Comparative Effectiveness of Discharge and Input Control for Reducing Nitrate Pollution

JIAHUA PAN[1]
Department of Land Economy
University of Cambridge
19 Silver Street
Cambridge CB3 9EP England

ABSTRACT / Nitrate pollution has caused serious environmental concerns, but its control is often complicated by its diffuse nature. In most cases, nitrate control has been linked to either nitrogen input or leaching. By incorporating the relationship among land use, fertilizer application, and nitrogen leaching into a linear programming model, this analysis investigates the comparative effectiveness between input and leaching control. The empirical results from a groundwater catchment in eastern England suggest that leaching control can be more cost-effective in nitrate reduction than fertilizer input control. The implications for control of nitrate leaching through incentives systems are discussed.

Fertilizers constitute nearly half of the total nitrogen inputs in UK agricultural land. Other major sources include livestock excreta, rainfall, and biological fixation (Royal Society Study Group 1983, p. 57). Besides plant uptake and other losses, more than 12% of the total nitrogen in the soil pool reaches surface water and groundwater through leaching. Excessive rates of nitrate leaching are responsible for high nitrate levels in water, which at certain levels are considered detrimental to human health. As a result, a nitrate limit of 50 mg NO_3/liter has been set on drinking water supplies for member countries of the European Community (EC 1980).

Nitrate pollution has been an important policy issue in Great Britain since the early 1980s. Nitrate levels in groundwater sources, which constitute as much as 70% of supplies for drinking water in parts of southern and eastern England, have been increasing. Over the last decade, the UK government has sponsored scientific and economic studies (e.g., NCG 1986, DOE 1988), acquired relevant evidence (SCEC 1989), and designated nitrate sensitive areas (MAFF 1990), but at the same time, Britain has failed to enforce the EC limit on nitrates in drinking water in parts of East Anglia and the Midlands and is facing charges in the European Court (Guardian 1992).

The economic and policy issues in regulating agricultural diffuse source pollution are well documented in the literature. For example, the conceptual dimensions of agricultural pollution are developed in Whitby and Hanley (1986), Segerson (1989), and Hodge (1991). However, nitrate pollution control is often complicated by the difficulty in identifying pollution sources and hydrogeological relationships (Hanley 1990, Moxey and others 1992). Due to environmental uncertainty and the high cost involved in water treatment (NCG 1986), economic analyses often focus on nitrogen input and discharge control. The impact of and options for reducing fertilizer use were assessed by England (1986), Dubgaard (1989), and Huang and Uri (1992). A number of economic studies have linked fertilizer use to nitrate levels in water (Taylor 1975, Hartley 1986, Andreasson 1990, Johnson and others 1991). The control of nitrate based on the relationship between nitrogen input and leaching has also been investigated (DOE 1988, Andreasson 1990). Control of nitrate discharges appears difficult because in many cases they are costly to monitor. Over the last decade, however, models have been developed in the UK (NCG 1986, Jones and Thomasson 1988) to estimate leaching rates. A number of economic analyses concerning leaching control and spatial management are found in NCG (1986), Seven Trent Water (1988), and Moore (1989).

Most empirical studies compare the cost-effectiveness of alternative incentive and regulatory instruments with respect to either nitrogen input or discharge (leaching) control. Few address their comparative effectiveness. Exceptions include Stevens (1988) and Johnson and others (1991). However, their analyses are not concerned with the achievement of a defined limit or limit compliance. For groundwater pollution, some nitrogen sources, especially those that are biologically fixed, may be ignored in linking input and nitrate levels. Although some environmental models are able to reveal the sig-

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[1] Present address: Hubei Academy of Social Sciences, 81 Dong Hu Road, Wyhan, People's Republic of China (post code, 430077).

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nificance of such neglect, few have used them in assessing the economic implications of limit compliance. Furthermore, the different approaches are likely to result in different distributional impacts among farms. Quantification of these economic and environmental aspects can make an important contribution to the debate on this issue.

