A COMPARATIVE STUDY OF POLICY MEASURES FOR GROUNDWATER POLLUTION CONTROL

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I. Introduction

Groundwater pollution creates externalities that lead to market failure. When an externality exists, government intervention may be necessary to move the economy to a Pareto-improvement position if market forces by themselves are unable to eliminate the prevailing inefficiencies (Dahlman, 1979; Kneese and Bower, 1984). By implementing suitable policies, appropriate markets can be established, and economic agents will take into account the external effects they generate(Dahlman, 1979).

The economic and environmental literature suggests various policy measures to alleviate market failures. These include: taxes on effluent itself or pollution generating activities or inputs; subsidies on pollution reduction activities; standards on effluent and input use; marketable permits for pollution emission or input use rights. However, developing and implementing these options are not costless.

In this study, efficiency and effectiveness of Pigouvian and input taxes which can be potentially used to control nitrate groundwater pollution caused by agricultural activities are compared theoretically and empirically.[1]

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[1] Limits on emission and input use, Pigouvian subsidies and marketable permits can be employed to regulate nitrate groundwater pollution. However, they are excluded from the discussion because the results of these policies are equivalent (in pollution control) to taxation under a setting of certainty which is a basic assumption in this study.

II. Theoretical Comparison

1. Pigouvian Taxes

Pigou(1932) recognized that an externality problem could be resolved by imposition of a tax. The idea behind a Pigouvian tax(also called pollution tax, effluent charge, corrective tax, etc.) is that the external costs generated by a farmer should be internalized when the farmer decides how much to produce. The proper level of the tax is the marginal social damage produced by the farmer. This can be illustrated with a highly abstract and simplified model as follows.

Consider a case in which a farmer(party A) cultivates a crop and contaminates groundwater(by leaching nitrates) that is used by an individual(party B) as a drinking water source. A's objective is to maximize his profit:

$$\pi^a = P_q Q - C(Q) \tag{1}$$

while B's is maximizing utility:

$$U^b = U(Z(Q)) \tag{2}$$

where Q is quantity of crop produced, P_q is price of the crop, C(Q) is a cost function, and Z is the level of the pollutant in drinking water as a function of Q, that is Z = Z(Q).[2] It is assumed that Z increases as Q increases($Z_Q > 0$), and that U decreases as Z increases ($U_Z < 0$), where the subscripted variables on the functional operator indicate the first partial derivatives, i.e., $Z_Q = \partial Z / \partial Q$, etc. The society's overall objective is represented by

$$\max W = [P_q Q - C(Q) + U(Z(Q))] \tag{3}$$

where W is social welfare. Assuming A is a price taker, the first-order

[2] The expression (2) implies that B's utility is a function of the drinking water quality. It is simplified form of $U^b = U(Z(Q); X)$ where X is a vector of ordinary consumption goods. One alternative expression is $U^b = U(D(Z(Q)))$ where D represents diseases caused by water-borne nitrates such as methemoglobinemia.

maximum condition is

$$P_q = C_Q - U_Z \cdot Z_Q \tag{4}$$

This condition depicts that marginal benefit(P_q) to the farmer from producing the crop is equal to marginal social costs, marginal private cost plus marginal social damage. Note that $U_Z \circ Z_Q$ is negative, and is interpreted as marginal damage incurred by B from A's activity.[3] A corrective tax can be used to make the farmer account for the marginal damage done to B, and hence, lead to an efficient allocation of resources.[4]

The pollution tax may reduce input uses which generate the pollution. Suppose the government imposes a pollution tax on each unit of nitrate leachate. The farmer's objective is to maximize profit(π) as;

$$\max \pi = P_y f(W, N;R) - r_w W - r_N N - b - T^p g(W, N) \tag{5}$$

where P_y represents a product price, $f(\circ)$ a production function that embodies all conditions of the neoclassical firm theory. W and N denote quantity of irrigation water and nitrogen fertilizer applied to the crop,[5] respectively, and r is factor costs for these inputs. R is a vector of fixed inputs, b fixed cost associated with R, T^p a per unit tax on pollution, and $g(\circ)$ the amount of nitrate leached as a function of irrigation and fertilization. It is assumed that $g(\circ)$ increases at an

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[3] The expression (3) has a problem in that profit can not be added to utility. That is why most authors take a consumer-consumer or producer-producer case when they analyze externalities mathematically. However, while the expression does not yield a single term (in monetary or utility), it is not incorrect conceptually. An alternative of this expression is
(3)' $\max W = U^a(\pi^a(Q)) + U^b(Z(Q))$.
where W is social welfare. The first order condition to this problem is
(4)' $P_q = \partial C/\partial Q - (\partial U^b/\partial Z)(\partial Z/\partial Q)/(\partial U^a/\partial \pi^a)$,
which is also interpreted as price equals marginal cost plus marginal social damage.

