variable costs of production (e.g., Taylor and Frohberg, 1977; Taylor *et al.*, 1978; Heady and Vocke, 1979; Swanson and Taylor, 1977; Huang and Lantin, 1993).

More recently, Lambert (1990) sought to distinguish the effects of sales tax and quantity restrictions on nitrogen fertilizer on optimal crop rotations of cotton, corn, wheat, and sugar beets in Arizona, taking into account the effect of a farmer's aversion to risk. He found that the expected return under a nitrogen quantity restriction was greater than that under a nitrogen sales tax, but the differences in expected returns decreased as the level of risk aversion increased. Risk is also a central focus of the theoretical studies by Kim and Hostetler (1991) and Kim *et al.* (1993) which estimate the net benefits of nitrogen use in the context of a dynamic model with water quality constraints. In their models, they include chance constraints on water quality such that nitrates in surface and groundwater do not exceed EPA's MCL with given probabilities. Taxes on nitrogen fertilizer and subsidies for reduced fertilizer use were also imposed in order to reduce nitrate runoff and leaching. The importance of their work is to demonstrate the need to incorporate the dynamics of nitrogen application and annual carryover into any empirical analysis of nitrogen leachate and runoff. If one disregards this time dimension in the model, the tax and subsidy programs result in over- or under-protection from nitrate contaminants in groundwater.

Despite past efforts, empirical studies that account specifically for the relationship between application rates and actual amounts of nitrogen runoff and leachate are relatively recent and have been made possible primarily because of recent advances in nutrient transport models. One of the early studies of this kind examined the feasibility of using the output from one of these transport models (CREAMS) to provide the agrichemical components to a representative farm linear programming model to simulate the effects of changes in farm practices on agricultural chemical losses and farm income (Crowder *et al.*, 1984). Taylor *et al.* (1992) have also incorporated output from an off-the-shelf biophysical simulation model, commonly known as EPIC, into linear programming models for five representative farms in the Willamette Valley. Similar work has been conducted for New York (Schmit, 1994).

Two detailed economic studies of regulating nitrates in groundwater are by Johnson *et al.* (1991) and Mapp *et al.* (1994). In the former, the authors, linked the results of a soil-specific dynamic programming model to a farm-level linear programming model to determine optimal crop production under various forms of nitrate regulation. Specifically, a dynamic programming model utilizing CERES (Hodges *et al.*, 1989; Jones and Kiniry, 1986; Ritchie *et al.*, 1985) crop and leaching simulation models determined optimal water and fertilizer applications within a growing season and the resulting crop yields. Nitrate leaching was also traced via the simulation model. After solving the dynamic programming model, the results were used in a linear programming model to determine optimal crop rotations under policies of nitrogen fertilizer taxes and regulation as well as direct regulation and Pigovian taxes on nitrates in the groundwater. Mapp *et al.* (1994), linked a crop growth/chemical transport model to a regional linear programming model and an aquifer model to examine the distribution of nitrate movements in response to restrictions and targeted policies in the central high plains.

In examining this previous research, we learn a great deal about the effects of commonly analyzed forms of environmental regulations, such as a tax or quantity restriction on pollution, as well as the nature of the essential components of a model for effective policy analysis. However, little attention has been given to more innovative, market-oriented regulatory tools, such as pollution permits (EPA, 1993, pp. 17-19), none of which has been within an analytical framework that is soil specific and accounts simultaneously for management responses, year-to-year nitrogen carryover, and the inherent uncertainty in both agricultural production and nitrate leaching.

Research Objectives

This research contributes to our knowledge of the biophysical and economic relationships between nitrogen fertilizer application rates, leachate, crop production, farm income, and environmental policy. Attention is focussed on dynamic aspects of the problem and the inherent risk in meeting environmental standards due to variability in weather and other factors affecting nitrate leaching. A soil-specific, stochastic, dynamic bioeconomic model of agricultural production is developed that maximizes farm profits resulting from the production of common crops within particular geographic regions while limiting nitrate leachate below the crop root zone. This model is used to: a) determine the effects on optimal crop rotations, nitrogen fertilizer use, and net farm income for specific soils of setting upper limits on the probability of serious nitrate leaching; and b) compare specific nitrate regulatory policies, such as a sales tax on nitrogen fertilizer, quantity restrictions on nitrogen fertilizer application or leachate, and various pollution permit schemes.

These comparisons of leachate and the probability levels and the various policies are empirically evaluated for typical agriculture and soils in a region of the Corn Belt, where nitrate leaching problems are thought to be severe, and in a region of the Northeast, where leaching problems are thought to be less widespread (Kellog *et al.*, 1992). Emphasis throughout the analysis is focussed on the implications for crop rotations, fertilizer use, farm income, and the distributional effects among farmers and between the farm and public sectors. Some attention is given to the administrative difficulties surrounding each of the various policies. The results have implications for implementing national policies to control nitrate leaching where soils and agricultural production differ widely across regions.

The remainder of this bulletin is organized into six additional sections. To place the empirical analysis into theoretical perspective, the next section compares the minimum cost method of achieving an effluent standard with taxes on the effluent and the polluting input, uniform effluent and polluting input restrictions, and two schemes of effluent permits. This is followed by a presentation of the bioeconomic models of typical agriculture production in New York and Corn Belt states, and a section describing the estimation of the crop production functions, nitrogen carryover parameters, nitrogen leaching relationships, etc. needed for the empirical applications of the models. Section 5 examines the solutions to the bioeconomic models for different soils in Iowa and New York, and it is followed by a comparative analysis of a tax on nitrogen fertilizer, quantity restrictions on both nitrogen fertilizer and nitrate leachate, and a system of nitrate pollution permits. The final section summarizes the policy implications, including problems associated with implementing the various regulatory policies.

A STANDARDS APPROACH TO REGULATING AN ENVIRONMENTAL EXTERNALITY

When the nitrate concentration in an underground aquifer increases because of leaching from nitrogen fertilizer applied by agricultural producers, the health risks to consumers from drinking water from that aquifer may rise as well. This situation is a classic example of a negative externality in that actions taken by one or more parties affect the technology, consumption set, or preferences of one or more other parties (Buchanan and Stubblebine, 1962). Zilberman and Marra (1993) argue that the absence of externalities is one of the first-best conditions under which a competitive equilibrium is also a Pareto efficient resource allocation. This results from the fact that externalities are not accounted for in the marketplace.

Pigou (1932), using an interventionist approach, and Coase (1960), using an approach involving negotiation among parties, provided the foundation for determining conditions under which the socially optimal resource allocation can be achieved in the presence of an externality.[2] While theoretical results provide important guidelines for policy, the conditions required by Coase and Pigou in the resolution of externalities rarely, if ever, exist in reality. Information, for example, may be limited, and the exact nature of the relationships between production and the externality may be uncertain. Costs of negotiation may be prohibitive.

This is particularly true for non-point source pollution, such as nitrates leaching from agricultural production. There is no way to know the socially optimal level of nitrates in groundwater. The social benefits of the improved environmental quality to both current and future generations are unknown, largely because of the uncertain health effects associated with the ingestion of nitrates. The non-point source nature of the problem adds to the uncertainty in estimating the social costs and benefits and complicates the enforcement of property rights because the relationship between agricultural production and groundwater contamination depends on many factors, some of which change randomly from year to year.

While there are methods for valuing environmental quality, estimates are generally derived for small areas and are difficult to generalize for use in setting regional or national policy. Therefore, as a basis for the empirical analysis of nitrogen leaching below, this section is devoted to a discussion of the standards approach proposed by Baumol and Oates (1971), as a second-best alternative to deal with environmental externalities. Under the approach, a regulatory policy is needed to achieve a regional effluent (pollution) standard.

Before applying this type of approach to the case of nitrate contamination, it is important to understand at a theoretical level the relative efficiency and implications for resource allocation of a number of alternative specifications of the standards approach. Six alternative policies are examined, including: taxing the effluent and the effluent-producing input, quantity restrictions on the effluent and effluent-producing input, effluent permits sold by a regulatory agency at a fixed price, and tradable effluent permits initially allocated by a regulatory agency.

A Graphical Analysis

Under the standards approach suggested by Baumol and Oates (1971), the government sets a regional target or standard for effluent. The target may be in terms of the total effluent

[2] See Thomas (1994) for a detailed discussion.

emitted in the region, or it may be an effluent concentration level. To enforce this standard, the government must implement an effective policy tool, such as a tax or a direct regulation.

By comparing taxes to direct regulation, Baumol and Oates (1971) demonstrated that the choice of policy instrument under the standards approach should be made carefully. Different instruments can affect parties in different ways while achieving the same standard. To illustrate the distributional consequences, consider a tax and direct regulation depicted in Figure 1, where S(MPC) is a firm's marginal private cost, or supply curve for a good, while D(MSB) is the marginal social benefit, or demand curve. Suppose that the government has determined an effluent standard for firms and that the level of output associated with the standard is Y^1. If there is no policy, the firm will produce Y^0. If the government levies a tax, t^1, on the firm's output to reduce it to Y^1, the firm receives areas a + b. The firm pays tax equal to area c, and society incurs a dead-weight loss of area d + e. If Y^1 is achieved through a direct quantity restriction on output at Y^1, the firm receives areas a + b + c. No public revenues are generated, but the dead-weight loss to society is area d + e, the same as under the tax.

Three important results come from this illustration. First, both taxes and quantity restrictions can be used to achieve the effluent standard at the same social cost to society, area d + e. Second, this cost, area d + e, is the least cost that society incurs if the effluent

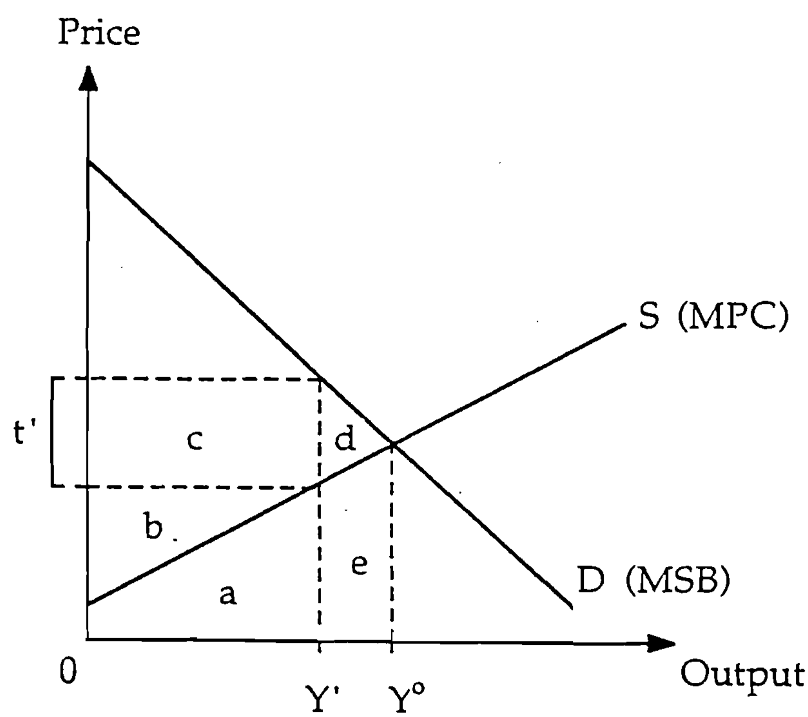

Figure 1. Using a Tax to Achieve a Pollution Standard

standard is achieved.[3] Third, strong incentives exist for the parties generating negative externalities to lobby for direct regulations as opposed to taxes because they will receive larger revenues under a direct regulation (Buchanan and Tullock, 1975).

Theoretical Comparisons of Policies to Achieve an Effluent Standard

Since Baumol and Oates' original work, many analysts have compared policies designed to achieve effluent standards at a theoretical level. While Baumol and Oates (1971) concluded that effluent charges (taxes) and effluent standards (quantity restrictions) meet regional effluent standards at a minimum cost, Weitzman (1974) showed that this may not be the case if policy makers are uncertain as to how an industry will react to a regulation. Buchanan and Tullock (1975) were the first to emphasize that standards may be a more desired form of regulation to polluters because standards can result in economic rents to polluters.

The use of pollution permits to achieve a desired level of environmental quality has also been examined at the theoretical level (e.g., McGartland and Oates, 1985; Tietenberg, 1985; Krupnick *et al.*, 1984; and Montgomery, 1972). Although these analyses often rely on different assumptions, they, along with Baumol and Oates (1988), demonstrate that a system of marketable permits can also achieve an effluent standard at least cost to society.

Taking a different approach, studies such as Helfand (1991), Besanko (1987), Harford and Karp (1983), and Thomas (1980) compared different forms of direct regulation, such as regulating pollution per unit of output, and pollution per unit of input, and pollution. They generally conclude that a mandate on pollution itself, rather than a mandate on some related alternative, leads to the most efficient resource allocation under an environmental standard.

Despite the value of these theoretical results, to date, there has been little attention given to comparing resource allocations associated with taxing or restricting an effluent-producing input with those of an effluent standard. It is to this task that we now turn.

The analysis begins with an abstract planner's problem that minimizes the costs to farmers for specified levels of output when an effluent standard is imposed. The resource allocation (inputs used in production) from the solution to this problem is characterized and then compared to the resource allocations under alternative nitrate reducing policies. To

[3] This assumes that the only way to reduce pollution is to reduce production, i.e. there is no pollution abatement equipment that a firm can install.

maintain consistency in the policy comparisons, the output that a farmer must produce is held constant and is equal to that level specified in the planner's problem.[4]

Minimum Cost to Farmers of Achieving a Nitrate Standard

Consider a region in which j farmers (j = 1,...,n) produce a crop, $y_j = f^j(x_{1j},..., x_{mj}, s_j;v_j)$ where $f_i^j > 0$, using the inputs $x_{1j},..., x_{mj}$ and nitrogen fertilizer, s_j. Production of y_j also depends on a vector of exogenous factors, v_j, including soil characteristics, precipitation, farm size and technology, etc. To produce the crop, nitrogen fertilizer used by farmer j, s_j, generates nitrate leachate, $z^j = z^j(s_j;v_j)$ where $z_s^j > 0$. Nitrate leachate also depends on v_j, which differs by farm, and any regulation is likely to affect the production and leachate differently.

Assume that a policy maker sets nitrate leachate at z^*, representing a "best guess" at a socially optimal level. To meet this standard at minimum cost to farmers, we have:

$$\min c = \sum_{j=1}^{n} \left[r_s s_j + \sum_{i=1}^{m} r_i x_{ij} \right]$$

subject to

$$f^j(x_{1j},...,x_{mj},s_j;v_j) \geq y_j^* \quad \text{for } j = 1,...,n$$

$$\sum_{j=1}^{n} z^j(s_j;v_j) \leq z^*$$

The Kuhn-Tucker conditions to obtain a minimum for i = 1,...,m and j = 1,...,n are:

(1) $\lambda_j f_i^j - r_i \leq 0, \quad x_{ij} \geq 0, \quad x_{ij}(\lambda_j f_i^j - r_i) = 0$

(2) $\lambda_j f_s^j - r_s - \mu z_s^j \leq 0, \quad s_j \geq 0, \quad s_j(\lambda_j f_s^j - r_s - \mu z_s^j) = 0$

(3) $f^j - y_j^* \geq 0, \quad \lambda_j \geq 0, \quad \lambda_j(f^j - y_j^*) = 0$

---

[4] The analysis assumes farmers produce the minimum level of output from the planner's problem. The models are highly stylized to facilitate comparisons. They abstract from the time dimension of agricultural production and nitrate leaching explicitly built into the bioeconomic models used in the empirical analysis.

$$(4)\quad z^* - \sum_{j=1}^{n} z^j(s_j; v_j) \geq 0, \quad \mu \geq 0, \quad \mu\left[z^* - \sum_{j=1}^{n} z^j(s_j; v_j)\right] = 0$$

where λ_j is the shadow price of increasing output for firm j, μ is the marginal cost of making the nitrate standard more stringent, f_i^j is the partial derivative of f^j with respect to x_{ij}, f_s^j is the partial derivative of f^j with respect to s_j, and z_s^j is the derivative of z^j with respect to s_j.

The equations in (1) are first-order conditions for non-polluting inputs. Assuming an interior solution, we have $f_i^j/f_h^k = r_i/r_h$ for all h, i, j, and k. The ratio of the marginal products are equal to the ratio of the marginal costs of the inputs across farmers and non-polluting inputs. Equations in (2) and (4) relate to nitrogen fertilizer. Equations in (2) are similar to those in (1), but contain an additional term (1), $\mu z_s^j > 0$, the marginal cost of increasing nitrate level through fertilizer application. The necessary condition for fertilizer is $f_s^j/f_i^j = (r_s + \mu z_s^j)/r_i$. To equate the ratio of marginal products to this "price" ratio requires that the marginal product of fertilizer be greater than what it would be if it were a conventional input implying less fertilizer application. If the nitrate standard is made more stringent, i.e. z^* is decreased, and this results in a higher marginal cost of meeting the standard (μ increases), then, *ceteris paribus*, nitrogen fertilizer use will decrease further. Equations in (3) ensure that at least y_j^* is produced.

With this solution as a base of comparison, one can examine the change in resource allocation under different nitrate reducing policies in order to determine which, if any, can achieve the same cost-minimizing resource allocation. That is, given a specific policy, if the Kuhn-Tucker conditions to farmer j's problem are consistent with the Kuhn-Tucker conditions to the policy maker's problem, then the policy can also be used to achieve the resource allocation at minimum cost. To explain, suppose the Kuhn-Tucker conditions to farmer j's problem are a subset of those for the policy maker. If solutions to both problems exist and are unique, they lead to the same input, output, and leachate levels used by farmer j. If the Kuhn-Tucker conditions for farmer j are not a subset of those for the policy maker, the policy will not meet the nitrate standard using the cost-minimizing resource allocation.

Taxing Nitrate Leachate. For this policy farmers pay a fixed tax of t_z per unit of nitrate leachate. From production theory (Varian, 1992), farmer j has a conditional demand for nitrogen fertilizer, $s_j(r, t_z, y_j^*)$, where r represents the vector of input prices. Nitrate leachate maintain consistency in the policy comparisons, the output that a farmer must produce is held constant and is equal to that level specified in the planner's problem.[4]

Minimum Cost to Farmers of Achieving a Nitrate Standard

Consider a region in which j farmers (j = 1,...,n) produce a crop, $y_j = f^j(x_{1j},\dots,x_{mj}, s_j;v_j)$ where $f_i^j > 0$, using the inputs $x_{1j},\dots,x_{mj}$ and nitrogen fertilizer, s_j. Production of y_j also depends on a vector of exogenous factors, v_j, including soil characteristics, precipitation, farm size and technology, etc. To produce the crop, nitrogen fertilizer used by farmer j, s_j, generates nitrate leachate, $z^j = z^j(s_j\,;v_j)$ where $z_s^j > 0$. Nitrate leachate also depends on v_j, which differs by farm, and any regulation is likely to affect the production and leachate differently.

Assume that a policy maker sets nitrate leachate at z^*, representing a "best guess" at a socially optimal level. To meet this standard at minimum cost to farmers, we have:

$$\min\ c = \sum_{j=1}^{n}\left[r_s s_j + \sum_{i=1}^{m} r_i x_{ij}\right]$$

subject to

$$f^j(x_{1j},\dots,x_{mj},s_j;v_j) \geq y_j^* \quad \text{for } j = 1,\dots,n$$

$$\sum_{j=1}^{n} z^j(s_j;v_j) \leq z^*$$

The Kuhn-Tucker conditions to obtain a minimum for i = 1,...,m and j = 1,...,n are:

(1) $\lambda_j f_i^j - r_i \leq 0,\ \ x_{ij} \geq 0,\ \ x_{ij}(\lambda_j f_i^j - r_i) = 0$

(2) $\lambda_j f_s^j - r_s - \mu z_s^j \leq 0,\ \ s_j \geq 0,\ \ s_j(\lambda_j f_s^j - r_s - \mu z_s^j) = 0$

(3) $f^j - y_j^* \geq 0,\ \ \lambda_j \geq 0,\ \ \lambda_j(f^j - y_j^*) = 0$

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[4] The analysis assumes farmers produce the minimum level of output from the planner's problem. The models are highly stylized to facilitate comparisons. They abstract from the time dimension of agricultural production and nitrate leaching explicitly built into the bioeconomic models used in the empirical analysis.

$$(4)\quad z^* - \sum_{j=1}^{n} z^j(s_j; v_j) \geq 0, \quad \mu \geq 0, \quad \mu\left[z^* - \sum_{j=1}^{n} z^j(s_j; v_j)\right] = 0$$

where λ_j is the shadow price of increasing output for firm j, μ is the marginal cost of making the nitrate standard more stringent, f_i^j is the partial derivative of f^j with respect to x_{ij}, f_s^j is the partial derivative of f^j with respect to s_j, and z_s^j is the derivative of z^j with respect to s_j.

The equations in (1) are first-order conditions for non-polluting inputs. Assuming an interior solution, we have $f_i^j/f_h^k = r_i/r_h$ for all h, i, j, and k. The ratio of the marginal products are equal to the ratio of the marginal costs of the inputs across farmers and non-polluting inputs. Equations in (2) and (4) relate to nitrogen fertilizer. Equations in (2) are similar to those in (1), but contain an additional term (1), $\mu z_s^j > 0$, the marginal cost of increasing nitrate level through fertilizer application. The necessary condition for fertilizer is $f_s^j/f_i^j = (r_s + \mu z_s^j)/r_i$. To equate the ratio of marginal products to this "price" ratio requires that the marginal product of fertilizer be greater than what it would be if it were a conventional input implying less fertilizer application. If the nitrate standard is made more stringent, i.e. z^* is decreased, and this results in a higher marginal cost of meeting the standard (μ increases), then, *ceteris paribus*, nitrogen fertilizer use will decrease further. Equations in (3) ensure that at least y_j^* is produced.

With this solution as a base of comparison, one can examine the change in resource allocation under different nitrate reducing policies in order to determine which, if any, can achieve the same cost-minimizing resource allocation. That is, given a specific policy, if the Kuhn-Tucker conditions to farmer j's problem are consistent with the Kuhn-Tucker conditions to the policy maker's problem, then the policy can also be used to achieve the resource allocation at minimum cost. To explain, suppose the Kuhn-Tucker conditions to farmer j's problem are a subset of those for the policy maker. If solutions to both problems exist and are unique, they lead to the same input, output, and leachate levels used by farmer j. If the Kuhn-Tucker conditions for farmer j are not a subset of those for the policy maker, the policy will not meet the nitrate standard using the cost-minimizing resource allocation.

Taxing Nitrate Leachate. For this policy farmers pay a fixed tax of t_z per unit of nitrate leachate. From production theory (Varian, 1992), farmer j has a conditional demand for nitrogen fertilizer, $s_j(r, t_z, y_j^*)$, where r represents the vector of input prices. Nitrate leachate for farmer j is $z^j(s_j(r, t_z, y_j^*); v_j)$. The tax is set so that $\sum_{j=1}^{n} z^j(s_j(r,t_z,y_j^*);v_j) \leq z^*$ and the farmer's problem is:

$$\min\ c_j = t_z z^j(s_j;v_j) + r_s s_j + \sum_{i=1}^{m} r_i x_{ij}$$

subject to

$$f^j(x_{1j},\ldots,x_{mj},s_j;v_j) \geq y_j^*$$

The Kuhn-Tucker conditions for this problem are the equations in (1), (3), and

(5) $\lambda_j f_s^j - r_s - t_z z_s^j \leq 0, \quad s_j \geq 0, \quad s_j(\lambda_j f_s^j - r_s - t_z z_s^j) = 0$

If the leachate tax, t_z, is set at μ from the poicy maker's problem, equations (5) are the same as in (2), and the first-order conditions to farmer j's problem are a subset of those for the policy maker's problem. Thus, a tax on leachate implies the same leachate level with the same minimum-cost resource allocation.

Taxing Nitrogen Fertilizer. For a tax on nitrogen fertilizer, the tax, t_s, is set such that $\sum_{j=1}^{n} z^j(s_j(r,t_s,y_j^*);v_j) \leq z^*$, and farmer j's problem is:

$$\min\ c_j = (1+t_s) r_s s_j + \sum_{i=1}^{m} r_i x_{ij}$$

subject to

$$f^j(x_{1j},\ldots,x_{mj},s_j;v_j) \geq y_j^*.$$

The Kuhn-Tucker conditions for this problem are the equations in (1), (3), and

(6) $\lambda_j f_s^j - (1+t_s) r_s \leq 0, \quad s_j \geq 0, \quad s_j(\lambda_j f_s^j - (1+t_s) r_s) = 0.$

For the Kuhn-Tucker conditions from the n farmers' problems to be consistent with those of the policy maker's problem, it is necessary for $t_s r_s$ from the farmers' problems to be equal to μz_s^j from the policy maker's problem. If this is true, equations in (6) will be identical to those in (2). In general, the solutions to the farmers' problems will differ from the policy maker's because $t_s r_s$ is constant, (e.g., the tax rate and price of nitrogen fertilizer are the same for all farmers. However, μz_s^j will vary by farm. Only if the marginal product of nitrate leachate with respect to nitrogen fertilizer is equal across farms, $z_s^1 = \ldots = z_s^n$, is it possible for the nitrogen fertilizer tax to achieve the nitrate standard at minimum cost. This is unlikely since soil characteristics, precipitation, and technology can vary dramatically within a region. Those exogenous factors, v_j, explicitly affect leaching and probably affect the marginal leachability of the soil with respect to nitrogen fertilizer use. *Ceteris paribus*, one would expect if farmer i has more leachable soils than farmer j, then marginal leachate of farmer i should be greater than the marginal leachate of farmer j, i.e. $z_s^i > z_s^j$.

Since this policy leads to a different resource allocation than the minimum regional cost allocation, it would be useful to know how production plans differ. Assuming interior solutions, the marginal productivity of fertilizer from the policy maker's solution is $f_s^j = (r_s + \mu z_s^j)/\lambda_j$ and from farmer j's solution is $f_s^j = (r_s + r_s t_s)/\lambda_j$. Farmer j's solution differs from the policy maker's solution when $t_s r_s < \mu z_s^j$ or $t_s r_s > \mu z_s^j$. One could speculate that the case where $t_s r_s < \mu z_s^j$ is more likely on more leachable soils where the increase in leachate given an incremental increase in nitrogen fertilizer, z_s^j, is relatively large. Conversely, the case where $t_s r_s > \mu z_s^j$ is probably more likely on less leachable soils. If $t_s r_s < \mu z_s^j$ and f^j is increasing and concave in s, then farmer j uses more nitrogen fertilizer than that identified in the planner's problem, provided that the shadow price on output is the same between the two problems. Thus, the tax on fertilizer leads to higher nitrate leachate produced by the farmer with relatively leachable soils. If $t_s r_s > \mu z_s^j$, farmer j uses less nitrogen fertilizer, and leachate is lower than that for the policy maker's problem.

