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Determining the economic gains from regulation at the extensive and intensive margins

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Summary

Among the second-best approaches for the regulation of pollution, little attention has been paid to the distorting effect of intensive margin policies on the extensive margin. This article shows, within a dynamic framework, that regulation of the intensive margin has to be complemented by regulation of the extensive margin. Depending on the elasticity of the pollution function with respect to nitrogen use, the appropriate regulation at the extensive margin is zero, a tax or a subsidy. We show empirically that combining a nitrogen tax with land-use taxes is about 18 per cent more cost efficient than a nitrogen tax alone and 58 per cent more efficient than off-site abatement in the form of groundwater treatment.

Keywords: cost efficiency, second-best policies, nitrate leaching, intensive and extensive margin, dynamic optimisation

JEL classification: Q12, Q18, Q25

1. Introduction

Non-point source pollution is a major concern for both developed and developing countries. Although there is general agreement among administrations, politicians, scientists and non-profit organisations that more effective measures have to be implemented (World Resources Institute, 2000; Worldwatch Institute, 2001), no consensus has been reached about what kind of action should be taken. Unfortunately, the economic literature does not provide a clear answer to this question either.

The difficulties in designing policies reside in several features of non-point source pollution (Wu and Babcock, 2001). Firstly, emissions-based instruments cannot be employed as discharges cannot be metered with a reasonable degree of accuracy at an acceptable cost. Secondly, non-point emissions and their consequences are highly stochastic. Thirdly, land and firm characteristics vary.

Ambient taxes have been proposed as a response to the first characteristic (Segerson, 1988; Xepapadeas, 1991, 1992). Although this approach has a strong appeal, its political acceptability may be severely limited as there is no direct relationship between current individual behaviour and the size of the actual fine (Shortle and Abler, 1998). Accordingly, a second approach in the economic literature focuses on indirect instruments that aim to control pollution indirectly; for instance, instruments that regulate inputs or management practices of the firm. However, to be applicable, regulations of inputs or management practices have to be limited to a subset of choices that are both easy to observe and highly correlated with emissions of the pollutant. Therefore, this type of regulation is only a second-best option.

The economic literature has analysed the optimal management of nitrate leaching from agricultural production within a static or dynamic context, depending on whether the nitrate enters surface water or accumulates in the groundwater. However, the literature seems to be incomplete because, to our best knowledge, no paper comparing different policy options has ever taken into account the fact that nitrate emissions from agricultural land depend to a great extent on the evolution of the nitrogen pool of the soil over time.

Moreover, apart from an article by Yadav (1997), in taking the choice of optimal crops into account, previous studies have limited the choice to a very small number of exogenously pre-specified sets of crop rotations. Farmers are only allowed to choose from among those rotations, implying that multiple-year decisions are made at a single point in time. In this case, the choice of crops cannot be considered a true decision. In contrast, our model does not rely on exogenously pre-specified crop mixes and therefore crop rotations arise endogenously. Consideration of the nitrogen pool allowed us to include the choice of crop as a true decision variable because it takes account of the preceding crop effect.

Among the second-best regulation of inputs, little attention has been paid to the choice of inputs to be regulated. Studies such as Mapp *et al.* (1994), Larson *et al.* (1996) and Vickner *et al.* (1998) have analysed the environmental and economic impact of regulating a contaminating input, either by the choice of the input itself and/or by a change in the applied technology. In an excellent paper providing an overview of the state of the art in non-point source pollution control, Shortle *et al.* (1998) determined the optimal design of different input policies when the set of regulated inputs is a subset of all input choices. To determine the optimal, yet static, input policy, Shortle *et al.*, took into account that a change in intensity of one input affects the intensity of all other inputs. Thus, the derived optimal policy is a function of all regulated and unregulated inputs. However, the optimal design of input policies affecting only the intensive margin is not adequate for the optimal design of input policies involving intensive and extensive margins. In this paper, the term extensive margin refers to the size of the area of a particular crop and not the total area of cultivated land.

This paper shows that the optimal policy with respect to the extensive margin is not only a function of all inputs, but also depends on the optimal policy instruments of the inputs affecting the intensive margin. Therefore, this article analytically specifies second-best policies that regulate the intensive and extensive margins simultaneously within a completely dynamic setting. In addition to the analytical work, we present the results of an empirical study in which we analysed and determined the relative efficiency gains resulting from simultaneous regulation of the intensive and extensive margins for an aquifer situated within the area of the watershed of Lake Baldegg in Switzerland.

We consider the case of nitrate leaching into the groundwater as a result of agricultural activities. In contrast to previous empirical studies, the extensive margin, as defined above and given by the size of the share of each production activity in the product mix, is not restricted to a pre-specified set of production activities. Thus, we are able to analyse whether regulating the production intensity in the form of a nitrogen-input tax or the extension of production activities in the form of a land-use tax are equally efficient on their own, or whether they have to be complemented by each other. In this way we can answer the question about the cost efficient mix of policies at the extensive and intensive margins within a dynamic context. The dynamic context is required not only because the pollutant may be stored temporarily in the nitrogen pool of the soil and finally accumulated at the receptor, but also because we consider the choice of crop to be a true decision variable. Moreover, the article compares the abatement cost of these two measures with the cost of water treatment at the receptor of the contaminated water, thereby determining the relative efficiency of on-site versus off-site abatement.

Our results show that regulating the intensive margin has to be complemented by regulating the extensive margin. Depending on the responsiveness of the pollution function as a result of a change in the use of nitrogen fertilisers (intensive margin), a tax on the nitrogen content of mineral fertilisers has to be complemented by a mixture of subsidies and taxes related to land-use. The use of both instruments is necessary when nitrogen contamination depends not only on the total amount of nitrogen used, but also on the specific crops to which it is applied, because for any given application amount different crops imply different uptake and hence different amounts of leaching to the groundwater. Although the tax on nitrogen use can account for the impact of total use, it cannot account for the impact of crop type unless it is differentiated by crop. To correct the distortion in the crop choice that continues to exist after the nitrogen tax is applied, a crop-specific land-use tax must be used. It should be noted that the utilised framework for the economic analysis is dynamic as a result of the nature of the problem analysed.

