THE FARM-LEVEL COSTS OF CONTROLLING NITRATE GROUNDWATER POLLUTION

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I. Introduction

Over the last several decades, agricultural production has largely increased through technological advances. Extensive use of agricultural chemicals, mainly fertilizers and pesticides, is a major cause of the advances. The use of these chemicals not only enhanced crop yield and quality but also permitted intensive cultivation of farm land. While the adoption of new technologies has kept food cost relatively low, there are potential environmental and human health costs associated with the heavy dependence on chemicals such as groundwater pollution. Although many sources contaminate groundwater quality (such as industrial wastes, municipal landfills, mining activities, and septic systems), evidence suggests that agriculture is a major contributor of groundwater pollution (Office of Technology Assessment; Hallberg).

Nitrogen, in the form of water-soluble nitrates (NO_3), is one of the most common and problematic chemical pollutants caused by agricultural activities. Nitrate is chemically unreactive in dilute aqueous solutions, and since nitrates and soil solids are both negatively charged, nitrates are not attracted to colloid surfaces and move freely through soil strata along with the flow of soil water (Keeney).

Nitrates may originate from a number of sources, both natural and human induced (Keeney). The U.S. Geological Survey indicates that groundwater nitrate levels below 3 mg N/1 (3 ppm) could be naturally occurring, but concentrations above 3 mg N/1 are generally assumed to reflect human contributions (USGS), usually from the use

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of inorganic fertilizers.

The best documented human health risk from nitrates is methemoglobinemia (blue baby disease). Once ingested, some proportion of nitrates are reduced to nitrites (NO_2) by bacteria in the intestinal tracts. Being reactive, nitrites interact with hemoglobin to produce methemoglobin, which cannot carry oxygen to body tissue. Oxygen levels are lowered, and when more than 60 percent of the hemoglobin is converted to methemoglobin, death may result. The fatality rate is reported to be 8 percent (Fan et al.). In addition, nitrates may cause gastric cancer, and degrade surface water quality.

Because of public concern over the potential consequences of groundwater pollution, pressure has been created for regislative actions to regulate the pollution sources. The reduction of nitrate groundwater pollution from agricultural activities will require some modification of farmer's management practices. Before regulations are promulgated to achieve such reductions, it is important that policy makers know what costs will be imposed on agriculture and its constituents to meet lower pollution standards. Equally important, efficient regulation requires that the action of farmers be understood so that appropriate regulatory procedures are used.

The overall objective of this study is to assess the farm-level economic effects (profits) of adopting alternative management strategies for reducing nitrate groundwater pollution. In order to meet this objective, a methodological framework which models the linkages between management practices, profits, and groundwater pollution at the farm level was developed. The framework identifies possible changes in farm management strategies for reducing nitrate pollution levels and the associated farm income. Policies for the reduction include improved irrigation and fertilization scheduling, taxes on pollution emission and inputs, and physical restrictions on nitrate leaching and input uses.

II. Study Area

This study focuses on two counties, Franklin and Benton, of Washington State in the United States. The two counties contain over 160,000 hectares of irrigated farmland, with alfalfa, winter wheat, potatoes and corn being the principal crops. The study area is one of the driest parts in the state. The mean annual precipitation is 200mm. Precipitation is light in the summer, increases in the fall, peaks in the winter, and decreases in the spring. During July and August, it is not unusual for 4 to 6 weeks to pass without measurable rainfall. The average maximum July temperature is about 32℃, and the minimum temperature 12℃. Because of the hot and dry weather in growing season, irrigation is essential for most crop production. A major irrigation system is center pivot, covering 40 to 45 percent of the irrigated area.

Nitrogen is applied to most crops except alfalfa, accounting for 10 to 20 percent of variable production costs. During the growing season, nitrogen fertilizer is applied with irrigation water, a technique commonly called fertigation. This method is intended to reduce nitrogen losses from leaching, to increase nitrogen use efficiency (Gascho et al.), to reduce labor cost, and to avoid crop damage caused by fertilizer broadcaster. Nitrogen application ranges from 170 to 450 kg/ha depending on crops.