The research reported here builds upon the conceptual and empirical approaches found in some existing studies to develop a comparative analysis of nitrate control. The overall objective is to examine the impact and cost-effectiveness of input and discharge control alternatives to reduce diffuse source nitrate pollution. The examination reflects the relationship between land uses, production, and nitrogen leaching, which determines groundwater quality (NCG 1986, Seven Trent Water 1988), by integrating environmental and economic models of farm level processes. Using this framework, the analysis (1) evaluates the costs of input and discharge control for achieving the EC limit, (2) assesses the impact of an input tax and a discharge tax on farm income and nitrate abatement, and (3) compares the financial implications for different types of farms. This is implemented in a case study of a catchment in eastern England.

Study Area

A groundwater catchment with an area of 20,700 ha on Cambridge chalk in South Cambridgeshire, in the east of England, was chosen for this research. The average annual rainfall between 1949 and 1990 was 554.9 mm, while the annual percolation rate between 1937–1938 and 1988–1988 averaged 200.3 mm. Geological and soil conditions are relatively homogeneous, and the land is generally favorable for arable cropping with minor limitations (Soil Survey of England and Wales 1979). Groundwater is extracted from eight boreholes scattered in the catchment to provide drinking water for the Cambridge area.

Nitrate profiles in the catchment were investigated through drilling and sampling and used to calibrate a hydrogeological model (NCG 1986). According to simulation results from the model, NO_3 in many boreholes would exceed the EC limit by the end of this century or early next century and are expected to reach 150–200 mg NO_3/liter in future if leaching losses remain uncontrolled (Croll and Hayes 1988). The actual records of borehole nitrates indicate a slow rising trend over the past four decades. With spatial and seasonal variations, nitrate concentrations ranged from around 35 mg NO_3/liter to well over 50 mg/liter, the EC limit, during the 1980s. The nitrate records of groundwater sources suggest that nonpoint nitrate pollution has reached a level for concern, in that action will be required to comply with EC limit on nitrate concentration. In this respect, the area is similar to a substantial proportion of the area of eastern England.

The current land-use pattern in the catchment selected for investigation is one of intensive agricultural production. More than 85% of the total agricultural land is used for arable cropping. Among arable crops, cereals account for about two thirds of the total area. Legumes have some importance in rotations that improve soil fertility, but this comprises only 8.1% of the land. The area of rapeseed is rising, although its percentage share is still low. The area under root crops (potatoes and sugar beets) is relatively low, but they generate higher farm income per unit of land than do the other arable crops.

Policy Response: Economics of Limit Compliance

Economic theory suggests that a market approach would achieve a prescribed environmental limit with least cost (Baumol and Oates 1971). This often involves imposition of an effluent tax or establishment of a pollution permit system. Polluting firms will equate their marginal abatement cost of pollution reduction or marginal benefit from pollution to the tax or the price of pollution permits. In this way the total cost of limit compliance is minimized.

Nitrate pollution can, in principle, be brought under control within this market framework. When the limit on nitrate in water is given, an appropriate tax or a volume of permits can be introduced so that economic incentives will lead to compliance. Since nitrate pollution results from diffuse sources, the nitrate limit is often related to nitrogen input. Input control involves restricting the amount of nitrogen fertilizers and other nitrate sources. An appropriately set fertilizer tax or permits for fertilizer use can be employed to implement this fertilizer limit. In response, farmers will make the value of marginal product of fertilizer use equal to the marginal cost of fertilizer use, which includes purchase price and a tax (permit price). The fertilizer limit is met with least cost. Whether the nitrate limit in water does so depends upon the relationship between fertilizer use and nitrate levels in water.

Alternatively, discharge control may be employed. In this case, either a tax on discharge will be determined to curb the amount of leaching or leaching permits allocated. Instead of balancing the cost and benefit of nitrogen input, farmers will compare the marginal benefit associated with each additional unit of discharge with the tax rate or the permit price. Farmers with a higher return from each unit of discharge will tend to produce more leaching, while those with a lower return produce less. Across all farms, marginal benefit of leaching will equate the discharge tax or permit price. Therefore the leaching limit is achieved at least cost.