However, the complementation of a regulation at the intensive margin by a regulation at the extensive margin would also be required if the problem itself were static.

2. The economic model

To achieve efficiency, the social net benefit of agricultural production and consumers' net benefits are maximised over calendar time t, $t \in [0,T]$. Agricultural production takes place within a catchment area that feeds a single cell aquifer. The aquifer has a constant water balance and is contaminated with nitrate from agricultural production. However, our analysis does not consider the entire catchment area but rather an area the size of a single farm. The characteristics of this farm are representative of agricultural production within the catchment area. Consequently, the volume of the aquifer analysed is chosen such that it corresponds to the original volume of the aquifer divided by the number of hectares of the farm. The decision variables are the amount and type of fertiliser j ($j = 1$ mineral, or $j = 2$ organic) and the choice of crops (activities) i, ($i = 1, \ldots, I$). If a crop can be cultivated either by minimum tillage or by conventional tillage, they are considered as different activities. Given the regional focus of the analysis, the nationally determined market prices are not influenced by production decisions taken within the region. Thus, consumers' utility is unaffected by production decisions with respect to prices but it is affected as far as the level of nitrate in the aquifer is concerned. Hence, the dynamic economic decision problem can be formulated as:

$$\max_{x_{ij}(t), y_{ij}(t)} \int_0^T \sum_{i=1}^{I} \sum_{j=1}^{2} \Big[(p_i f_{ij}(x_{ij}(t), n(t)) - a_j x_{ij}(t) - c_i f_{ij}(x_{ij}(t), n(t)) - k_{ij}) y_{ij}(t) - \psi(s(t)) \Big] e^{-\delta t} \, \mathrm{d}t + e^{-\delta T} \zeta(n(T), s(T)) \tag{1}$$

subject to

$$\dot{s} = \sum_{i=1}^{I} \sum_{j=1}^{2} g_{ij}(x_{ij}(t), n(t)) y_{ij}(t), \quad s(0) = s_0 \tag{2}$$

$$\dot{n} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{2} \phi_{ij}(x_{ij}(t), n(t)) y_{ij}(t)}{\sum_{i=1}^{I} \sum_{j=1}^{2} y_{ij}(t)}, \quad n(0) = n_0 \tag{3}$$

$$x_{ij}(t) \geq 0, \quad y_{ij} \in Y, \quad i = 1, \ldots, I; \quad j = 1, 2; \quad Y \subset \aleph^I \tag{4}$$

where i, $i = 1, \ldots, I$ denotes the crop (activity), t the time, and T the final point in time of the planning horizon. Index j, $j = 1, 2$, indicates mineral and organic fertiliser respectively.

The model uses the following parameters:

p_i price of crop i (CHF[1]/dt),
a_j price of fertiliser j (CHF/kg),
c_i costs of crop i that are related to the yield (harvest cost, drying cost, etc.) (CHF per ton),
k_{ij} fixed cost per hectare of crop i (capital, labour and costs that vary with the type of the applied fertiliser) (CHF),
δ discount rate,
Y set of constraints (i) on admissible crop rotations with respect to y_{ij}, (ii) on the total amount of available land and (iii) on the non-negativity of the choice variables;

Variables:

$x_{ij}(t)$ fertiliser j applied per hectare for crop i (kg),
$y_{ij}(t)$ hectare of cultivated land with crop i, utilising fertiliser j,
$n(t)$ average amount of nitrogen in the nitrogen pool in the soil per hectare (kg/ha),
$s(t)$ amount of nitrate in the groundwater (kg), and

Functions:

f_{ij} production of crop i per hectare as a function of the amount and type of fertiliser j and the nitrogen pool, with $f_x > 0$ and $f_n > 0$ for all i, j (dt/ha),
g_{ij} leaching of nitrate per hectare into the groundwater as a function of the amount and type of fertiliser j and the nitrogen pool, with $g_x > 0$ and $g_n > 0$ for all i, j (kg/ha),
ϕ_{ij} change in the amount of nitrogen in the nitrogen pool as a function of the amount and type of fertiliser j and the nitrogen pool, with $\phi_x > 0$ and $\phi_n < 0$ for all i, j (kg/ha),
ψ monetary damages as a result of the amount of nitrate in the groundwater[2] and the volume of groundwater, with $\psi' \geq 0$ (CHF),
ζ terminal value as a function of the amount of nitrogen in the nitrogen pool and the nitrate concentration in the groundwater evaluated at the terminal point of time, with $\zeta_n > 0$ and $\zeta_s > 0$ (CHF),

where a subscript of function with respect to a variable indicates the partial derivative of the function regarding this variable, and a dot over a variable indicates the operator d/dt. The formulation of the model presented will be modified later to incorporate different policy instruments analysed in the empirical part of the paper.

The model exhibits constant returns to scale with respect to land, in line with the previous literature in this field (see Claassen and Horan, 2001: 8). The

1 1 CHF (Swiss Franc) = €0.617 in 1999, our base year.

2 We assume that consumers' utility is quasi-linear with respect to the traded goods and externality. Thus, the optimal level of externality is independent of the consumers' expenditures, and it is possible to derive a utility function that depends only on the externality $s(t)$ (Mas-Colell *et al.*, 1995). It is given by $\psi(s(t))$.

leaching function g_{ij} is on a per hectare basis, and thus, the differential equation (2) describes the change in the amount of nitrate in the groundwater as a function of the nitrate emission of the entire cultivated land. According to the existing literature (Mapp *et al.*, 1994; Yiridoe and Weersink, 1998), the nitrate leaching function is crop-specific and depends on the amount and type of fertiliser j and the nitrogen pool n. The differential equation (3) describes the average change of nitrogen in the nitrogen pool of the soil. Because the change in the amount of nitrogen in the nitrogen pool ϕ_{ij} is defined on a per hectare basis, the average change in the amount of nitrogen of one cultivated hectare is obtained by weighting ϕ_{ij} with the share of each crop within the crop rotation, i.e. by $y_{ij}/\sum_{i=1}^{I}\sum_{j=1}^{2} y_{ij}$. The definition of $n(t)$ on a per hectare basis is necessary as this state variable enters the production and leaching functions that are defined per ha. Restriction (4) puts non-negativity constraints on the decision variable x_{ij} and summarises further restrictions with respect to y_{ij}, such as non-negativity, the total amount of available farm land and crop rotation constraints.