Uniform Quantity Restrictions on Nitrate Leachate. Suppose there is a uniform quantity restriction on nitrate leachate, $\hat{z}$, on each firm. Here, $\hat{z}$ must be set such that $n\hat{z} \leq z^*$, and farmer j's problem becomes:

$$\min\ c_j = r_s s_j + \sum_{i=1}^{m} r_i x_{ij}$$

subject to

$$f^j(x_{1j}, \ldots, x_{mj}, s_j; v_j) \geq y_j^*$$

$$z^j(s_j; v_j) \leq \hat{z}$$

The Kuhn-Tucker conditions for this problem are the equations in (1), (3), and

$$(7)\quad \lambda_j f_s^j - r_s - \mu_j z_s^j \leq 0, \quad s_j \geq 0, \quad s_j(\lambda_j f_s^j - r_s - \mu_j z_s^j) = 0$$

$$(8)\quad \hat{z} - z^j(s_j; v_j) \geq 0, \quad \mu_j \geq 0, \quad \mu_j(\hat{z} - z^j(s_j; v_j)) = 0$$

where μ_j is the marginal cost (shadow price) of increasing farmer j's leachate restriction. Intuitively, this policy is inconsistent with the planner's problem because the restriction is on leachate levels for individual farmers rather than for total leachate within a region. Also the policy does not allow for differences in leachability across farms as the planner's problem does. Equations in (7) are inconsistent with those in (2) because there is no reason for $\mu_j = \mu$. For $\mu_j > \mu$, the uniform leachate restriction results in less nitrogen fertilizer applied and less leaching for farmer j than does the regional cost-minimizing problem. For $\mu_j < \mu$, the leachate restriction increases nitrogen fertilizer applied and the leaching by farmer j.

To understand the full implications of this policy, one would like to be able to establish whether or not more leachable soils result in $\mu_j > \mu$ or $\mu_j < \mu$. To establish the relationship between the leachability of the soil and μ_j, recall that the shadow price on the uniform leachate restriction, μ_j, is the marginal change in farmer j's cost given a marginal change in the upper bound on leachate, $\hat{z}$. One might expect a more leachable soil to have a greater shadow price on leachate because as the leachate constraint is relaxed by a small amount, the allowable increase in production may be smaller than on less leachable soils. This leads to a relatively small increase in farm costs, implying $\mu_j < \mu$, and causes fertilizer and leaching to rise for farmer j under the uniform leachate restriction compared with policy maker's problem. Conversely, if a soil is less leachable, then one might expect $\mu_j > \mu$, resulting in less fertilizer and leaching for farmer j under the uniform leachate restriction. Since it is both the leachability and productivity of the soil that determine the relationship between μ_j and μ because μ_j and μ relate marginal changes in leachate to marginal changes in costs, it is difficult to know for which farms these relationships hold. It is clearly an empirical question.

<u>Uniform Quantity Restrictions on Nitrogen Fertilizer Application.</u> The government could also place a uniform quantity restriction on the amount of nitrogen fertilizer that a farmer can apply. The limit, s^*, on s_j is such that $\sum_{j=1}^{n} z^j(s_j;v_j) \leq z^*$. The problem for farmer j is:

$$\min\ c_j = r_s s_j + \sum_{i=1}^{m} r_i x_{ij}$$

subject to

$$f^j(x_{1j},\ldots,x_{mj},s_j;v_j) \geq y_j^*$$

$$s_j \leq s^*$$

The Kuhn-Tucker conditions for this problem are the equations in (1), (3), and

(9) $\lambda_j f_s^j - r_s - \phi_j \leq 0, \quad s_j \geq 0, \quad s_j(\lambda_j f_s^j - r_s - \phi_j) = 0$

(10) $s^* - s_j \geq 0; \quad \phi_j \geq 0; \quad \phi_j(s^* - s_j) = 0$

where ϕ_j is the shadow price for the restriction on nitrogen fertilizer applied by farmer j. Equations in (2) and (9), are inconsistent unless $\phi_j = \mu z_s^j$, which is likely only if exogenous factors, v_j, are identical across farms. If $\phi_j > \mu z_s^j$, where μz_s^j comes from the policy maker's problem, then less fertilizer is applied by farmer j under the fertilizer restriction than under the policy maker's regional cost minimizing problem. Conversely, if $\phi_j < \mu z_s^j$, then farmer j uses less nitrogen fertilizer, resulting in less leachate than that under the regional minimum-cost allocation.

One cannot easily determine the linkage between the leachability of the soil and whether $\phi_j > \mu z_s^j$ or $\phi_j < \mu z_s^j$. ϕ_j and μz_s^j are the marginal costs associated with an incremental increase in fertilizer use from the farmer's problem here and the policy maker's problem, respectively. For ϕ_j, this is easy to see because ϕ_j is the shadow price of the fertilizer restriction. For μz_s^j, recall that μ is the marginal cost associated with incrementally increasing leachate and that z_s^j is the marginal increase in leachate given an incremental increase in fertilizer application. These two pieces together give the marginal cost associated with increasing fertilizer use in the policy maker's problem. Unfortunately, there is no general relationship between the leachability of a soil and the marginal cost associated with increasing fertilizer application.

Leachate Permits Sold at a Fixed Price. Another instrument to reduce regional nitrate leachate is the effluent permit. By assuming farmers are required to purchase leachate permits at a fixed price, p_z, this policy is equivalent to taxing every unit of pollution. If $p_z = t_z$ farmer j's problem is identical to farmer j's problem under the leachate tax, and the policy can achieve the regional cost-minimizing production and resource allocation.

Tradable Leachate Permits. An alternative form of leachate permit, similar to the one implemented for SO_2 emissions in the United States (Kete, 1992), is that in which a regulatory agency allocates an initial distribution of leachate permits, $(z^{1*},..., z^{n*})$, among the farmers, who can then trade permits among themselves. The initial distribution of permits must be set such that $\sum_{j=1}^{n} z^{j*} \leq z^*$. Assuming that the permit market is perfectly competitive and is in equilibrium at p_z,[5] farmer j's problem is:

$$\min\ c_j = p_z[z^j(s_j;v_j) - z^{j*}] + r_s s_j + \sum_{i=1}^{m} r_i x_{ij}$$

subject to

$$f^j(x_{1j},\ldots,x_{mj},s_j;v_j) \geq y_j^*$$

where $z^j - z^{j*} > 0$ indicates $z^j - z^{j*}$ permits are purchased by farmer j and $z^j - z^{j*} < 0$ indicates that $z^{j*} - z^j$ permits are sold by farmer j. The Kuhn-Tucker conditions are identical to those of the previous permit scheme and the leachate tax, again indicating the consistency of this policy instrument with the regional cost-minimizing allocation.

Summary

In summary, the analysis shows that effluent taxes, effluent permits sold at fixed prices, and tradable effluent permits that are initially allocated by a regulatory agency are all capable of achieving the policy maker's minimum-cost resource allocation. Uniform quantity restrictions on fertilizer or leachate and taxing fertilizer do not.

Although ignored here, the administrative costs and problems with enforceability of various policies should be considered as well. With the exception of the tax on the polluting input, effective enforcement of the policies requires a constant monitoring effort, either of the effluent or the effluent-producing input. This monitoring is extremely difficult because of the non-point source nature of the problem. Under the tax on the polluting input, no such monitoring is needed, which makes this regulatory option more attractive to policy makers, despite the fact it does not result in the cost-minimizing resource allocation.

It is also important to remember that the actual costs of the different polices to individual farmers and farmers as a whole within the region can differ even if they achieve the same resource allocation as the policy maker's problem. For example, both effluent permit schemes, lead to the same amount of output using the same set of inputs, but the regional farm costs for producing the output are greater when the government sells permits at a fixed price

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[5] If this assumption is not made and farmer j has significant market power and influence on the permit price, then farmer j may be able to realize excess revenues from the permit market. For instance, he may emerge as a price leader, creating a market similar to the Stackelberg model of duopoly (Gibbons, 1992).

rather than initially allocating tradable permits. Thus, permits sold at a fixed price generate public revenues, but the tradable permits initially allocated freely to farmers do not.

To begin to shed some light on the relative magnitude of these costs and financial transfers, the next section is devoted to constructing a framework for determining the net farm revenues associated with different levels of nitrate leachate. This framework is used to empirically assess the differences in farm costs and public revenues associated with restricting nitrate leachate using different policy instruments.

THE BIOECONOMIC MODELS

Although the basis of comparison in the stylized analysis above is a social planner's problem with regional leachate constraints, the primary building blocks of this model are the production models for individual farms. Here, the bioeconomic models of agricultural production and nitrate leachate needed for the empirical evaluation of regulatory policies are formulated. Separate models for agricultural production with chance constraints on nitrate leachate are formulated for the Corn Belt and Northeast.

Overview

The dynamic, bioeconomic models are much more realistic than the stylized framework above; but despite advances in solution methods, they must still include a great deal of abstraction. They must include only the most essential features of the agricultural production and nitrate leaching processes, such as the major decision alternatives and land resource differences. They focus only on the predominant field crops in each region for which nitrogen leaching may be a problem and on the crops normally grown in rotation with them.

The model of the Corn Belt, for example, obviously contains corn and soybeans. In Iowa, a typical Corn Belt state, corn and soybeans are grown on 75% of the cropland (*Agricultural Statistics, 1992*). Because of the large corn acreages and the high rates of nitrogen fertilizer application on corn, there is the potential for significant nitrogen leaching across much of the state (Kellog *et al.*, 1992).

In the Northeast, where agriculture is dominated by dairy,[6] crop production is generally more diverse than in the Corn Belt, but corn and alfalfa are commonly grown in rotation in support of the dairy operations. Corn (for both silage and grain) and alfalfa are grown on about 40% of the cropland in New York (*Agricultural Statistics, 1992)*. Although corn acreage is not as extensive as in the Midwest, there are some parts of the Northeast where the amount of nitrogen leached as a result of the fertilizer applied to corn may result in a substantial risk of nitrate contamination in groundwater (Kellog *et al.*, 1992). Because of the predominance of dairy in the Northeast, the risk of nitrate contamination can be exacerbated through the application of manure to cropland as a supplement to the inorganic nitrogen fertilizer for corn production.

By including the two major field crops from each region in the models, the management responses to policies designed to limit nitrogen fertilizer are reflected both in the choice of crop rotation and nitrogen fertilizer application rates. The dynamics of the model account for the year-to-year carryover of nitrogen in the crop root zone. Precipitation, which affects both crop yields and the amount of nitrate leachate, is incorporated in the models as a random variable. Nitrogen leaching resulting from corn production is restricted using a chance constraint (Charnes and Cooper, 1959), which can be used to reduce the frequency of worst-case leaching scenarios by allowing leachate above a harmful level to occur with only a small probability. Because soil characteristics affect both productivity and leaching, a model accounts for production and leaching on only one soil. To evaluate regional impacts of nitrate reducing policies, models are formulated for several representative soils, and other soils in the regions are matched to these soils based on their productivity and leaching characteristics.

In these empirical models, nitrate leachate below the crop root zone on a farmer's field is restricted rather than the actual nitrate concentration in an aquifer. This simplification is necessary because of the lack of information on the precise linkage between nitrate leachate below the crop root zone on an individual field and the actual nitrate concentration in an aquifer. This simplification also ignores the time lag between nitrates leaching below the root zone and actually entering the aquifer. By using a sufficiently long planning horizon and conducting a regional rather than site-specific analysis, the effects of this latter simplification on the policy analyses should be minimized.

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[6] In New York, dairy generates over 48% of the farm marketings (*New York Agricultural Statistics, 1992-1993*). Placing second are greenhouse and nursery products, with only 12% of farm marketings.

A Bioeconomic Model of "Corn Belt" Agriculture

Consider a typical farmer in the Corn Belt growing corn grain and soybeans in rotation on one acre of a specific soil. The corn produced (bu./acre), C = C(x,z), is assumed to depend on the nitrogen available in the crop root zone, x (lbs./acre), and precipitation, z (inches). The soybeans produced (bu./acre), S = S(z), are assumed to depend only on precipitation because this legume crop fixes its own nitrogen for uptake. The amount of nitrogen in the crop root zone available for corn production, x, depends on the amount of nitrogen applied, x_a (lbs./acre), nitrogen mineralized by the soil organic matter or accumulated through precipitation, N_m (lbs./acre), and nitrogen carried over from the previous year if corn was grown during the previous year or nitrogen fixed by soybeans if soybeans were grown during the previous year. Nitrogen carryover is some fraction, γ_1, of nitrogen in the crop root zone that is neither uptaken by the plant, nor denitrified, nor leached. Nitrogen uptaken by the plant is given by $\gamma_2 x$. Nitrogen that is denitrified is $\gamma_3 x^a$, and nitrogen leached is L (lbs./acre). Leachate, L, is some proportion, g(z) where $0 \leq g(z) \leq 1$, of the nitrogen that is neither uptaken nor denitrified. The proportion leached, g(z), depends explicitly on precipitation.

Assuming that the discounted value of expected net farm revenue from producing corn and soybeans is maximized, the problem is:

$$\max \sum_{t=1}^{T} \rho^t \int_a^b [[p_{c,t} C(x_{1,t}, z_t) - r_t x_{1,t}^a] \delta_{1,t}$$

$$+ [p_{c,t} C(x_{2,t}, z_t) - r_t x_{2,t}^a] \delta_{2,t}$$

$$+ [p_{s,t} S(z_t)] \delta_{3,t}] f_{Z_t}(z_t) \, dz_t$$

subject to

$$(11) \quad x_{1,t} = x_{1,t}^a + N_m + N_f$$

$$(12) \quad x_{2,t} = x_{2,t}^a + N_m + \gamma_1 [(\delta_{1,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1 - \gamma_2) x_{1,t-1} - \gamma_3 x_{1,t-1}^a - L_{1,t-1})$$

$$+ (\delta_{2,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1 - \gamma_2) x_{2,t-1} - \gamma_3 x_{2,t-1}^a - L_{2,t-1})]$$

$$(13) \quad \delta_{1,t} \leq \delta_{3,t-1}, \quad (14) \quad \delta_{2,t} \leq \delta_{1,t-1} + \delta_{2,t-1}, \quad (15) \quad \delta_{1,t} + \delta_{2,t} + \delta_{3,t} \leq 1$$

$$(16)\quad L_{1,t} = g(z_t)[(1-\gamma_2)x_{1,t} - \gamma_3 x^a_{1,t}]$$

$$(17)\quad L_{2,t} = g(z_t)[(1-\gamma_2)x_{2,t} - \gamma_3 x^a_{2,t}]$$

$$(18)\quad \text{Prob}[\delta_{1,t}L_{1,t} + \delta_{2,t}L_{2,t} \geq L_U] \leq \alpha$$

$$(19)\quad x^a_{1,t},\ x^a_{2,t},\ \delta_{1,t},\ \delta_{2,t},\ \delta_{3,t} \geq 0$$

$$(20)\quad x_{1,0},\ x^a_{1,0},\ x_{2,0},\ x^a_{2,0},\ \delta_{1,0},\ \delta_{2,0},\ \delta_{3,0} \text{ known}$$

where $\rho = 1/(1+\delta)$ is the discount factor for a discount rate, δ; $p_{c,t}$ is the net revenue per bushel of corn in year t, net of all costs except nitrogen fertilizer; r_t is the price of nitrogen fertilizer per pound; subscript "1" on the decision variables refers to activities on land producing corn following soybeans; subscript "2" refers to activities on land producing corn following corn; the subscript "3" refers to activities on land producing soybeans; $\delta_{1,t}$ is the fraction of the acre producing corn in year t following soybeans in t-1; $\delta_{2,t}$ is the fraction of the acre producing corn in year t following corn in t-1; $\delta_{3,t}$ is the fraction of the acre producing soybeans in year t; and $f_{Zt}(z_t)$ is the probability density function for precipitation.

The objective is to maximize the discounted value of expected net farm revenue over time for three production activities: corn following soybeans, corn following corn, and soybeans. Expectations are taken because of the stochastic precipitation component. Land variables are needed for each of the three production activities because of the differences in the amounts of nitrogen in the crop root zone carried over from the previous years. Other than the land variables, decision variables include the amount of nitrogen fertilizer applied on corn following soybeans and corn following corn.

Equations (11) and (12) are state equations for the amount of nitrogen available in the crop root zone on corn following soybeans and corn following corn, respectively. Equations (13) through (15) are natural restrictions on land. Land producing corn following soybeans is land that produced soybeans the previous year, equation (13). Land producing corn following corn cannot be land that produced soybeans in the previous year, equation (14). Total land activities cannot exceed the land available, equation (15). Nitrogen leached below the crop root zone, identified in equations (16) and (17), is restricted using a probabilistic chance constraint, equation (18), where leaching above a harmful bound, L_u, can occur with only a small probability. Equations (19) and (20) are the non-negativity restrictions on the decision variables and the initial conditions for the decision and state variables, respectively.

To obtain some idea of how this model behaves, Thomas (1994) examined the necessary conditions for optimization by specifying a certainty-equivalent form using expected precipitation in both the corn production function and the constraint on nitrate leachate. Because of the number of necessary conditions and their complexity, obtaining an exact interpretation of each is difficult, and these detailed results are not repeated here. However, by making a few key assumptions, the effects of the leachate constraint on the optimal amount of nitrogen in the crop root zone and nitrogen fertilizer applied could be determined. The addition of the leachate constraint increases the marginal cost of increasing nitrogen in the root zone. Thus, *ceteris paribus*, the amount of nitrogen in the crop root zone on corn following soybeans decreases as a result of the constraint on leachate. Because of the positive relationship between nitrogen fertilizer applied and the amount of nitrogen in the crop root zone from equation (11), one would expect nitrogen fertilizer application to decrease.

It is also important to determine the effect of the leaching constraint on the crop rotation, but establishing this relationship is not as straightforward as it is for the relationship between the leaching constraint and the nitrogen variables. Without solving the first-order conditions as a whole, one may obtain counter-intuitive results. These can only be explained away through the empirical solutions to the bioeconomic models below.

A Bioeconomic Model of Agriculture in the Northeast

Now consider a typical farmer in the Northeast growing corn silage and alfalfa in rotation. The bioeconomic model for this situation is similar to that for corn and soybeans grown in rotation, but there are some important differences, as well. Corn silage produced (t./acre), $C = C(x,z)$, is assumed to depend on the amount of nitrogen available in the crop root zone and precipitation. Because of the relatively large number of dairies in the Northeast, applied nitrogen comes from two sources: nitrogen fertilizer, x^{fa}, and manure, x^{ma}. Alfalfa produced (t./acre), $a = a(z)$, depends only on precipitation because alfalfa, like soybeans, is a legume crop that fixes its own nitrogen for uptake. Factors affecting the amount of nitrogen in the crop root zone are similar to those for corn and soybeans grown in rotation.

One important difference between this model and the model for the Corn Belt is the fact that alfalfa is a perennial crop. Once planted, alfalfa typically remains in rotation for three years in New York (personal communication with Ed McClenahan, manager of Cornell University's Caldwell experiment station). Therefore, three separate land activities are needed for alfalfa, one for each year in the rotation. In addition, alfalfa yields are lower for alfalfa in the first year of rotation while the crop is being established. To accomodate these differences in yields, two production functions are specified for alfalfa production, $a_1 = a_1(z)$ for first year alfalfa and $a_2 = a_2(z)$ for second- and third-year alfalfa.

Mathematically, the bioeconomic model is:

$$\max \sum_{t=1}^{T} \rho^t \int_a^b [[p_{c,t} c(x_{1,t}, z_t) - r_{f,t} x_{1,t}^{fa} - r_{m,t} x_{1,t}^{ma}]\delta_{1,t}$$

$$+ [p_{c,t} c(x_{2,t}, z_t) - r_{f,t} x_{2,t}^{fa} - r_{m,t} x_{2,t}^{ma}]\delta_{2,t}$$

$$+ [p_{a1,t} a_1(z_t)]\delta_{3,t} + [p_{a2,t} a_2(z_t)](\delta_{4,t} + \delta_{5,t})] f_{Z_t}(z_t) dz_t$$

subject to

$$(21) \quad x_{1,t} = x_{1,t}^{fa} + x_{1,t}^{ma} + N_m + N_f$$

$$(22) \quad x_{2,t} = x_{2,t}^{fa} + x_{2,t}^{ma} + N_m$$

$$+ \gamma_1 [(\delta_{1,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1-\gamma_2) x_{1,t-1} - \gamma_3 x_{1,t-1}^{fa} - 2\gamma_3 x_{1,t-1}^{ma} - L_{1,t-1})$$

$$+ (\delta_{2,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1-\gamma_2) x_{2,t-1} - \gamma_3 x_{2,t-1}^{fa} - 2\gamma_3 x_{2,t-1}^{ma} - L_{2,t-1})]$$

$$(23) \quad \delta_{1,t} \le \delta_{5,t-1}, \quad (24) \quad \delta_{2,t} \le \delta_{1,t-1} + \delta_{2,t-1}, \quad (25) \quad \delta_{4,t} \le \delta_{3,t}$$

$$(26) \quad \delta_{5,t} \le \delta_{4,t-1}, \quad (27) \quad \sum_{i=1}^{5} \delta_{i,t} \le 1$$

$$(28) \quad x_{1,t}^{ma} \le \bar{x}^m, \quad (29) \quad x_{2,t}^{ma} \le \bar{x}^m$$

$$(30) \quad L_{i,t} = g(z_t)[(1-\gamma_2) x_{i,t} - \gamma_3 x_{i,t}^{fa} - 2\gamma_3 x_{i,t}^{ma}] \text{ for } i = 1,2$$

(31) $\text{Prob}[\delta_{1,t}L_{1,t} + \delta_{2,t}L_{2,t} \geq L_U] \leq \alpha$

(32) $x_{1,t}^{fa},\ x_{1,t}^{ma},\ x_{2,t}^{fa},\ x_{2,t}^{ma},\ \delta_{1,t},\ \delta_{2,t},\ \delta_{3,t},\ \delta_{4,t},\ \delta_{5,t} \geq 0$

(33) $x_{1,0},\ x_{1,0}^{fa},\ x_{1,0}^{ma},\ x_{2,0},\ x_{2,0}^{fa},\ x_{2,0}^{ma},\ \delta_{1,0},\ \delta_{2,0},\ \delta_{3,0},\ \delta_{4,0},\ \delta_{5,0}$ known

where $\delta_{1,t}$ is the fraction of the acre producing corn in year t following alfalfa in t-1; $\delta_{2,t}$ is the fraction of the acre producing corn in year t following corn in t-1; $\delta_{3,t}$ is the fraction of the acre producing first-year alfalfa; $\delta_{4,t}$ is the fraction of the acre producing second-year alfalfa; $\delta_{5,t}$ is the fraction of the acre producing third-year alfalfa; and $\bar{x}^m$ is an upper bound on the rate at which manure can be applied, since rarely is an unlimited supply of manure available.

The objective function maximizes the expected discounted value of net farm revenue over time for five production activities: corn following alfalfa, denoted with subscript "1"; corn following corn, denoted with subscript "2"; first year alfalfa, denoted with subscript "3"; second year alfalfa, denoted with subscript "4", and third year alfalfa, denoted with subscript "5". Other than the land variables, decision variables in the model include the amounts of nitrogen fertilizer and manure applied on both corn following alfalfa and corn following corn. Again, expectations are taken because of the stochastic precipitation component.

Equations (21) and (22) are the state equations for the amount of nitrogen in the crop root zone on corn following alfalfa and corn following corn, respectively. Differences between these equations and those in (11) and (12) from the Corn Belt model are the addition of manure as both a source of nitrogen and a source of denitrification. Manure denitrifies at a rate approximately twice that of inorganic fertilizer (Meisinger and Randall, 1991).

Equations (23) through (27) are restrictions on the land activities. Land producing corn following alfalfa must be land that produced third-year alfalfa in the previous year, equation (23). Land producing corn following corn must be land that produced corn in the previous year, equation (24). Land producing second-year alfalfa must be land that produced first-year alfalfa in the previous year, equation (25). Land producing third year alfalfa must be land that produced second-year alfalfa in the previous year, equation (26). Total land activities cannot exceed the land available, equation (27).

The remaining equations are restrictions on the amount of manure that can be applied, equations (28) and (29); leachate restrictions, equations (30) and (31); non-negativity restrictions, equation (32); and initial conditions, (33). Nitrate leachate below the crop root zone is restricted using a probabilistic chance constraint, the same approach as used in the Corn Belt model, in order to protect against worst-case leaching scenarios.

By examining the necessary conditions for a certainty-equivalent form of this model, arguments nearly identical to those made with the Corn Belt model can be used to establish that imposing the leachate constraint results in less nitrogen in the crop root zone and less nitrogen fertilizer and manure applied on both corn following corn and corn following alfalfa. Again, however, no straightforward, intuitively-correct relationship between the crop rotation and leachate constraint can be easily established.

ESTIMATING THE COMPONENTS OF THE BIOECONOMIC MODELS

Now that the bioeconomic models are specified, we must identify the study regions and identify the various prices and parameters needed to apply the bioeconomic models empirically. The corn and legume response functions are estimated, as are the nitrate leaching equations, the precipitation distributions, and the final form of the chance constraint on nitrate leachate.

The Study Regions

The areas in the Corn Belt and Northeast chosen for the policy analyses, Boone County in Iowa and a two-county area in New York, Genesee and Wyoming Counties, are representative of major agricultural regions in the two states. Boone County, located in central Iowa, is part of the glacial till region of central and northeastern Iowa. Genesee and Wyoming Counties are located in the glacial till and outwash region of the western plain in New York.

Agriculture in the two regions is quite different. There are just over a thousand farms in Boone County, 93% of which are crop farms. Three-quarters of them are commercial farms, defined here as a farm with gross sales over $10,000. There are just under 1,500 farms in Genesee and Wyoming Counties, where dairy is a dominant agricultural activity; 42% are dairy farms; the average herd size is 86 cows. About 62% of the farms are commercial farms. There are about 315 acres of cropland per farm in the Iowa region, compared with 218 acres per farm in the New York region (*1987 Census of Agriculture*).