Farmers' responses differ between an input tax and a discharge tax. First, these two taxes may not result in the same overall production level. When nitrogen input is limited, farmers will tend to concentrate on land uses with higher return per unit nitrogen applied, while with a limit on discharge, farmers tend to shift towards land uses with high returns per unit nitrogen leached. However, there is not a direct relationship between fertilizer use and leaching. For instance, nitrates are not applied to legumes, which fix their own nitrogen, yet they do cause nitrogen leaching. Leaching also arises from both organic and inorganic nitrogen sources. In many cases, biologically fixed nitrogen and often organic nitrogen are ignored and so a higher tax on inorganic fertilizers will be required to take account of these other nitrogen input sources. Consequently, the total output for the economy may differ under these two tax schemes. Second, when environmental linkages are not well understood and are variable spatially, it is unlikely that the input tax will secure a preselected ambient standard. Third, transaction costs may further complicate this comparison. Since nitrate pollution is caused by diffuse sources, it would be costly to identify and monitor discharges. This gives a limit on nitrogen input an advantage. However, the environmental models developed in the UK relate land uses, management practices, and fertilizer uses to nitrogen leaching and thus make it possible to assess the cost-effectiveness of discharge control.

Methodology

Nitrogen Input, Discharge, and Nitrate Levels

Based on nitrate profiles obtained by drilling through the unsaturated zones of aquifers and comparisons with historical records of fertilizer and land uses (NCG 1986), a nitrate model was developed to estimate nitrogen losses resulting from different fertilizer uses and management practices. Basically this model assumes that N loss is proportional to N applied for a given soil type. Fertilizer applied joins the nitrogen cycle, and the estimated leaching is based on the loss over a three-year period following the year of fertilizer application. An exception are leguminous crops, which do not receive nitrogen fertilizer but can produce a higher rate of leaching than some other arable crops. However, zero N input does not imply no leaching. Two situations are considered in the model. In urban and woodland areas, the estimate of leaching rates is based on the amount of nitrogen in the rainfall concentrated by evaporative losses at 5 kg N/ha (Seven Trent Water 1988, p. 39). Based on nitrate profiles and records in the catchment for the 1940s and 1950s when inorganic nitrogen was not widely applied, leaching from arable cropping without inorganic N fertilizers is estimated at 10–15 kg N/ha per annum. Management systems are also important variables. The annual leaching from a cut grass system, for instance, is typically around 5–10 kg/ha whereas that from ploughed grass may be well over 100 kg/ha. Leaching under arable crops also depends upon management practices. In the NCG (1986, p. 23) model, denitrification is assumed negligible in the downward leaching process and in the unconfined zones.

The NCG environmental model is used here to link land use, management practice, and fertilizer use to leaching and thereby nitrate levels in water. In using the model, it is assumed that the ADAS (1988) fertilizer recommendations are followed so that malpractice, such as bad timing and excessive application, is excluded as a significant factor affecting nitrogen leaching. The rates of fertilizer application, derived from recent fertilizer surveys, also are adjusted to take into account organic nitrogen on the farm based on stocking rates. However, nitrogen in the rainfall and from biological fixation is not included as fertilizers. Using the average annual percolation rate and soil conditions from soil surveys, the leaching rate required to meet the EC limit on drinking water supplies is calculated as 22.6 kg N/ha/yr. This figure is similar to the estimates for East Anglia by Jones and Thomasson (1988) and SCEC (1989).

If a leaching limit or a discharge tax is imposed, the environmental model would be able to provide farmers with information to make adjustment in land use, management, and fertilizer use levels. It must be noted that, however, the achievement of nitrate reduction in the model does not necessarily mean the realization of a nitrate target in practice. As the leaching limit does not consider variations in rainfall and percolation, nitrate levels in water may vary with climatic factors from year to year. Therefore, this limit represents a long-term average requirement rather than a short-term precise prescription. Furthermore, information on marginal abatement cost and marginal damage due to nitrogen leaching is often insufficient as to set an appropriate tax prior to the decision to select crop mix and fertilizer use levels. An inappropriate tax rate can be adjusted, but such adjustment is not cost free and causes environmental uncertainty. As this study focuses on the comparative effectiveness of input and discharge control, the setting of an appropriate tax is not pursued here.

In addiition, this leaching model does not consider land-use change in the past and the downward movement of drainage water to aquifers. Due to the complexities of the mineralization and hydrogeological processes and data availability, the dynamic aspects of nitrate leaching and movement are not considered in the model. While this limitation represents an area for further refinement of the model, the estimated leaching losses and nitrate level in drainage water can be informative in assessing the immediate impacts of nitrate control policies.