[4] Note that equation (4) implies reduction in farmer's activity which generates pollution. This relationship is geometrically illustrated by Oh(1991), Turvey(1963) and Boadway and Wildasin(1984) in various ways.

[5] The two inputs are controllable factors which affect nitrate leaching to the groundwater.

increasing rate with the levels of W and N,[6] and that W and N are separable in f(•) and g(•). The first-order conditions for maximum profit are

$$P_y f_W = r_W + T^p g_W \qquad (6)$$
$$P_y f_N = r_N + T^p g_N.$$

That is, marginal value product of each input equals marginal factor cost plus marginal tax payment(unit tax multiplied by marginal contribution of the input to total leachate), meaning that reduction in input uses. Notice that the Pigouvian tax affects both inputs which determine nitrate leaching.

The result of this analysis is illustrated in Figure 1. The diagram is drawn for the single factor(fertilizer) case for simplicity. The curves f(N) and g(N) represent crop production and pollution generation functions, respectively. Without an institutional constraint, the farmer will choose the fertilization level N^0 where MVP_N equals r_N, and create g^0 amount of nitrate leaching and y^0 amount of yield. If the tax option is imposed, N^0 is no longer profitable since MVP_N is less than the new marginal factor cost modified by the policy(r_N + c). Instead, the farmer will select N^* at which MVP_N equals r_N + c. The size of c is equal to $T^p \cdot g_N$. Accordingly, nitrate leaching will decrease to g^*, yield to y^*, and the farmer's profit also will be reduced by the amount indicated by the shaded area. The reduction in profit is the abatement cost incurred by the farmer to obtain the low level of pollution. The cost will be estimated in the next section.

Although the Pigouvian tax is theoretically appropriate for large numbers cases, as Baumol(1972) asserts, serious problems exist in implementing it for the nitrate groundwater pollution. First, it is not easy to obtain a reasonable estimate of the social damage costs of the pollution. Although several studies have attempted to determine the value of clean groundwater(Rancher, 1983, 1986; Edwards, 1988; Walker and Hoehn, 1988), these values do not necessarily represent

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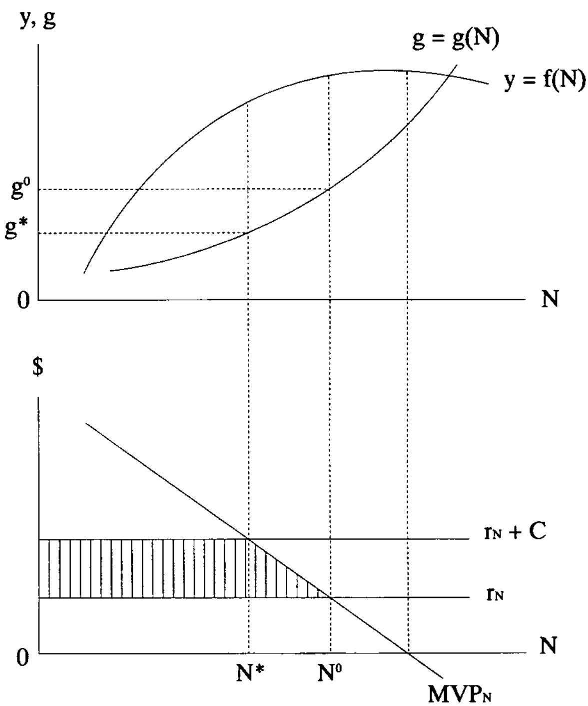
6 It is believed that nitrogen uptake by a crop is subject to diminishing returns, so that additional use of nitrogen should increase marginal nitrate leaching(Letey et al., 1977). Dinar, Knapp, and Letey(1989) also assumed a convex emission function.

FIGURE 1. Graphical Illustration of Optimal Input Use Under Various Policy Options



marginal damages incurred by the society from the nitrate leaching. Moreover, as Crocker, Forster and Shogren(1991) point out, these assessments fail to include the full set of physical and economic consequences associated with groundwater contamination, resulting in an undervaluation of contamination effects. To complicate matters, the optimal tax level on nitrate leaching is not equal to the marginal social damage it generates initially, but rather to the damage it would cause after a natural purifying or degradation process. Second, since the nonpoint agricultural pollutant(nitrogen leachate) comes from a large diffuse population through a complicated process, monitoring it is either infeasible or economically impractical. Third, even if the tax rate can be determined, the rate should be periodically readjusted because of economic and technological changes in society.