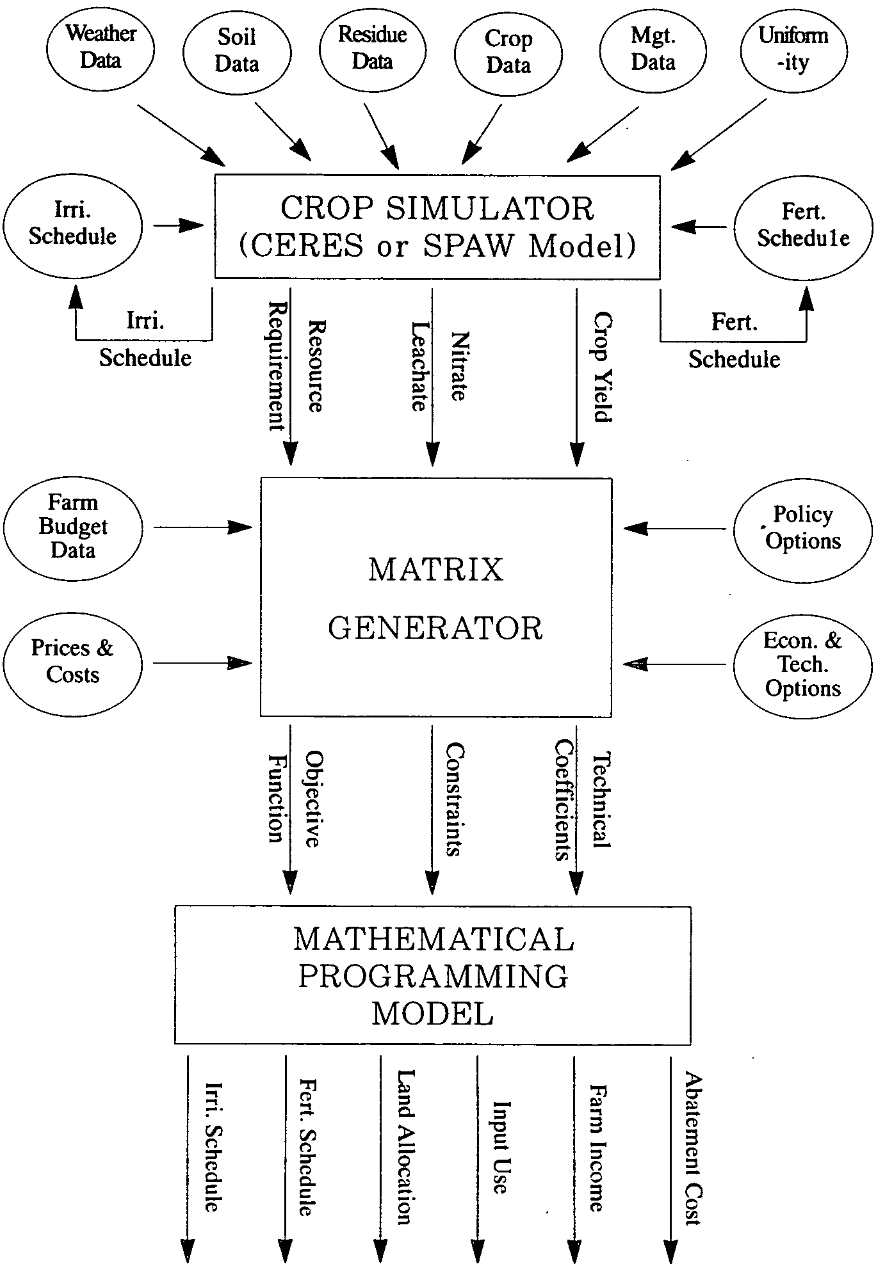
Prevailing soils in the irrigated area are coarse textured with moderate to rapid permeability. Loamy fine sands and very fine sandy loams cover over 70 percent of the irrigated area. Aquifer material consists of silt-clay, sand-gravel, and basalt. The aquifer is recharged primarily by irrigation water, accounting for 90 percent of the recharge sources. Nitrate level in groundwater are high; over 40 percent of 115 sampled wells exceed 10 ppm(maximum contamination level set by the government) with maximum of 92 ppm.

III. The Analytical Model

1. Two-Stage Mathematical Model

A two-stage mathematical model has been developed to analyze the effects of policy options on pollution abatement and the associated costs incurred by farmers and society. The model has been specifically designed to address a variety of production activities differing in environmental, economic, managerial, and institutional conditions. Figure 1 shows major components of this model: crop

FIGURE 1 Schematic Diagram of the Two-Stage Mathematical Model



simulator, matrix generator, mathematical programming model, and the linkage between these components.