Yield Responses

Since continuous fertilizer–yield response curves for most crops are unavailable, this analysis adapts the results from the experiments with discrete fertilizer applications designed and used for over a century at the Rothamsted Agricultural Experiment Station (Dyke and others 1983). The four fertilizing regimes included in this study are specified as conventional (current rates), reduced (⅔ of current rates), low (⅓), and zero nitrogen applications. Farmyard manure is added to total nitrogen applied but biologically fixed nitrogen is not included. For arable cropping activities, conventional output uses recent survey data, while others are estimated in accordance with the yield response relations from the Rothamsted experimental records. For livestock activities, yield responses to various fertilizer rates follow the studies from Hawkins and Ross (1979), Forbes and others (1980) and MAFF (1988). When land is not used in arable and livestock production, it is assumed that no fertilizer is applied.

Linear Programming Model

A linear programming (LP) model, similar to the standard crop mix model formulated by Johnson and others (1991), has been constructed to estimate the costs to farmers of policies imposed on them to restrict nitrogen input or nitrogen leaching for nitrate control. The model's objective is to find an optimal mix of agricultural production activities representing various land uses under different management and fertilizing regimes, subject to various constraints on farm level nitrogen input and discharge (leaching):

$$\text{Max } G(X_{ij}, t^{\alpha;\beta} p^{\alpha;\beta}_{\mathrm{j}}) = \sum_{i=1}^{4} \sum_{j=1}^{48} (a_{ij} - t^{\alpha;\beta} p^{\alpha;\beta} X_{ij}) X_{ij} \tag{1}$$

where G is the total gross margin for the catchment, given the rate of tax on fertilizer input (t^{α}) or leaching (t^{β}), the amount of input ($p_j{}^{\alpha}$) or leaching ($p_j{}^{\beta}$) that is associated with land use activities, X_{ij}, in terms of acreage allocated to land use j on farm type i. α and β represent the policy alternatives, relating to input and discharge respectively. a_{ij} is the gross margin of activity j on farm i. The tax rate is uniform across all land-use activities on all farm types, in terms of per kilogram nitrogen applied (α) or leached (β). As fertilizer use and leaching are associated with specific land uses and fertilizing regimes as represented by X_{ij}, it is clear from the right-hand side of equation 1 that the introduction of an input (discharge) tax will change the rate of net-of-tax gross margin resulting from a specific land use X_{ij}.

Based on the farm classification used in the eastern counties farm business survey in England (Murphy 1991), four farm types (mainly cereals, mixed cropping, mainly dairy, and mixed farms) were identified to represent farms in the catchment. This enables the impact on different types of farms to be assessed and compared. Based on current acreage shares in the catchment, contributions to farm income, and leaching risks by various land uses, 12 activities have been defined as land-use options under each of the four fertilizing regimes. These include eight arable cropping activities, three livestock production activities, and an option of land retirement, i.e., withdrawal from agricultural production such as under set-aside (MAFF and others 1990). Therefore, there are 48 activities in total on each farm. Using data from Murphy (1989–1991) and Nix (1988) and from yield responses and the environmental model discussed above, a farm planning matrix, containing four farm types in the catchment, was constructed.

The environmental model is incorporated in the LP as constraints. These consist of nitrogen fertilizer limit P^{α} and leaching limit P^{β}. These will take the form

$$\sum_{i=1}^{4} \sum_{j=1}^{48} p_j^{\alpha} X_{ij} \leqslant P^{\alpha} \tag{2}$$

for input limit control or

$$\sum_{i=1}^{4} \sum_{j=1}^{48} p_j^{\beta} X_{ij} \leqslant P^{\beta}$$

for leaching limit control.

In addition to the above environmental constraints, others include land (catchment area and land for each farm type), rotational, and institutional requirements. Leguminous crops are in a five-year rota-

Table 1. Gross margin, fertilizer use, leaching, and cost-effectiveness

Nitrogen control alternatives	Gross margin (£/ha)	Nitrogen application (kg/ha)	Nitrogen leaching (kg/ha)	Changes in gross margin (£/ha)	Cost-effectiveness (£/ha)[a]
Base run (no nitrate control)	578.93	168.7	45.1	n.a.	n.a.
Limit compliance with least cost					
Limit on N leaching (NL, 22.6 kg/ha)	426.00	71.9	22.6	−152.93	3.18
Limit on N input (NF, 71.9 kg/ha)[b]	482.90	71.9	33.5	−96.03	4.00
Limit on N input to meet NL target (NFL)	347.50	27.6	22.6	−231.43	5.03
Taxes on input and discharges					
Tax on N input (200% increase in N price)	445.11	121.8	39.6	−133.82	10.62
Tax on N leaching (£3.4/kg N leached)	454.47	131.4	37.0	−124.46	6.96

[a] Average cost for reducing each milligram nitrate (NO_3) per liter in drainage water.