2. Input Taxes

The prescription discussed above has a practical difficulty: the amount of nitrate leachate must be estimated for each farmer. A solution to this problem can be an excise tax on pollution-creating inputs such as fertilizer and irrigation water. The tax will induce farmers to use those inputs more efficiently, so that less nitrate will leach beyond the root zone.

This can be explained by using the same model described in the discussion of pollution tax policy. Society's objective under this setting is to maximize social welfare(*SW*), the sum of the farmer's profit and the victim's utility,

$$\max SW = P_y\, f(W,N;R) - r_w W - r_N N - b + U(g(W,N)) \qquad (7)$$

The first-order condition of this maximization problem is:

$$P_y\, f_i - r_i + U_g\, g_i = 0. \quad (i = N,W) \qquad (8)$$

Condition (8) can be rewritten, with an assumption that $U_g < 0$ and $g_i > 0$,[7] as

$$MVP_i = r_i + MD_b. \quad (i = N,W) \qquad (9)$$

Condition (9) depicts that marginal value product of an input equals its marginal factor cost plus marginal social damage done by each additional unit of the input used. This implies the efficient allocation of a resource can be achieved by placing an excise tax on each input at a rate that equals its marginal social damage. As illustrated in Figure 1, with setting $c = MD_b = T^f$, where T^f is an excise tax on fertilizer, use of the taxed input will be decreased.

The input tax policy is easy to implement because the government can directly charge suppliers of inputs(e.g. the irrigation district or fertilizer manufacturers). However, the effectiveness of this

[7] Notice that the assumption $g_i > 0$ does not always hold. For example, nitrogen leaching could be low even though much nitrogen fertilizer is used if the fertilizer were ideally distributed and consumed by the crop.

policy is doubtful for several reasons. First, it is impossible or costly to estimate marginal social damage from the use of the inputs. An arbitrary setting of tax rates may result in distortion of resource allocation even worse than the *status quo*. Moreover, the tax rate should be set for each polluter, for each crop, and for each field because g_i can vary from farm to farm, from crop to crop, and even from field to field. Any across-the-board tax will be economically inefficient(Stevens, 1988). Second, because of the inelastic nature of demand for irrigation water and fertilizer(Roberts, 1986), there is no guarantee that input taxes would decrease the use of these inputs without an unrealistically high tax rate. Third, two inputs, water and fertilizer, affect the nitrate leaching simultaneously. Thus, controlling one input may not resolve the problem. For example, taxes on fertilizer may increase water use, resulting in an increase in nitrate leaching rather than a decrease, and vise versa. To increase effectiveness of the policy, all the inputs which cause pollution must be taxed simultaneously, decreasing the practicability. Fourth, pollution does not increase monotonically with the level of input use. In many cases, especially in agriculture, management is much more important than total use of inputs for pollution reduction. Taxing an input does not provide an incentive to improve technology to reduce nitrate leaching. Finally, if the policy were implemented locally, say statewide, farmers would transport inputs from adjacent states, making the policy ineffective(Taylor, 1975).

3. Comparison of the Policy Alternatives

As shown above, the two policy options can achieve an optimum pollution level under particular assumptions. This fact was explored formally by Griffin and Bromley(1982) and tested empirically by knapp, Dinar, and Nash(1990). However, in case of nitrate groundwater pollution, the policies are not equally efficient in terms of social costs for pollution abatement. Under the pollution tax policy, farmers can freely adjust either water or fertilizer application, or any combination of them, to minimize reduction in profit, yet meeting the policy constraint. Under the input tax policy, the flexibility is not provided, imposing higher abatement costs and/or decreasing practicability.

On the other hand, Stevens(1988) compared the effects of effluent charges and input taxes on producer profits. Producer profits are equal, greater, and less under effluent charges if d=1, d>1, and d<1, respectively where d represents the degree of homogeneity of the nonpoint pollution production function. Dinar, Knapp, and Letey (1989) show a similar result that a pollution tax gives greater profit to a producer when the pollution is a convex function of inputs used.

The amount of information necessary to achieve efficiency is different among the policy measures. Griffin and Bromley(1982) identified that the number of parameters required to achieve the optimal pollution level at least cost is one for pollution tax, and $N*J$ for input tax, where J is the number of firms and N the number of goods or activities. In general, a measure which charges pollution directly is more effective than taxation on inputs(Hartwick and Olewiler, 1986; Johnson, Perry, and Adams, 1989).