In the first stage, biophysical simulation is used to analyze the relationship between crop production and nitrate leaching to specified irrigation and fertilization schedules. The schedules are estimated using automatic irrigation and fertilization options of the simulation models. A separate simulator is developed for four crops(corn, potatoes, wheat, and alfalfa), incorporating weather, soil, residue, management, crop characteristics, and irrigation system uniformity. The simulators generate one-hectare production activities composed of input requirements, nitrate leaching and crop yields. The simulations are done for each irrigation and fertilization strategy, creating thousands of production activities.

The production activities created in the first stage are then entered into the second stage farm-level mathematical programming model. Because of a large quantity of output from the simulation stage, a computer program, named the matrix generator, has been developed to link the two stages. The generator arranges the simulator output into a specific form required by the programming model, including an objective function, constraints and technical coefficients. At this stage, pertinent data including farm budget, output and input prices, economic and technical options, and policy constraints are incorporated.

The mathematical programming model is then run for a variety of economic, technical, and institutional conditions. The objective of this stage is to determine the crop mix, and irrigation and fertilization schedules that maximize farm income subject to a given set of constraints. The policy constraints considered in this analysis are; limits on nitrate emission(NLCHLIM), water supply(WATLIM) and fertilizer use(FERTLIM); unit taxes on pollution(NLCHTAX), water (WATTAX) and fertilizer(FERTTAX). The programming model provides farm income and pollution abatement cost which can be used as a measure of comparing policy options for their superiority under a given condition.

2. Simulation Models

Two groups of simulation models are used in this study; CERES models for corn, potatoes and winter wheat, and SPAW model for alfalfa.

The CERES(Crop Expectation through Resource and Environmental Synthesis) models are physiologically based crop growth models which simulates growth, development and yields of crops(John and Kiniry; Ritchie et al.; Hodges; Hodges and Johnson). The models also simulate water and nitrogen balances including movement, transformation, and leachate of water and nitrogen.

The simulation starts by calculating stress indexes for water, nitrogen, and temperature. Water and nitrogen stress indexes are determined based on supply and demand. Supply implies the amounts of water and nitrogen absorbed by the plant, whereas demand is the amounts required to maintain existing plant body and to expand new tissues. Temperature stress indicates how much daily temperature deviates from optimal temperature for the crop. These indexes are then used to calculate actual photosynthesis from potential photosynthesis which is determined by weather(mainly solar radiation and temperature), accumulated biomass, leaf area, and genetic characteristics. The photosynthate is distributed to the various parts of the plant for growth based on the stage of plant development and genetics(partitioning factor). Yield is merely a sum of the photosynthate partitioned to grain(maize and wheat models) or tuber (potato model) over the growing period.

Once the yield accumulation starts, nitrogen absorbed is partitioned to grain(corn and wheat) or tuber(potatoes). When nitrogen is limiting, the existing nitrogen accumulated in leaves and stems is re-partitioned to grain or tuber, and thus, new growth of leaves and stems is restricted. If nitrogen supply is enough for grain or tuber growth, yield reduction would not occur; otherwise yield would be decreased by the ratio of demand over supply.

Since the CERES family does not have alfalfa model, SPAW (Soil-Plant-Atmosphere-Water) model was selected for the crop. The model simulates plant growth, development, and yield as well as water balance(Saxton). Actual yield(Y_a) is estimated from plant water stress and the maximum yield(Y_m) determined exogenously by the user as:

$$Y_a=Y_m-k_y\left(\sum_{i=1}^{n} WS_i \cdot CS_i\right) \tag{1}$$

where WS_i is daily plant water stress index, CS_i is crop yield susceptibility factor, n is the number of days in the growing season, and k_y is an empirically derived slope of the relationship between yield and water stress index. In this study, 0.8 was taken for k_y following Doorenbos and Kassam. Relative transpiration is used to measure daily water stress index. That is,

$$WS_i=1-\frac{AT_i}{PT_i} \tag{2}$$

where: AT_i=actual transpiration in day i
PT_i=potential transpiration in day i

Unlike the CERES models, SPAW model does not have a nitrogen routine. Therefore, it was assumed that alfalfa growth is not affected by nitrogen and that no nitrate leaches from alfalfa fields.[1]

The two simulation models were modified to incorporate non-uniform nature of irrigation systems, application losses of water and fertilizer, automatic irrigation and fertilization options, and several other changes necessary to tailor the model to the study area.[2] Validation of the modified models suggests that prediction of crop phenological stages is adequate for all crops, and yield estimations are accurate for corn and potatoes and slightly high for wheat. Nitrate leaching forecasted for corn and potatoes are supported by experimental data found in the literature. No validation was possible on leaching for wheat because of a lack of existing data.