[b] The fertilizer applied under NL.

tion and so less than 20% of the total area in one year. Milk production has been restricted by quotas since 1984 (MAFF 1988), and current rate of production was used as the limit. Limitations were also imposed on potato, sugar beet, and livestock production. The highest levels for these activities between 1988 and 1990 were taken as the upper limits.

Policy Options

The above methodology is used to investigate the changes in gross margins, fertilizer uses and nitrogen leaching, and comparative cost-effectiveness of input and discharge control. The analyses reported here include: (1) a least-cost solution under a nitrogen leaching limit, (2) a least-cost solution under a nitrogen input limit, (3) a nitrogen input tax, (4) a tax on leaching, and (5) a base case that represents the optimal solution without any environmental considerations. The first two will show the differences in cost-effectiveness in limit compliance. Since a limit is imposed as a constraint in the form of equation 2, no taxes will be included in the objective function. However, the dual solutions of leaching and input constraints may be used to suggest the required tax level for achieving the limit. The other two will compare the effects of a tax on the environment and farm income. A tax will be introduced as shown in equation 1, and the environmental model given in equation 2 will be used for assessment of the environmental outcome instead of limit imposition. In order to even out the influence of climate and financial variations, the solutions were sought for 1988, 1989, and 1990 separately and then their averages were used as the results for analysis. Unlike environmental results in this calculation, all financial analyses used 1990 prices.

Results

The results for the catchment area from nitrogen input and discharge control are presented in Table 1. The table contains gross margins, fertilizer applications, leaching, and cost-effectiveness in terms of loss of income per hectare for each milligram of nitrate reduced for the above five analyses. The cost-effectiveness is a useful indicator here because the change of gross margins itself is not explicitly related to changes in water quality. The base case, representing a situation in which no environmental constraints are imposed, provides a benchmark against which the effects of alternative regulatory policies can be evaluated. All the figures in the table are weighted averages of different farms for the whole catchment. Farm variations are discussed later in this section.

In the base case, the gross margins and fertilizer uses are rather close to those recorded in the farm business survey (Murphy 1989–1991) and survey of fertilizer practices (FMA 1990). The leaching rate is also consistent with several existing estimates for and around the study area (NCG 1986, Moore 1989, SCEC 1989).

Limit Compliance: Input versus Discharge Control

Under limit compliance, an aggregate limit was imposed for the catchment as a whole and farmers were

Table 2. Land-use changes under input and leaching control[a]

Land uses	Share of total acreage (%)					
	Base run	NL	NF	NFL	TL	TF
Cereals	83.1	63.7	60.7	35.1	87.3	75.3
Root crops	7.3	6.0	7.3	7.3	7.4	7.5
Legumes	0.1	0.0	20.0	20.0	0.0	9.4
Other arable	6.0	1.8	2.4	3.0	2.6	5.2
Intensive grass	3.5	0.0	2.5	2.4	2.7	2.6
Extensive grass	0.0	13.5	7.0	11.4	0.0	0.0
Set-aside	0.0	15.0	0.1	20.8	0.0	0.0
Total (20,700 ha)	100.0	100.0	100.0	100.0	100.0	100.0

[a] NL: limit on nitrogen leaching; NF: limit on nitrogen fertilizer input; NFL: limit on nitrogen fertilizer input to comply with the leaching limit; TL: tax on leaching; TF: tax on fertilizer input.

given the freedom to optimize their land-use mix under the limit. Thus with discharge control (NL), a nitrogen leaching limit was set in line with the EC limit on nitrate in water. The changes of land uses are given in Table 2. Some land was set aside and activities with low return per unit of leaching such as rapeseed and leguminous crops were excluded. Livestock production became less intensive. Since cereals have a relatively low rate of leaching, they accounted for nearly two thirds of the total area. However, the area under root crops was not severely affected because of their high gross margins. Fertilizer use was more than halved. This reduced farmers' gross margin by £152.93/ha.