To summarize, in relation to the problem of nitrate pollution of groundwater, the Pigouvian tax is the most preferred and economically efficient measure in theory. It requires less abatement and transaction costs than the others. However, in practice, it has critical problems in setting the rate and estimating the leachate level. The input tax has appealing advantages in that it can be implemented relatively easily and measuring the leachate is not necessary. However, its effectiveness is doubtful because of the inelastic nature of demand for irrigation water and fertilizer. Setting the appropriate tax level is also a complex and difficult task.

There is no perfect policy measure to control nitrate groundwater pollution caused by agriculture. The policy alternatives discussed can, in theory, achieve efficient levels of pollution. At the same time, they have problems in application. The government must choose the most effective, least cost, and most workable policy(or combination of them) case by case.

III. Empirical Comparison

1. Analytical Model

To analyze and compare the effect of the policy options empirically, a two-stage mathematical programming model has been developed. In the first stage, biophysical simulation is used to create a number of production activities differing in irrigation and fertilization strategies. CERES models are used for corn, potatoes and winter wheat, and the SPAW model for alfalfa. The simulators generate input requirements, nitrate leaching and crop yields for each activity.

The production activities(approximately 1,600) created in the first stage are entered into a second-stage farm-level mathematical programming model, which maximizes farm income subject to a given set of constraints. The policy constraints considered in this analysis are unit taxes on nitrate leachate(NTAX), irrigation water(WTAX) and nitrogen fertilizer(FTAX). The programming model provides a series of optimal(profit maximizing) production schedules, and associated nitrate leaching, farm income and pollution abatement costs.[8]

2. Results of Analysis

The two-stage model is applied to a representative farm in the Columbia Basin Irrigation Project area of Washington State, United States.[9] The farm is composed of 450 hectares of land, producing corn, potatoes, winter wheat, and alfalfa. The results of the application are as follows.

(1) No policy option(NOPOL)

The NOPOL scenario provides an optimal solution in which improved management practices are incorporated without policy constraint, such as N^0, y^0 and g^0 in Figure 1. Therefore, this scenario gives the best solution to the farmer whose objective is to maximize profit. Farm income, nitrate leachate, water and fertilizer uses of this

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[8] For a detailed description of the two-stage model including biophysical simulators, refer to Oh(1991, 1992).

[9] A detailed description of the Project area is given in Oh(1991, 1992).

scenario for the whole farm(450 hectares) are $414,973, 10,625kg N, 310,690mm ha, 67,500kg N, respectively. The farm income predicted by the NOPOL scenario serves as a benchmark from which pollution abatement costs are calculated for each policy alternative.

(2) Taxes on nitrate leaching(NTAX)

The NTAX policy levies a series of unit taxes($0-50kg/ N) on nitrate leachate. Since the policy imposes real prices on nitrate leaching, profit maximizing behavior reduces emissions voluntarily to an optimal level.

The relationship between taxes and pollution emissions is depicted in Figure 2. Nitrate leaching is sensitive to the tax when the leaching rate is high. A tax of less than $1.00 per kilogram of N leachate reduces pollution by 21 percent, while a tax of $3.24/kg N decreases nitrate leaching to 8,000kg N for the whole farm. The emission becomes insensitive to the tax as abatement increases, and hence, higher taxes are required to decrease pollution further. To reduce nitrate leaching to 6, 000kg N, a tax of $14.00 per kg N is necessary.