3. Mathematical Programming Model

With the large number of production possibilities provided by the simulation models, it becomes necessary to develop a technique to select a set of possibilities which maximizes farm income under a

[1] A detailed description of the CERES and SPAW models is available in Oh.
[2] For the modification in detail. see Oh.

given policy constraint such as limits on input use or pollution standards. Since linear programming(LP) "deals with the problem of allocating limited resources among competing activities in the best possible way" (Hillier and Lieberman, p.16), it is the technique that was chosen to analyze policy options in this study.

The LP model can be expressed algebraically as follows:

$$\text{maximize } Z=\sum_{i=1}^{ni} P_i \cdot Y_i - \sum_{i=1}^{ni} \sum_{j=1}^{nj} C_{ij} \cdot X_{ij} - \sum_{k=1}^{m} C_k \cdot R_k \tag{3}$$

$$\text{subject to, } AX \leq B$$
$$X \geq 0$$

where: Y_i = the quantity of the i-th crop produced
P_i = the price received for the i-th crop
X_{ij} = the process of producing i-th crop using the j-th irrigation/fertilization schedule combination
C_{ij} = the per hectare production cost of process Xij
n_i = the number of crops
n_j = the number of irrigation/fertilization schedule combinations for crop i
R_k = the quantity of the k-th resource used
C_k = the cost of resource Rk
m = the number of resources employed
A = an M × N matrix of technical coefficients
X = an N × 1 vector of production activities
B = an M × 1 vector of resource constraint levels

Major constraints considered in this analysis are land limits, water and fertilizer availabilities, pollution emission, sell activities of crops, labor and energy requirements, and buying activities for production inputs. The institutional restrictions to control nitrate groundwater pollution were incorporated in the programming model as objective function coefficients or right hand side constants. For example, the effects of pollution tax(NLCHTAX) were evaluated by changing price(negative) of nitrate leachate in the objective function. A parametric programming technique was used to create a series of optimal solutions in response to changing parameters of the policy constraints.

IV. Results

The two-stage model was applied to a representative farm in the study area. The farm is composed of 450 hectares producing corn, potatoes, winter wheat, and alfalfa with nine center pivot systems. The results of the application are presented in Table 1.

Table 1 Optimal Solutions for Alternative Policy Options on a 450-Hectare Farm

Scenarios	Input Use		Nitrate	Income	Abatement Cost[1]	
	Water	N Fert.	Leachate		Social	Private
	(1,000mm)	(1,000kg N)	(kg N)	($1,000)	($)	($)
CURRENT	349.3	82.1	17,760	404.5	-	-
BASE	310.7	67.5	10,625	415.0	-	-
Policy Options						
NLCHLIM						
8,000kg N	299.8	66.3	8,000	412.3	2,683	2,683
6,000kg N	288.3	65.0	6,000	393.8	21,143	21,143
NLCHTAX						
$0.96/kg N	305.2	67.5	8,375	405.4	1,588	9,611
$3.24/kg N	299.8	66.3	8,000	386.5	2,683	28,461
$14.0/kg N	288.3	65.0	6,000	320.2	21,143	94,780
WATLIM						
243,000mm	243.0	55.0	8,380	403.1	11,844	11,844
200,000mm	200.0	57.5	8,940	388.7	26,262	26,262
WATTAX						
$0.29/mm	243.0	55.0	8,380	333.7	11,844	81,234
$0.42/mm	200.0	57.5	8,940	304.7	26,262	110,262
FERTLIM						
40,000kg N	274.9	40.0	8,010	398.6	16,377	16,377
27,500kg N	224.3	27.5	6,090	354.8	60,198	60,198
FERTTAX						
$0.42/kg N	310.7	63.8	10,190	387.1	1,327	27,872
$0.97/kg N	274.9	40.0	8,010	359.6	16,377	55,341
$4.62/kg N	224.3	27.5	6,090	227.6	60,198	187,332

NOTE: 1) Social abatement cost does not include tax payment which is transfer cost, whereas private cost includes it.