With nitrogen input control, the limit was given in terms of nitrogen fertilizers, consisting of both inorganic and organic (farmyard manures) input. In this run, the fertilizer applications resulting from discharge control (NL) were taken as the limit on nitrogen input (NF). As expected, this led to a shift from nitrogen-intensive crops to those with low nitrogen requirements (Table 2). Leguminous crops were brought in to their rotational maximum and land was not retired. This gave a higher gross margin than the leaching control option. However, these legumes have a higher leaching rate than some other arable crops such as cereals and added more leaching to the total amount in the area. Consequently the leaching rate was much higher than the limit level although some reduction in leaching was observed (Table 1).

It is assumed that stricter restrictions on fertilizer uses alone were able to meet the leaching limit (NFL). By iterating the LP model with reduced fertilizer applications, the rate satisfying the leaching limit was obtained, 27.6 kg/ha, an 83.6% reduction from current practice. This is largely attributable to leguminous crops as they do not respond to the nitrogen input limit. This strict limit resulted in agricultural production being less extensive and further reduction in gross margins. Farmers' losses under NFL, being £231.43/ha, were much higher than those under NL and NF.

In terms of the cost of reducing nitrate 1 mg/liter in water, NL outperforms the other two, with an average figure of £3.18/ha. Although NFL achieved a higher gross margin than NL, it was not effective in reducing nitrogen leaching and therefore insufficient to meet the nitrate limit. This would suggest that a discharge limit is more cost-effective than an input limit for nitrate pollution control. In this catchment, the former would cost one third less than the latter to meet the nitrate level in water.

Incentives: Input versus Discharge Taxes

The dual solutions of leaching and fertilizer limits from the above analysis may be taken as the tax rate. The marginal gross margin for leaching limit was £13.65/kg N leached. This would eliminate all arable crop production, although it would satisfy the limit requirement. The dual solutions of fertilizer limit under NF and NFL were £2.64 and £4.01/kg N fertilizer respectively. These indicate that the tax rate could be 7–12 times as high as fertilizer prices. These high taxes would exclude all nitrogen-intensive production activities and make legumes highly advantageous. However, the average gross margin per hectare would be only around £200 or lower. This suggests that a tax would be less cost-effective in achieving the leaching limit, similar to findings of some existing studies (e.g., Atkinson and Tietenberg 1984, Miltz 1987). Moreover, the dual solutions from both NF and NFL do not correlate with discharge when the tax is levied on fertilizer input. Since this research does not aim at comparing cost-effectiveness between limit and incentives approaches, a moderate tax rate was used to illustrate the comparative effects of input and discharge control.

Since few have considered taxation on nitrogen leaching, we first consider the setting of a tax on nitrogen input. Most studies indicate that the demand for nitrogen fertilizers is highly inelastic (England 1986, Hanley 1990). According to a calculation by Dubgaard (1989), to achieve a 30% reduction in nitrogen use (the Danish government target) required a tax rate equal to 150% of the then-current nitrogen fertilizer price. The results from England (1986) in Britain are even more striking. Doubling the nitrogen price would only lead to about a 13% reduction in fertilizer use; a 400% increase would reduce nitrogen application by about 40%. Therefore, a 200% tax rate, which is clearly insufficient to meet the leaching limit, was used to assess the effects of the tax and to make comparison with a discharge tax.

With a 200% tax on nitrogen input, the profitability of nitrogen-intensive activities was reduced and those with lower nitrogen applications improved their relative position. The results in Table 1 show that, in comparison with the base-run results, fertilizer use was reduced by 27.8%, leaching by 12.2%, and gross margin by 23.1%. These trends are consistent with theoretical predictions. At this rate, the tax disadvantaged some high-input cereals crops, but hardly changed the financial ranking of high-input, high-leaching-risk root crops. Although the tax does not target biologically fixed nitrogen, it was not sufficient to cause a significant switch to legumes. Only 8.6% of the land was shifted to pulse crops, compared with the rotational maximum of 20% under an input limit (Table 2).