Figure 3 portrays farm income plus social and private abatement

FIGURE 2. Pollution Tax and Nitrate Leaching in the NTAX Policy

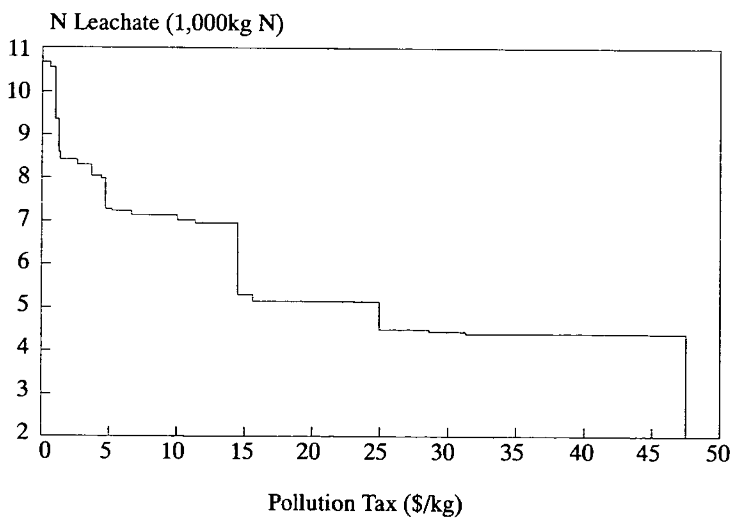
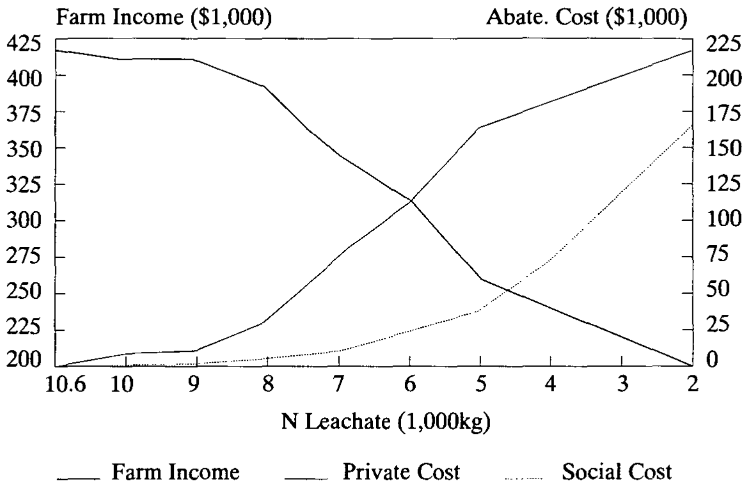


FIGURE 3. Farm Income and Pollution Abatement Costs for Each Level of Nitrate Leaching in the NTAX Policy



costs for each level of pollution.[10] Farm income decreases slowly until the level of 9,000kg N of nitrate leaching is reached, after which farm income declines rapidly. The private abatement cost curve shows symmetry to the farm income curve since the costs are derived by subtracting farm income from the NOPOL scenario solution($414, 973). The distance between the social and the private cost curves represents tax revenue for each pollution level.

From society's point of view, there is a large potential for reducing nitrate groundwater pollution from irrigated agriculture. Social cost is only $2,683(0.6 percent of NOPOL solution) when nitrate emission is reduced to 8,000kg N(24.7 percent reduction). When pollution is lowered to 6,000kg N, substantial increase in social cost is still avoided; a 43.5 percent decrease in pollution results in a 5.1 percent increase in society's loss. Through the conjunctive management

[10] The private abatement cost includes tax payment, while the social cost does not.

of water and fertilizer, deficit irrigation, and crop mix, a large reduction in nitrate leaching can be attained with relatively little effect on society.

From the standpoint of the private sector, however, relatively high cost occurs to abate the pollution because of tax payment. For example, a 6.9 percent decrease in farm income is required to reduce pollution by 24.7 percent, and 25.3 percent for 43.5 percent reduction of pollution.

(3) Taxes on water use(WTAX)

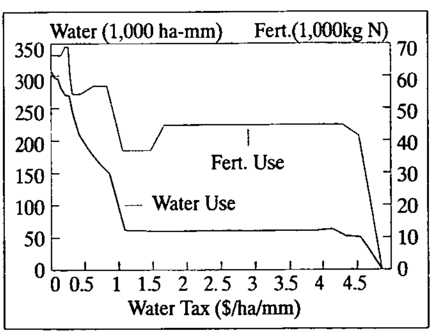
The WTAX policy imposes a unit tax on irrigation water to achieve a price that balances nitrate groundwater pollution and farm income. The tax rates considered range from zero to $4.7 per mm/ha of water at which no crop is profitable.

Water and fertilizer use and the resulting pollution levels are shown in Figure 4 for the range of water taxes considered. Water and fertilizer use levels decrease dramatically as the tax rate increases up to $1.00/mm/ha. These decreases stem mainly from deficit irrigation and elimination of low profit crops from production. Corn is removed at a tax rate of $0.29/mm/ha and wheat is eliminated at $0.84/mm/ha. When the tax rate exceeds $1.50/mm/ha, only potatoes are profitable.

Nitrate leaching does not decrease until the tax rate reaches $0.