As in many parts of the Corn Belt, agriculture in Boone County is dominated by corn and soybeans. These crops are grown on over 95% of the cropland acreage (*1987 Census of Agriculture*). About 90% of land in farms is cropland. Agriculture in Genesee and Wyoming Counties is less homogenous. Approximately 76% of the farmland is cropland, and corn and alfalfa are the two most important crops (*New York Agricultural Statistics, 1992-1993*), accounting for over half of the total cropland harvested (*1987 Census of Agriculture*). About half of the corn is for silage. Since about 42% of the farms are dairy farms, much of the crop production is for feed (*1987 Census of Agriculture*).

Soils in the two regions also differ. Many soils in Boone County are loam or clay loam (*Soil Survey of Boone County, Iowa*). Silt loam soils and gravelly silt loams are common in Genesee and Wyoming Counties (*Soil Survey of Genesee County, New York and Soil Survey of Wyoming County, New York*). In Boone County, over 75% of the cropland capable of growing corn is from hydrologic group B.[7] Soils are much more diverse in New York. Of the cropland suitable for corn in Genesee and Wyoming Counties, about 10% are from hydrologic group A, 39% are from hydrologic group B, and 51% are from hydrologic group C (National Resources Inventory, 1982; SCS Soils-5).

Because of the differential productivity and leachability among soils, the bioeconomic models are formulated for several soils. Five soils are used to represent the diversity of soils in the Iowa region, and seven soils reflect the diversity of the New York region (Table 1). The specific soils are chosen because of the availability of crop yield response data on each soil and their ranges of leaching and productivity (Table 1)[8]. These soils should capture major differences in leaching among soils (Knisel, 1993). Four of the five base soils in the Iowa region are hydrologic group B. Soil I-C is somewhat heavier, resembling many soils in

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[7] The hydrologic group, which reflects the capacity of a soil to permit infiltration (Smith and Cassel, 1991), reflects both its leachability and productivity (Knisel, 1993). Hydrologic groups are A, B, C, and D, with group A soils allowing the most infiltration and group D soils allowing the least. In general, soils in group A and B tend to leach more than group C and D soils, but group A and B soils are usually more productive (Knisel, 1993). Also, corn generally is not grown on hydrologic group D soils in either region (Soil Survey of Boone County, Iowa; Soil Survey of Genesee County, New York; Soil Survey of Wyoming County, New York).

[8] These characteristics can be found in SCS Soils-5 data.

Table 1. General Characteristics of the Base Soils in the Iowa and New York Regions

Base Soil	Soil Name	USDA Texture Class	Hydrologic Group	Average Organic Matter (%)	Average Slope	Drainage Classification
Iowa Region						
I-A	Tama	Silty Clay Loam	B	3.5	3	Well Drained
I-B	Clarion	Loam	B	4.0	3	Well Drained
I-C	Canisteo	Clay Loam	B/D	6.0	1	Poorly Drained
I-D	Nicollet	Loam	B	6.0	2	Moderately Well Drained
I-E	Dinsdale	Silty Clay Loam	B	4.0	3	Well Drained
New York Region						
N-A	Chenango	Gravelly Loam	A	4.0	3	Well Drained
N-B	Tunkhannock	Gravelly Silt Loam	A	3.0	5	Well Drained
N-C	Lima	Silt Loam	B	4.0	3	Moderately Well Drained
N-D	Unadilla	Silt Loam	B	4.5	9	Well Drained
N-E	Collamer	Silt Loam	C	3.5	4	Moderately Well Drained
N-F	Minoa	Very Fine Sandy Loam	C	4.5	0	Somewhat Poorly Drained
N-G	Bath	Channery Silt Loam	C	4.5	5	Well Drained

hydrologic group B but also some soils in group D.[9] In the New York region, two base soils are from hydrologic group A, two from group B, and three from group C.

Slope, drainage, and organic matter affect a soil's productivity and leachability (Shaffer *et al.*, 1991). As the slope increases, one expects more nitrogen runoff and less leaching; but the effects of slope are probably minor because nearly all the soils are relatively flat. Drainage does vary among the 12 base soils; it is related both to slope and hydrologic group (Table 1). A soil's organic matter affects productivity and nitrate leachate because organic matter is itself a source of nitrogen (Knox and Moody, 1991). The soils in the Iowa region have slightly higher organic matter content than those in the New York region (Table 1).

To compare nitrate reducing policies, soils suitable for corn and legume rotation within a region are matched to one of the base soils. Soils are grouped according to characteristics that most affect productivity and nitrate leaching. Data to allocate soils to the base groups are from the 1982 National Resource Inventory data.[10] Soil characteristics for individual soils are found using SCS Soils-5 data and county soil surveys. The procedures used to group the soils are in Table 2, as are the distributions of acreages for the empirical analysis. The most prominent soil in the Iowa region is I-B (47%), with between 20 and 25% in the other two major groups, I-D and I-C, respectively. In New York, soils N-D and N-F are the most prominent, with about 30% in each group.

Following Crutchfield *et al.* (1992), who classify nitrate leaching potential of soils using annual precipitation and hydrologic group, the primary sort on soils within regions in this study is by hydrologic group.[11] This classification should capture the major differences in soils, but other characteristics are used to classify soils, as well. In New York, soils are sorted by organic matter content because drainage and slope are highly related to hydrologic group. However, drainage is used to distinguish further between soils matched to N-F and N-G base groups because both these soils are in hydrologic group C soils with an average organic matter of 4%. In Iowa, since only one base soil (I-C) is not in hydrologic group B, and this soil is

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[9] No hydrologic group A soils are chosen because no yield response data were available for a hydrologic group A soil.

[10] National Resource Inventory data from 1982 rather than 1987 were used because 1987 data contained fewer sampling points, making county estimates of cropland acreages for individual soils less accurate.

[11] Annual precipitation is assumed to be the same on the different soils within a region and, as such, cannot be used to differentiate leaching potential.

heavier, all soils in Boone County that are not in hydrologic groups A or B are matched with I-C soil. Average corn yields from the county soil survey area are used to match soils to the remaining four base soils (Table 2).[12]

Prices and Production Costs

Estimates of the yearly costs and returns for growing corn and the legume crops are also an important part of the empirical analysis. Prices are assumed constant over time.

Table 2. Classification of Soils into the Base Soil Groups by Region

	Classification				Cropland in Study Regions	
Base Soil	Hydrologic Group	Organic Matter (%)	Drainage Class[a]	Average Corn Yield (bu./acre)	Percent[b]	Acres[c]
New York						
N-A	A	≥ 4	All		3.9	5,106
N-B	A	< 4	All		5.8	7,594
N-C	B	< 4	All		7.4	9,689
N-D	B	≥ 4	All		31.9	41,768
N-E	C	< 4	All		4.7	6,154
N-F	C	≥ 4	Not WD or MWD		28.0	36,661
N-G	C	≥ 4	WD or MWD		18.3	23,961
Iowa						
I-A	A or B			< 80	4.2	9,949
I-B	A or B			95 to < 110	47.2	111,811
I-C	not A nor B			All	24.7	58,511
I-D	A or B			≥ 110	19.3	45,719
I-E	A or B			80 to < 95	4.5	10,660

[a] WD denotes Well Drained and MWD denotes Moderately Well Drained soils.

[b] Percentages are calculated using cropland acreages from the 1982 National Resource Inventory data.

[c] Based on 236,000 acres of corn and soybean harvested in Iowa and 130,933 acres of corn and alfalfa acres harvested in New York (*1987 Census of Agriculture*). Detail may not add due to rounding.

[12] Of soils I-A, I-B, I-D, and I-E, soil I-D is the most productive, followed by I-B, I-E, and then I-A. These differences in soil productivity are demonstrated in the next section by the differences in the intercept dummy variables for the soils in the estimated corn response relationship.

For the Iowa models, 1991 prices are obtained from *Agricultural Prices, 1991 Summary*. The prices of corn grain and soybeans are \$2.35/bu. and \$5.55/bu, respectively. The inorganic nitrogen fertilizer cost of \$0.1305/lb. is based on \$214/ton anhydrous ammonia, which contains 82% nitrogen (Meisinger and Randall, 1991). Variable costs per acre excluding the cost for nitrogen fertilizer are \$135.54 and \$102.56 for corn and soybeans, respectively. These costs are from the comprehensive USDA production budgets constructed for 1985 and are available for Iowa in *Iowa Agricultural Statistics, 1987*. The variable cost of seed and chemicals in the USDA production budgets for soybeans, \$31.78/acre, however did seem low; it is increased to \$74.15/acre, reflecting estimates from *Iowa Agricultural Statistics, 1990*.[13] Based on these estimates and a corn yield of 135 bu./acre, the net revenue for corn grain, net of all variable costs except nitrogen fertilizer, is \$1.49/bu.

Most prices in the New York models are 1991 prices from *New York Agricultural Statistics, 1992-93*, but some information for the New York models is slightly more difficult to obtain than that for the Iowa models. For instance, many dairy farmers produce their own corn silage for feed, and the price reported in *New York Agricultural Statistics, 1992-93* is based on a "thin" market and may not accurately reflect the cost of corn silage for most farmers. Also, little is known about the average variable cost of spreading manure as a source of nitrogen.

To resolve these difficulties, a corn grain equivalent price, reflecting its opportunity cost, is used as the price for corn silage. Using the 1991 New York average corn grain yield/acre of 98 bu., the corn grain price of \$2.70/bu., and the corn silage yield/acre of 14 tons/acre, the New York corn grain equivalent price for silage is \$18.90/ton. This is lower than the reported corn silage price of \$23.80/ton. Inorganic nitrogen fertilizer costs are \$0.27/lb., based on \$243/ton urea and a concentration of 900 lbs. of nitrogen per ton of urea.

Variable costs per acre for corn silage, first-year alfalfa, and established alfalfa of \$191.39, \$252.13, and \$188.36, respectively, are from the 1990 the Pennsylvania State University production budgets reported in Greaser (1991). Assuming that corn silage production is 18 tons/acre, the variable net revenue for corn silage, net of all costs except nitrogen fertilizer, \$9.92/ton. The cost of applying a pound of nitrogen from manure of \$0.19 is based on worksheets from Cornell's Pro-Dairy program that assumes a cost of \$2.20 per mile hauled, a round-trip travel distance of three miles, 10 tons of manure being hauled per

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[13] Production costs in *Iowa Agricultural Statistics, 1990* were not used for the entire budget calculations because they do not distinguish between fixed and variable costs of production, whereas the USDA budgets do.

load, and 3.5 lbs. of nitrogen per ton of manure.[14] Finally, the price of alfalfa is $84.50/ton, the 1991 price from *New York Agricultural Statistics, 1992-93.*

Corn Yield Response to Nitrogen and Precipitation

Base-soil corn yields for grain in Iowa and silage in New York are estimated as a quadratic function (e.g., Hexem and Heady, 1978; Heady and Dillon, 1961) of nitrogen and water from data on yield, nitrogen available in the crop root zone (both from fertilizer and non-fertilizer sources), and precipitation. Data are from several sources.

Iowa data for corn response to nitrogen fertilizer application on the five base soils are from agronomic experiments conducted by the Department of Agronomy, Iowa State University during 1986 and 1987 (McClenahan, 1987). The data set contains 629 observations. At an experimental site, data typically consist of six nitrogen fertilization rates, varying from zero to 200 lbs./acre in 25 to 40 lb. increments, with four repetitions of each rate. The county locations of the experimental sites for the 1987 trials are assumed the same as for the 1986 trials. New York data for corn silage response to nitrogen fertilization on the seven base soils are from agronomic experiments conducted from 1985 to 1991 by Klausner in the Department of Soil, Crop, and Atmospheric Sciences, Cornell University. The 276 observations include four repetitions of six fertilization rates ranging from zero to 225 lbs./acre.

Since the total amount of nitrogen in the crop root zone and precipitation were not collected for either data set, these data were collected differently. Precipitation data in New York for the nearest weather stations are from the Northeast Regional Climate Center, Cornell University. In Iowa, the only geographic information recorded is the county in which the 1986 experiments were conducted. Thus, Iowa precipitation data are regional Iowa data from the World Weather Disk. Monthly precipitation levels in 1986 and 1987 for the corn response functions are assigned by matching the county locations of the agronomic experiments with the regions defined by the World Weather Disk. Precipitation during the growing season (April-September) is used in the corn yield response functions.

The remaining variable needed to estimate the corn production functions is the amount of nitrogen in the crop root zone. There has been little empirical research to determine the exact amount and movement of nitrogen in the crop root zone on specific soils. Researchers,

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[14] The variable cost of nitrogen from manure consists of the labor, fuel, and machinery costs of spreading which are affected by the distance and number of trips to the field, the nitrogen content of the manure, and the spreading rate (Pro-Dairy worksheet).

however, have developed a number of nutrient simulation models (e.g. GLEAMS (Leonard *et al.*, 1987), EPIC (Williams *et al.*, 1984), NLEAP (Shaffer *et al.*, 1991), CERES (Jones and Kiniry, 1986), LEACHN (Hutson and Wagenet, 1991), etc.) designed to trace the amount and movement of nitrogen in the crop root zone.

NLEAP (Nitrogen Leaching and Economic Analysis Package) is used here to find the amount of nitrogen in the crop root zone other than that from fertilizer. It is also used below to obtain data for estimating the nitrate leaching equations. NLEAP was selected primarily because it is designed to find monthly or annual site-specific estimates of nitrate leaching using basic soils and climate data readily available (Shaffer *et al.*, 1991). Other nutrient simulation models typically require more detailed data and trace nitrate movement on either an hourly, daily, or monthly basis. This additional detail would be of little use in the bioeconomic models to trace annual nitrogen movement on specific soils.

The model was run on each of the 12 base soils using primarily the climate and soils databases developed specifically for NLEAP. Other data needed were found in *Soil Survey of Boone County, Iowa; Soil Survey of Genesee County, New York; Soil Survey of Wyoming County, New York*; and Follett *et al.* (1991). NLEAP separately distinguishes the sources of nitrogen in the root zone, which include that from the soil's organic matter and precipitation, as well as nitrogen fertilizer and residual nitrogen. These estimates of other sources of nitrogen are combined with the fertilization rates in the two experimental data sets to approximate the total nitrogen available in the crop root zone.

The estimated corn yield response functions to nitrogen available in the crop root zone and growing season precipitation are given in Table 3. In New York, separate production functions are estimated for the different hydrologic groups to account for differential productivity.[15] Because all base soils but one in Iowa are from the same hydrologic group, the production function in Iowa contains only dummy variables to account for productivity differences.

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[15] Originally, the production function was estimated separately for group A soils, but the parameters for x, x^2, and xz each had t-ratios less than two and the parameter for x was negative. Partially accounting for this is the fact that only 52 observations were available for the group A soils, as compared to 112 observations for both groups B and C. The production function for hydrologic group A is estimated using pooled data with intercept dummy variables accounting for differences between hydrologic groups.

Table 3. Corn Yield Response to Nitrogen in the Crop Root Zone and Precipitation[a]

New York--Hydrologic Group A[b] $(n = 276,\ R^2 = 0.50)$

$$C(x,z) = \underset{}{-10.16} + \underset{(2.63)}{1.59\, d_A} - \underset{(-4.56)}{2.90\, d_B} + \underset{(7.56)}{0.1918\, x} - \underset{(-5.41)}{0.0016\, x^2}$$

$$\underset{(-0.38)}{-0.2224\, z} + \underset{(2.63)}{0.0348\, z^2} - \underset{(-4.45)}{0.0032\, xz}$$

New York--Hydrologic Group B $(n = 112,\ R^2 = 0.76)$

$$C(x,z) = 71.24 + \underset{(7.32)}{0.2218\, x} - \underset{(-5.32)}{0.00019\, x^2} - \underset{(-5.25)}{7.8497\, z} + \underset{(6.30)}{0.1988\, z^2}$$

$$- \underset{(-3.60)}{0.0036\, xz}$$

New York--Hydrologic Group C $(n = 112,\ R^2 = 0.61)$

$$C(x,z) = -62.20 + \underset{(3.76)}{0.1166\, x} - \underset{(-4.53)}{0.00018\, x^2} + \underset{(4.27)}{7.2716\, z} - \underset{(-4.68)}{0.2165\, z^2}$$

$$- \underset{(1.10)}{0.0014\, xz}$$

Iowa[c] $(n = 629,\ R^2 = 0.57)$

$$C(x,z) = -490.39 - \underset{(-8.58)}{36.80\, d_1} + \underset{(3.18)}{11.63\, d_2} - \underset{(0.41)}{2.59\, d_3} + \underset{(4.27)}{33.00\, d_4}$$

$$\underset{(9.47)}{+2.35\, x} - \underset{(-7.33)}{0.00209\, x^2} + \underset{(2.40)}{11.16\, z} + \underset{(0.22)}{0.02041\, z^2} - \underset{(-6.04)}{0.0246\, xz}$$

[a] C denotes corn yield (tons of silage per acre in New York and bushels of grain per acre in Iowa). The amount of nitrogen in the crop root zone is x (lbs./acre), and April through September precipitation is z (inches).

[b] This function is used for hydrologic group A soils, but it is estimated using pooled data from all three hydrologic groups. To account for differences between groups, intercept dummy variables are used. The dummy variables for groups A and B are denoted by d_A and d_B, respectively; the intercept corresponds with group C soils.

[c] Intercept dummy variables for I-A, I-B, I-C, and I-D soils are denoted by d_1, d_2, d_3, and d_4. The intercept alone is that for I-E soil.

Although the R^2 values for the estimated production functions are somewhat low, nearly all of the signs on the parameters are as expected; the t-ratios are generally greater than two. In the Iowa function, the sign on the parameter for precipitation squared is unexpectedly positive, indicating corn yields increase at an increasing rather than a decreasing rate with precipitation. But the t-ratio for this parameter is low. The t-ratio for the dummy variable for I-C soil is low, as well, 0.22; but the soil dummy variables as a whole significantly affect corn yield (F = 53.23). In the estimated New York models for hydrologic groups A and B, the linear and squared precipitation parameters are also incorrectly signed if precipitation increases corn yields at a decreasing rate. However, if one evaluates the marginal product of corn with respect to precipitation at the means for the nitrogen and precipitation data, then the marginal products are positive, as one would expect.[16]

To obtain some idea of the behavior of these production functions, the elasticities of production with respect to nitrogen in the root zone are evaluated at the means of the nitrogen and precipitation data. These elasticities are 0.58, 0.53, and 0.43 for the hydrologic group A, B, and C functions in New York, respectively. In the estimated function for Iowa, the elasticity of production with respect to nitrogen is 0.96. In addition, optimal static fertilizer application rates and corn yields are determined.[17] Results are in Table 4.

By way of comparison, the average fertilization rate in Iowa is 128 lbs./acre; average corn yield is 118 bu./acre (*Iowa Agricultural Statistics, 1990*). In New York, the average corn silage yield is 14 tons/acre (*New York Agricultural Statistics, 1992-1993*), and the fertilizer recommendation for continuous corn is 120 lbs./acre (*1994 Cornell Recommends for Integrated Field Crop Management*). Not surprisingly, estimates are larger than the state averages or recommendations because they are based on experimental data. Typically, experimental yields are thought to be greater than those on farms of better or more intensive management conditions; field and harvest losses are probably lower as well.

While these estimates can be explained, they may distort the results from the bioeconomic models, especially the larger yields, by inflating farm returns and providing

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[16] At the means for the nitrogen variable, the marginal products of corn with respect to precipitation are positive for precipitation greater than 14.0 and 22.0 inches for the hydrologic group A and B functions, respectively. The mean precipitation levels for the group A and B functions are 19.6 and 24.2 inches, respectively.

[17] Mathematically, this problem is: Max $p_c\ C(x,z^*) - rx^a$, where x is equal to the fertilizer applied, x^a, plus other nitrogen in the root zone, and z^* is average precipitation.

Table 4. Optimal Fertilizer Application Rates and the Resulting Corn Yields in a Static Framework Using the Estimated Corn Yield Response Functions

Soil	Nitrogen Applied (lbs./acre)	Corn Yield[a] (yield/acre)
Iowa		
I-A	181	121
I-B	163	146
I-C	129	155
I-D	142	190
I-E	173	157
New York		
N-A	211	25.1
N-B	217	25.1
N-C	157	20.6
N-D	141	20.6
N-E	172	25.2
N-F	153	25.2
N-G	199	25.2

[a] Bushels of corn grain on the Iowa soils and tons of corn silage on the New York soils.

inaccurate estimates of the effects of restricting nitrate leachate on different soils. Thus, in the objective functions of the bioeconomic models, the production functions are multiplied by 0.8 and 0.9, respectively, to reflect 20% field and harvest losses in New York and 10% in Iowa,[18] the former accounting for greater transportation and storage losses for corn silage (Bolsen and Ilg, 1980). The high predicted nitrogen application rates are less worrisome than yields because its cost is such a small proportion of total production cost, and the relative effects on corn yields and leachate by soil probably remain valid.

Soybean and Alfalfa Yield Response to Precipitation

The bioeconomic models also require production functions for alfalfa and soybean response to precipitation for each soil. Unfortunately, soil-specific data for these crops are unavailable and the responses of alfalfa and soybeans to precipitation are assumed to be the same for all soils in the region. To obtain the expected legume response, we use county

[18] Others have adjusted experimental yields or yields under best management practices (BMP) downward to depict actual farm yields. Knoblauch and Milligan (1981) decrease BMP corn silage yields from SCS Form 5 information by 25 to 37%.

average yields. The average soybean yield for 1979 through 1987 is 41.1 bu./acre (*Iowa Agricultural Statistics*). In Wyoming and Genesee Counties, only county average yields of all alfalfa stands are reported in *New York Agricultural Statistics*; separate yields for first-year and established alfalfa are not available. Also, 1992 county average yields (2.4 and 2.3 tons/acre, respectively) are considered low by farm managers because the data include lighter alfalfa mixes, such as alfalfa and orchard grass (Knoblauch and Milligan, 1994). To reflect these conditions, expected alfalfa yields are assumed to be 3 tons/acre and 4 tons/acre for first-year and established alfalfa, respectively. Both these yields are set at the lower end of the three to six tons/acre range in the *Cornell Field Crops Handbook* to reflect harvest and field losses.

Nitrogen Leaching

Another integral component of the bioeconomic model is the equation for leachate. Nitrogen leached below the crop root zone annually is given by: $L = g(z_{12})NAL$, where $g(z_{12})$ is between zero and unity and depends on 12-month precipitation, denoted z_{12}. NAL is the nitrogen in the crop root zone neither uptaken by the plant nor denitrified and, thus, available for leaching.[19] We set $g(z_{12}) = 1 - \exp(-\lambda z_{12})$, which bounds it between zero and one and makes it increasing in precipitation. This cumulative exponential form is also similar to that of EPIC, another nitrate leaching simulation model (Williams *et al.*, 1984).

To estimate this leaching equation we need data for L, NAL, and z_{12}. Since actual data on leachate are unavailable for the base soils, data for L are simulated for a reasonable range of z_{12} and NAL also using NLEAP. These simulated data are used to estimate the parameter, λ, of the equation for L. For each soil, 110 observations are generated by varying annual precipitation in two-inch increments from 24 to 44 inches for Iowa soils and 28 to 48 inches for the New York soils. These ranges bracket the two 30-year annual precipitation levels for central Iowa and the Portageville weather station in Wyoming County. Fertilizer application rates are varied from 20 to 200 lbs./acre in 20 lb. increments for each precipitation level.[20]

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[19] From before, NAL is equal to $(1-\gamma_2)x - \gamma_3 x^a$ for the Iowa models. In the New York models, NAL differs slightly because both manure and inorganic nitrogen fertilizer are sources of nitrogen. Manure denitrifies at approximately twice the rate of inorganic fertilizer (Meisinger and Randall, 1991). Therefore, NAL for the New York models is $(1-\gamma_2)x - \gamma_3 x^{fa} - 2\gamma_3 x^{ma}$.

[20] NLEAP estimates NAL from data on annual precipitation and fertilizer applied, accounting for soil properties and crops. NAL is the nitrogen in the root zone after plant uptake and denitrification. This information is used to estimate the amount of nitrogen leached.

One can estimate λ in the leaching equation by non-linear least squares (NLS); or by ordinary least squares (OLS) from the logarithm of the inverted function which is linear in λ:

$$\ln\left[\frac{NAL - L}{NAL}\right] = -\lambda z_{12}.$$

Both estimates of λ are in Table 5, but the NLS are used in the empirical applications because this procedure minimizes the sum of squared errors about L directly. The slightly larger OLS estimates of λ would imply slightly larger leaching levels.

Table 5. Estimated Parameters for the Leaching Equations

Soil	Estimation Method	λ	t-ratio	R^2 [a]
N-A	NLS	0.029440	83.81	0.93
	OLS	0.030857	95.50	0.84
N-B	NLS	0.010155	90.72	0.91
	OLS	0.019034	95.90	0.84
N-C	NLS	0.006871	44.13	0.68
	OLS	0.007064	43.26	0.59
N-D	NLS	0.023017	44.99	0.77
	OLS	0.024903	51.51	0.69
N-E	NLS	0.005567	31.73	0.60
	OLS	0.005713	33.06	0.56
N-F	NLS	0.009497	30.73	0.59
	OLS	0.009982	33.30	0.56
N-G	NLS	0.006510	31.69	0.63
	OLS	0.006707	33.28	0.56
I-A	NLS	0.006365	37.72	0.68
	OLS	0.006514	39.57	0.64
I-B	NLS	0.007171	37.50	0.68
	OLS	0.007364	39.56	0.64
I-C	NLS	0.002421	19.37	0.48
	OLS	0.002451	19.62	0.43
I-D	NLS	0.006188	37.66	0.67
	OLS	0.006335	39.55	0.64
I-E	NLS	0.006492	37.75	0.68
	OLS	0.006647	39.62	0.64

[a] The R^2 values indicate the goodness of fit. However, they cannot be interpreted as true R^2 values either because λ is estimated using NLS or because λ is estimated using OLS without an intercept (Judge, *et al.*, 1988).