To make a leaching tax comparable with the input tax, the rate was obtained by dividing the amount of the input tax levied (£100.6/ha) by the discharge rate attributable to the use of fertilizers and agricultural production (29.6 kg/ha, which is total leaching minus 10.0 kgh/ha, the leaching rate without inorganic fertilizer application). This resulted a figure of £3.4 for each kilogram of nitrogen leached. This tax led to similar changes (Table 1) to the input tax, with fertilizer use, leaching, and gross margin being reduced by 21.5%, 18.0%, and 22.1%, respectively. Similar to the input tax, this discharge tax made some crops such as cereals and rapeseed slightly more profitable under lower fertilizer rates than under conventional rates but was insufficient to have this impact on root crops. Leguminous crops were excluded from the solution because of their high leaching rates and low gross margin relative to other arable crops (Table 2).

A comparison between the input and discharge tax reveals some noteworthy features. First, an input tax is more effective in reducing nitrogen input than a discharge tax, while the effectiveness of leaching reduction is the other way round. For each kilogram of nitrogen fertilizer reduced, an input tax would incur a cost of £2.85/ha, compared with £3.34/ha under the discharge tax. For each kilogram reduction in leaching, however, a discharge tax costs less (£15.37/ha) than does an input tax (£24.33/ha). Second, these two taxes resulted in very similar gross margins, there being a mere 2% gap. If the input tax levied (£100.60/ha) and discharge tax collected (£90.30/ha) were to be returned to farmers, the gross margins would be only 4% lower than the base rate level. Third, despite their positive effects on leaching reduction, neither of the two was able to meet the leaching limit. In fact, the leaching rates under both input and discharge taxes were considerably higher than the required level. This suggests that the dual solutions from limit control, although very high indeed, would be required to meet the EC limit on nitrate.

Impact on Different Types of Farming

Among the four farm types identified in the catchment, mainly cereals farms account for 65% of the total area, while mainly dairy farms hold a 2% share, with 25% and 8% for mixed cropping and mixed farms, respectively. The base-run results for these four types of farms are given in Table 3. There are variations in fertilizer use between farm types, but the difference is very small, being less than 4%. However, the leaching rates vary substantially across farms. Cereals farms generate the least leaching, while dairy farms produce the highest rates. The reasons are associated with land use activities specific to each farm type.

The results of the imposition of a limit or tax for different farm types are presented in Table 3. NF is excluded since it does not meet the leaching limit. The figures are given as percentage reductions in gross margins from the base case.

Under limit compliance, the leaching limit causes lower losses to all farms than does the limit on inputs. However, dairy farms suffer a lower loss than do all the other farms. Mixed cropping farms are less flexible to make changes since high leaching crops constitute a significant proportion of farm income. A tax policy has different implications. For cereals farms, a discharge tax would be more advantageous than an input tax. For mixed farms, a nitrogen input tax would give a better outcome than a leaching tax, despite the highest fertilizer applications on them under the base case. Again dairy farms achieve the lowest income losses among all the farms. Unlike limit com-

Table 3. Financial impact on different farm types

	Mainly cereals	Mixed cropping	Mainly dairy	Mixed farms
Base run				
Gross margin (£/ha)	531.30	654.21	989.06	628.12
Fertilizer use (kg/ha)	168.74	166.75	172.02	173.89
N leaching (kg/ha)	40.0	50.3	68.5	64.4
	% reductions in gross margins			
Limit compliance				
limit on N leaching (NL)	23.67	31.81	22.08	29.56
limit on N input to meet NL target (NFL)	39.38	40.77	31.90	44.71
Incentives				
N input tax	24.42	21.07	18.47	22.59
discharge tax	21.27	21.37	17.31	25.15

pliance, this tax rate is not sufficiently high to exclude high leaching temporary grasses. For mixed cropping farms, the difference between an input tax and a leaching tax is very small, being only 0.3%. From the above analysis, a general conclusion may be derived that less polluting farms such as cereals farms would prefer a leaching tax to an input tax, while high polluting farms such as mixed farms would rank them in the other order.

Discussion

Nitrogen input control can be effective in reducing fertilizer use, but this is not the ultimate objective. In order to achieve a desired water quality and to comply with the EC limit, control on leaching would result in a much lower loss to farmers than control on fertilizer use. The cost-effectiveness of discharge control holds on all farm types. However, a nitrogen input tax is likely to incur a higher loss to cereals farms than a discharge tax, while the latter tax would disadvantage mixed farms.