The mathematical model presented by equations (1)–(4) does not require the specification of a particular crop rotation beforehand. The model is formulated in such a way that the choice of each crop itself is considered as a decision variable. To take account of the preceding crop effect, which is of great importance for the correct determination of the optimal crop rotation, it was necessary to incorporate a variable that captures the preceding crop effect and passes it on to the next crop within the crop rotation. Considering the nitrogen pool as a stock variable serves this purpose precisely and allows the preceding crop and its significance for the subsequent crop within the crop rotation to be taken into account. Thus, the inclusion of the two stock variables ($s(t)$, $n(t)$) permits us to take account of nitrate leaching from the nitrogen pool of the soil, the accumulation of nitrate at the aquifer and the endogenous determination of the optimal crop rotation over time.

3. Design of policies

The current Hamiltonian value for the social problem can be written as

$$\begin{aligned} H = &\sum_{i=1}^{I}\sum_{j=1}^{2}(p_i f_{ij}(x_{ij}(t), n(t)) - a_j\, x_{ij}(t) - c_i\, f_{ij}(x_{ij}(t), n(t)) - k_{ij})y_{ij}(t) \\ &- \psi(s(t)) + \lambda(t)\sum_{i=1}^{I}\sum_{j=1}^{2} g_{ij}(x_{ij}(t), n(t))y_{ij}(t) \\ &+ \mu(t)\frac{\sum_{i=1}^{I}\sum_{j=1}^{2}\phi_{ij}(x_{ij}(t), n(t))y_{ij}(t)}{\sum_{i=1}^{I}\sum_{j=1}^{2} y_{ij}(t)}. \end{aligned} \tag{5}$$

By taking into account the constraints formulated in (4), the Hamiltonian is transformed into the Lagrangian function, L. Because the constraints do not influence the results presented later, we do not present the Lagrangian function. The first-order conditions for a maximum of the Lagrangian function and the corresponding transversality conditions are presented and discussed in Section A1 of the Appendix.

Given that, for technical or economic reasons, the regulator cannot observe the individual emissions of the polluters, the regulator is left with second-best instruments. Because of the focus of this article, the following analysis concentrates on second-best policies for the extensive and intensive margins. Moreover, to simplify the notation the argument t is suppressed in the remaining part of the paper unless it is required for an unambiguous notation.

A private decision-maker does not take nitrate leaching into account and thus the economic damage of the nitrate concentration in the groundwater, $\psi(s)$, is not considered. We assume that the regulator considers the imposition of an input tax τ_{ij} on the amount of nitrogen x_{ij} applied (regulation at the intensive margin) and the imposition of a land-use tax σ_{ij} per hectare differentiated according to the cultivated crop (activity) i and the type of fertiliser j (regulation at the extensive margin). Given these taxes the Hamiltonian of the private decision problem H^p is given by

$$H^p = \sum_{i=1}^{I}\sum_{j=1}^{2}\left(p_i f_{ij}\left(x_{ij}, n\right) - a_j x_{ij} - c_i f_{ij}\left(x_{ij}, n\right) - k_{ij} - \tau_{ij} x_{ij} - \sigma_{ij}\right) y_{ij} + \frac{\mu \sum_{i=1}^{I}\sum_{j=1}^{2}\phi_{ij}(x_{ij}, n) y_{ij}}{\sum_{i=1}^{I}\sum_{j=1}^{2} y_{ij}}. \tag{6}$$

The constraints formulated in (4) that already form part of the social problem also apply identically to the private problem. Thus, the private Hamiltonian is transformed into the private Lagrangian function L^p. The first-order conditions of the private decision problem are presented in Section A2 of the Appendix.

A comparison of the first-order conditions for the social problem (12)–(17) (see Appendix) with the first-order conditions of the private problem (19)–(22) (see Appendix) suggests that the time-dependent nitrogen input tax τ_{ij}(t) is given by

$$\tau_{ij}(t) = -\lambda^* g_{ij_x}(x_{ij}^*(t), n^*(t)). \tag{7}$$

To determine the sign of τ_{ij} we first need to determine the sign of $\lambda(t)$ by solving equation (16). Making use of the transversality conditions (18) allows the following particular solution of equation (16) to be obtained:

$$\lambda(t) = -e^{\delta(t-T)}\zeta_s(n^*(T),\ s^*(T)) - e^{\delta t}\int_t^T \psi'(s(\theta) e^{-\delta\theta}\, \mathrm{d}\theta < 0 \tag{8}$$

where an asterisk indicates the evaluation of the variable at its optimal value. Hence, the nitrogen input tax τ_{ij} is always positive and therefore it is always a proper tax. To analyse the time-dependent land-use tax $\sigma_{ij}(t)$, we distinguish between the case where the regulator has not imposed a nitrogen input tax and the case where a nitrogen input tax has been imposed. In the first case, where $\tau_{ij}(t)$ is equal to zero, we obtain from equations (13) and (20) the following equation:

$$\sigma_{ij}(t) = -\lambda^*(t) g_{ij}(x^*_{ij}(t), n^*(t)) \geq 0. \tag{9}$$

In the second case, where a nitrogen input tax is present, equations (13) and (20) yield the following equation:

$$\sigma_{ij}(t) = -\tau_{ij} x^*_{ij}(t) - \lambda^*(t) g_{ij}(x^*_{ij}(t), n^*(t)) \gtreqless 0. \tag{10}$$

Defining the pollution elasticity, $\varepsilon_x^{g_{ij}}$, as

$$\varepsilon_x^{g_{ij}} = \frac{\partial g_{ij}(x^*_{ij} n^*)}{\partial x_{ij}} \frac{x_{ij}}{g_{ij}} > 0$$

the land-use tax can be written as

$$\sigma_{ij}(t) = \lambda^*(t) g_{ij}(x^*_{ij}(t), n^*(t))(\varepsilon_x^{g_{ij}} - 1) \gtreqless 0. \tag{11}$$

A comparison of equations (9) and (10) shows that they differ by the term in the pollution elasticity. According to equation (9), the land-use tax as a single instrument will either be zero or a proper tax. However, if a nitrogen input tax is present, equation (11) shows that the land-use tax σ_{ij} is positive, leading to a proper tax, if the pollution elasticity is smaller than one. If the pollution elasticity is greater than one, the land-use tax will be negative, leading to a land-use subsidy.