Since L is increasing in λ, the estimates of λ are consistent with general expectations. The smaller values for λ for the heavy soil in Iowa, I-C, indicate less leaching potential than on the lighter soils. Likewise, in New York the lighter soils from hydrologic groups A and B, i.e. soils N-A, N-B, N-C, and N-D, generally have larger estimates of λ than the hydrologic group C soils, i.e. soils N-E, N-F, and N-G. However, the relative magnitude of λ for N-C, a group B soil, indicates that it leaches more than N-B soil, a group A soil; for N-D, another B soil, leaches less than N-E and N-G, both hydrologic group C soils.

The estimated leaching equations appear to both fit the data well and predict leaching well (Table 5). The t-ratios for the estimated parameters are large. The R^2 values generally indicate good overall fits, although they are not true R^2 values either because λ is estimated using NLS or OLS without an intercept (Judge *et al.*, 1988). The estimated leaching equations predict leachate well for all fertilizer levels at precipitation levels near the middle of the precipitation ranges used to generate the data. For the higher and lower extremes of the precipitation data, the leaching equations do not predict as well. Typically, given any fertilizer level, the estimated leaching equations over-predict leachate at low precipitation levels and under-predict leachate levels at high precipitation levels, acting to pull leachate levels closer to the mean. (See Thomas (1994) for details). Since this predictive behavior is consistent across all soils, the bias is not terribly disturbing because for the purposes of this study the relative leaching potential across soils is affected very little. In addition, the relatively high fertilizer levels from the corn yield response functions should compensate for the implied under-prediction of leachate at high precipitation levels.

The Distribution of Precipitation

Probability distributions for two random precipitation variables, six-month and annual precipitation, must also be estimated. Given the nature of precipitation data, any probability function used to estimate these distributions must be for a non-negative random variable and allow for possible asymmetry in the distribution. The highly flexible beta density accommodates both considerations and also contains many other families of distributions as special cases of itself (Johnson and Kotz, 1970, pp. 37-56). The beta density for a random variable z_i is:

$$f(z_i;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \frac{z_i^{\alpha-1}(z_u - z_i)^{\beta-1}}{z_u^{\alpha+\beta-1}} \quad \text{for } 0 \le z_i \le z_u;\ \alpha,\beta > 0$$

where

$$\Gamma(\Psi) = \int_0^{\infty} e^{-t} t^{\Psi - 1} dt$$

and z_u is the upper bound on the random variable.

The magnitude and relative magnitude of the parameters, α and β, affect all moments of the beta distribution. The mean of the distribution, μ, is given by $\frac{\alpha z_u}{\alpha + \beta}$; the standard deviation, σ, is given by $\left[\frac{\alpha \beta z_u^2}{(\alpha + \beta)^2 (\alpha + \beta + 1)} \right]^{1/2}$; and the skewness coefficient of the distribution, τ, is given by $\frac{2\alpha\beta(\beta - \alpha) z_u^3}{\sigma^3 (\alpha + \beta)^3 (\alpha + \beta + 1)(\alpha + \beta + 2)}$. *Ceteris paribus*, increasing α raises the expected z_i, and increasing β decreases expected z_i. The standard deviation of z_i increases as either α or β increase. Skewness depends on the relative magnitude of the parameters. The distribution is symmetric for $\alpha = \beta$. For $\alpha > \beta$, the distribution is skewed left. Conversely, $\alpha < \beta$ indicates that the distribution is skewed right. Thus, an increase in the absolute magnitude of α, *ceteris paribus*, causes the distribution to be skewed more to the left; and an increase in the absolute magnitude of β causes the distribution to be skewed more to the right.

Estimates of the beta density parameters are obtained using maximum likelihood (ML). The ML estimate of a parameter is that value of a parameter for which the current sample, $z_1, \ldots, z_n$, would most likely be drawn if the ML estimate is the population parameter of the distribution (Casella and Berger, 1990, p. 290).

If precipitation is identically and independently distributed, the likelihood function is:

$$L(\alpha, \beta; z_1, \ldots, z_n) = \left[\frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \right]^n \cdot \frac{\prod_{i=1}^{n} z_i^{\alpha - 1} (z_u - z_i)^{\beta - 1}}{z_u^{n(\alpha + \beta - 1)}}.$$

The log likelihood used in maximum likelihood estimation is:

$$\ln L = n \ln \left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \right] + (\alpha-1)\sum_{i=1}^{n} \ln z_i + (\beta-1)\sum_{i=1}^{n} \ln(z_u - z_i) - n(\alpha+\beta-1)\ln z_u .$$

When maximizing the likelihood function, standard differentiation with respect to α and β is not possible because the parameters are contained in the gamma functions. Dai *et al.* (1993), estimate a beta density for soil moisture by calling an IMSL, FORTRAN subroutine to numerically approximate integrals within MINOS, a FORTRAN based optimization program. This procedure, however, is cumbersome and requires extensive, original FORTRAN code. As an alternative, Casella in the Department of Plant Breeding and Biometry, Cornell University, suggested that Mathematica, which calls the gamma function directly (Wolfram, 1991), be used for the maximum likelihood estimation.

To obtain the ML estimates for the six- and 12-month precipitation variables, data for a number of years are needed for both variables, as are upper bounds on precipitation. The two 30-year precipitation data series described above are used for this purpose. [21] The upper bound on precipitation is set so that it covers the precipitation ranges of all weather stations used in the corn-nitrogen-precipitation data.

The maximum likelihood estimates, means, standard deviations, and skewness coefficients for the distributions are reported in Table 6. As one would expect, the means and standard deviations for annual precipitation are greater than those for 6-month precipitation. Mean annual precipitation is slightly greater in New York than in Iowa, but the standard

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[21] Information from Iowa for six-month and annual precipitation, respectively, are:

$\sum_{i=1}^{30} \ln z_{6,i} = 94.66$, $\sum_{i=1}^{30} \ln(z_{6,u} - z_{6,i}) = 69.74$, $n = 30$, and $z_{6,u} = 35$, and

$\sum_{i=1}^{30} \ln z_{12,i} = 104.80$, $\sum_{i=1}^{30} \ln(z_{12,u} - z_{12,i}) = 67.91$, $n = 30$, and $z_{12,u} = 45$.

For New York we have:

$\sum_{i=1}^{30} \ln z_{6,i} = 88.38$, $\sum_{i=1}^{30} \ln(z_{6,u} - z_{6,i}) = 89.68$, $n = 30$, and $z_{6,u} = 40$, and

$\sum_{i=1}^{30} \ln z_{12,i} = 105.50$, $\sum_{i=1}^{30} \ln(z_{12,u} - z_{12,i}) = 96.99$, $n = 30$, and $z_{12,u} = 60$.

Table 6. Maximum Likelihood Estimates and Distributional Characteristics of the Precipitation Variables

Precipitation Variable	α_{ML}	β_{ML}	Mean[a]	Standard Deviation[a]	Skewness[a]	$D\sqrt{n}$[b]
Iowa						
12-month	6.80	2.32	33.6	6.2	-0.64	0.89
6-month	9.19	4.28	23.9	4.3	-0.39	0.41
New York						
12-month	17.66	13.42	34.1	5.2	-0.09	0.71
6-month	9.00	9.38	19.6	4.5	0.02	0.80

[a] Formulas for these characteristics of the beta density are given above in the text.

[b] $D\sqrt{n}$ is the test statistic for the Kolmogorov-Smirnov test for goodness of fit.

deviation is smaller in New York. All else equal, leachate may be greater in New York. But, on the other hand, leachate will vary less due to random variation in precipitation in New York than in Iowa because of the smaller standard deviation of precipitation in New York. For the 6-month distributions that affect crop yields, mean precipitation is slightly greater in Iowa than in New York, and the standard deviations are approximately the same. The distributions in Iowa are skewed left, indicating that precipitation near z_u is more frequently observed than precipitation near zero. In New York, the skewness coefficients are near zero, especially for 6-month precipitation, which indicates that the distributions are nearly symmetric.

After obtaining the ML estimates and selected moments, the surface of the log-likelihood function was examined to assure that the estimates are not local maxima. Specifically, the log-likelihood function was plotted in Mathematica using first a broad range of the parameters (zero to 100) and then a more narrow range about the ML estimates (generally from near 0 to 15 or 5 to 20, depending on the value of the ML estimate). In all cases, the surface of the log-likelihood function appears to be generally well-behaved, i.e. there appears to be only a single local and global maximum. Thomas (1994) contains a detailed discussion of this issue.

To test the hypothesis that precipitation is indeed distributed beta, a goodness of fit test is needed. Two such tests commonly used are the Chi-square test (Snedecor and Cochran, 1989, pp. 76-79) and the Kolmogorov-Smirnov test (Spanos, 1986, pp. 228-229). The Kolmogorov-Smirnov test for goodness of fit is used here rather than the Chi-squared test because the Kolmogorov-Smirnov hypothesis test evaluates the fit of the distribution at all sample points. The Chi-squared test, on the other hand, evaluates the fit of the distribution over intervals of the sample. Outcomes of the Chi-squared hypothesis test depend explicitly on how these intervals are specified, which makes the test somewhat subjective. No such subjectivity is involved in the Kolmogorov-Smirnov test.[22]

The test statistics for the four precipitation densities, $D\sqrt{n}$, are given in Table 6. All four test statistics are less than $y_{.10} = 1.23$, indicating that the beta distributions with the ML estimates cannot be rejected as the true distributions for the random variables. The beta densities appear to be consistent with the precipitation data in both study regions.

The Chance Constraint on Nitrate Leachate

With the leaching equations and distribution of 12-month precipitation now estimated, the chance constraint can be manipulated into its final form. Equations (16) and (17) can be substituted into equation (18) to give:

$$\text{Prob}[\delta_1 g(z_{12})NAL_1 + \delta_2 g(z_{12})NAL_2 \geq L_U] \leq \alpha$$

where $NAL_i = (1-\gamma_2)x_i - \gamma_3 x_i^a$ and $g(z_{12}) = 1 - \exp(-\lambda z_{12})$. Since $g(z_{12})$ is invertible and separable, the left hand side can be rewritten as:

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[22] The Kolmogorov-Smirnov hypothesis test for goodness of fit is:
H_0: $f(z; \alpha,\beta) = f(z; \alpha_{ML},\beta_{ML})$
H_1: $f(z; \alpha,\beta) \neq f(z; \alpha_{ML},\beta_{ML})$
Define the empirical cumulative distribution, $F_n^*(z)$, as
$F_n^*(z) = (1/n)(\text{number of } z_i\text{s} \leq z)$
where the z_is are the iid precipitation values from the sample, $z_1,\ldots,z_n$. Then define:
$D = \max |F_n^*(z) - F(z; \alpha_{ML},\beta_{ML})|$
The test statistic for the Kolmogorov-Smirnov test for goodness of fit is $D\sqrt{n}$. As $n \rightarrow \infty$, the limiting cumulative distribution of $D\sqrt{n} = y$ is:

$$F(y) = 1 - 2\sum_{k=1}^{\infty} \exp(-2k^2y^2) \quad \text{for } y \in \Re_+$$

Using this cumulative distribution, one can determine y_α such that $\Pr\{y > y_\alpha\} = \alpha$ and reject H_0 at the $100(1-\alpha)\%$ level of significance if $y > y_\alpha$ is observed. Common values for y_α are $y_{.10} = 1.23$, $y_{.05} = 1.36$, and $y_{.01} = 1.67$.

$$\text{Prob}\left[z_{12} \geq -\frac{1}{\lambda}\ln\left[1-\frac{L_U}{\delta_1 NAL_1+\delta_2 NAL_2}\right]\right].$$

Using the density estimated above, $z_{12,\alpha}$ can be found such that $\text{Prob}[z_{12} \geq z_{12,\alpha}] = \alpha$. The chance constraint becomes:

$$z_{12,\alpha} \geq -\frac{1}{\lambda}\ln\left[1-\frac{L_U}{\delta_1 NAL_1+\delta_2 NAL_2}\right]$$

which reduces to:

$$(1-\exp(-\lambda z_{12,\alpha}))[\delta_1 NAL_1+\delta_2 NAL_2] \leq L_U.$$

This latter equation is the form of the chance constraint explicitly used in the bioeconomic model for given values of α, L_U, and the calculated value of $z_{12,\alpha}$. Two levels of α are used to form separate, chance-constrained empirical models. These values are 0.05 and 0.25, i.e. leachate is restricted so that the probability that leachate exceeds an upper bound, L_U, is 0.05 in one model and 0.25 in another model. The corresponding values for $z_{12,\alpha}$ are $z_{12,0.05} = 42.1$ and $z_{12,0.25} = 38.3$ inches in Iowa and $z_{12,0.05} = 42.6$ and $z_{12,0.25} = 37.8$ in New York. L_U is parametrically varied with each level of α to cover a wide range of leaching scenarios.

Other Parameters and Restrictions

Remaining parameters in the bioeconomic models are the discount rate and the parameters that affect the amount of nitrogen in the crop root zone: γ_1, γ_2, γ_3, N_m, and N_f. The discount rate is assumed to be 5% in all models. The fraction of nitrogen in the root zone on corn in year t carried over to year t+1 is given by γ_1. Unknown nitrogen losses (losses other than plant uptake, denitrification, and leaching) are accounted for in γ_1. Corn uptakes approximately 60% of nitrogen available, implying $\gamma_2 = 0.6$ (Bock and Hergert, 1991). Denitrification rates of inorganic nitrogen fertilizer, γ_3, depends on the soil organic matter content and drainage classification (Meisinger and Randall, 1991), and are estimated to range from 0.1 to 0.175 in New York and 0.1 to 0.25 in Iowa. Nitrogen mineralized by the soil organic matter or accumulated through precipitation, N_m, varies by soil (Shaffer *et al.*, 1991). These values are obtained using NLEAP.

Researchers know little about the amount of nitrogen fixed by legume crops on specific soils (Schepers and Mosier, 1991). The amount of nitrogen fixed by a previous year's soybean crop varies from approximately 50 to 85 lbs./acre in the Midwest (Evans and Barber, 1977). Schepers and Mosier (1991) report that the recommendations for several Midwestern states are for nitrogen fertilizer application to be reduced by 30 lbs./acre in a year following soybean production. Another "rule of thumb" is that the amount of nitrogen fertilizer applied per acre be reduced by one pound for every bushel of soybean yield per acre in the previous year (Schepers and Mosier, 1991). Given the uncertainty surrounding N_f, it is jointly manipulated along with the parameter for the unknown sources of nitrogen loss, γ_1, so that the reduction in nitrogen fertilizer on corn following soybeans is in the range of 30 to 85 lbs. from the studies reported above. As is seen below, values of $N_f = 80$ and $\gamma_1 = 0.4$ yield a reasonable fertilizer credit from 30 to 45 lb./acre.

According to research by Evans and Barber (1977), values for nitrogen fixed by alfalfa in the New York models in the year prior to planting corn, N_f, range from 115 lbs./acre to more than 300 lbs./acre. Fertilizer credits from a previous year's alfalfa vary from 100 to 200 lbs./acre, according to *1994 Cornell Recommends for Integrated Field Crop Management* and the *Cornell Field Crops Handbook* (1978). As is the case for the Iowa models, γ_1 and N_f are jointly manipulated in the empirical models so that a fertilizer credit of 100 to 200 lbs./acre is achieved. Values of $N_f = 175$ and $\gamma_1 = 0.4$ result in reasonable fertilizer credits from 125 to 150 lbs./acre.

Finally, a restriction is needed on the amount of manure that a farmer can spread as a source of nitrogen in the New York models. In the previous section on farm prices and costs, the cost of nitrogen from manure is relatively cheaper than inorganic nitrogen fertilizer, yet farmers generally supplement manure with inorganic nitrogen fertilizer. This is due to the fact that farmers generally have a limited supply of manure. For this reason, per acre manure application rates are restricted to be no more than 15 tons per acre, a typical rate for spreading manure in New York (Schmit, 1994). Assuming each ton of manure contains 3.5 lbs. of nitrogen (*1994 Cornell Recommends for Integrated Field Crop Management*), the amount of nitrogen fertilizer from manure is restricted to be no more than 52.5 lbs./acre.

SOLVING THE BIOECONOMIC MODELS

For a number of years, bioeconomic models have been used to study a wide variety of problems, ranging from fishing, hunting, and timber harvesting rates (Conrad, 1992; Clark, 1985; Reed, 1984; Berck, 1979), optimal groundwater extraction and quality (Knapp, 1984; Gisser and Sanchez, 1980), and to pest and weed control and nutrient management in crop production (Lazarus and Dixon, 1984; Taylor and Burt, 1984; Johnson *et al.*, 1991). Most empirical models involving a small number of state and control variables were solved using the forward or backward induction methods of dynamic programming (Bellman, 1957) or by the calculus of variations, whereby models are formulated using a Hamiltonian or an inter-temporal Lagrangean function (Kamien and Schwartz, 1991).

Larger models, which also include other complexities such as non-linearities and the presence of both equality and inequality constraints, cannot be solved readily with these traditional methods. The bioeconomic models developed here fall into this category, their complexity rivaling that of Standiford and Howitt's (1992) chance-constrained model of rangeland management. Recognizing, as they did, that our models are large, inter-temporal Lagrangean problems (Canon, *et al.*, 1970), we also code them in GAMS, a modelling interface to access a FORTRAN based general non-linear solver called MINOS (Brooke *et al.*, 1992).

Despite the availability of non-linear solvers such as MINOS, however, they must be applied with care. The major challenge is to formulate the model so that the routine converges to a local, as well as global optimum. On balance, this was only a minor concern, but we did perform a number of experiments with the models to ensure that the routines was converging properly. Thomas (1994) discusses this strategy in detail. In summary, we selected initial values and bounds on the variables carefully, and solved the models for a wide range of initial conditions to guarantee that the routine would converge to the same solution. Scaling seemed not to be an issue, perhaps in large measure due to specifying the models on a per acre basis. Although some initial experiments appeared problematic, the difficulties were resolved by setting very small non-zero lower bounds on the endogenous variables and by decreasing the optimality tolerance in MINOS from the default of 1.0E-6 to 1.0E-9. Finally, the same solutions were obtained using CONOPT, another non-linear solver supported by the GAMS interface.

The Base Solutions

To initiate the empirical analysis, we solved models for both the Iowa and New York soils using initial conditions and starting values given in Table 7; γ_1 = 0.4, N_f = 50 lbs./acre for Iowa, and N_f = 125 lbs./acre for New York. There are no constraints on nitrate leachate. A 20-year time horizon is long enough for the solutions not to depend heavily on initial conditions and the terminal period. Initial conditions and starting values are selected based

Table 7. Initial Conditions and Starting Values for the Bioeconomic Models

Iowa	New York
$x_{1,t}^{a} = 115$	$x_{1,t}^{fa} = 0$
$x_{2,t}^{a} = 150$	$x_{1,t}^{ma} = 52.5$
$x_{2,t} = 300$	$x_{2,t}^{fa} = 100$
$\delta_{1,t} = 0.300$	$x_{2,t}^{ma} = 52.5$
$\delta_{2,t} = 0.300$	$x_{2,t} = 300$
$\delta_{3,t} = 0.400$	$\delta_{1,t} = 0.300$
	$\delta_{2,t} = 0.301$
	$\delta_{3,t} = 0.133$
	$\delta_{4,t} = 0.133$
	$\delta_{5,t} = 0.133$

Note: Initial conditions are for year zero; starting values are for years one through 20. The variables are described above in the text.

on current practices, with soybeans (alfalfa) accounting for 40% of the land in corn and soybeans in Iowa and in corn and alfalfa in New York. Non-fertilizer sources of nitrogen can account for 100 to 200 lbs. of nitrogen in the crop root zone (Meisinger and Randall, 1991). The values for N_f and γ_1 are chosen because they result in reasonable fertilizer credits for the legume crops.

Two sets of base models are described, ones with and without minimum crop rotation restrictions imposed. The ones with minimum rotations imposed are used as the base for policy comparisons, but when compared with solutions where no rotation restrictions are imposed, we obtain a good estimate of the inherent benefits to the environment resulting from growing crops in rotation. The difference in objective function values is the opportunity cost of the rotation, which reflects the minimum value of the pest control provided by the rotation. In addition, one can compare the expected annual nitrate leachate values between the models to determine the reduction in leachate that results from growing the crops in rotation.

Models Without Crop Rotation Restrictions

To characterize the solutions to the bioeconomic models without restrictions on crop rotations, nearly complete solutions to the models for I-B soil in Iowa and N-E soil in

New York are given in Tables A1 and A2 of Appendix A.[23] Solutions to the models for the other base soils in the two regions are similar. Average annual production, fertilizer, and expected nitrate leachate for all soils are given in Table 8.

For these conditions, the models adjust to continuous corn.[24] Grain yields per acre (after field and harvest losses) range from 110 bu./acre on I-A soil to 170 bu./acre on I-D soil. Silage yields (after losses) are around 21 tons/acre on the better group A and B soils. On the poorer group C soils, yields average 16 tons/acre. Fertilizer application rates (x_2^a) are high as expected, ranging from 135 to 210 lbs./acre. Nitrogen credits from legume crops (x_2^a - x_1^a) are around 125 lbs./acre for alfalfa and 35 lbs./acre for soybeans. Expected nitrate leachate on most soils in Iowa is between 25 and 30 lbs./acre, with the exception of the heavier, I-C soil with only 9 lbs./acre. In New York, some of the lighter hydrologic group A and B soils leach as much as 60 lbs./acre, whereas the heavier hydrologic group C soils typically leach only 20 lbs./acre. The more fertile soils in Iowa are more profitable than those in New York, with expected 20-year net farm revenues typically around $2,200/acre and $1,800/acre, respectively.

Characterizing the dynamics of the bioeconomic models, the solutions appear to adjust to approximate steady states (Tables A1 and A2). In Iowa, steady state is reached in one year. Adjustments toward steady state in the New York models generally take longer. Because the initial alfalfa rotation imposed in year zero avoids the first-year establishment cost of alfalfa, it is more profitable to complete the initial alfalfa rotation before switching to continuous corn.

These solutions reflect the net farm returns and leachate if continuous corn could be sustained over a 20-year period, but they fail to account for existing crop rotations used by most farmers to mitigate weed and pest problems (e.g. see Lazarus and Dixon, 1984; Lazarus and Swanson, 1983; Taylor and Headley, 1975; and Hueth and Regev, 1974). If used as a basis of policy comparisons, they would surely overestimate leachate and expected net returns, and overstate adjustments needed to comply with nitrate reduction policies.

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[23] For New York models, the total fertilizer application rate is the sum of that from manure and inorganic fertilizer. The 15 tons of manure are always applied before any inorganic fertilizer is applied because it is only about two-thirds the cost per pound of N.

[24] These crops are in rotation, but only at their minimum bounds of 0.002 acres. If no minimum rotation were imposed, these land fractions would be zero.

Table 8. Average Per Acre Annual Production, Annual Leachate, and Farm Returns by Soil for the Bioeconomic Models with No Rotation Imposed[a]

Soil	20-Yr. Discounted Expected Net Return	$E(C_1)$	$E(C_2)$	x_1[a]	x_2[a]	Fraction of Acre in Corn	Fraction of Acre in Legume Crop	Expected Leachate
New York								
N-A	$1888.77	21.2	20.6	53	184	0.99	0.01	61.0
N-B	1910.44	21.1	20.7	53	181	0.99	0.01	28.9
N-C	2048.34	21.7	21.2	36	157	0.99	0.01	20.5
N-D	2060.95	21.7	21.2	20	150	0.99	0.01	56.2
N-E	1542.44	16.8	16.2	20	137	0.99	0.01	17.4
N-F	1581.45	16.7	16.2	0	123	0.99	0.01	25.9
N-G	1456.79	16.8	16.2	49	165	0.99	0.01	20.6
Iowa								
I-A	$1583.40	108	108	176	211	0.99	0.01	26.5
I-B	2380.08	152	152	158	193	0.99	0.01	29.9
I-C	2205.84	139	139	123	159	0.99	0.01	9.3
I-D	2756.46	171	171	136	170	0.99	0.01	26.6
I-E	2183.63	141	141	166	201	0.99	0.01	27.2

[a] In order to minimize the effects of initial conditions and terminal period, the averages are calculated using years six through 15 rather than the entire 20-year time horizon.

Note: See the text for a description of the variables.

Models with Minimum Legume Rotations Imposed

The base scenarios used in the policy analysis include minimum legume rotations. Because little is known about how the value of increased pest and weed control due to crop rotations varies by soil, minimum soybean (alfalfa) rotations of 40% (roughly the two state averages) are imposed on all soils.

Solutions for these restricted models for I-B and N-E soils are in Tables A3 and A4. Average data for all soils are in Table 9. Both the reduction in annual expected leachate and minimum value of the pest control provided by the rotation are given in Table 10. By growing crops in rotation, nitrate leachate decreases by 35 to 40% in both the Iowa and New York regions. The minimum value to the farmer of the increased pest and weed control from the rotation varies more dramatically, both within and between regions. In Iowa this implicit value is only $16/acre on I-A soil, because it has the lowest corn yields. For the better soils, the value of it is above $250/acre on all other soils and reaching nearly $500/acre on I-D soil. In New York, the implicit value of the rotation for pest control is generally less than in Iowa,

Table 9. Average Per Acre Annual Production, Annual Leachate, and Farm Returns by Soil for the Bioeconomic Models with a Minimum Legume Rotation Imposed[a]

Soil	20-Yr. Discounted Expected Net Return	$E(C_1)$	$E(C_2)$	x_1[a]	x_2[a]	Fraction of Acre in Corn	Fraction of Acre in Legume Crop	Expected Leachate
New York								
N-A	$1672.12	21.2	20.5	53	182	0.6	0.4	38.9
N-B	1681.92	21.1	20.6	53	178	0.6	0.4	18.2
N-C	1765.07	21.7	21.2	35	154	0.6	0.4	13.1
N-D	1774.55	21.7	21.1	19	148	0.6	0.4	35.8
N-E	1449.59	16.7	16.2	19	133	0.6	0.4	11.2
N-F	1474.14	16.7	16.2	0	119	0.6	0.4	17.1
N-G	1399.68	16.8	16.2	47	162	0.6	0.4	13.0
Iowa								
I-A	$1567.31	108	108	174	209	0.6	0.4	16.2
I-B	2046.63	151	151	156	191	0.6	0.4	18.2
I-C	1942.25	139	139	123	156	0.6	0.4	5.9
I-D	2271.57	171	171	134	167	0.6	0.4	16.2
I-E	1928.08	141	141	164	199	0.6	0.4	16.6

[a] To minimize the effects of initial conditions and terminal period, the averages here are calculated using years six to 15 rather than the entire 20-year time horizon.