FIGURE 4. Water and Fertilizer Use and Associated Nitrate Leaching for Each Level of Water Tax in the WTAX Policy

Panel 1: Water and Fert. Use



Panel 2: N Leaching

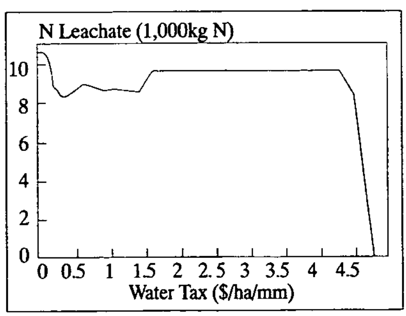


TABLE 1. Farm Income and Pollution Abatement Costs on a 450-Hectare Farm in the WTAX Policy

Nitrate Leachate (1,000kg N)	Farm Income ($)	Social Cost ($)	Private Cost ($)
10.6	414,973	0	0
10.0	364,926	2,960	50,047
9.0	361,113	3,744	53,860
8.4	308,975	11,844	105,998

07/mm/ha. At the tax rate of $0.29/mm/ha, nitrate leaching reaches its lowest level, about 8,400kg N. When the tax rate exceeds $1.50, however, the emission increases again due to factor substitution for potatoes; the farmer increases use of untaxed input(fertilizer) to maintain potato yield.[11]

Table 1 presents social and private costs necessary to achieve pollution abatement in the WTAX policy. Social cost required to reduce pollution by 21 percent(to 8,400kg N) is moderate: $11.844, 2. 9 percent of the NOPOL solution. Private cost for pollution abatement increases rapidly, however, owing to reductions in yield and the tax payment. Private cost to reduce nitrate leaching to 8,400kg N is about $106,000(25.5 percent), a much higher cost than the NTAX policy.

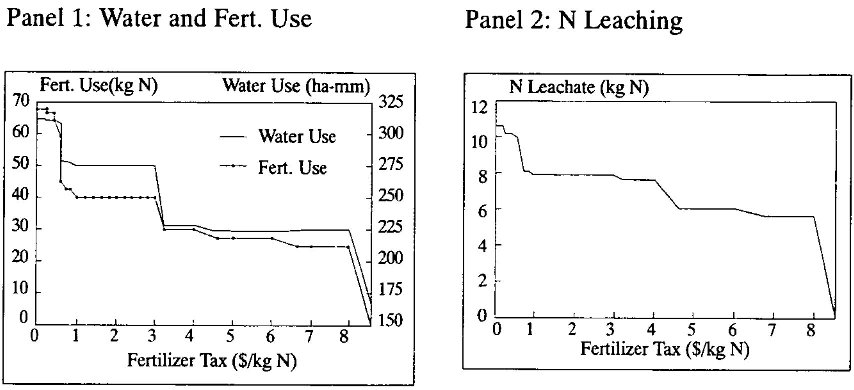
(4) Taxes on fertilizer use(FTAX)

The FTAX policy is employed to forecast impacts of taxing fertilizer on nitrate groundwater pollution and farm income. A series of fertilizer taxes ranging zero to $8.60/kg N are examined.

Figure 5 depicts input uses and the resulting nitrate leaching for each level of fertilizer tax. Fertilizer and water use drop stepwise as the tax rate increases. The first drop is caused by removal of corn acreage from production and the second by elimination of wheat. As the tax rate exceeds $3.00/kg N, only potatoes are profitable. A tax

[11] Although this fact has not been verified in the field, many agronomists agree with the results.

FIGURE 5. Water and Fertilizer Use and Associated Nitrate Leaching for Each Level of Fertilizer Tax in the FTAX Policy



rate of $0.42/kg N(66 percent of fertilizer market price) eliminates only 4.1 percent of the leaching. To reduce the emission to about 8,000kg N, it is necessary to raise the tax rate to $0.93/kg N(152 percent of fertilizer price). However, even with an unrealistically high tax rate, nitrate leaching will not decline below 5,700kg N because potatoes emit a large amount of nitrate.

Table 2 presents costs for pollution abatement and farm income

TABLE 2. Farm Income and Pollution Abatement Costs on a 450-Hectare Farm in the FTAX Policy

Nitrate Leachate (1,000kg N)	Farm Income ($)	Private Cost ($)	Social Cost ($)
10.6	414,973	0	0
10.0	377,303	37,670	4,563
9.0	374,071	40,902	12,881
8.0	356,524	58,449	17,497
7.0	251,033	163,940	53,746
6.0	212,035	202,938	64,867

for the FTAX policy. A reduction in pollution to 8,000kg N(24.7 percent reduction) requires a 14.1 percent decrease in farm income. Further reduction in nitrate leaching requires restriction of potato production which increases the farmer cost. To achieve 6,000kg N of leachate, half of farm income will be lost. Social costs are much lower than private cost: $17,497(4.2 percent) and $64,867(15.6 percent) are anticipated to reduce pollution level to 8,000kg N and 6,000kg N, respectively.