Equations (9) and (10) also illustrate the difference in the optimal design of policies affecting the intensive and/or extensive margin. Equation (9) shows that the optimal nitrogen input tax depends on the input affecting the intensive margin whereas equation (10) reveals that the optimal land-use tax depends not only on the input but also on the *tax on the input* affecting the intensive margin. The intuition behind this result is that a tax on land-use is a tax where the farmer already had to pay taxes on the inputs affecting the intensive margin. This double payment has to be corrected so that the land-use tax corresponds to the difference between what the farmer had to pay per hectare and what he already paid per hectare in the form of other input taxes. A single tax on the input affecting the intensive margin establishes the socially optimal intensity but affects each crop differently. Consequently, it distorts the socially optimal crop mix and the imposition of a land-use tax/subsidy is necessary to correct this distortion.

The previous results require information about the value of the pollution elasticity. When the pollution elasticity is not known, the following proposition helps to determine the sign of the land-use tax.

Proposition 1

(*a*) *If the pollution function* g_{ij} *is strictly convex in the amount of applied nitrogen* x_{ij}, *and if the amount of applied nitrogen* x_{ij} *is essential for the leaching of nitrate, i.e.* $g_{ij}\,(0, n^*) = 0$, *i.e. the background load is zero, the land-use tax is a subsidy for the crop* y_{ij}.

(*b*) *If the pollution function* g_{ij} *is strictly concave in the amount of applied nitrogen* x_{ij}, *the land-use tax is a tax for the crop* y_{ij}.

(*c*) *If the pollution function* g_{ij} *is linear in the amount of applied nitrogen* x_{ij}, *and if the amount of applied nitrogen* x_{ij} *is essential for the leaching of nitrate, i.e.* $g_{ij}\,(0, n^*) = 0$, *the land-use tax for the crop* y_{ij} *is zero.*

The proof is presented in Section A3 of the Appendix. According to our previous results, Proposition 1*c* shows that if the pollution function is linear in the amount of applied nitrogen, then a tax on input is equivalent to a tax on emissions, and therefore no regulation is needed at the extensive margin.[3]

The proposed time-dependent taxes are differentiated by the cultivated crop and the type of fertiliser applied. Thus, their actual imposition requires that the regulator is able to observe these characteristics. However, as shown below in the empirical section, the taxes can be simplified and still maintain their effects on the intensive and extensive margins.

4. An empirical study

The previous section demonstrated the need for accompanying regulation at the intensive margin by regulation at the extensive margin. Although it offers theoretical insight, it does not show the magnitude of the efficiency gain resulting from joint regulation. Therefore, this section provides an empirical study to determine the magnitude of the gain in efficiency based on the theoretical model presented above. The area of the empirical study corresponds to the catchment area of an aquifer situated in the watershed of Lake Baldegg, Switzerland, where nitrate leaching has severely affected the groundwater. The specified farm model presents a farm in the area with 20 ha of arable land (Eidgenössische Forschungsanstalt für Landwirtschaftlichen Pflanzenbau, 1983; Schudel *et al.*, 1991), which is typical with respect to the size, biophysical data and the available crops for cultivation. The planning horizon of the farmer is assumed to span 30 years, i.e. $T = 30$ years.

Numerical solution of the mathematical model (equations (1)–(4)) required the functions and parameters to be specified. The functions $f_{ij}(\cdot)$, $g_{ij}(\cdot)$, and

3 Likewise, as noted by one of the reviewers, no regulation at the extensive margin is necessary if fertiliser is a common pool input, i.e. the production and the leaching functions are not crop-specific.

$\phi_{ij}(\cdot)$ were estimated utilising biophysical data, which were previously generated with a process-oriented biophysical model (Erosion Productivity Impact Calculator, EPIC).[4] The EPIC model is able to reproduce the biophysical processes in the soil and the process of plant growth as a function of cultivation techniques and weather. It consists of different sub-models that are sequentially and interactively connected. For the weather sub-model a so-called weather generator is available, which allows the weather to be simulated according to previously fixed design parameters. The EPIC model was calibrated to reflect local conditions in line with our experience in previous studies (Maurer *et al*., 1995; Schaub *et al*., 1998). The actual data generation or simulation was carried out for each individual crop i and each fertilisation regime j, a set of biophysical characteristics (soil type, etc.), weather conditions and cultivation techniques. Regarding weather conditions, a wet, normal and dry year were chosen. However, the *total* amount of precipitation in a year does not take into account its *distribution* over the year. Hence, as a proxy for the amount of precipitation and its distribution we chose the distribution function of soil loss, as it depends on the amount and the annual distribution of the precipitation. The distribution function of soil loss was taken from an earlier study by Maurer *et al.* (1995). To reflect the non-symmetry of the distribution function of soil loss, the average values for the lower 35 per cent (wet year), for the middle 50 per cent (normal year) and for the upper 15 per cent (dry year) of the distribution function were determined. The three sets of weather conditions that produced these erosion events were selected and utilised for the operation of the weather generator of EPIC.[5]

Prior to use, EPIC requires the amount of nitrogen in the soil to be specified. Unfortunately, EPIC does not calculate the change in nitrogen in the pool as a result of different agricultural activities, and of specifically chosen fertilisation intensities. However, it does allow us to estimate the changes in the nitrogen pool as a residual value of variables such as: HMN, mineralised nitrogen from organic material; YNO3, superficial NO_3^- (nitrate) runoff; PRKN, NO_3^- leaching; SSFN, lateral NO_3^- runoff; AVOL, volatilisation of nitrogen in the form of NH_3^- N (nitrogen in form of ammonia); DORNST, change in the nitrogen concentration of the stable pool of the soil; UNO3, nitrogen uptake by the plant; and, finally, the amount of N fertiliser applied. Based on this nitrogen balance, it is possible to obtain values for n that correspond to specific agricultural activities and to particular fertilisation intensity levels.