Note: See the text for a description of the variables.

ranging from $50 to $100/acre on the less productive, group C soils to $200 to $300/acre on the more productive, group A and B soils. Expressed as a percent of the 20-year expected net revenue from growing continuous corn, the minimum value of the pest control from growing crops in rotation over the 20-year period varies from one to 18%.

Solutions to the Chance-Constrained Bioeconomic Models

In the solutions where a chance constraint on leachate is imposed the values of $\alpha = 0.05$ and $\alpha = 0.25$ reflect the probability that leachate exceeds some upper bound, L_U, is less than 5 and 25%, respectively. Because of the uncertainty surrounding the effects of high nitrates on human health and the environment, L_U is also varied in 2.5 lbs./acre increments from the unconstrained leachate levels found in the base models to leachate near zero. While the objective function values and expected annual leachate levels for these solutions are critical for the policy analysis below, there is too much data to be reported here. The detail is in Thomas (1994); the information is used below in estimating the value of leachate permits. Complete solutions for soils I-B and N-E, are in Tables A5 through A12.

Table 10. Farm and Environmental Values from Growing the Legume in Rotation with Corn

Soil	Minimum Value of Pest and Weed Control from Rotating Crops[a] ($/acre)	Value of the Pest and Weed Control as a % of Net Revenue from Continuous Corn	Leachate Reduction from Rotating Crops[b] (lbs./acre)	Leachate Reduction as a % of Leachate from Continuous Corn
Iowa				
I-A	$16.09	1.0	10.4	38.9
I-B	333.45	14.0	11.7	39.1
I-C	263.59	12.0	3.4	36.6
I-D	484.89	17.6	10.4	39.1
I-E	255.55	11.7	10.6	39.0
New York				
N-A	$216.64	11.5	22.1	36.2
N-B	228.52	12.0	10.7	37.0
N-C	283.26	14.3	7.4	36.1
N-D	286.40	13.9	20.4	36.3
N-E	92.85	6.0	6.2	35.6
N-F	107.31	6.8	8.7	34.0
N-G	57.12	3.9	7.6	36.9

[a] Calculated as the difference in the objective function values between the bioeconomic models with no rotation imposed and a 40% legume rotation.

[b] Calculated as the difference in annual expected leachate between the bioeconomic models with no rotation imposed and a 40% legume rotation.

The Iowa models respond to decreases in L_U and decreases in α by increasing the fraction of the land in soybeans and corn following soybeans and decreasing the amount of nitrogen fertilizer applied and, in turn, the amount of nitrogen available in the crop root zone. These shifts are expected because by decreasing L_U and/or decreasing α, the chance constraint is more restrictive, resulting in lower nitrogen fertilizer application rates and a shift of land out of continuous corn. Similar observations can be made regarding the impact of decreasing L_U and α in the New York models.

Comparing the solutions for I-B in Iowa more closely, decreasing L_U from 20 to 10 lbs./acre while keeping α constant at 0.05 (Tables A5 and A6) results in only a small decrease in the fertilizer application rates, 2 to 3 lbs./acre; whereas the majority of the adjustment takes place in the crop rotation--a shift from 43 to 71% of the land in soybeans. On the other hand, if L_U is decreased from 20 to 10 lbs./acre while α is 0.25 rather than 0.05 (Tables A7 and A8), then a more dramatic decrease occurs in the nitrogen fertilizer application rates, 20 to 30 lbs./acre. The land in soybeans increases from 40 to 79%, similar to the rotations with α = 0.05 and L_U set at 20 and 10 lbs./acre, respectively.

Examining the various chance-constrained solutions for N-E soil brings out an important difference between the chance-constrained solutions to the New York and Iowa models: in the New York models there are benefits from rotating crops in cycles. For instance, in Table A10 the fraction of the land in first year alfalfa, $\delta_{3,t}$, tends to vary from a relatively high value in one year to a relatively low value in the next year, followed by an intermediate value in the next year. Then this cycle begins again by returning to a high value, then a low value, and then an intermediate value, and so on.

As a result of the cyclical behavior in the crop rotations, comparing the solutions for the N-E soil is not as straightforward as it is for the I-B soil. As seen in Tables A9 and A10, decreasing L_U from 10 to 5 lbs./acre while maintaining α at 0.05 typically increases the land in alfalfa from around 55% with L_U at 10 lbs./acre to between 75 and 85% with L_U at 5 lbs./acre. Nitrogen fertilizer application rates on continuous corn with L_U at 10 lbs./acre are typically 90 to 125 lbs./acre; whereas they drop to between 55 and 125 lbs./acre with L_U at 5 lbs./acre. The fertilizer application rates and crop rotations in Tables A9 and A10 are similar to those in Tables A11 and A12, where L_U is set at 10 and 5 lbs./acre but α is 0.25 rather than 0.05.

Some perspective on differential effects of a chance constraint on net farm revenues between soils are seen in Table 11. The chance constraint reduces 20-year expected net returns the most, \$368, on I-D, the most productive soil. In contrast, the chance constraint is not binding and has no effect on I-C soil. Similarly, the chance constraint reduces farm revenues very little (only \$33) on I-A soil because it is the least productive soil. In the New York models, the chance constraint with L_U set at 10 lbs./acre and $\alpha = 0.05$ results in larger decreases in net revenue for the more productive group A and B soils (N-A through N-D). These decreases, \$175 to \$435, are comparable to those on the most productive Iowa soils.

COMPARING POLICIES THAT REDUCE NITRATE LEACHATE

We can use the solutions to the bioeconomic models to compare policies to reduce nitrate leachate. Emphasis is on the changes in production and income, and in this sense, we determine the economic stakes involved in policy choice. This is an important first step in evaluation, but is separate from administrative issues. The latter issues affect the economic viability of each policy and are addressed briefly in our concluding remarks. Six policies, all variations of the standards approach outline above, are compared: a sales tax on nitrogen fertilizer, a uniform quantity restriction on annual nitrogen fertilizer applied, a restriction on

Table 11. The Effect of the Leachate Chance Constraint on the Discounted Present Value of 20-Year Expected Net Farm Returns

Soil	Objective Function,[a] Base Model ($)	Objective Function,[a] Prob[L ≥ 10] ≤ 0.05 ($)	Difference ($)
I-A	1,567	1,534	33
I-B	2,047	1,752	295
I-C	1,942	1,942	0
I-D	2,272	1,904	368
I-E	1,928	1,715	213
N-A	1,672	1,314	358
N-B	1,682	1,463	219
N-C	1,765	1,593	172
N-D	1,775	1,339	436
N-E	1,450	1,408	41
N-F	1,474	1,343	131
N-G	1,400	1,362	38

[a] The objective function measures the discounted present value of 20-year expected net farm returns.

annual expected leachate, and three schemes of pollution permits for annual expected leachate. These include: (i) permit sales at a fixed price, (ii) a permit auction, and (iii) a system of tradable permits.

The policy objectives are stated in terms of reducing annual expected leachate by 10 and 25%. This strays somewhat from the notion of a chance constraint, but that is unavoidable given that all soils could not be incorporated into a regional model. However, the expected leachate for a soil has an associated upper bound on leachate L_U for a given probability level: $Prob[L \geq L_U] \leq \alpha$. By finding an average of these upper bounds for all soils weighted by acreage, we can *ex post* approximate the regional upper bound on leachate that will not be exceeded for a given probability level. More is said about this below.

Regional production, leaching, and farm returns in Table 12 are used as a base of comparison for the policy analysis. By reflecting current crop rotations, expected nitrate leachate is already 9.3 and 12.7 pounds per acre less in Iowa and New York, respectively, than if continuous corn were being raised. On a per acre basis net farm returns in the Iowa region are 28% higher than in the New York region. This difference is due in large measure to the relative productivity of the soils and is reflected in the value of farm real estate as well.

Table 12. Current Annual Production, Annual Leachate, and 20-Year Net Farm Returns on an Acre of a Composite Soil

	New York	Iowa
20-Yr. Net Farm Returns (,000)	$209,033	$482,481
Corn Production (,000)	1,470 tons	21,251 bu.
Legume Production (,000)	191 tons	3,890 bu.
Nitrogen Fertilizer (,000)	9,300 lbs.	22,185 lbs.
Land in Corn	78,560 acres	142,132 acres
Land in Legumes	52,373 acres	94,755 acres
Expected Annual Leachate (,000)	2,972 lbs.	3,459 lbs.
Expected Leachate/Acre	22.7 lbs.	14.6 lbs.
Corn Yield [a]	20.6 tons	150 bu.
Nitrogen Fertilizer/Acre[a]	164 lbs.	179 lbs.

Note: Calculated from data in Tables 2 and 9.

[a] These quantities are for continuous corn.

Recent estimates by USDA for the value of land and buildings are $1,157 and $1,031 per acre in Iowa and New York, respectively *(New York Agricultural Statistics, 1992-93)*.

A Tax on Nitrogen Fertilizer

Conceptually it is easy to determine the effects of this policy on agricultural production and leachate by merely raising the cost of nitrogen fertilizer in the bioeconomic models by the amount of the tax. The situation, however, is more complicated because each model deals with a single soil and any particular tax would not necessarily lead to the same percentage reduction in expected leachate. Therefore, soil-specific models are solved for a given tax rate, and the reduction in leachate on a composite acre is calculated as a weighted average. Finally, this procedure is repeated using successively higher tax rates until the desired reduction in expected annual leachate on the composite acre (10 or 25%) is reached.

The tax rates that lead to a decrease in annual expected leachate by 10% are 38 and 129% in New York and Iowa, respectively. To reduce expected leachate by 25%, the tax rates needed are much higher, 141 and 260% in New York and Iowa, respectively (Table 13). These tax rates are high, but they do embody an accurate reflection of the transition of applied

Table 13. Changes in Farm Returns and Production for a Tax on Nitrogen Fertilizer

Item	10% Decrease in Expected Leachate		25% Decrease in Expected Leachate	
	Iowa	New York	Iowa	New York
Tax Rate (%)	129	38	141	260
	----------------Percent Change From Base----------------			
20-Yr. Net Farm Returns	-8	-3	-14	-4
Corn Production	-6	-10	-21	-23
Legume Production	6	11	23	24
Land Producing Corn	-5	-7	-15	-16
Land Producing Legume	6	11	23	24
Total Nitrogen Applied	-22	-30	-53	-66
Corn Yield/Acre[a]	-3	-15	-8	-29
Nitrogen Applied/Acre[a]	-15	-32	-31	-68

[a] These per acre quantities are for continuous corn.

inorganic nitrogen fertilizer into nitrogen leached. They reflect the inelastic nature of the implicit price elasticity of demand for nitrogen fertilizer implied in the production response.[25] They are also consistent with other studies. For instance, Pan and Hodge (1994) needed a tax of 790% to reduce nitrate leachate by 50%, while Taylor *et al.* (1992) found that a 50% tax on nitrogen fertilizer resulted in less than a 2% decrease in nitrate leachate. For Johnson *et al.* (1991) a 100% tax on nitrogen fertilizer was needed for a one-third reduction in leachate.

The taxes on nitrogen fertilizer decrease net farm income over the 20-year time horizon by less than 5% in New York (Table 13). In Iowa, the percentage decreases in net farm returns are slightly higher, 8% for a 10% reduction in leachate and 14% for a 25% reduction in leachate. The relatively higher reductions in farm returns for the Iowa region reflect the higher productivity of Iowa soils in growing corn and the relative profitability of growing soybeans in Iowa compared to alfalfa in New York.

The nitrogen tax also decreases total corn production, increases total legume production, decreases the amount of land producing corn, and decreases the total amount of nitrogen

[25] These implicit price elasticities range from -0.23 to -0.28 for New York soils and are consistently about -0.19 for all Iowa soils.

fertilizer applied in a region (Table 13). The fact that corn production falls by more than does land in corn is due to the effects on corn yields from the large reductions in the use of nitrogen fertilizer applied--22 and 30% decreases for a 10% reduction in leachate in Iowa and New York, respectively, and 53 and 66% decreases for a 25% reduction in leachate in Iowa and New York, respectively. Corn yields decrease relatively more in the New York region. In general, the shift away from corn and toward using less nitrogen fertilizer is more dramatic in the New York region.

A Quantity Restriction on Nitrogen Fertilizer Application

To study the effects of the fertilizer restriction, the base bioeconomic models are adapted by adding a constraint for the nitrogen fertilizer application rate. To find the uniform fertilizer restriction, the models are solved for different restrictions on fertilizer application rates until the desired reductions in annual leachate on a composite acre are identified.

Restrictions on the maximum amount of nitrogen fertilizer that can be applied per acre which lead to the desired 10 and 25% reductions in expected leachate are 104 and 47 lbs./acre, respectively, in New York and 117 and 75 lbs./acre, respectively, in Iowa (Table 14). The percentage reductions in the total fertilizer use in New York and Iowa to realize a 10% reduction in leachate are nearly the same. However, moving beyond this point to a 25% reduction in leachate requires a substantially greater reduction in fertilizer application in the New York region. This can only be explained by the differential nature of the leaching and nitrogen response between the two regions. Also, in the base scenario, per acre leachate is higher in New York than in Iowa. Thus, reducing leachate by 25% requires leachate to be reduced by nearly 6 lbs./acre in New York, compared with about 3.5 lbs./acre in Iowa.

Shifts in income and production are similar to those incurred under a nitrogen fertilizer tax. The uniform fertilizer restrictions decrease 20-year net farm income in the New York region less than 5% for both the 10 and 25% reductions in leachate (Table 14). The income reductions in Iowa are again slightly higher. Changes in production and land use are similar to those resulting from the fertilizer tax.

Perhaps the most important contrast is that when compared with the tax on fertilizer, a direct restriction on fertilizer leads generally to larger reductions in total nitrogen applied and to less substitution of legumes for corn. These differences are in large measure due to the fact that by taxing fertilizer one decreases the profitability of growing corn over the entire possible range of nitrogen application rates and corn yields. The fertilizer restriction, on the other hand,

Table 14. Changes in Farm Returns and Production for a Uniform Restriction on Nitrogen Fertilizer Application Rates

	10% Decrease in Expected Leachate		25% Decrease in Expected Leachate	
Item	Iowa	New York	Iowa	New York
Restriction (lbs./Acre)	117	104	75	47
	-----------------Percent Change From Base---------------			
20-Yr. Net Farm Returns	-2	-1	-7	-5
Corn Production	-5	-7	-19	-25
Legume Production	1	2	13	21
Land Producing Corn	1	1	-8	-13
Land Producing Legume	1	2	13	21
Total Nitrogen Applied	-26	-28	-56	-71
Corn Yield/Acre[a]	-10	-17	-22	-30
Nitrogen Applied/Acre[a]	-35	-37	-58	-71

[a] These per acre quantities are for continuous corn.

only limits the profitability of corn at nitrogen levels above the restriction. Thus, for the tax on nitrogen fertilizer, legumes become relatively more profitable.

A Restriction on Expected Annual Nitrate Leachate on All Soils

The most direct policy for decreasing leachate is to restrict expected leachate itself on each soil by 10 and 25% relative to base levels. This is accomplished by adding an expected leachate constraint to the base bioeconomic models. Results are in Table 15.

In general, shifts in production and income are similar to those found under either the tax or quantity restriction on fertilizer, although regional farm incomes are slightly higher, nitrogen fertilizer applications rates remain higher, and there is a larger increase in legume acreage. The explanation is simple. We know from our theoretical discussion that if the objective is to restrict total leachate in the region, then the least-cost solution is to restrict total leachate directly rather than indirectly by taxing or restricting a polluting input. Put differently, this is the least-cost solution because farmers remain free to choose the proper substitution between crop rotation and fertilizer application to achieve the leachate level. And it is more

Table 15. Changes in Farm Returns and Production for a Uniform Percentage Reduction in Base Leachate Level on Each Soil

Item	10% Decrease in Expected Leachate		25% Decrease in Expected Leachate	
	Iowa	New York	Iowa	New York
	-----------------Percent Change From Base---------------			
20-Yr. Net Farm Returns	-2	-1	-6	-4
Corn Production	-8	-8	-23	-25
Legume Production	6	7	32	30
Land Producing Corn	-5	-5	-22	-20
Land Producing Legume	8	7	32	30
Total Nitrogen Applied	-23	-27	-41	-58
Corn Yield/Acre[a]	-3	-15	-3	-19
Nitrogen Applied/Acre[a]	-13	-29	-15	-41

[a] These per acre quantities are for continuous corn.

profitable to substitute away from corn to more legume acreage but sustain higher fertilizer application rates on the remaining corn. Despite its advantages, however, this policy restricts leachate on every soil and disregards differences in the value of leaching between individual soils. The best way to assess the importance of these differences is through a comparison with leachate permit schemes which by design impute these values to the various soils.

Pollution Permits for Every Pound of Expected Annual Nitrate Leachate

To examine the three systems of pollution permits, we must organize the output from the models to: (i) derive soil-specific demands for leachate permits, (ii) determine how the leachate reduction is achieved by each scheme, (iii) develop an analytical procedure for eliciting the differences in farm returns, production, and public revenues among schemes, and (iv) formulate a programming procedure for allocating permits among soils.

Soil-Specific Demands for Leachate Permits. Since restrictions on expected annual nitrogen leachate restrict farmers' production alternatives, a step-wise demand schedule for leachate permits can be derived directly from solutions to models with successively tighter restrictions on annual expected leachate. This is done simply by dividing the difference between the objective function values for the two solutions by the difference in annual expected leachate levels. The numerous chance-constrained solutions to the models described above and their corresponding 20-year expected net returns and annual leachate levels are used for this purpose. The step-wise, parametric demand functions for leachate permits based on these data are given in Appendix B. It is clear from the schedules that permits on the more leachable soils do not always carry the highest price. The value of a permit on a particular soil is determined by the combination of the leachability and productivity of the soil. For example, N-A soil is a highly leachable but relatively productive soil from hydrologic group A, and N-E soil is a much less leachable but also less productive soil from hydrologic group C. Permits are worth up to $18 on N-A soil and $36 on N-E soil.

Reaching the Desired Reduction in Expected Nitrate Leachate. Although farmers' demand schedules for leachate permits do not change across the three permit schemes, the ways in which they are used to reach a reduction in expected leachate does. Consider a scheme where permits sell at P^*, the price which calls out the desired regional reduction in expected leachate, L^*. In order to reduce total leachate in the region to L^*, P^* must be set such that $\sum_{i=1}^{n} \omega_i L_i^* \leq L^*$ where n is the number of soils within the region, ω_i is the number of acres of soil i in the region, and L_i^* is the quantity of permits demanded per acre of soil i at price P^*, from Appendix B. If permits are auctioned rather than sold at a fixed price, there is no need to know the per acre permit demands to achieve the desired regional reduction in leachate. An agency simply determines the desired leachate, L^*, and auctions that many permits.[26] Under the third permit scheme, an agency initially allocates the L^* permits in proportion to base-case leachate levels, and allows farmers to trade those permits. Similar to the auction, the agency simply determines L^* and then distributes those L^* permits in proportion to base-case levels.[27]

A Graphical Analysis of the Differences in the Three Permit Schemes. Although the expected leachate levels of all three permit schemes are the same, one may expect shifts in production and net farm returns to differ among the three leachate permit mechanisms. A graphical analysis is used to illustrate the differences (Figures 2-4). It is shown that under each of the three permit schemes, agricultural production is identical because expected leachate levels for the soils are identical. Net farm returns, on the other hand, differ.

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[26] It is assumed permits are auctioned one at a time and that farmers bid the exact amount that each individual permit is worth to them, essentially allowing the regulatory agency to act as a perfectly price discriminating monopolist.

[27] Suppose one wants a 10 % reduction in expected leachate. For a farmer with 100 acres of one soil that leaches 15 lbs./acre/year under base conditions and 200 acres of another that leaches 30 lbs./acre/year, the agency initially allocates 0.9[15(100) + 30(200)] = 5400 permits.

First, consider a farmer's demand for permits on soil i (Figure 2).[28] If a farmer can freely leach nitrates, then he/she leaches $L_{i\,c}$ and obtains the economic surplus associated with areas A + B + C.[29] If permits are sold at a fixed price, P^*, a farmer demands L_i^* permits on soil i and pays an amount associated with area B ($P^* \cdot L_i^*$). The loss in surplus is area C. On the other hand, assuming that farmers bid the amount for each permit corresponding to the intersection of a price line and their demand curve, an agency, acting as a perfectly discriminating monopolist and auctions permits, extracts all of the area under the demand up to L_i^*, areas A + B (Figure 2). The last permit auctioned sells for P^* on each soil. Loss to the farmer is area C because his leachate is reduced from $L_{i\,c}$ to L_i^*.

To compare the costs of the previous two permit schemes with those in which permits are initially allocated proportionally to base leachate levels and then traded, it is assumed that the market for tradable permits must be perfectly competitive and in equilibrium at P^*, and no farmers can possess large enough shares of permits to effectively increase or decrease the price.[30] Under these conditions, there is an excess supply of permits on some soils and an excess demand on others. If the initial distribution of permits on soil i is $L_i > L_i^*$ at P^* (Figure 3), a farmer sells the $L_i - L_i^*$ permits and collects revenue equal to area D + E. Conversely, if the initial distribution of permits is $L_i < L_i^*$ at P^* (Figure 4), the farmer purchases $L_i^* - L_i$ permits for area G, with a gain equal to area F + G. The net gain is area F. After all trading has occurred among farmers, all farmers will possess L_i^* permits per acre of soil i, and expected nitrate leachate on each acre of soil i is identical.

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[28] We use a smooth demand curve, but implications for step-wise demands are the same.

[29] The area under the demand curve is the value (surplus) of leaching on an acre of soil.

[30] If these assumptions are not made, then per acre amounts farmers pay for permits or gain from selling permits may differ across farmers for a specific soil. For instance, suppose a farmer possesses a large excess supply of permits compared to all other farmers. He may emerge as a permit price leader, similar to a Stackelberg leader (Gibbons, 1992), creating additional revenues from selling his permits compared to farmers selling only a small number of permits. To assess regional effects of these situations, the existence and type of equilibrium would have to be known, including the exact approach path taken towards the equilibrium price, P^*, provided that such an equilibrium is eventually reached. This would require information on the individual market shares for all farmers and their exact reactions to permits bought and sold by all other farmers. Because this information is not known, the permit market is assumed to be perfectly competitive and in equilibrium.

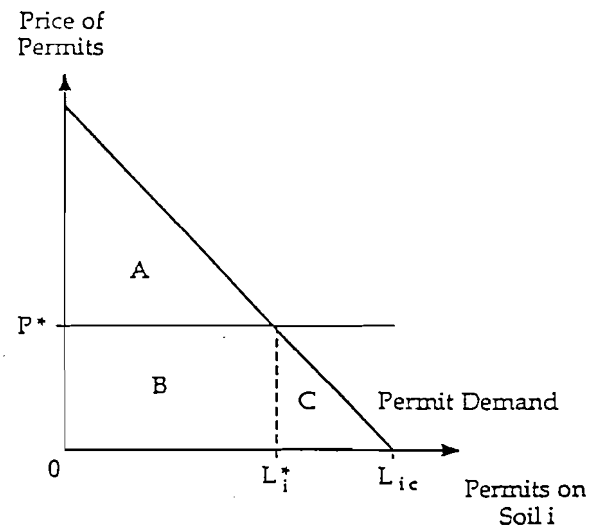

Figure 2. Reducing Leachate by Selling Permits at a Fixed Price

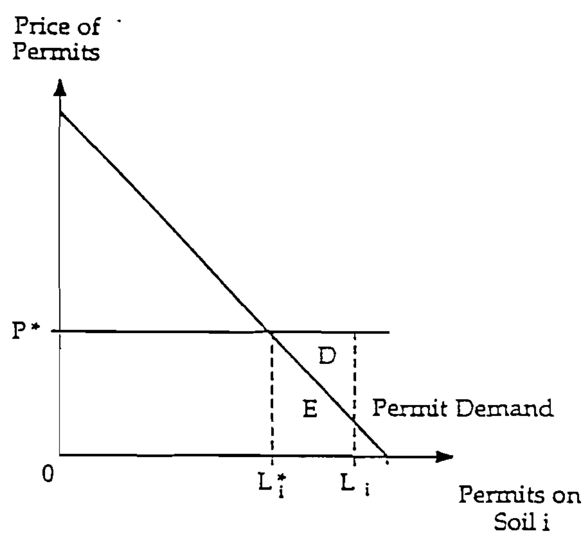

Figure 3. Excess Supply of Permits Given an Initial Allocation of Tradable Permits

Corn and legume production on soil i are the same for each permit scheme, as is the amount of nitrogen fertilizer applied and the crop rotation. This must be the case because: (i) each of the permit schemes results in an expected leachate level of L_i^* on soil i, (ii) L_i^* is determined using the permit demand for soil i, and (iii) the permit demand is based on maximizing net farm returns subject to leaching being less than or equal to L_i^*.

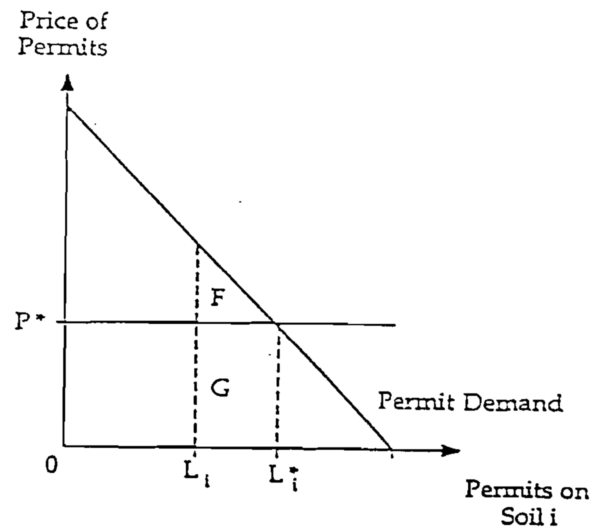

Figure 4. Excess Demand of Permits Given an Initial Allocation of Tradable Permits

A Programming Model to Allocate Permits by Soil. To continue the policy comparisons, a method is needed to find the quantity of permits demanded on specific soils (L_i^*) in both regions so that regional expected annual leachate is reduced by 10 and 25%. If P^* is known, L_i^* can be easily found using the step-wise permit demand schedules. To simplify things, a linear programming model is formulated to calculate the soil-specific quantities of permits demanded at a given price. The problem maximizes the sum of the economic surpluses under the individual soils' per acre demands but above the permit price. This model, resembling an allocation or a separable programming model (Gass, 1985), is:

$$\max \sum_{i=1}^{n} \sum_{j=1}^{m_i} v_{ij} L_{ij}$$

subject to

$$L_{ij} \le \bar{L}_{ij}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m_i} w_i L_{ij} \le L^*$$

$$L_{ij} \ge 0 \text{ for all } i, j$$

where i represents the soil type (i = 1,...,n); j represents a step along the per acre permit demand schedule for soil i that where (j = 1,...,m_i); step j = 1 along a permit is the step associated with the highest price along the demand, step j = 2 is the step associated with the second highest price along the demand, and so on; v_{ij} is the price associated with step j along the permit demand for soil i less the agency's given permit price, $\bar{L}_{ij}$ is the width of step j in the permit demand schedule for soil i, L_{ij} is the quantity of permits endogenously determined that are associated with step j along the per acre demand for soil i, w_i is the number of acres of soil i in the region, and L^* is the desired regional expected leachate level.