The use of market approaches to agricultural nitrate pollution control has received considerable support in recent debate. While the potential gains from this type of policy are real, their realization depends upon a number of conditions. In principle, a tax regime has the potential to achieve environmental targets with least cost. It offers continuous incentives for pollution reduction and has the advantage of being simple to administer. In the case of nitrate control, however, some practical difficulties may prevent such a tax from being introduced. This analysis further confirms that the tax rate needs to be high to have an effect. Moreover, inadequate information often renders its effects uncertain and its determination difficult in practice. The input tax does not correlate with discharge, and the discharge tax relates to leaching, which is difficult to monitor. Its imposition is further complicated by some political considerations. It may help reduce agricultural surpluses in the EC, but the polluter-pays principle would not be popular among farming communities where farm incomes are falling.

Nevertheless, controls on discharge are seen to be preferable. Although there are difficulties in measuring nitrate concentrations and in establishing the liability of individual producers, this analysis suggests that much of the adjustment to the discharge control takes the form of changes between types of land use. This confirms the finding by Moxey and others (1992) that selective application of land-use restrictions may be more efficient than intervention in the fertilizer market. Therefore, an alternative approach would be to allocate permits with respect to specific land uses (Pan 1992). Total leaching permits are determined by an environmental agency in accordance with the EC limit on nitrate. This would secure the nitrate level given soil and hydrogeological conditions. The permits may be distributed to farmers without payment in the first instance with respect to the area of land farmed. Since land uses are identifiable, official or mutual inspections may not involve much cost for policing.

Each farmer would be required to hold permits. The number of permits required for each type of land use would depend upon the extent of nitrate leached from it. Thus farmers would be free to maximize their return to land use, subject to an overall leaching constraint. The total number of permits available would be defined on a catchment basis and permits would be tradable within the catchment. Farmers would be free to crop some of their land intensively and put the rest into land uses with little or no leaching, such as forestry. For instance, if the farmer plans to plough grass, he has to retire some of his land due to the permit constraint. Assuming an initial allocation of permits based on land area, farmers on good land would have an incentive to purchase permits; those on poorer land or within borehole protection zones to sell them. With the establishment of a permit trade market, the least-cost leaching control could be implemented.

However, this permit system gives no incentive for reducing nitrogen inputs, and leaching targets are likely to be exceeded without strict restrictions on changes in the cropping pattern. Moreover, discharge control through inspection on land-use changes may be insufficient to meet the leaching limit. This is especially true where there exists geographical diversity within a catchment or a farm. In this case the discharge tax or permits associated with land uses must vary spatially so that geographical diversity can be taken into account. Such spatial variation may be further modeled empirically, although it becomes more difficult to monitor at an operational level. It may also be suggested that the discharge permit system be complemented by input control (permits or a tax) so that the restrictions on land use could be relaxed. While the policy design can be very complex and the transaction costs involved high, there may be a possiblity to combine input and discharge control measures through incentive systems to tackle the diffuse source pollution problems like the nitrate case. Apparently more information and research are needed in this area.

Concluding Remarks

Some analytical features are worth noting from interpreting the results and furthering this analysis. First, the nitrogen input defined in this analysis excluded biologically fixed nitrogen. This may partly explain why nitrogen input control is less effective in reducing leaching. When this source is included in nitrogen input, the result may change. However, this does not change the difference in terms of efficient resource allocation between input and leaching control. Second, a water treatment option is not considered. Since source control appears expensive, water treatment may be cheaper for farmers to pay. However, while this may be possible in achieving drinking water standards, it would not meet the requirement of the EC Draft Directive (88/708, see SCEC 1989) on nitrate pollution. Third, the yield–response functions with respect to fertilizer applications and nitrogen leaching are discontinuous in this model due to data availability and the computation work involved. The results from this analysis would be made more accurate by further refinement of the yield–response functions. However, the methodology does reflect the relationship between land-use activities, fertilizer applications, nitrogen leaching, and farmers' income. The results from this groundwater catchment can be helpful in understanding the difference between input and discharge control for reducing agricultural nitrate pollution and in designing environmental policies in a wider context.

In conclusion, economic incentives can be used to comply with an environmental standard. Whether the economic outcome is the most cost-effective depends upon enviornmental relations. Comparative economic analysis between different environmental targets can generate important information for environmental policy making.

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