1. Current Versus Base Scenario

The CURRENT scenario reflects the actual irrigation and fertilization schedule currently practiced by the model farmer. The BASE scenario represents the optimal management strategies under no policy constraint. The two scenarios were compared to demonstrate how much the current practices differ from the optimal strategies. Farm income and nitrate leaching of the current practice for the whole farm are $404,500 and 17,760 kg N, respectively, while those of the BASE scenario are $415,000 and 10,625kg N. The comparison analysis found that the current practice uses water and fertilizer inefficiently. The representative farmer applies too much water, 12.4 percent more than the optimal solution. Farmers tend to over-apply water to reduce risk and maximize physical yields in belief that they also maximizes farm income.

Non-uniformity of the irrigation system contributes to the excessive irrigation. Since the actual distribution pattern of irrigation is unknown, the farmer over-irrigates to insure that no part of the field is stressed. The result is to increase nitrate leaching and production cost. Timing of irrigation is also inappropriate. The irrigation scheduling conducted by the current farmer is based on fixed time intervals rather than considering soil, weather and crop conditions. This strategy usually results in a low soil water content during the peak water demand periods and unnecessarily high water content in other growth stages.

The current practice applies too much fertilizer, a 21.6 percent more than the optimal fertilization rate. Since nitrogen content in the soil is unknown, the farmer applies enough fertilizer as an insurance against nitrogen stress. Pre-plant fertilization is often too heavy. The current practice applies half of the seasonal fertilizer use before planting. Although moderate fertilization before planting is often recommended in the agronomy literature, too much pre-plant fertilization will increase leaching loss, and thus, lower nitrogen use efficiency.

The inefficiency in input use decreases farm income and increases nitrate groundwater pollution. The analysis indicates that, farm income can be increased by 2.6 percent and, more importantly, nitrate leaching can be reduced by 40 percent by adopting improved irrigation and fertilization management practices.

2. Policy Analysis

The analysis of the NLCHLIM policy demonstrates a large potential of reducing nitrate emission from irrigated agriculture. As the pollution limit becomes restrictive, irrigation rates are decreased to reduce deep percolation of water and nitrate leaching. Fertilizer use is not affected significantly. This implies that the farmer reduces the input most directly responsible for nitrate leaching, water. Pollution can be reduced significantly with relatively little effect on producer income. Under this policy, producer can freely adjust water or/and fertilizer whichever gives less impact on farm income in meeting the imposed pollution standards. Income losses required to decrease pollution by 25 percent and 44 percent from the BASE scenario solution are less than 1 percent and 5 percent, respectively. When compared to the current practice, pollution can be reduced over 60 percent without loss of current income.

The NLCHTAX policy imposes a series of unit taxes on nitrate leaching. Under this policy, nitrate leaching is sensitive to the tax when the pollution level is high. A tax of less than $1.00/kg N leachate reduces pollution by 21 percent. However, pollution emission becomes insensitive to the tax as abatement increases. To reduce nitrate leaching to 6,000 kg N (44 percent reduction), a tax of $14.00/kg N leachate is necessary. The NLCHTAX policy is the price dual of the pollution limits option(NLCHLIM). The two solutions are identical for resource allocation, pollution generation and social abatement cost. However, significant divergence exists when private sector cost is considered. Farm income is less under the tax policy than under the limits option. To reduce pollution by 25 percent and 44 percent, a 6.9 percent and a 25.3 percent decrease in income is required, respectively. Unless subsidized in some form, producers will prefer the standards approach to taxation. Neither policy option presents a practical alternative, however, because monitoring individual farmer effluent is not possible under current technology.

The water limit policy(WATLIM) may be useful to achieve a pollution level of 8,400 kg N (21 percent reduction from the BASE model). However, the policy should not be expected to reduce the emission to very low levels because, as water supply becomes restrictive, water is usually diverted from low profit crops to high profit crops such as potatoes which emit a lot of nitrates(potato-emphasizing behavior).[3] Furthermore, fertilizer substitutes for water, resulting(in certain cases) in even more nitrate leaching to the groundwater than when water is less restrictive. Social cost to reduce pollution by 21 percent is moderate; $11,844 or a 2.9 percent decrease from the BASE model solution. When compared to the current practice, a 53 percent pollution reduction can be obtained with a 2.9 percent decrease in farm income.

The water tax policy(WATTAX) is a price dual of the WATLIM model. Pollution can be lowered up to 8,400 kg N (21 percent reduction) with a moderate tax rate of $0.29/mm/ha. Further reduction in pollution may not be obtained due to the potato-emphasizing behavior and the factor substitution. Income loss required to reduce nitrate leaching by 21 percent is 20 percent, a much higher cost than the WATLIM model.