The step-wise nature of the demands, however, poses a small problem when trying to find the permit price that by itself would result in farmers leaching the desired regional level of leachate. The problem is that at a relatively low permit price, the desired regional leachate level will be met by the permit demands calculated in the programming model because of the restriction in the model. But in reality at relatively low permit prices, farmers may demand more permits than those calculated by the programming model because farmers will not observe any such restriction on regional leachate. To find that price which by itself results in the desired regional leachate level, the model is solved for relatively high prices so that the regional leachate constraint is not binding. The price is lowered sequentially until a price which gives the desired reduction in expected leachate is found.[31]

Empirical Evaluation of the Three Permit Mechanisms. The permit prices needed to achieve 10 and 25% reductions in expected annual leachate are the same for all permit schemes, and are estimated at $8.43 and $15.55, respectively, in the New York region and $25.49 and $31.89, respectively, in the Iowa region (Table 16). As one would expect, the permits are worth more to farmers in the Iowa region than in New York because of the relatively higher profitability of the Iowa soils.

Leachate permits demanded per acre are in Table 16. In New York, generally more permits are demanded on the soil in hydrologic groups A and B; they are more productive yet typically leach more than the hydrologic group C soils. In Iowa, no permits are demanded on I-A soil, mainly because it is the least productive soil for growing corn. The more productive yet more leachable soils, I-B and I-D soils, have the greatest quantities of permits demanded (more than 10 permits/acre). Although a few permits are demanded on I-C soil (about 6 permits/acre), this leachate level corresponds to its unrestricted leachate level.

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[31] By reducing leachate by exactly 10 or 25%, the permits demanded for one soil in the region falls along one step (or between solutions to the bioeconomic models) rather than at the end of a step (or at one solution to a bioeconomic model). Thus, information on production and farm returns presented below are interpolations between the two solutions.

Table 16. Permit Prices and Leachate Quantities Demanded (Lbs./Acre)

Soil	Per Acre Quantities of Permits Demanded for a 10% Decrease in Expected Leachate	Per Acre Quantities of Permits Demanded for a 25% Decrease in Expected Leachate
New York	Price = $8.34	Price = $15.55
N-A	32.8	17.6
N-B	16.6	16.0
N-C	12.3	12.3
N-D	32.4	29.0
N-E	10.2	10.2
N-F	16.0	12.4
N-G	10.6	6.8
Iowa	Price = $25.49	Price = $31.89
I-A	0.0	0.0
I-B	17.2	13.8
I-C	5.9	5.9
I-D	15.5	15.5
I-E	13.3	0.0

The relative changes in crop production, fertilizer rates, and crop rotations in Table 17 are generally similar to those under other policies, with a few exceptions. In Iowa, the permit schemes for a 10% reduction in leachate result a greater reduction in land producing corn and a higher nitrogen fertilizer application rate than do other policies. However, for a 25% reduction in leachate, the least amount of land in corn and the greatest nitrogen fertilizer application rate occurs under the uniform restriction on leachate. In New York, the permit schemes result in the highest nitrogen fertilizer application rates of all policies for both the 10 and 25% reductions in leachate. The permit schemes result in relatively little corn acreage compared with other policies in New York. Only the nitrogen fertilizer tax for a 10% decrease in leachate results in less corn acreage in New York than do the permit schemes.

As can be expected, the most costly permit mechanism in terms of reductions in farm returns is the permit auction (Table 18). For example, for a 10% reduction in leachate in the New York region , if permits are auctioned, net farm returns (including the cost of permits to farmers) are $152 million, compared with $185 million when permits are sold at a fixed price

Table 17. Changes in Annual Production when Annual Expected Leachate is Reduced by All Three Leachate Permit Schemes

	10% Decrease in Expected Leachate		25% Decrease in Expected Leachate	
Item	Iowa	New York	Iowa	New York
	------------------Percent Change From Base---------------			
Corn Production	-6	-8	-18	-26
Legume Production	9	8	27	34
Land Producing Corn	-7	-5	-18	-23
Land Producing Legume	9	8	27	34
Total Nitrogen Applied	-16	-27	-33	-58
Corn Yield/Acre[a]	-4	-14	-9	-17
Nitrogen Applied/Acre[a]	-11	-28	-20	-37

[a] These per acre quantities are for continuous corn.

Table 18. 20-Year Net Farm Returns and Leachate Permit Costs for Three Permit Schemes

Region	Net Returns	Farm Cost Fixed Price	Farm Cost Auction	Net Returns Fixed Price (% Δ from Base)	Net Returns Auction (% Δ from Baseline)	Net Returns Tradable Permits (% Δ from Base)
	------------------$ million------------------					
10% Decrease Expected Leachate						
NY	208	23	55	185 (-12)	152 (-27)	208 (0)
IA	478	79	126	399 (-17)	352 (-27)	478 (-0)
25% Decrease Expected Leachate						
NY	202	35	50	167 (-20)	152 (-27)	202 (0)
IA	464	83	111	381 (-21)	353 (-27)	464 (-0)

and $208 million when tradable permits are allocated initially. Not surprisingly, all net benefits (economic surpluses or rents) a farmer could potentially gain from leaching nitrates are extracted by the discriminating monopolist. These regional surpluses are 27% in both regions for a 10% reduction in leachate and are also roughly the same in both for a 25% reduction in leachate.[32] Selling permits at a fixed price extracts less economic surplus from farmers than does the permit auction. Tradable permits[33] is the least costly to the farm community, but there is a redistribution of income among individual farmers.

For the system of tradable permits, it is important to examine the initial and final distributions of permits (Tables 19 and 20). The largest number of permits traded per acre occurs on N-A, N-G, I-A and I-E soils. While per acre trade is not always large, a substantial number of permits is traded in total. In New York for the 10 and 25% reductions in leachate, respectively, roughly 37,000 (1%) and 144,000 (7%) of the initial permits are traded. In Iowa, about 162,000 (5%) and 253,000 (10%) permits are traded, respectively. Interestingly, a much higher proportion of permits are traded in the case where expected leachate is restricted most severely. Under these circumstances, their value at the margin is raised for all soils, because there are fewer permits available, and there is more to be gained from trade.

Distribution of Benefits, Policy Costs, and Revenue Transfers

To do a complete evaluation of the alternative policies that achieve an environmental standard, one must have some idea of the distribution of benefits and costs among various groups in society. We are not able to estimate the health benefits here, but we can approximate the upper bounds on the chance constraints which provide some relative measure of the safety associated with each policy. Also, the costs to firms and the public revenues generated under the various policies are of general interest.

<ins>The Chance Constraint</ins>. Because the models are formulated by soil, the best that can be done to identify the relative safety for each policy is to approximate the upper bound on the regional chance constraint. Recalling that a chance constraint restricts leachate by limiting the probability that leachate exceeds some harmful upper bound, we can for each policy and probability level, approximate the upper bounds by aggregating the specific soil results. In the

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[32] These surpluses are calculated by weighing the per acre surplus on an individual soil by the number of acres of soil (Table 2).

[33] Base leachate levels for the soils are the expected annual leachate levels (Table 9).

Table 19. Initial Allocation of Leachate (Lbs.) Permits Per Acre under the Tradable Permit Scheme and the Number of Permits Bought or Sold Per Acre by Soil

	10% Reduction in Leachate			25% Reduction in Leachate		
Soil	Initial Allocation	Permits Demanded	Permits Bought (Sold)	Initial Allocation	Permits Demanded	Permits Bought (Sold)
New York						
N-A	35.0	32.8	(2.2)	29.1	17.6	(11.5)
N-B	16.3	16.6	0.3	13.6	16.0	2.4
N-C	11.8	12.3	0.5	9.8	12.3	2.5
N-D	32.2	32.4	0.2	26.8	29.0	2.2
N-E	10.0	10.2	0.2	8.4	10.2	1.8
N-F	15.4	16.0	0.6	12.8	12.4	(0.4)
N-G	11.7	10.6	(1.1)	9.7	6.8	(2.9)
Iowa						
I-A	14.5	0.0	(14.5)	12.1	0.0	(12.1)
I-B	16.4	17.2	0.8	13.7	13.8	0.1
I-C	5.3	5.9	0.6	4.4	5.9	1.5
I-D	14.6	15.5	0.9	12.2	15.5	3.3
I-E	14.9	13.3	(1.6)	12.4	0.0	(12.4)

Table 20. Total Regional Leachate Permits (Lbs./Acre) Traded by Soil After an Initial Allocation of Permits is Distributed Proportionally to Base-Level Leaching[a]

	10% Reduction in Leachate		25% Reduction in Leachate	
Soil	Permits Bought	Permits Sold	Permits Bought	Permits Sold
New York	(2.7 Million Initial Permits)		(2.2 Million Initial Permits)	
N-A	0	11,154	0	58,949
N-B	1,981	0	99,691	0
N-C	5,137	0	18,940	0
N-D	8,147	0	13,433	0
N-E	1,089	0	17,921	0
N-F	21,033	0	0	15,537
N-G	0	25,652	0	69,880
Iowa	(3.1 Million Initial Permits)		(2.6 Million Initial Permits)	
I-A	0	144,751	0	120,626
I-B	87,517	0	15,659	0
I-C	34,352	0	85,880	0
I-D	41,270	0	152,476	0
I-E	0	17,301	0	132,477

[a] Due to rounding of the per acre demands, the total number of permits bought in a region may not exactly equal the total number of permits sold.

aggregation, the soil-specific upper bounds per acre are multiplied by the number of acres of the soil in the region and then summed for all soils in the region (Table 21).

Typically, there is not much difference in the upper bound on regional leachate among policies. However, the threat of regional leachate exceeding harmful levels is either the smallest or next to the smallest under the permit schemes. The uniform restriction on expected leachate is the only policy that results in less of a threat, and that occurs only in the New York region. For example, the uniform restriction on expected leachate on all soils results in an upper bound of 3.11 million pounds of leachate with a probability of no more than 5% under the 10% reduction in expected regional leachate. This is compared to an upper bound of 3.14 million pounds of leachate under the permit schemes. While the uniform restriction on expected leachate in New York may be the least threatening in terms of observing high leachate levels, it is the most threatening in Iowa when expected regional leachate is reduced by 10%. Similarly, the restriction on fertilizer is the most threatening in Iowa for a 25% reduction in expected regional leachate and in New York for a 10% reduction in expected regional leachate. Under the 25% reduction in expected leachate in New York, the tax on nitrogen fertilizer results in the highest upper bound on leachate for a given probability level.

Costs and Transfers. Regional net farm returns, public revenues, and the net costs of the individual policies, defined here as the decrease in net farm returns from the base case less any public revenues generated from the policies, are in Tables 22 and 23.[34] It is no surprise that the tradable permit scheme results in the least net cost, approximately $2 and $7 million (or 1 and 2% of base net income) for the 10 and 25% reductions in leachate, respectively, in New York and $4 and $19 million (or 2 and 4% of the base net income) for the 10 and 25% reductions in leachate, respectively, in Iowa. The net cost of the permit policies should be lowest because under each of the permit mechanisms, farmers obtain permits in such a way that leachate occurs on those soils that have the highest returns from leaching. No other policy allows farmers as a whole to freely adjust nitrogen fertilizer and crop rotations among soils so that the regional reduction in leachate is achieved. The ordering of the net costs of policies other than those associated with permit schemes varies by region and the percentage reduction in expected leachate. Generally, the most costly policy is the uniform restriction on the fertilizer application rate, with regional costs of $2.3 and $10.1 million for the 10 and 25% reductions in leachate, respectively, in New York and $10.2 to $34.0 million for the 10 and

[34] All costs and revenues reported in this section, unless otherwise stated, are the discounted present value of the costs and revenues over the 20-year time horizon.

Table 21. Approximate Upper Bounds on Regional Leachate and Probability Levels under Different Policies

Region	% Decrease in Expected Leachate	Probability Upper Bound Exceeded	Upper Bound on Leachate (thousand pounds) Base	Fertilizer Tax	Fertilizer Restriction	Expected Leachate Restriction	Permit Schemes
New York	10%	0.05	3,497	3,140	3,146	3,107	3,138
Iowa	10%	0.05	4,243	3,811	3,826	3,837	3,717
New York	10%	0.25	3,215	2,888	2,891	2,857	2,885
Iowa	10%	0.25	3,905	3,508	3,521	3,531	3,421
New York	25%	0.05	3,497	2,647	2,616	2,572	2,575
Iowa	25%	0.05	4,243	3,155	3,185	3,133	3,119
New York	25%	0.25	3,215	2,435	2,407	2,364	2,367
Iowa	25%	0.25	3,905	2,903	2,931	2,883	2,870

Table 22. 20-Year Net Farm Returns, Public Revenues, and Net Costs[a] of the Policies ($ million)

	Base Case	Fertilizer Tax	Restriction on Fertilizer	Restriction on Leachate	Leachate Permits: Sale at Fixed Price	Auctioned	Tradable
10% Reduction in Expected Leachate							
NY Revenue							
Farm	209	204	207	207	185	152	208
Public	--	4	--	--	23	55	--
Net Cost	--	2	2	2	2	211	2
IA Revenue							
Farm	482	443	472	473	399	352	478
Public	--	33	--	--	79	126	--
Net Cost	--	7	10	9	4	4	4
25% Reduction in Expected Leachate							
NY Revenue							
Farm	209	200	199	201	167	152	202
Public	--	0	--	--	35	50	--
Net Cost	--	9	10	8	7	7	7
IA Revenue							
Farm	482	413	449	454	381	353	464
Public	--	20	--	--	83	111	--
Net Cost	--	50	34	28	19	19	19

[a] Net costs are calculated as the decrease in net farm returns from the base case less the public revenue generated.

Table 23. Per Acre 20-Year Net Farm Returns, Public Revenues, and Net Costs[a] of the Policies

	Base Case	Fertilizer Tax	Restriction on Fertilizer	Restriction on Leachate	Leachate Permits: Sell at Fixed Price	Leachate Permits: Auctioned	Leachate Permits: Tradable
10% Reduction in Expected Leachate							
NY Revenue							
Farm	$1596	$1555	$1579	$1584	$1413	$1162	$1585
Public	--	28	--	--	172	423	--
Net Cost	--	14	18	13	11	11	11
IA Revenue							
Farm	$2037	$1872	$1994	$1999	$1684	$1487	$2018
Public	--	137	--	--	335	532	--
Net Cost	--	27	43	38	18	18	18
25% Reduction in Expected Leachate							
NY Revenue							
Farm	$1596	$1528	$1520	$1534	$1278	$1162	$1543
Public	--	0	--	--	264	380	--
Net Cost	--	68	77	62	54	54	54
IA Revenue							
Farm	$2037	$1743	$1893	$1917	$1608	$1489	$1958
Public	--	83	--	--	349	469	--
Net Cost	--	211	144	120	79	79	79

[a] Net costs are calculated as the decrease in net farm returns from the base case less the public revenue generated.

25% reductions in leachate, respectively, in Iowa. An exception is that the fertilizer tax is the most costly policy for the 25% reduction in leachate in Iowa, with a net cost of $50 million.

Perhaps more important to policy makers is the distribution of the net costs of the policies between losses in net farm returns and gains in public revenues. For all cases considered, the greatest net costs are $211 per acre on a composite soil in the Iowa region for a fertilizer tax and $77 per acre on a composite soil in the New York region for a fertilizer restriction (Table 23). These costs represent only 18 and 7% of the land values in Iowa and New York.[35]

These percentage changes are substantially greater if one looks only at the costs to farmers (Table 24). By far the most costly policies to farmers as a whole within the regions

[35] The land values used are USDA's 1991 estimates of the state average value of farm land and buildings. They are $1157 in Iowa and $1031 in New York (*New York Agricultural Statistics, 1992-1993*).

Table 24. Per Acre Costs of the Policies to Farmers Expressed as a Percent of Current Net Farm Returns and Farm Land Values on a Composite Soil

	Fertilizer Tax	Restriction on Fertilizer	Restriction on Expected Leachate	Permits Sold at a Fixed Price	Auctioned Permits	Tradable Permits Initially Allocated
New York Region--10% Decrease in Expected Annual Leachate						
Farm Cost ($)	42	18	13	183	434	11
% of Farm Returns	3	1	1	12	27	1
% of Land Value	4	2	1	18	42	1
Iowa Region--10% Decrease in Expected Annual Leachate						
Farm Cost ($)	165	43	38	353	550	18
% of Farm Returns	8	2	2	17	27	1
% of Land Value	14	4	3	31	48	2
New York Region--25% Decrease in Expected Annual Leachate						
Farm Cost ($)	68	77	62	318	434	54
% of Farm Returns	4	5	4	20	27	3
% of Land Value	7	7	6	31	42	5
Iowa Region--25% Decrease in Expected Annual Leachate						
Farm Cost ($)	294	144	120	428	548	79
% of Farm Returns	14	7	6	27	27	4
% of Land Value	25	12	10	47	47	7

Note: Current farm returns are the net returns associated with the base case for the New York and Iowa regions, $1596 and $2037, respectively. Land values are the U.S.D.A. estimates for the average value per acre of land and buildings in New York and Iowa, $1119 and $1245, respectively (*New York Agricultural Statistics, 1992-1993*).

are the permits sold at a fixed price or at auction, especially those sold at auction. The economic stakes involved with these policies are high. On an average size crop farm of 315 acres in the Iowa region and 218 acres in the New York region (*1987 Census of Agriculture*), these permit schemes cost as much as $172,600 and $94,700, respectively. These costs represent about a 27% decline in a farmer's current net returns. Land values, which will eventually reflect the losses in farm returns, would decrease 42 to 47%. One may argue that the government could redistribute the public revenues generated from these policies back to the farmers using a lump-sum transfer to bring the farmers' costs down, but in reality such transfers may not work efficiently (Gardner, 1987).

Among the policies, the least costly to farmers is the tradable permit scheme with a free initial allocation of permits proportional to base leachate. Even for the 25% reductions in leachate, these costs represent only about 3 to 4% of current net farm returns and 5 to 7% of land values. On an average size crop farm with average soils, these costs would be $24,900 in the Iowa region and $11,700 in the New York region. Among policies other than the permit schemes, farm costs are less than 15% of net returns or land values, with the exception of the fertilizer tax in Iowa for a 25% reduction in leachate.

SUMMARY AND POLICY IMPLICATIONS

The purpose of the research on which this bulletin is based is to develop an analytical framework for studying the effects of regulating nitrates that leach into groundwater from agricultural production. The bioeconomic models developed for this purpose account for management response for crop rotations and nitrogen fertilizer use and incorporate the dynamics and uncertainty surrounding both the agricultural production and nitrate leaching processes.

Because of the heightened interest in innovative, market-oriented approaches for resolving water pollution problems (EPA, 1993), much of the policy analysis centers around leachate permits as an instrument for reducing regional nitrate leachate. The implications of three permit schemes are also compared with more traditional instruments: a tax on nitrogen fertilizer and quantity restrictions on either fertilizer application or leachate.

The empirical analysis evaluates the performance of these policy options for two regions, one representative of agriculture in the Corn Belt and the other representative of agricultural areas in the Northeast. The Corn Belt's relatively homogeneous soils are among the most productive for growing corn and soybeans; and because of the intensive use of fertilizer, groundwater is highly vulnerable to nitrate contamination. Parts of the Northeast are vulnerable as well, but soils are generally less homogenous and less productive. Corn and alfalfa are commonly grown in rotation to support dairy. Manure is a significant source of applied nitrogen in addition to inorganic fertilizer and contributes to the leaching problem. To the extent that the regions studied, Boone County in Iowa and Genesee and Wyoming Counties in New York, are representative of these major agricultural areas, the results of the policy analysis may be generalizable to other parts of the Corn Belt and the Northeast.

As the basis for the comparative analysis, current agricultural practices are identified on specific soils in the regions. These base scenarios reflect current crop rotations (40% alfalfa and 40% soybeans in New York and Iowa, respectively), which imply approximately 35 to 40% less leaching than the leachate levels under continuous corn production. This substantial improvement in environmental quality is largely a by-product of using crop rotations to resolve weed and pest problems.

Once the base scenarios are identified, the different nitrate leachate reducing policies are compared both within and between regions. The regional net costs are identified under the various policies, along with the costs to farmers and public revenues generated.[36]

The Policy Implications

Throughout the empirical analysis, emphasis is placed on estimating what is at stake when reducing regional leachate by a given percentage. Generally in the Corn Belt there is more at stake than in the Northeast. If annual expected leachate is reduced by 25% in the Iowa region, the leachate policies reduce net farm returns from 4 to 10%. In New York, these policies lead to only a 3 to 5% reduction in farm income. The differences in the costs between Iowa and New York are accounted for primarily by the productivity differences between the soils and the relative value of the legume crops in the two regions. Corn yields are more responsive to nitrogen fertilizer on Iowa soils, making the relative value of growing corn compared with a legume higher in Iowa than in New York. Thus, as leachate is reduced, the costs, in terms of corn yields from reduced fertilizer and/or the substitution of the legume crop, are relatively higher in Iowa than in New York.

As suggested by theory, the leachate permit schemes lead to the smallest net costs of any policy for both regions. However, the ranking of other policies by net cost differ by region and by the level of reduction in regional leachate, although the range in net costs is relatively narrow (3 to 10%). To illustrate the differences for a 25% reduction in expected annual leachate, the regional net costs associated with the three permit schemes are 3 and 4 % of net farm returns in the New York and Iowa regions, respectively. The costs of the other policies expressed as a percentage of net farm returns in the New York and Iowa regions, respectively, are: 4 and 10% for the fertilizer tax, 5 and 7% for the fertilizer restriction, and 4 and 6% for the leachate restriction.

Because leachate permits are bought and sold on the basis of their value of production, one would expect that these schemes are the minimum net cost policy alternatives. However,

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[36] The costs and public revenues reported here are the discounted present values of expected costs and revenues over a 20-year time horizon. The regional net cost is defined as the decrease in the discounted present value of 20-year expected net farm returns to farmers less any public revenues generated under a policy.

two of the permit schemes (the permits auctioned and sold at a fixed price) transfer substantial revenues from farmers to the public treasury. The permit auction, for example, extracts all the economic surplus that farmers gain from leaching nitrates and essentially leaves them indifferent between purchasing permits to grow some corn in rotation and growing all legume crops. Farmers' costs under the permit auction are substantial, about 27% of 20-year discounted net returns in both regions. Similarly, if permits are sold at a fixed price, income transfers from farmers to the public are also substantial, ranging from 11 to 21% of discounted net farm returns. Based on the size of these transfers, it is unlikely that either of these alternatives would be politically acceptable.

In contrast, by regulating leachate through a system of tradable permits the net costs to the farm sector are much reduced--less than 4% of discounted net farm returns even for a 25% reduction in leachate; put differently, these costs represent between 5 and 7% of land values. Clearly, the chance of this scheme being politically acceptable is much improved, although there is substantial redistribution of income between buyers and sellers of permits. Any adverse distributional consequences are in part mitigated by allocating initial permits based on historical production patterns, a strategy consistent with how participation in other farm programs is determined.

The distributional consequences among farms are minimal for the fertilizer tax and for fertilizer and leachate restrictions. A tax, however, is particularly costly to farmers in Iowa, 14% of net returns or 25% of the value of land. In contrast, the fertilizer and leachate restrictions lead to reductions in farm income only slightly larger than those for the tradable permits. Since these two policies rank closely behind the tradable permits, the desirability of each must turn on considerations other than net costs and farm costs. One major consideration is the differential impacts of the policies for the leaching on individual soils, particularly if it is in the public interest in some locations to restrict leachate on the most leachable or highly vulnerable soils. The other major consideration is administrative feasibility.

In this regional analysis, it is not possible to determine the exact linkage between leachate below the crop root zone on particular soils and the resulting increase in the nitrate concentration of the major drinking water sources within the region. Yet, if it is known that a localized aquifer is the primary source of drinking water for people in a region and that highly leachable soils lie above this aquifer, a policy that transfers leaching rights from these soils to other soils in the region could be an effective means of dealing with the contamination problem. In these extreme cases, it may be in the public interest to implement a permit scheme that would eliminate all corn production in such an area and perhaps compensate farmers in return. If specific soils are targeted using the policies analyzed in empirical analysis, then the fertilizer and leachate restrictions generally result in the least leaching on the more vulnerable hydrologic groups A and B soils. Even if these policies are implemented, there is still a small probability that leachate on the vulnerable soils may exceed harmful levels, as evidenced by the chance-constraint on nitrate leachate. But, by targeting vulnerable areas and transferring the leaching rights, this probability can be reduced further, if not to zero.

Similar targeting of agricultural contamination is being considered under the Coastal Zone Management Act. For example, Letson *et al.* (1993) examined the potential for trading pollution between point and nonpoint sources in coastal watersheds. Of the 35 areas in which nonpoint source agricultural pollution is a significant contributor to the pollutant loadings in the watershed, they found that trading would be feasible and improve water quality in 19 areas. Feasibility was measured primarily in terms of the farm and transactions costs associated with trading. More specifically, in order for trading to be feasible in a watershed, a few large nonpoint source polluters had to be present in order to keep the transactions costs of trading low, and the nonpoint source polluters (the farmers) had to have alternative land uses and technologies available so that the cost of abating nonpoint source pollution would be low.