Various functional forms such as von Liebig, Mitscherlich-Baule, polynomial square root, Cobb Douglas or Spillmann could be used to specify

4 For more details, see the documentation of the EPIC model (Sharpley and Williams, 1990a, 1990b).

5 For each set of weather conditions, we simulated the yields, nitrate emissions and changes in the amount of nitrogen in the nitrogen pool. Their expected values were obtained by calculating the sum of the simulated yields, the sum of nitrate emissions, and the sum of changes in the amount of nitrogen in the nitrogen pool, each of them weighted with the probabilities of the event of these weather conditions. The expected values of yields, nitrate emissions, and changes in the amount of nitrogen in the nitrogen pool were then employed as the dependent variable to estimate the functions f_{ij}, g_{ij}, and ϕ_{ij}.

the production function $f_{ij}(\cdot)$. Currently, there is no particular form of the production function that is unanimously considered to be superior to alternative specifications. Fuchs and Löthe (1998), for instance, compared the quadratic, square root, Mitscherlich, von Liebig and the Cobb Douglas functions. According to their results, the specification of the production function as a second-degree polynomial is the best way to model the input/output response with respect to fertiliser. Ackello-Ogutu *et al*. (1985) reported that the von Liebig function performed better in modelling crop growth than polynomial functions. However, Frank *et al*. (1990) concluded from a comparison of the Quadratic, von Liebig and Mitscherlich functions that the 'law of minimum', as proposed by von Liebig, cannot generally be accepted. In light of these somewhat contradictory results, we specified the production function as a quadratic function, as adopting a von Liebig function may have caused difficulties in obtaining a numerical solution. Likewise, the data generated showed that the functions describing g_{ij} and the change in the amount of nitrogen in the nitrogen pool ϕ_{ij} were best represented by a quadratic function. Moreover, the specification of the leaching function is in line with the results of Yiridoe and Weersink (1998).

The parameters of the functions f_{ij}, g_{ij}, and ϕ_{ij} were estimated using the nonlinear least-squared regression procedure in EViews (Quantitative Micro Software, 1998). Before estimating, the functions were written in logarithmic form so that what matters are the relative, and not the absolute, deviations of the estimated value from the observed value (Greene, 2000).

As an alternative to the procedure described in this paper for estimating the functions $f_{ij}(\cdot)$, $g_{ij}(\cdot)$, and $\phi_{ij}(\cdot)$, one could consider an approach using only observed empirical data. However, this approach would be problematic because the data are often not available or the existing time series do not allow isolation without causing ambiguity between endogenous variables and exogenous variables of interest (Goetz *et al*., 1998). Moreover, observed empirical data are generated conditional on policies employed during the period of observation. Thus, the use of observed empirical data may exclude the economic evaluation of new policies.

With respect to choice of crops, the farmer can choose between potatoes (conventional tillage), maize (conventional tillage with or without a cover crop during winter, or minimum tillage), winter wheat (conventional or minimum tillage), winter barley (conventional or minimum tillage), oats (conventional with or without a cover crop during winter or minimum tillage) and annual or biennial grassland. Thus, the number of activities I is equal to 13. As the choice of crop is endogenous in the economic model, each crop was simulated independently from the other crops over a time span of 1 year. This short simulation period, however, does not take into account the preceding crop effect, which is of great importance for the endogenous determination of the optimal crop rotation. To incorporate the preceding crop effect and to pass it on to the next crop within the crop rotation, we included the nitrogen pool of the soil in the mathematical model. Thus, the dynamic context of the model together with the nitrogen pool allow the optimal crop rotation to be determined over time, although the estimated and employed functions f_{ij}, g_{ij}, and ϕ_{ij} were estimated on a 1 year basis.

According to the mathematical model and given the set of alternatively specified EPIC parameters, one obtains 3,120 simulated processes of growth, leaching and nitrogen pool movement, which are available for the estimation of the functions f_{ij}, g_{ij}, and ϕ_j. For instance, if one employs for one crop two different types of fertilisers and three different weather conditions, the total number of simulated biophysical process is six. Overall, we have 13 crops $\times$ 2 types of fertiliser $\times$ 3 weather conditions $\times$ 5 levels of nitrogen in the nitrogen pools$\times$8 application rates for the nitrogen fertiliser (=3,120). It was possible to slightly reduce the number of simulations, as not all crops can be combined with the two types of fertiliser and the types of tillage. Nevertheless, each simulation generates a very large set of data (1.5 Mbytes), which requires careful data management.

As the model relates to a single cell aquifer, equation (2) had to be specified correctly to reflect the hydrological conditions of the aquifer. Moreover, in contrast to our previous definition, equation (2) is now expressed in mg/l instead of kg. (For details, see Section A4 of the Appendix.) Furthermore, a discount rate of $\delta = 0.03$, a depth of the single cell aquifer of $h = 10{,}000$ mm, and an initial value of the nitrate concentration of the groundwater of $s_0 = 46$ mg NO_3^- mg/l were chosen to specify the parameters of the model formed by equations (1)–(4). The parameter value of the initial value of the nitrogen pool in the soil n_0 was set equal to 8364 g N/1,000 kg soil, which is a representative value for the soil found in the region analysed (Maurer *et al*., 1995; Schaub *et al*., 1998). The remaining parameters p_i, a_j, c_i, k_{ij} of the model were determined based on data published annually by an extension service (LBL, 1998–1999). Additionally, we have considered a set of crop restrictions as they correspond to common agricultural practice expressed as $y_{ij} \in Y$. After completing the specification of the functions and parameters, the economic decision problem was programmed in AMPL (Algebraic Modeling Programming Language) (Fourer *et al*., 1999) and solved with the solver MINOS (Murtagh and Saunders, 1995).