(5) Comparison of policy options

Figure 6 and 7 compare efficiency of the three policies analyzed above for pollution abatement in terms of social and private costs, respectively. The diagrams demonstrate that the policy that deals with the externality directly(NTAX) provides the most efficient solution. Under this policy, the producer freely selects to restrict water and/or fertilizer, whichever is most efficient to reduce nitrate leaching, the taxed resource. Although this policy is most efficient in pollution

FIGURE 6. Comparison of Social Costs for Pollution Abatement in NTAX, WTAX and FTAX Policies

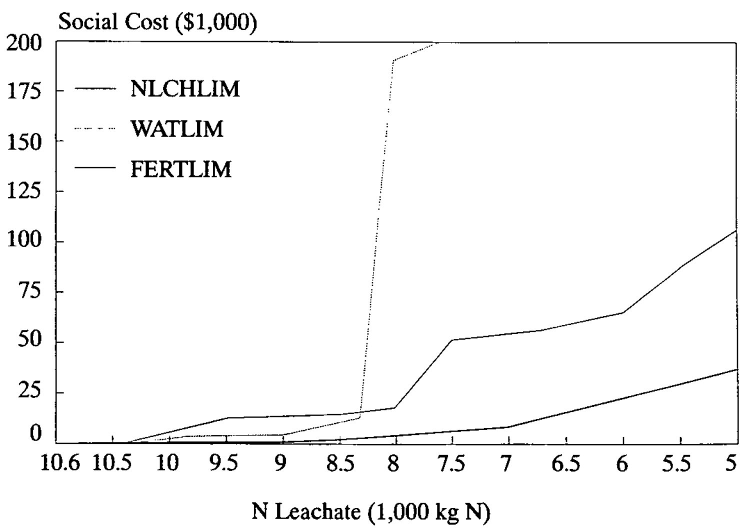
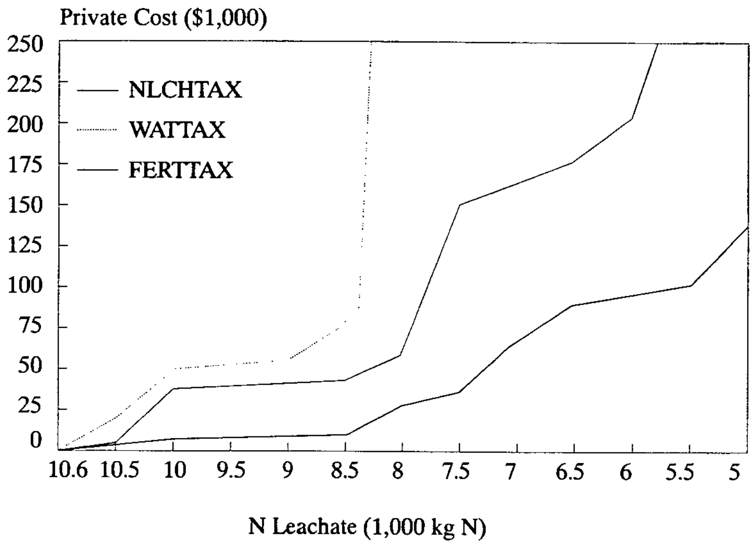


FIGURE 7. Comparison of Private Costs for Pollution Abatement in NTAX, WTAX and FTAX Policies



control, it has a critical problem in practice, that is, monitoring nitrate leaching is infeasible or too costly under current technology.

Taxing water(WTAX) and fertilizer(FTAX) are alternative approaches to controlling nitrate pollution. The WTAX policy is more efficient than taxing fertilizer, from the standpoint of society(Figure 6), until pollution is decreased to 8,400kg N. Up to this level, the marginal pollution generation of water is greater than that of fertilizer while the marginal abatement cost is smaller. The FTAX policy is the least efficient up to 8,400kg N of nitrate leaching. Restricting fertilizer use in this range imposes a relatively large cost to society. Beyond this level, however, the superiority for pollution abatement of the two policies changes.

From the farmer's perspective, the story is different. Taxation on fertilizer use is superior to the WTAX policy for the whole range of the pollution. The change in relative superiority of the FTAX and WTAX policies in the 10,600-8,400kg N of pollution reflects the relatively high amount of tax payment under the WTAX policy in the range.[12]

IV. Conclusion

The Pigouvian tax, which charges the effluent directly, is the most efficient measure to control nitrate groundwater pollution, but it has a critical problem in implementation. Both taxing-water and taxing-fertilizer options are useful and practicable for moderate levels of abatement, but should not be expected to reduce pollution to very low levels. Relative superiority of the two input-related policies vary depending on pre-policy levels of pollution and viewpoint. Water tax policy is superior to taxation on fertilizer from society's standpoint but inferior from the farmer's perspective. Choice of policies depends upon available information, enforcement, practicability, transactions costs, and government objectives(efficiency or equity) in implementing the policy.