Under the fertilizer limits policy(FERTLIM model), production of potatoes is not affected by the policy until the limit becomes very restrictive. As the limit becomes restrictive, more proportion of fertilizer is allocated to potatoes which emit substantial amount of pollution. Due to the potato-emphasizing behavior, nitrate leaching does not drop significantly until one third of fertilizer limit is deprived. No significant substitution occurs between fertilization and irrigation under this policy since intensive irrigation would results in a decrease in yield. Income losses anticipated to reduce pollution by 21 percent and 43 percent are $16,377 and $60,198, which are 3.9 and 14.5 percent of the baseline solution, respectively. These pollution levels are 55 percent and 66 percent reduction from the current practice.

The FERTTAX policy imposes a series of taxes on fertilizer. Nitrate leaching is affected little by the policy when the tax rate is low. A tax rate of $0.42/kg N (66 percent of fertilizer market price) reduces only 4.1 percent of nitrate leaching. To eliminate the emission by 25 percent, it is necessary to raise the tax rate to $0.97/kg N which

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[3] Potatoes emit a lot of nitrates because of shallow rooting depth and intensive irrigation and fertilization.

is 152 percent of fertilizer price. A very high tax is required to drop the pollution level by 43 percent because of the potato-emphasizing behavior. Income loss required to reduce pollution by 25 percent is \$55,341, a 13.3 percent reduction from the optimal solution. To lower the pollution by 43 percent, nearly half of farm income is lost.

V. Conclusions and Implications

It is important to emphasize the role of water management for controlling nitrate groundwater pollution. If water does not percolate below the root zone, no leaching of nitrate can occur. Fertilization management is also important to reduce nitrate leaching. If a proper amount of fertilizer were applied with appropriate timing, there would be no leaching even if water percolates below the root zone.

The results of this study indicates that primary reason of the prevailing nitrate groundwater pollution is inefficient use of inputs; that is, too much application of water and fertilizer with inappropriate timing. In the setting of this analysis, over 40 percent of pollution can be reduced with a 2.6 percent increase in farm income by eliminating the inefficiency in input use.

To increase the input use efficiency, several changes should be made in the current management practices and producer support services. Irrigation and fertilization scheduling should be related to the soil, climatic and crop conditions, especially on coarse-textured soils. Periodic soil testing for soil water and nitrogen are necessary throughout the growing period. This may require some capital investment for testing equipment such as tensiometers, neutron probes, infra red guns, and/or computers.

An accurate weather forecast and report services for the region is required. Weather conditions (precipitation, temperature, and solar radiation) affect the amounts of soil water and mineral nitrogen in the root zone which, in turn, affect nitrate leaching. Farmer's decision making on irrigation and fertilization is also affected by future weather. It is recommended to provide an accurate irrigation scheduling service for each crop based on meteorological, pan evaporation and soil moisture data.

An improvement in the irrigation system is also recommended to apply water more evenly throughout the field. A study reports that lowering uniformity of water application by 10 percent will result in increases in water use by 34 percent, fertilizer use by 20 percent, and nitrate emission by over 100 percent(Oh). This may require capital investment and improvement in engineering technology.

Lastly, and most important, farmers must understand the economic principle of profit maximization and the consequences of nitrate groundwater pollution. An active education is necessary for this purpose.

Further reduction in nitrate groundwater pollution can be obtained by implementing appropriate policy instruments. The most efficient measure is to restrict pollutant emission directly either by setting standards or by imposing taxes. Under these policies, producer can freely adjust water or/and fertilizer to meet the desired pollution standards, and thus, minimize costs. However, these policies have a critical problem in practice since nitrate leaching from individual farm cannot be monitored or too costly.

Both water-related and fertilizer-related options are practicable. The water-related policies can reduce the pollution 21 percent without a large impact on farm income, but an excessive restriction should be avoided since it does not decrease pollution but only increase farmer cost. The fertilizer-related options also reduce the pollution by 25 percent with relatively small effect on producer income. To reduce the pollution further, however, substantial costs would be required. Relative superiority of the two input-related policies vary. Furthermore, farmers prefer limit policies to tax options. Accordingly, the pollution control authority should choose appropriate policy case by case depending on available information, transactions costs, enforcement, practicability and government objectives of implementing the policy.

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