The processes of the different components of the model that we have described and the relationships between them are presented schematically in Figure 1, which illustrates both the temporal sequence and the interaction of the different components of the model.

5. Results

Given that the damage function $\psi(s)$ is often not well known, the socially optimal level of pollution cannot be determined. Consequently, the designed policy instruments are not able to establish the optimal outcome. Therefore, the objective of the empirical study is to compare the relative efficiency of different policy instruments or, in other words, to produce a ranking with respect to the abatement cost of the different policy instruments, given a

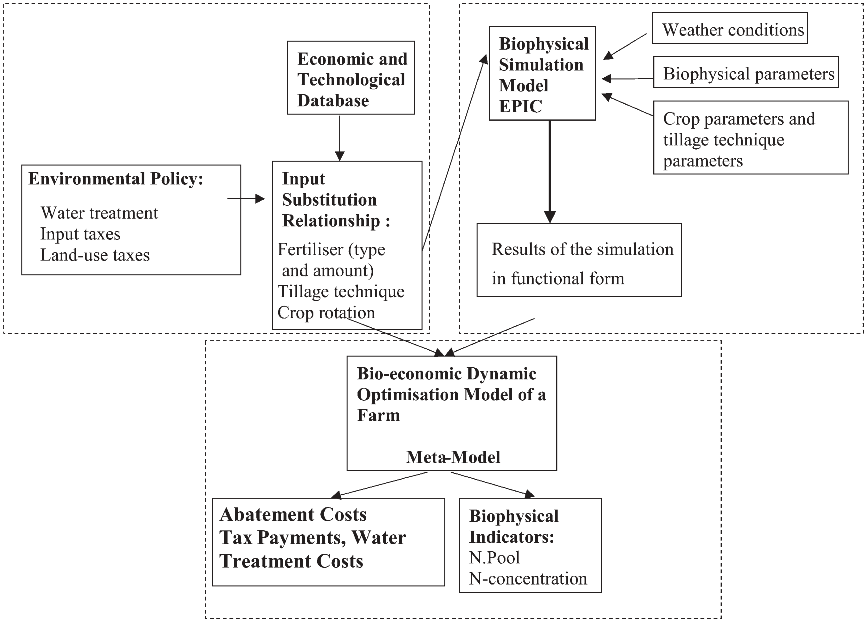

Figure 1. Components of the model and scheme of the economic analysis.

certain nitrate concentration in the aquifer. Other costs related to the different policies, such as transaction, administration, control and enforcement costs, are also important; however, they are not included in this analysis. The selected nitrate concentration for the comparison of the different policy instruments was chosen so that it would be an intermediate outcome of the three policy options analysed.

Initially, we calculated a base case, i.e. the optimal solution of the mathematical model formulated in equations (1)–(4), where the damage function is zero and no policy is in place. In the base case, nitrate leaching does not have any financial consequences. Because the evaluation of the base case and of the different policies always includes a time horizon of 30 years, and all monetary values are discounted, we have presented the results of the empirical part of the article in the form of average discounted values, to shorten the presentation. For the base case we obtain average farm net benefits of 1174 CHF/ha and the nitrate concentration of the aquifer *settles at 46 mg/l in the long run*. Hence, the choice of an initial value of the nitrate concentration of the groundwater of 46 mg/l allows the effect of the policy instruments on the average nitrate concentration of the groundwater to be isolated and eliminates the distorting effect of an initial value of the nitrate concentration that is different from the long-run equilibrium.

To take account of each of the three formulated policies, the mathematical model is adapted accordingly. In particular, the damage function is eliminated and the three policy instruments in the form of water treatment costs, a nitrogen input tax and the combination of a land-use tax and nitrogen input tax are successively put in place.

5.1. Water treatment

The water treatment costs of the extracted water from the aquifer are measured by the costs incurred to comply with Swiss law, which stipulates a target value of 25 NO_3^- mg/l and a minimum standard of 40 NO_3^- mg/l (Bundesamt für Umwelt Wald und Landschaft, 1998). Based on the literature (in particular, Rohmann and Sontheimer (1985), Weingarten (1996) and Fuchs and Löthe (1998)), we adopt a water treatment cost function, $\omega(s)$, given by $\omega(s) = \varphi(s - 25)$, where φ takes values between 0.002 and 0.01 CHF. Thus, for a reduction from 50 to 25 mg/l and for $\varphi = 0.002$ CHF, we obtain a treatment cost of 0.05 CHF/m^3 of extracted water.[6] These values fall within the range of the water treatment costs found in the literature mentioned above. Because the water balance of the aquifer is constant, the amount of treated water does not vary from year to year, and therefore, the water treatment costs vary only with the nitrate concentration of the extracted water. The water treatment costs were incorporated into the mathematical decision model to determine the resulting level of abatement. Hence, the solution of the model provides the optimal choice between on-site abatement (farmer) and off-site abatement (water treatment). We refer to this solution as the social outcome, which consists of the private net benefits minus the water treatment costs.

Unfortunately, there are no empirical data to estimate a water treatment cost function specifically for the region analysed. Therefore, the function was parameterised and five values of φ were considered in the analysis. For all values of φ considered, the resulting nitrate concentration of the aquifer, s^*, is above the target value of 25 mg and below the minimum standard of 40 mg of nitrate per litre of water. Table 1 summarises the most important results of the outcomes of the calculations.