[12] The relative superiority may differ depending upon crop and field condition.

REFERENCE

Baumol, W. J. "On Taxation and the Control of Externalities." *American Economic Review*, 62(2):307-22, 1972.

Baumol, W. J., and W. E. Oates. *The Theory of Environmental Policy*, 2nd ed. New York: Cambridge University Press, 1988.

Boadway, R. W., and D. E. Wildasin. *Public Sector Economics*, 2nd ed. Boston, MA: Little Brown & Company Limited, 1984.

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

Crocker, T. D., B. A. Forster, and J. F. Shogren. "Valuing Potential Groundwater Protection Benefits." *Water Resources Research*, 27(1): 1-6, 1991.

Dahlman, C. J. "The Problem of Externality." *Journal of Law and Economics*, 22(1):141-62, 1979.

Dinar, A., K. C. Knapp, and J. Letey. "Irrigation Water Pricing Policies to Reduce and Finance Subsurface Drainage Disposal." *Agricultural Water Management*, 16:155-71, 1989.

Edwards, S. F. "Option Prices for Groundwater Protection." *Journal of Environmental Economics and Management*, 15(4):475-87, 1988.

Griffin, R. C., and D. W. Bromley. "Agricultural Runoff as a Nonpoint Externality: A Theoretical Development." *American Journal of Agricultural Economics*, 64(3):547-52, 1982.

Hartwick, J. M., and N. D. Olewiler. *The Economics of Natural Resource Use*. New York: Harper & Row, Publisher, Inc., 1986.

Johnson, S. L., G. M. Perry, and R. M. Adams. *Managing Groundwater Pollution from Agriculture Related Sources: An Economic Analysis.* Department of Agricultural and Resource Econ., Oregon State Univ., Corvallis, 1989.

Knapp, K. C., A. Dinar, and P. Nash. "Economic Policies for Regulating Agricultural Drainage Water." *Water Resources Bulletin*, 26(2):289-98, 1990.

Kneese, A. V., and B. T. Bower. *Managing Water Quality: Economics, Technology, Institutions*. Washington D. C.: Resources for the Future, 1984.

Letey, J., J. W. Blair, D. Devitt, L. J. Lund, and P. Nash. "Nitrate-Nitrogen in Effluent from Agricultural Tile Drains in California." *Hilgardia*, 45: 289-319. 1977.

Meade, J. E. "External Economies and Diseconomies in a Competitive Situation." *Economy Journal*, 62:54-67, 1952.

______. *The Theory of Economic Externalities. The Control of Environmental Pollution and Similar Social Costs*. Leiden, Sweden, 1973.

Oh, S. I. *Managing Nitrate Groundwater Pollution from Irrigated Agriculture: An Economic Analysis*. Ph. D. Dissertation. Department of Agricultural Economics, Washington State University, 1991. Reprinted in Korea.

______. "The Farm-Level Costs of Controlling Nitrate Groundwater Pollution." *Journal of Rural Development*, 15:41-56, Korea Rural Economic Institute, Seoul, Korea, 1992.

Pigou, A. C. *The Economics of Welfare*. London, 1932.

Plott. C. R. "Externalities and Corrective Taxes." *Economics*, 33(129):84-87, 1966.

Rancher, R. L. "A Conceptual Framework for Measuring the Benefits of Groundwater Protection." *Water Resources Research*, 19(2):320-326, 1983.

______. "The Benefits and Costs of Policies Related to Groundwater Contamination." *Land Economics*, 62(1): 33-45, 1986.

Roberts, R. K. "Plant Nutrient Demand Functions for Tennessee with Prices of Jointly Applied Nutrients." *Southern Journal of Agricultural Economics*, 18(2):107-12, 1986.

Spulber, D. F. "Effluent Regulation and Long-Run Optimality." *Journal of Environmental Economics and Management*, 12(2):103-16, 1985.

Stevens, B. K. "Fiscal Implications of Effluent Charges and Input Taxes." *Journal of Environmental Economics and Management*, 15(3):285-96, 1988.

Taylor, C. R. "A Regional Market for Rights to Use Fertilizer as a Means of Achieving Water Quality Standards." *Journal of Environmental Economics and Management*, 2(1):7-17, 1975.

Turvey, R. "On Divergences between Social Cost and Private Cost." *Economica*, 30:309-13, 1963.

Walker, D. R., and J. P. Hoehn. *The Economic Costs of Nitrate Contamination in Rural Groundwater Supplies*. Department of Agricultural Economics, Michigan State University, East Lansing, Agricultural Economics Report No. 525, 1989.

빈 면