The case for using a system of nitrate permits to target only selected areas where the "stakes are high" also makes sense from an administrative standpoint. The implementation of a permit policy that substantially reduces leachate in certain areas would mean that soils be classified according to their vulnerability and leaching potential. In addition, farmers would probably have to report production plans that include both fertilizer application rates and the number of acres producing individual crops.

In this sense the data requirements would be substantial, but in New York such a permit scheme might well be "piggy-backed" on the administrative infrastructure already in place for the state's agricultural use-value assessment program, where farmland is already classified into 10 different value groups based on estimated productivity. To apply for agricultural value assessment, a farmer is required to bring tax maps into the local ASCS office where the tax maps are overlaid on county soil maps in order to determine the farmer's acreage in each of the state's major soil mapping units (of which there are several hundred). Each soil mapping unit has been assigned to one of the 10 different value groups. The value of a farmer's land for tax purposes is calculated by finding the farmer's acreage in each of the value groups and summing the values for those acreages across groups (Gardner and Bills, 1991).

Assigning each of the state's soil mapping units to a group based on leaching potential would perhaps be even more difficult and contentious than assigning productivity classes, but the difficulties could be minimized by focussing on the soils only in those targeted areas where a source of groundwater is at risk. Substantial work is already underway in some states to rank soils by leaching potential as a management tool for farmers.

In addition, the idea of farmers registering production plans and fertilizer use is not new, and most of the administrative structure is in place. For example, to participate in government farm programs, farmers have had to register crop production on individual parcels in order to form base acreages and program yields. Also, provisions in the 1990 Food Security Act require farmers to register their use of certain chemicals.

Although there may well be a number of agricultural areas where extremely vulnerable groundwater supplies could justify the administrative expense of a permit system, other policies that are less costly administratively may be appropriate in areas where concerns about nitrate contamination are more general and less severe. Administratively, a leachate restriction would involve costs similar to those for the permit schemes because soil-specific production and leaching information would have to be known; but the tax on nitrogen fertilizer, for example, would be much less costly to implement. A fertilizer tax would simply require that fertilizer dealers collect the appropriate tax revenues from the farmers. A uniform restriction on the nitrogen fertilizer application rate could be administered by requiring farmers to register the number of acres of corn they are growing and limiting the amount of fertilizer a farmer can purchase by multiplying the number of acres of corn by the maximum fertilizer application rate allowed under the quantity restriction. These alternative policies are slightly less efficient in terms of their net regional costs, but the savings in administrative costs may well compensate for the difference.

REFERENCES

Agricultural Prices, 1991 Summary. U.S.D.A., Washington, D.C.: U.S. Government Printing Office, 1992.

Agricultural Statistics 1992. U.S.D.A., Washington, D.C.: U.S. Government Printing Office, 1992.

Baumol, W.J. and W.E. Oates. *The Theory of Environmental Policy, Second Edition.* New York: Cambridge University Press, 1988.

Baumol, W.J. and W.E. Oates. "The Use of Standards and Prices for Protection of the Environment," *Swedish Journal of Economics.* LXXIII (1971):42-54.

Bellman, R. *Dynamic Programming.* Princeton, New Jersey: Princeton University Press, 1957.

Berck, P. "The Economics of Timber: A Renewable Resource in the Long Run," *The Bell Journal of Economics.* 10 (1979):447-462.

Besanko, D. "Performance versus Design Standards in the Regulation of Pollution," *Journal of Public Economics.* 34 (1987):19-44.

Bock, B.R. and G.W. Hergert. "Fertilizer Nitrogen Management," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Bolsen, K. and H. Ilg. "How to Make Good Silage," Kansas State Univeristy, Cooperative Extension Service, File Code An. Sc. 2-4, Manhattan, Kansas, 1980.

Brooke, A., D. Kendrick, and A. Meeraus. *GAMS Release 2.25: A User's Guide.* San Francisco: The Scientific Press, 1992.

Buchanan, J.M. and W.C. Stubblebine. "Externality," *Economica.* 20 (1962):371-384.

Buchanan, J.M. and G. Tullock. "Polluters' Profits and Political Response: Direct Controls Versus Taxes," *American Economic Review.* 65 (1975):139-147.

Canon, M.D., J.R. Cullum, and E. Polok. *Theory of Optimal Control and Mathematical Programming.* New York: McGraw-Hill Book Company, 1970.

Casella, G. and R.L. Berger. *Statistical Inference.* Pacific Grove, California: Wadsworth & Brooks/Cole Advanced Books & Software, 1990.

Charnes, A. and W.W. Cooper. "Chance-Constrained Programming," *Management Science.* 6 (1959):73-79.

Clark, C.W. *Bioeconomic Modelling and Fisheries Management.* New York: Wiley-Interscience, 1985.

Coase, R.H. "The Problem of Social Cost," *Journal of Law and Economics.* 3 (1960):1-44.

Conrad, J.M. "A Bioeconomic Model of the Pacific Whiting," *Bulletin of Mathematical Biology.* 54 (1992):219-240.

Cornell Field Crops Handbook, Cornell University, New York State College of Agriculture and Life Sciences, Ithaca, NY, 1978.

Crowder, B.M., D.J. Epp, H.B. Pionke, C.E. Young, J.G. Beierlein, and E.J. Partenheimer. "The Effects on Farm Income of Constraining Soil and Plant Nutrient Losses: An Application of the CREAMS Simulation Model", Bulletin 850, Agricultural Experiment Station, The Pennsylvania State University, University Park, PA., May 1984.

Crutchfield, S.R., M.O. Ribaudo, L.T. Hansen, and R. Quiroga. *Cotton Production and Water Quality.* AER Report 664, Economic Research Service, USDA, Washington, D.C., 1992.

Dai, Q., J.J. Fletcher, and J.G. Lee. "Incorporating Stochastic Variables in Crop Response Models: Implications for Fertilizer Decisions," *American Journal of Agricultural Economics.* 75 (1993):377-386.

Edwards, S.F. "Options Prices for Groundwater Protection," *Journal of Environmental Economics and Management.* 15 (1988):475-487.

Evans, H.J. and L.E. Barber. "Biological Nitrogen Fixation for Food and Fiber Production," *Science.* 197 (1977):322-339.

Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Fox, G., A. Weersink, G. Sarwar, and S. Duff. "Comparative Economics of Alternative Agricultural Production Systems: A Review," *Northeastern Journal of Agricultural and Resource Economics.* 20 (1991):124-137.

Gardner, B.L. *The Economics of Agricultural Policies.* New York: Macmillan Publishing Company, 1987.

Gardner, K.V. and N. Bills. "Agricultural District Legislation in New York As Amended Through 1990," A.E. Ext. 91-6, Department of Agricultural Economics, Cornell University, Ithaca, NY, 1991.

Gass, S.I. *Linear Programming: Methods and Applications, Fifth Edition.* New York: McGraw-Hill Book Company, 1985.

Gibbons, R. *Game Theory for Applied Economists.* Princeton, New Jersey: Princeton University Press, 1992.

Gisser, M. and D.A. Sanchez. "Competition versus Optimal Control in Groundwater Pumping," *Water Resources Research.* 16 (1980):638-642.

Greaser, G.L. *The Farm Management Handbook*, The Pennsylvania State University, College of Agriculture, File No. IVG1 1M291, 1991.

Harford, J.D. and G. Karp. "The Effects and Efficiencies of Different Pollution Standards," *Eastern Economics Journal.* 9 (1983):79-89.

Heady, E.O. and J.L. Dillon. *Agricultural Production Functions.* Ames, Iowa: Iowa State University Press, 1961.

Heady, E.O. and G. Vocke. "Programmed Impacts of Environmental Restrictions Applied to U.S. Agriculture," *Journal of Environmental Quality.* 8 (1979):143-148.

Helfand, G.E. "Standards versus Standards: The Effects of Different Pollution Restriction," *American Economic Review.* 81 (1991):622-634.

Hexem, R.W. and E.O. Heady. *Water Production Functions for Irrigated Agriculture.* Ames, Iowa: Iowa State University Press, 1978.

Hodges, T., T. Mogusson, S.L. Johnson, and B. Johnson. *Substor Potato Model*, FORTRAN Program, 1989.

Huang, W. and R.M. Lantin. "A Comparison of Farmers' Compliance Costs to Reduce Excess Nitrogen Fertilizer Use Under Alternative Policy Options," *Review of Agricultural Economics.* 15 (1993):51-62.

Hueth, D. and U. Regev. "Optimal Agricultural Pest Management with Increasing Pest Resistance," *American Journal of Agricultural Economics.* 56 (1974):543-555.

Hutson, J.L. and R.J. Wagenet. "Simulating Nitrogen Dynamics in Soils Using a Deterministic Model," *Soil Use and Management.* 7 (1991):74-78.

Iowa Agricultural Statistics, 1990. Iowa Agricultural Statistics, Iowa Department of Agriculture and Land Stewardship, 1990.

Johnson, N.L and S. Kotz. *Continuous Univariate Distributions, Volume 2.* New York: John Wiley & Sons, 1970.

Johnson, S.L., R.M. Adams, and G.M. Perry. "The On-Farm Costs of Reducing Groundwater Pollution," *American Journal of Agricultural Economics.* 73 (1991):1063-1072.

Jones, C.A. and J.R. Kiniry. *CERES-Maize: A Simulation Model of Growth and Development.* College Station, Texas: Texas A&M University Press, 1986.

Jordan, J.L. and A.H. Elnagheeb. "Willingness to Pay for Improvements in Drinking Water Quality," *Water Resources Research.* 29 (1993):237-245.

Judge, G., R. Hill, W. Griffiths, H. Lutkepohl, and T. Lee. *Introduction to the Theory and Practice of Econometrics*, 2nd ed. New York: John Wiley & Sons, 1988.

Kamien, M.I. and N.L. Schwartz. *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management, Second Edition.* Amsterdam: North-Holland, 1991.

Kellog, R.L., M.S. Maizel, and D.W. Goss. *Agricultural Chemical Use and Groundwater Quality: Where are the Potential Problem Areas?* Soil Conservation Service, USDA., Washington, D.C., 1992.

Kete, N. "The U.S. Acid Rain Control Allowance Trading System," in *Climate Change: Designing a Tradeable Permit System.* Paris: O.E.C.D. Documents, 1992.

Kim, C.S., J.E. Hostetler, and G. Amacher. "The Resulation of Groundwater Quality with Delayed Responses," *Water Resources Research.* 29 (1993):1369-1377.

Kim, C.S. and J.E. Hostetler. "Policy Implications of a Water Quality-constrained Dynamic Model of Nitrogen Fertilizer Use," *Canadian Journal of Agricultural Economics.* 39 (1991):781-791.

Knapp, K.C. "Steady-State Solutions to Soil Salinity Optimization Problems," *American Journal of Agricultural Economics.* 66 (1984):279-285.

Knisel, W. Hydrology Engineer, Agricultural Research Service, USDA, Tifton, Georgia, personal communication, April 1993.

Knoblauch, W.A. and R.A. Milligan. "Economic Profiles for Corn, Hay and Pasture," Cornell University, A.E. Ext. 81-1, Department of Agricultural Economics, Cornell University, Ithaca, NY, 1981.

Knoblauch, W.A. and R.A. Milligan. Professors at Cornell University, Department of Agricultural, Resource, and Managerial Economics, personal communication, February 1994.

Knox, E. and D.W. Moody. "Influence of Hydrology, Soil Properties, and Agricultural Land Use on Nitrogen in Groundwater," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Krupnick, A., W.E. Oates, and E. Van De Verg. "On Marketable Air Pollution Permits: The Case for a System of Pollution Offsets," *Journal of Environmental Economics and Management.* 10 (1983):233-247.

Lambert, D.K. "Risk Considerations in the Reduction of Nitrogen Fertilizer Use in Agricultural Production," *Western Journal of Agricultural Economics.* 15 (1990):234-244.

Lazarus, W.E. and B.L. Dixon. "Agricultural Pests as Common Property: Control of the Corn Rootworm," *American Journal of Agricultural Economics.* 66 (1984):456-465.

Lazarus, W.F. and E.R. Swanson. "Insecticide Use and Crop Rotation under Risk: Rootworm Control in Corn," *American Journal of Agricultural Economics.* 65 (1983):738-747.

Leonard, R.A., W.G. Knisel, and D.A. Still. "GLEAMS: Groundwater Loading Effects of Agricultural Management Systems," *Transactions of the ASAE.* 30 (1987):1403-1418.

Letson, D., S. Cruchfield, and A. Malik. "Point-Nonpoint Source Trading for Managing Agricultural Pollutant Loadings: Prospects for Coastal Watersheds", AER-674, Economic Research Service, U.S.D.A., Washington, D.C., 1993.

Malone, P. and R. Barrows. "Groundwater Pollution's Effects on Residential Property Values, Portage County, Wisconsin," *Journal of Soil and Water Conservation*, 45 (1990):346-348.

Mapp, H.P., D.J. Bernardo, G.J. Sabbagh, S. Gelata, and K.B. Watkins. "Economic and Environmental Impacts of Limiting Nitrogen Use to Protect Water Quality: A Stochastic Regional Analysis", *American Journal of Agricultural Economics*, 76(1994):889-903.

McCarl, B. "Economics of Integrated Pest Management: An Interpretive Review of the Literature," Special Report 636, Agricultural Experiment Station, International Plant Protection Center and the Department of Agricultural and Resource Economics, Oregon State University, August 1981.

McClenahan, E.J. "Evaluation of N Uptake by Corn in a Corn-Soybean Rotation and the Corn Stem Nitrate-N Content-Grain Yield Relationship," Unpublished M.S. Thesis, Iowa State University, 1987.

McClenahan, E.J. Manager of the Caldwell experiment station, Cornell University, personal communication, November 1993.

McGartland, A. and W.E. Oates. "Marketable Permits for the Prevention of Environmental Deterioration," *Journal of Environmental Economics and Management.* 12 (1985):207-228.

Meisinger, J.J. and G.W. Randall. "Estimating Nitrogen Budgets for Soil-Crop Systems," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Montgomery, W.E. "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory.* 5 (1972):395-418.

National Resources Inventory. Soil Conservation Service, USDA, Washington, D.C., 1982.

New York Agricultural Statistics, 1992-1993. New York Agricultural Statistics Service, Department of Agriculture and Markets, Division of Statistics, Albany, NY, 1993.

Nielson, E.G. and L.K. Lee. *The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals: A National Perspective.* Staff Report, Natural Resource Economics Division, Economic Research Service, USDA, Washington, D.C., 1987.

1994 Cornell Recommends for Integrated Field Crop Management. Cornell University, Cornell Cooperative Extension Publication, Ithaca, NY, 1993.

Osteen, C.D., E.B. Bradley, and L.J. Moffitt. "The Economics of Agricultural Pest Control: An Annotated Bibliography, 1960-80," ESS, USDA, Bibliographies and Literature of Agriculture No. 14, Washington, D.C., 1981.

Pan, J.H. and I. Hodge. "Land Use Permits as an Alternative To Fertilizer and Leaching Taxes for the Control of Nitrate Pollution," *Journal of Agricultural Economics.* 45 (1994):102-112.

Pigou, A.C. *The Economics of Welfare, 4th Edition.* London: Macmillan & Co., Ltd., 1932.

Poe, G.L. "Information, Risk Perceptions and Contingent Values: The Case of Nitrates in Groundwater," Unpublished Dissertation, University of Wisconsin-Madison, 1993.

Poe, G.L. and R.C. Bishop. "Application of a Convolutions Approach to Measuring the Differences in Benefit Measures from Dichotomous Choice Contingent Valuation," Selected Paper, Annual Meetings of the American Agricultural Economics Association, 1992.

Poe, G.L. and R.C. Bishop. "Measuring the Benefits of Groundwater Protection from Agricultural Contamination: Results from a Two-Stage Contingent Valuation Study," Staff Paper No. 341, Department of Agricultural Economics, University of Wisconsin-Madison, May 1992.

Randall, A. *Resource Economics: An Economic Approach to Natural Resource and Environmental Policy, Second Edition.* New York: John Wiley & Son, 1987.

Reed, W.J. "The Effects of the Risk of Fire on the Optimal Rotation of a Forest," *Journal of Environmental Economics and Management.* 11 (1984):180-190.

Ritchie, J.T., D.C. Godwin, and S. Otter-Nacke. *CERES-Wheat: A Simulation Model of Wheat Growth and Development*, 1985.

Schepers, J.S. and A.R. Mosier. "Accounting for Nitrogen in Nonequilibrium Soil-Crop Systems," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Schmit, T.M. *The Economic Impact of Nutrient Loading Restrictions on Dairy Farm Profitability.* Unpublished M.S. Thesis, Cornell University, Ithaca, NY, 1994.

SCS Soils-5: United States. CD-ROM Database, Boulder, Colorado: Earth-Info, 1993.

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. "Nitrate Leaching and Economic Analysis Package (NLEAP): Model Description and Application," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Smith, S.J. and D.K. Cassel. "Estimating Nitrate Leaching in Soil Materials," in *Managing Nitrogen for Groundwater Quality and Farm Profitability.* Follett, R.F., D.R. Keeney, and R.M. Cruse, Eds. Madison, Wisconsin: Soil Science Society of America, Inc., 1991.

Snedecor, G.W. and W.G. Cochran. *Statistical Methods, Eighth Edition.* Ames, Iowa: Iowa State University Press, 1989.

Soil Survey of Boone County, Iowa. Soil Conservation Service, U.S.D.A., Washington, D.C., 1981.

Soil Survey of Genesee County, New York. Soil Conservation Service, U.S.D.A., Washington, D.C., 1969.

Soil Survey of Wyoming County, New York. Soil Conservation Service, U.S.D.A., Washington, D.C., 1969.

Spanos, A. *Statistical Foundations of Econometric Modelling.* Cambridge: Cambridge University Press, 1986.

Standiford, R.B. and R.E. Howitt. "Solving Empirical Bioeconomic Models: A Rangeland Management Application," *American Journal of Agricultural Economics.* 74 (1992):421-433.

Sun, H. "An Economic Analysis of Groundwater Pollution by Agricultural Chemicals," Unpublished M.S. Thesis, University of Georgia, 1990.

Sun, H., J.C. Bergstrom, and J.H. Dorfman. "Estimating the Benefits of Groundwater Contamination Control," *Southern Journal of Agricultural Economics.* 24 (1992):63-71.

Swanson, E.R. and C.R. Taylor. "Potential Impact of Increased Energy Costs on the Location of Crop Production in the Corn Belt," *Journal of Soil and Water Conservation.* 32 (1977):126-129.

Taylor, C.R. and O.R. Burt. "Near-Optimal Management Strategies for Controlling Wild Oates in Spring Wheat," *American Journal of Agricultural Economics.* 66 (1984):50-60.

Taylor, C.R. and K.K. Frohberg. "The Welfare Effects of Erosion Controls, Banning Pesticides, and Limiting Fertilizer Application in the Corn Belt," *American Journal of Agricultural Economics.* 59 (1977):25-35.

Taylor, C.R., K.K. Frohberg, and W.D. Seitz. "Potential Erosion and Fertilizer Controls in the Corn Belt: An Economic Analysis," *Journal of Soil and Water Conservation.* 33 (1978):173-176.

Taylor, C. R. and J. C. Headley. "Insecticide Resistance and the Evolution of Control Strategies for an Insect Population", *Canadian Entomologist.* 107 (1975):232-242.

Taylor, M.L., R.M. Adams, and S.F. Miller. "Farm-Level Response to Agricultural Effluent Control Strategies," *Journal of Agricultural and Resource Economics.* 17 (1992):173-185.

Thomas, A. "The Bioeconomics of Regulating Nitrates in Groundwater From Agricultural Production: Comparing Taxes, Quantity Restrictions, and Pollution Permits", Unpublished Ph.D. Thesis, Cornell University, August 1994.

Thomas, V. "Welfare Cost of Pollution Control," *Journal of Environmental Economics and Management.* 7 (1980):90-102.

Tietenberg, T. *Emissions Trading: An Exercise in Reforming Pollution Policy.* Washington, D.C.: Resources for the Future, 1985.

U.S. Department of Commerce, Bureau of the Census. *1987 Census of Agriculture: Iowa State and County Data.* Volume 1, Part 32, Washington, D.C., 1989.

U.S. Department of Commerce, Bureau of the Census. *1987 Census of Agriculture: New York State and County Data.* Volume 1, Part 32, Washington, D.C., 1989.

U.S. Environmental Protection Agency, Office of Water. *National Water Quality Inventory: 1990 Report to Congress*, Washington, D.C., 1992.

U.S. Environmental Protection Agency, Office of Water. *Coastal Nonpoint Pollution Control Program*, Washington, D.C., 1993.

U.S. Geological Survey. *1986 National Water Summary*. Water Supply Paper 2325, Washington, D.C., 1988.

Varian, H.R. *Microeconomic Analysis, Third Edition*. New York: W.W. Norton & Company, 1992.

Weitzman, M.L. "Prices Vs. Quantities," *Review of Economic Studies*. 41 (1974):477-491.

Williams, J.R., C.A. Jones, and P.T. Dyke. "A Modeling Approach to Determining the Relationship between Erosion and Soil Productivity," *Transactions of the ASAE*. 27 (1984):129-144.

Wise, S. and S.R. Johnson. "A Comparative Analysis of State Regulations for Use of Agricultural Chemicals," in *Commodity and Resource Policies in Agricultural Systems*. R.E. Just and N. Bockstael, Eds., Berlin: Springer-Verlag, 1991:46-71.

Wolfram, S. *Mathematica: A System for Doing Mathematics by Computer, Second Edition*. Redwood City, California: Addison-Wesley Publishing Company, Inc., 1991.

Zilberman, D. and M. Marra. "Agricultural Externalities," in *Agricultural and Resource Economics*. G.A. Carlson, D. Zilberman, and J.A. Miranowski, Eds., New York: Oxford University Press, 1993:221-267.

APPENDIX A

Table A1. Solution for I-B Soil in Iowa with No Leachate Constraint

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(C_1)$	$E(C_2)$	$E(L)$
0	115	150	300	0.300	0.300	0.400	145	125	15.1
1	158	200	399	0.400	0.598	0.002	152	152	30.I
2	158	193	399	0.002	0.996	0.002	152	152	29.9
3	158	193	399	0.002	0.996	0.002	152	152	29.9
4	158	193	399	0.002	0.996	0.002	152	152	29.9
5	158	193	399	0.002	0.996	0.002	152	152	29.9
6	158	193	399	0.002	0.996	0.002	152	152	29.9
7	158	193	399	0.002	0.996	0.002	152	152	29.9
8	158	193	399	0.002	0.996	0.002	152	152	29.9
9	158	193	399	0.002	0.996	0.002	152	152	29.9
10	158	193	399	0.002	0.996	0.002	152	152	29.9
11	158	193	399	0.002	0.996	0.002	152	152	29.9
12	158	193	399	0.002	0.996	0.002	152	152	29.9
13	158	193	399	0.002	0.996	0.002	152	152	29.9
14	158	193	399	0.002	0.996	0.002	152	152	29.9
15	158	193	399	0.002	0.996	0.002	152	152	29.9
16	158	193	399	0.002	0.996	0.002	152	152	29.9
17	158	193	399	0.002	0.996	0.002	152	152	29.9
18	158	193	399	0.002	0.996	0.002	152	152	29.9
19	158	193	399	0.002	0.996	0.002	152	152	29.9
20	155	191	397	0.002	0.996	0.002	151	151	29.7

Note: See text for a description of the variables.

Table A2. Solution for N-E Soil in New York with No Leachate Constraint

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(C_1)$	$E(C_2)$	$E(L)$
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	20	133	315	0.133	0.599	0.002	0.133	0.133	16.8	16.2	13.5
2	20	135	315	0.133	0.730	0.002	0.002	0.133	16.8	16.2	15.8
3	20	136	315	0.133	0.861	0.002	0.002	0.002	16.8	16.2	18.1
4	20	136	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
5	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
6	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
7	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
8	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
9	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
10	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
11	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
12	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
13	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
14	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
15	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
16	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
17	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
18	20	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
19	19	137	315	0.002	0.992	0.002	0.002	0.002	16.8	16.2	17.4
20	15	129	307	0.002	0.992	0.002	0.002	0.002	16.7	16.0	17.0

Note: See text for a description of variables.

Table A3. Solution for I-B Soil in Iowa with No Leachate Constraint and a Minimum Soybean Rotation Imposed

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(c_1)$	$E(c_2)$	E(L)
0	115	150	300	0.300	0.300	0.400	145	125	15.1
1	156	199	398	0.400	0.200	0.400	151	151	18.2
2	156	191	398	0.400	0.200	0.400	151	151	18.2
3	156	191	398	0.400	0.200	0.400	151	151	18.2
4	156	191	398	0.400	0.200	0.400	151	151	18.2
5	156	191	398	0.400	0.200	0.400	151	151	18.2
6	156	191	398	0.400	0.200	0.400	151	151	18.2
7	156	191	398	0.400	0.200	0.400	151	151	18.2
8	156	191	398	0.400	0.200	0.400	151	151	18.2
9	156	191	398	0.400	0.200	0.400	151	151	18.2
10	156	191	398	0.400	0.200	0.400	151	151	18.2
11	156	191	398	0.400	0.200	0.400	151	151	18.2
12	156	191	398	0.400	0.200	0.400	151	151	18.2
13	156	191	398	0.400	0.200	0.400	151	151	18.2
14	156	191	398	0.400	0.200	0.400	151	151	18.2
15	156	191	398	0.400	0.200	0.400	151	151	18.2
16	156	191	398	0.400	0.200	0.400	151	151	18.2
17	156	191	398	0.400	0.200	0.400	151	151	18.2
18	156	191	398	0.400	0.200	0.400	151	151	18.2
19	156	191	398	0.400	0.200	0.400	151	151	18.2
20	155	191	397	0.400	0.200	0.400	151	151	18.2

Note: See text for a description of the variables.

Table A4. Solution for N-E Soil in New York with No Leachate Constraint and a Minimum Alfalfa Rotation Imposed

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(c_1)$	$E(c_2)$	E(L)
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	19	131	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
2	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
3	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
4	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
5	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
6	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
7	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
8	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
9	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
10	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
11	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
12	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
13	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
14	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
15	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.2
16	19	133	313	0.133	0.468	0.133	0.133	0.133	16.7	16.2	11.1
17	17	130	309	0.133	0.468	0.133	0.133	0.133	16.7	16.1	11.1
18	20	135	315	0.133	0.206	0.395	0.133	0.133	16.8	16.2	6.6
19	19	133	315	0.133	0.337	0.002	0.395	0.133	16.8	16.2	8.9
20	15	126	307	0.133	0.468	0.002	0.002	0.395	16.7	16.0	11.0

Note: See text for a description of the variables.