Table 1 shows that the sum of the discounted social net benefits for the cultivation of 20 ha over 30 years drops from 704,000 CHF to 515,000 CHF for an increase in the water treatment costs from 0 to 1 Rappen (1 CHF = 100 Rappen) per NO_3^- mg/l per m^3 of water. Thus, the average social net benefit of farming over 30 years falls from 1,174 CHF to $1{,}174 - 316.3 = 853.7$ CHF/ha. The reduction in the average social net benefits is accompanied by a reduction in the average NO_3^- concentration in the groundwater over 30 years from 46 mg/l to $46 - 10.6 = 35.4$ mg/l. Dividing the values of the

6 Foess *et al.* (1998) compared the cost of different processes applied in the USA to remove biological nutrient from water, and reported water treatment costs that range from 1.4 to 21 US\$/m^3. The great cost discrepancy between the literature cited in this article and the study by Foess *et al.*, can be explained in part because the authors considered the cost of nitrate reduction down to 10 mg/l and independent of the pre-treatment nitrate level. Moreover, the literature cited in this study assumes that sufficient clean and cheap water is available for mixing with the contaminated water to reduce the nitrate concentration to the desired level.

Table 1. Outcomes in the presence of water treatment costs

Outcome	Water treatment costs in Rappen (1 Rappen = 0.01 CHF) per NO_3^- mg/l and m^3 of water						
	0	0.2	0.36	0.4	0.6	0.8	1
Sum of the social net benefits of farming over 30 years for the entire farm (in 1,000 CHF/20 ha)	704	648	**618**	611	577	545	515
Changes in the average social net benefits of farming in CHF/ha (1,174 CHF/ha with no water treatment cost)[a]	0 (0%)	−93.4 (−8%)	**−144.3** (−12.3%)	−156.0 (−13.3%)	−212.5 (−18.1%)	−265.8 (−22.7%)	−316.3 (−27.0%)
Average water treatment cost (CHF/ha)	0	67.1	**105.7**	116.0	164.1	207.0	245.0
Changes in the average NO_3 concentration in the groundwater in mg/l (46 mg/l with no water treatment costs)[a]	0 (0%)	−6.7 (−16.2%)	**−8.5** (−18.5%)	−8.7 (−21.3%)	−9.4 (−23.0%)	−10.0 (−24.5%)	−10.6 (−26.0%)
Average abatement and water treatment costs in CHF per NO_3^- mg/l[a]	0	14	**16.9**	17.9	22.6	26.5	29.9
Changes in the nitrogen pool in the final year of the planning horizon in g/ton of soil with respect to the initial value of 8364 g/ton	259	−885	**−1079**	−1208	−1382	−1367	−1284

[a]The stated values are the average values over the entire planning horizon of 30 years.

Table 2. Average crop rotation plan over time for different water treatment costs (in hectares per type of land-use)

Type of land-use	Water treatment costs (Rappen) per mg/l NO_3^- and m^3 of water						
	0	0.2	**0.36**	0.4	0.6	0.8	1
Maize (conventional tillage, mineral fertiliser)	6.0	6.00	**3.6**	3.6	3.5	3.5	3.60
Maize with a cover crop (conventional tillage, organic fertiliser)			**2.4**	2.4	2.5	2.3	2.0
Pasture (mineral fertiliser)	4.0	4.0	**4.0**	4.0	4.0	4.1	4.4
Winter wheat (conventional tillage, mineral fertiliser)	10.0	10.0					
Winter wheat (minimum tillage, mineral fertiliser)			**10.0**	10.0	10.0	10.0	10.0

third line by the values of the fifth line of Table 1, we obtain the average abatement and water treatment cost over 30 years per mg/l NO_3^-. Our calculations show that these costs rise from 0 to 29.9 CHF per NO_3^- mg/l. Moreover, compared with the results of the base case, the introduction of water treatment costs results in a decrease of the nitrogen pool at the end of the planning horizon to avoid future leaching.

The optimal crop rotation, presented as an average crop rotation over the entire planning horizon, varies with an increase in the water treatment cost as shown in Table 2. An increase in the water treatment costs leads to a substitution of conventionally tilled maize by maize cultivated with a cover crop, and of conventionally tilled winter wheat by winter wheat cultivated with minimum tillage.

With respect to the use of nitrogen fertiliser, we can observe in Figure 2a that the introduction of water treatment costs leads initially to a sharp decrease in the average fertiliser use over the entire planning horizon. Although it continues thereafter, it is far less pronounced, and it nearly comes to a complete stop for water treatment costs of 0.6 Rappen. Figure 2b shows the development of the nitrate concentration of the groundwater over the entire planning horizon. Although the nitrate concentration decreases with an increase in water treatment costs, the target value of 25 mg/l cannot be achieved even with water treatment costs of 1 Rappen. Further calculations, not presented here, show that the target value can only be achieved if part of the land is retired from production.

5.2. Tax on nitrogen

As an alternative to the water treatment policy, the regulator may wish to apply a tax on nitrogen. In contrast to the previous policy, it aims for an on-site rather