Table A5. Solution for I-B Soil in Iowa with Nitrate Leachate Restricted by Prob[L ≥ 20] ≤ 0.05

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(c_1)$	$E(c_2)$	E(L)
0	115	150	300	0.300	0.300	0.400	144.8	125.1	15.1
1	127	170	369	0.400	0.174	0.426	147.5	147.5	16.4
2	127	165	369	0.426	0.147	0.427	147.4	147.4	16.4
3	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
4	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
5	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
6	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
7	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
8	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
9	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
10	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
11	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
12	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
13	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
14	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
15	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
16	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
17	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
18	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
19	127	165	369	0.427	0.146	0.427	147.4	147.4	16.4
20	126	164	368	0.427	0.148	0.425	147.1	147.1	16.4

Note: See text 3 for a description of the variables.

Table A6. Solution for I-B Soil in Iowa with Nitrate Leachate Restricted by Prob[L ≥ 10] ≤ 0.05

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(c_1)$	$E(c_2)$	E(L)
0	115	150	300	0.300	0.300	0.400	145	125	15.1
1	125	168	367	0.284	0.002	0.714	147	147	8.2
2	125	162	367	0.284	0.002	0.714	147	147	8.2
3	125	162	367	0.284	0.002	0.714	147	147	8.2
4	125	162	367	0.284	0.002	0.714	147	147	8.2
5	125	162	367	0.284	0.002	0.714	147	147	8.2
6	125	162	367	0.284	0.002	0.714	147	147	8.2
7	125	162	367	0.284	0.002	0.714	147	147	8.2
8	125	162	367	0.284	0.002	0.714	147	147	8.2
9	125	162	367	0.284	0.002	0.714	147	147	8.2
10	125	162	367	0.284	0.002	0.714	147	147	8.2
11	125	162	367	0.284	0.002	0.714	147	147	8.2
12	125	162	367	0.284	0.002	0.714	147	147	8.2
13	125	162	367	0.284	0.002	0.714	147	147	8.2
14	125	162	367	0.284	0.002	0.714	147	147	8.2
15	125	162	367	0.284	0.002	0.714	147	147	8.2
16	125	162	367	0.284	0.002	0.714	147	147	8.2
17	125	162	367	0.284	0.002	0.714	147	147	8.2
18	125	162	367	0.284	0.002	0.714	147	147	8.2
19	125	162	367	0.284	0.002	0.714	147	147	8.2
20	125	162	367	0.284	0.002	0.714	147	147	8.2

Note: See text for a description of the variables.

Table A7. Solution for 1-B Soil in Iowa with Nitrate Leachate Restricted by Prob[L ≥ 20] ≤ 0.25

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(c_1)$	$E(c_2)$	E(L)
0	115	150	300	0.300	0.300	0.400	144.8	125.1	15.1
1	145	188	387	0.400	0.200	0.400	150.3	150.3	17.7
2	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
3	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
4	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
5	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
6	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
7	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
8	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
9	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
10	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
11	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
12	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
13	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
14	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
15	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
16	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
17	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
18	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
19	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7
20	144	181	386	0.400	0.200	0.400	150.2	150.2	17.7

Note: See text for a description of the variables.

Table A8. Solution for 1-B Soil in Iowa with Nitrate Leachate Restricted by Prob[L ≥ 10] ≤ 0.25

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	$E(c_1)$	$E(c_2)$	E(L)
0	115	150	300	0.300	0.300	0.400	144.8	125.1	15.1
1	125	168	367	0.309	0.002	0.689	146.9	146.9	8.9
2	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
3	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
4	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
5	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
6	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
7	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
8	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
9	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
10	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
11	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
12	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
13	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
14	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
15	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
16	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
17	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
18	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
19	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9
20	125	162	367	0.308	0.002	0.690	146.9	146.9	8.9

Note: See text for a description of the variables.

Table A9. Solution for N-E Soil in New York with Nitrate Leachate Restricted by Prob[L ≥ 10] ≤ 0.05

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(c_1)$	$E(c_2)$	E(L)
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	0	80	262	0.133	0.346	0.255	0.133	0.133	16.4	14.5	8.2
2	6	111	288	0.133	0.322	0.157	0.255	0.133	16.5	15.5	8.2
3	17	131	309	0.133	0.258	0.197	0.157	0.255	16.7	16.1	7.4
4	0	87	268	0.255	0.167	0.224	0.197	0.157	16.4	14.8	8.2
5	7	109	291	0.157	0.285	0.137	0.224	0.197	16.5	15.6	8.2
6	13	123	303	0.197	0.222	0.220	0.137	0.224	16.6	15.9	8.2
7	0	91	273	0.224	0.207	0.212	0.220	0.137	16.4	14.9	8.2
8	8	112	292	0.137	0.311	0.120	0.212	0.220	16.5	15.6	8.2
9	11	118	298	0.220	0.195	0.253	0.120	0.212	16.6	15.8	8.2
10	0	95	277	0.212	0.222	0.194	0.253	0.120	16.4	15.1	8.2
11	8	113	293	0.120	0.333	0.101	0.194	0.253	16.5	15.6	8.2
12	9	115	294	0.253	0.154	0.299	0.101	0.194	16.6	15.7	8.2
13	2	97	280	0.194	0.244	0.163	0.299	0.101	16.4	15.2	8.2
14	8	113	293	0.101	0.360	0.078	0.163	0.299	16.5	15.6	8.2
15	7	113	291	0.299	0.093	0.367	0.078	0.163	16.5	15.6	8.2
16	2	96	281	0.163	0.286	0.106	0.367	0.078	16.4	15.2	8.2
17	3	104	283	0.078	0.402	0.047	0.106	0.367	16.4	15.3	8.2
18	6	111	288	0.367	0.002	0.478	0.047	0.106	16.5	15.5	8.2
19	0	89	276	0.106	0.367	0.002	0.478	0.047	16.4	15.1	8.2
20	0	88	265	0.047	0.472	0.002	0.002	0.478	16.4	14.7	8.2

Note: See text for a description of the variables.

Table A10. Solution for N-E Soil in New York with Nitrate Leachate Restricted by Prob[L ≥ 5] ≤ 0.05

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(c_1)$	$E(c_2)$	E(L)
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	0	53	235	0.102	0.133	0.499	0.133	0.133	16.4	13.3	4.1
2	9	117	295	0.133	0.068	0.167	0.499	0.133	16.6	15.7	4.1
3	15	123	307	0.133	0.018	0.183	0.167	0.499	16.7	16.0	3.3
4	0	53	239	0.184	0.002	0.464	0.183	0.167	16.4	13.5	4.1
5	3	96	282	0.167	0.025	0.162	0.464	0.183	16.4	15.3	4.1
6	5	101	286	0.183	0.002	0.189	0.162	0.464	16.5	15.4	4.1
7	0	60	246	0.184	0.002	0.463	0.189	0.162	16.4	13.9	4.1
8	0	79	266	0.162	0.034	0.152	0.463	0.189	16.4	14.7	4.1
9	2	96	280	0.184	0.002	0.200	0.152	0.463	16.4	15.2	4.1
10	0	66	253	0.184	0.002	0.462	0.200	0.152	16.4	14.1	4.1
11	0	66	252	0.152	0.050	0.136	0.462	0.200	16.4	14.1	4.1
12	3	101	284	0.183	0.002	0.216	0.136	0.462	16.4	15.3	4.1
13	0	70	256	0.184	0.002	0.462	0.216	0.136	16.4	14.3	4.1
14	0	55	241	0.136	0.076	0.110	0.462	0.216	16.4	13.6	4.1
15	5	106	288	0.183	0.002	0.244	0.110	0.462	16.5	15.5	4.1
16	0	71	258	0.184	0.002	0.460	0.244	0.110	16.4	14.4	4.1
17	0	53	239	0.110	0.118	0.068	0.460	0.244	16.4	13.5	4.1
18	8	113	292	0.182	0.002	0.287	0.068	0.460	16.5	15.6	4.1
19	0	71	258	0.184	0.002	0.459	0.287	0.068	16.4	14.4	4.1
20	0	53	239	0.066	0.186	0.002	0.459	0.287	16.4	13.5	4.1

Note: See text for a description of the variables.

Table A11. Solution for N-E Soil in New York with Nitrate Leachate Restricted by Prob[L ≥ 10] ≤ 0.25

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(c_1)$	$E(c_2)$	E(L)
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	0	92	274	0.133	0.393	0.208	0.133	0.133	16.4	15.0	9.1
2	3	105	283	0.133	0.385	0.141	0.208	0.133	16.4	15.3	9.1
3	17	131	309	0.133	0.355	0.163	0.141	0.208	16.7	16.1	9.1
4	0	97	277	0.208	0.287	0.201	0.163	0.141	16.4	15.1	9.1
5	5	107	286	0.141	0.368	0.126	0.201	0.163	16.5	15.4	9.1
6	14	125	304	0.163	0.321	0.189	0.126	0.201	16.6	15.9	9.1
7	1	99	279	0.201	0.293	0.190	0.189	0.126	16.4	15.2	9.1
8	6	110	289	0.126	0.386	0.109	0.190	0.189	16.5	15.5	9.1
9	12	121	299	0.189	0.291	0.221	0.109	0.190	16.6	15.8	9.1
10	2	100	281	0.190	0.306	0.174	0.221	0.109	16.4	15.2	9.1
11	7	111	291	0.109	0.408	0.089	0.174	0.221	16.5	15.6	9.1
12	10	118	296	0.221	0.251	0.266	0.089	0.174	16.6	15.7	9.1
13	3	102	283	0.174	0.326	0.145	0.266	0.089	16.4	15.3	9.1
14	7	112	291	0.089	0.434	0.066	0.145	0.266	16.5	15.6	9.1
15	9	117	294	0.266	0.193	0.330	0.066	0.145	16.6	15.7	9.1
16	4	103	285	0.145	0.363	0.095	0.330	0.066	16.4	15.4	9.1
17	7	112	291	0.066	0.465	0.043	0.095	0.330	16.5	15.6	9.1
18	7	114	291	0.330	0.108	0.424	0.043	0.095	16.5	15.6	9.1
19	2	97	281	0.095	0.436	0.002	0.424	0.043	16.4	15.2	9.1
20	0	93	270	0.043	0.529	0.002	0.002	0.424	16.4	14.9	9.1

Note: See Chapter 3 for a description of the variables.

Table A12. Solution for N-E Soil in New York with Nitrate Leachate Restricted by Prob[L ≥ 5] ≤ 0.25

Yr.	x_1^a	x_2^a	x_2	δ_1	δ_2	δ_3	δ_4	δ_5	$E(c_1)$	$E(c_2)$	E(L)
0	53	153	300	0.300	0.301	0.133	0.133	0.133	17.2	15.8	11.8
1	0	53	235	0.079	0.202	0.452	0.133	0.133	16.4	13.3	4.5
2	10	120	296	0.133	0.096	0.186	0.452	0.133	16.6	15.7	4.5
3	15	124	307	0.133	0.025	0.204	0.186	0.452	16.7	16.0	3.4
4	0	53	238	0.205	0.002	0.403	0.204	0.186	16.4	13.5	4.5
5	3	96	283	0.186	0.027	0.180	0.403	0.204	16.4	15.3	4.5
6	5	101	286	0.204	0.002	0.211	0.180	0.403	16.5	15.4	4.5
7	0	60	246	0.205	0.002	0.402	0.211	0.180	16.4	13.9	4.5
8	0	80	266	0.180	0.038	0.169	0.402	0.211	16.4	14.7	4.5
9	2	96	280	0.204	0.002	0.222	0.169	0.402	16.4	15.2	4.5
10	0	66	253	0.205	0.002	0.402	0.222	0.169	16.4	14.1	4.5
11	0	66	252	0.169	0.056	0.151	0.402	0.222	16.4	14.1	4.5
12	3	101	284	0.204	0.002	0.241	0.151	0.402	16.4	15.3	4.5
13	0	70	256	0.205	0.002	0.401	0.241	0.151	16.4	14.3	4.5
14	0	55	241	0.151	0.085	0.122	0.401	0.241	16.4	13.6	4.5
15	5	106	288	0.204	0.002	0.272	0.122	0.401	16.5	15.5	4.5
16	0	71	258	0.205	0.002	0.400	0.272	0.122	16.4	14.4	4.5
17	0	53	239	0.122	0.131	0.076	0.400	0.272	16.4	13.5	4.5
18	8	113	292	0.203	0.002	0.320	0.076	0.400	16.5	15.6	4.5
19	0	71	258	0.205	0.002	0.398	0.320	0.076	16.4	14.4	4.5
20	0	53	239	0.074	0.207	0.002	0.398	0.320	16.4	13.5	4.5

Note: See text for a description of the variables.

APPENDIX B

STEPWISE LEACHATE PERMIT DEMANDS

The soil-specific, stepwise demands for leachate permits are calculated in the following tables.

Table B.1 Stepwise Demand for Leachate Permits on Iowa Soils

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
I-A Soil				
1567.3122	16.1654			
1566.2829	15.5016	1.0293	0.6638	1.55
1564.2541	14.2667	2.0288	1.2349	1.64
1561.8688	13.2871	2.3853	0.9796	2.43
1556.3019	12.2286	5.5669	1.0585	5.26
1550.2224	11.0726	6.0795	1.1560	5.26
1545.4694	10.1905	4.7530	0.8821	5.39
1538.2196	8.8581	7.2498	1.3324	5.44
1534.3800	8.1524	3.8396	0.7057	5.44
1526.1703	6.6435	8.2097	1.5089	5.44
1523.2905	6.1143	2.8798	0.5292	5.44
1514.1209	4.4290	9.1696	1.6853	5.44
1512.2011	4.0762	1.9198	0.3528	5.44
1502.0715	2.2145	10.1296	1.8617	5.44
1501.0187	2.0381	1.0528	0.1764	5.97
I-B Soil				
2046.6298	18.2002			
2043.8606	17.7408	2.7692	0.4594	6.03
2026.5699	16.9634	17.2907	0.7774	22.24
2008.3935	16.3502	18.1764	0.6132	29.64
1990.2121	15.7371	18.1814	0.6131	29.65
1983.8681	15.5232	6.3440	0.2139	29.66
1978.0881	15.3283	5.7800	0.1949	29.66
1947.6753	14.3065	30.4128	1.0218	29.76
1930.7225	13.7751	16.9528	0.5314	31.90
1915.7444	13.3056	14.9781	0.4695	31.90
1899.4238	12.7941	16.3206	0.5115	31.91
1882.4703	12.2627	33.2741	1.0429	31.91
1844.9507	11.0880	37.5196	1.1747	31.94
1817.1333	10.2189	27.8174	0.8691	32.01
1773.9721	8.8704	43.1612	1.3485	32.01
1751.7182	8.1751	22.2539	0.6953	32.01
1702.9936	6.6528	48.7246	1.5223	32.01
1686.3032	6.1313	16.6904	0.5215	32.01
1632.0151	4.4352	54.2881	1.6961	32.01
1620.8882	4.0876	11.1269	0.3476	32.01
1561.0366	2.2176	59.8516	1.8700	32.01
1555.4731	2.0438	5.5635	0.1738	32.01
I-C Soil				
1942.2511	5.8710			
1832.1162	4.3984	110.1349	1.4726	74.79
1802.6626	4.0195	29.4536	0.3789	77.73
1661.1218	2.1992	141.5408	1.8203	77.76
1646.3927	2.0098	14.7291	0.1894	77.77

Table B.1 Stepwise Demand for Leachate Permits on Iowa Soils (cont.)

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
I-D Soil				
2271.5696	16.2158			
2271.3112	16.0910	0.2584	0.1248	2.07
2269.7345	15.8873	1.5767	0.2037	7.74
2266.7230	15.6836	3.0115	0.2037	14.78
2262.7005	15.4969	4.0225	0.1867	21.55
2256.3954	15.2763	6.3051	0.2206	28.58
2210.5193	14.2579	52.1812	1.2390	42.12
2162.8014	13.2830	47.7179	0.9749	48.95
2110.4280	12.2210	52.3734	1.0620	49.32
2052.0324	11.0692	58.3956	1.1518	50.70
2007.1639	10.1842	44.8685	0.8850	50.70
1939.7089	8.8554	67.4550	1.3288	50.76
1903.7599	8.1473	35.9490	0.7081	50.77
1827.3016	6.6415	76.4583	1.5058	50.78
1800.3399	6.1105	26.9617	0.5310	50.78
1714.8943	4.4277	85.4456	1.6828	50.78
1696.9198	4.0737	17.9745	0.3540	50.78
1602.4870	2.2138	94.4328	1.8599	50.78
1593.4998	2.0368	8.9872	0.1770	50.78
I-E Soil				
1928.0806	16.5701			
1911.4519	15.5051	16.6287	1.0650	15.61
1906.1916	15.2925	5.2603	0.2126	24.74
1880.9531	14.2730	25.2385	1.0195	24.76
1856.5997	13.2901	24.3534	0.9829	24.78
1850.1038	13.0496	6.4959	0.2405	27.01
1844.4993	12.8457	5.6045	0.2039	27.49
1833.2901	12.4379	11.2092	0.4078	27.49
1827.6856	12.2340	28.9141	1.0561	27.49
1795.8300	11.0750	31.8556	1.1590	27.49
1771.5855	10.1950	24.2445	0.8800	27.55
1734.7207	8.8600	36.8648	1.3350	27.61
1715.2783	8.1560	19.4424	0.7040	27.62
1673.5529	6.6450	41.7254	1.5110	27.62
1658.9711	6.1170	14.5818	0.5280	27.62
1612.3852	4.4300	46.5859	1.6870	27.62
1602.6640	4.0780	9.7212	0.3520	27.62
1551.2174	2.2150	51.4466	1.8630	27.62
1546.3568	2.0390	4.8606	0.1760	27.62

Table B.2 Stepwise Demand for Leachate Permits on New York Soils

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
N-A Soil				
1672.1201	38.8630			
1670.6098	37.4771	1.5103	1.3859	1.09
1661.9102	35.2061	8.6996	2.2710	3.83
1661.5377	35.1347	0.3725	0.0714	5.22
1648.1416	33.0057	13.3961	2.1290	6.29
1646.4311	32.7924	1.7105	0.2133	8.02
1626.9370	30.8053	19.4941	1.9871	9.81
1622.8899	30.4501	4.0471	0.3552	11.39
1601.2416	28.6049	21.6483	1.8452	11.73
1595.3137	28.1078	5.9279	0.4971	11.92
1574.7189	26.4046	20.5948	1.7032	12.09
1566.9176	25.7655	7.8013	0.6391	12.21
1547.6879	24.2042	19.2297	1.5613	12.32
1537.8157	23.4232	9.8722	0.7810	12.64
1519.3157	22.0038	18.5000	1.4194	13.03
1507.0478	21.0808	12.2679	0.9230	13.29
1489.3887	19.8034	17.6591	1.2774	13.82
1473.9344	18.7385	15.4543	1.0649	14.51
1456.7253	17.6030	17.2091	1.1355	15.16
1437.3740	16.3962	19.3513	1.2068	16.04
1421.4357	15.4027	15.9383	0.9935	16.04
1399.7899	14.0539	21.6458	1.3488	16.05
1386.1135	13.2023	13.6764	0.8516	16.06
1362.1466	11.7116	23.9669	1.4907	16.08
1350.7095	11.0019	11.4371	0.7097	16.12
1324.1422	9.3693	26.5673	1.6326	16.27
1314.4569	8.8015	9.6853	0.5678	17.06
1284.1839	7.0269	30.2730	1.7746	17.06
1276.9198	6.6011	7.2641	0.4258	17.06
1244.1452	4.6846	32.7746	1.9165	17.10
1239.2764	4.4008	4.8688	0.2838	17.16
1203.3968	2.3423	35.8796	2.0585	17.43
1200.8381	2.2004	2.5587	0.1419	18.03
N-B Soil				
1681.9227	18.1628			
1672.8029	16.6074	9.1198	1.5554	5.86
1665.5534	16.0089	7.2495	0.5985	12.11
1638.5399	14.5315	27.0135	1.4774	18.28
1617.9666	13.7219	20.5733	0.8096	25.41
1584.3656	12.4555	33.6010	1.2664	26.53
1556.6776	11.4349	27.6880	1.0206	27.13
1526.8950	10.3796	29.7826	1.0553	28.22

Table B.2 Stepwise Demand for Leachate Permits on New York Soils (cont.)

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
N-B Soil (cont.)				
1490.1028	9.1479	36.7922	1.2317	29.87
1462.7021	8.3037	27.4007	0.8442	32.46
1412.7892	6.8609	49.9129	1.4428	34.59
1390.7095	6.2278	22.0797	0.6331	34.88
1332.7583	4.5740	57.9512	1.6538	35.04
1317.5686	4.1518	15.1897	0.4222	35.98
1248.7062	2.2870	68.8624	1.8648	36.93
1240.8851	2.0759	7.8211	0.2111	37.05
N-C Soil				
1765.0716	13.0924			
1758.6966	12.3133	6.3750	0.7791	8.18
1736.6802	11.3836	22.0164	0.9297	23.68
1690.9747	10.2611	45.7055	1.1225	40.72
1636.1761	9.1069	54.7986	1.1542	47.48
1592.8392	8.2089	43.3369	0.8980	48.26
1524.4780	6.8302	68.3612	1.3787	49.58
1490.3356	6.1567	34.1424	0.6735	50.69
1407.5311	4.5534	82.8045	1.6033	51.65
1383.8131	4.1044	23.7180	0.4490	52.82
1286.4759	2.2767	97.3372	1.8277	53.26
1274.4419	2.0522	12.0340	0.2245	53.60
N-D Soil				
1774.5453	35.8145			
1773.4436	34.8735	1.1017	0.9410	1.17
1761.1118	32.5486	12.3318	2.3249	5.30
1760.0974	32.4281	1.0144	0.1205	8.42
1737.9271	30.2662	22.1703	2.1619	10.26
1737.3829	30.2237	0.5442	0.0425	12.80
1704.4076	28.1043	32.9753	2.1194	15.56
1700.8973	27.8988	3.5103	0.2055	17.08
1666.8708	25.9424	34.0265	1.9564	17.39
1660.3772	25.5739	6.4936	0.3685	17.62
1628.6755	23.7806	31.7017	1.7933	17.68
1619.2381	23.2490	9.4374	0.5316	17.75
1589.8308	21.6187	29.4073	1.6303	18.04
1577.2029	20.9241	12.6279	0.6946	18.18
1550.0661	19.4568	27.1368	1.4673	18.49
1533.8812	18.5992	16.1849	0.8576	18.87
1508.8624	17.2950	25.0188	1.3042	19.18
1489.1891	16.2743	19.6733	1.0207	19.27

Table B.2 Stepwise Demand for Leachate Permits on New York Soils (cont.)

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
N-D Soil (cont.)				
1467.0987	15.1331	22.0904	1.1412	19.36
1443.9387	13.9494	23.1600	1.1837	19.57
1424.6080	12.9712	19.3307	0.9782	19.76
1397.9716	11.6245	26.6364	1.3467	19.78
1381.8231	10.8094	16.1485	0.8151	19.81
1351.8439	9.2996	29.9792	1.5098	19.86
1338.7460	8.6475	13.0979	0.6521	20.09
1305.0821	6.9747	33.6639	1.6728	20.12
1295.2393	6.4856	9.8428	0.4891	20.12
1258.2608	4.6498	36.9785	1.8358	20.14
1251.6517	4.3237	6.6091	0.3261	20.27
1210.2162	2.3249	41.4355	1.9988	20.73
1206.7849	2.1619	3.4313	0.1630	21.05
N-E Soil				
1449.5859	11.1514			
1442.6305	10.2132	6.9554	0.9382	7.41
1424.3115	9.0904	18.3190	1.1228	16.32
1408.2365	8.1706	16.0750	0.9198	17.48
1380.5702	6.8178	27.6663	1.3528	20.45
1364.3304	6.1279	16.2398	0.6899	23.54
1317.9966	4.5452	46.3338	1.5827	29.28
1303.7512	4.0853	14.2454	0.4599	30.97
1243.9359	2.2726	59.8153	1.8127	33.00
1235.7070	2.0426	8.2289	0.2300	35.78
N-F Soil				
1474.1380	17.1340			
1472.5366	16.5689	1.6014	0.5651	2.83
1467.9643	15.9943	4.5723	0.5746	7.96
1448.3699	14.4978	19.5944	1.4965	13.09
1437.0729	13.7094	11.2970	0.7884	14.33
1417.9961	12.4267	19.0768	1.2827	14.87
1402.2615	11.4245	15.7346	1.0022	15.70
1383.9580	10.3555	18.3035	1.0690	17.12
1360.5438	9.1396	23.4142	1.2159	19.26
1343.0902	8.2844	17.4536	0.8552	20.41
1313.8687	6.8547	29.2215	1.4297	20.44
1300.7414	6.2133	13.1273	0.6414	20.47
1266.2129	4.5698	34.5285	1.6435	21.01
1256.6720	4.1422	9.5409	0.4276	22.31
1215.0366	2.2849	41.6354	1.8573	22.42
1210.1967	2.0711	4.8399	0.2138	22.64

Table B.2 Stepwise Demand for Leachate Permits on New York Soils (cont.)

Objective Function	Expected Leachate or Permits Demanded	Change in Objective Function (i)	Change in Quantity of Permits (ii)	Permit Price (i)/(ii)
N-G Soil				
1399.6750	12.9910			
1397.9517	12.2975	1.7233	0.6935	2.48
1391.1055	11.3780	6.8462	0.9195	7.45
1381.5712	10.2479	9.5343	1.1301	8.44
1371.1762	9.1024	10.3950	1.1455	9.07
1361.5224	8.1983	9.6538	0.9041	10.68
1343.6844	6.8268	17.8380	1.3715	13.01
1332.1444	6.1488	11.5400	0.6780	17.02
1292.4754	4.5512	39.6690	1.5976	24.83
1281.1710	4.0992	11.3044	0.4520	25.01
1230.4717	2.2756	50.6993	1.8236	27.80
1223.5763	2.0496	6.8954	0.2260	30.51

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