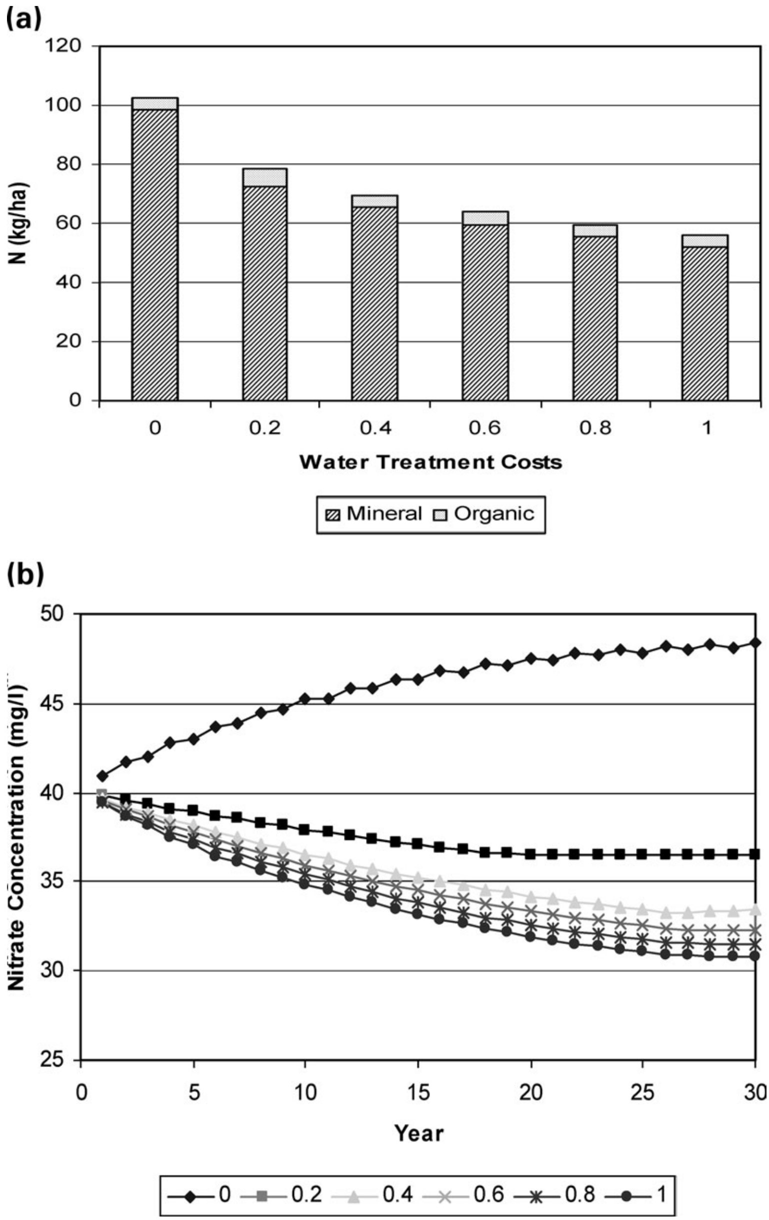

Figure 2. (a) Average fertiliser use (kg/ha) over time for different water treatment costs. (b) Nitrate concentration of the groundwater (mg/l) over time for different water treatment costs.

than an off-site abatement of nitrate. With the introduction of this policy, policymakers aim to control the intensive margin; however, they are often unaware that this policy affects the extensive margin as shown in the theoretical part of the paper. As the objective of the empirical study is not to replicate exactly the policy instruments discussed in the previous section concerning 'the economic model', but to evaluate the relative efficiency of single versus joint policy instruments, we decided on a tax design that can be implemented in reality. Thus, in contrast to the input tax proposed in the previous section, the tax on nitrogen is not crop-specific and is constant over time. We opted to analyse this particular policy because it is frequently discussed as a policy option. The following section analyses the effect of this tax without allowing for the substitution of mineral fertilisers by organic fertilisers. We assume that no organic fertiliser is available or its use is restricted by law[7] and, hence, the tax is applied only to the nitrogen content of mineral fertiliser.

Additionally, we assume that there are no costs to public funds. This means that every Swiss Franc raised by the government will be fully returned to society.[8] Hence, social net benefits are the net benefits of farming plus tax payments. We need to add the tax payments as they are a pure transfer that does not affect overall welfare. The results of our calculations are summarised in Table 3.

Table 3 shows that the sum of the farm's discounted net benefits over 30 years fall from 704,000 CHF with no fertiliser tax to 606,000 CHF for a nitrogen tax that increases the fertiliser price by 200 per cent. Consequently, the farm's average net benefits from farming over 30 years fall from 1174 CHF to $1174 - 163.3 = 1006.7$ CHF per ha. This reduction in net benefits goes together with a decrease in the average NO_3^- concentration in the groundwater over 30 years from 46 mg/l to $46 - 9.6 = 36.4$ mg/l. Abatement costs and tax payments, however, rise from zero to approximately 17 CHF per mg/l NO_3^- with the introduction of the lowest tax rate of 40 per cent. Additional tax increases do not substantially change abatement costs and tax payments per NO_3^- mg/l. The results show that the sum of abatement costs and tax payments grows more or less proportionally to the reduction in nitrate emissions. Finally, Table 3 indicates that the terminal state of the nitrogen pool decreases with the introduction of the nitrogen tax. With respect to the average crop rotation over the entire planning horizon, we can conclude from Table 4 that the average crop rotation is insensitive to successive increases in the nitrogen tax.

7 In a different optimisation run, we allowed for the substitution of mineral fertilisers by organic fertiliser. As one would expect, the imposition of a tax on the nitrogen content of mineral fertiliser does not result in a reduction in nitrate emissions as the cutback in the use of mineral fertiliser is nearly completely compensated by an increase in organic fertiliser. Hence, one needs to restrict the use of organic fertiliser. For the case studied here, the restriction with respect to organic fertiliser corresponds to the amount of organic fertiliser prior to the introduction of the tax.

8 We are aware of the fact that our assumption with respect to the costs of public funds is not correct. However, according to a recent study for OECD countries the costs of public funds for Switzerland are, compared with those for other OECD countries, very low (14 per cent), and thus we decided not to incorporate them (Jacobsen Kleven and Thustrup Kreiner, 2003). Moreover, the cost of public funds is not particularly important for our study, as we compare different instruments and the omission of these costs affects the policy instruments equally per unit of currency spent.

Table 3. Outcomes in the case of an N-input tax

Outcome	Input tax on the nitrogen content of mineral fertiliser						
	0%	40%	80%	120%	145%	160%	200%
Sum of the farm's net benefits over 30 years (in 1,000 CHF/20 ha)	704	678	655	635	**627**	621	606
Changes in the average farm's net benefits of farming in CHF/ha (1,174 CHF/ha with no abatement costs and tax payments)[a]	0 (0%)	−43.0 (−3.4%)	−81.1 (−6.9%)	−115.5 (−9.8%)	**−128.4** (−10.9)	−138.4 (−11.8%)	−163.3 (−13.9%)
Average tax payments (CHF/ha)	0	41.0	71.1	93.0	**99.6**	104.9	117.8
Changes in the average NO_3 concentration in the groundwater in mg/l (46 mg/l with no abatement costs and tax payments)[a]	0 (0%)	−2.4 (−5.2%)	−4.7 (−10.2%)	−6.9 (−15%)	**−8.5** (−18.5%)	−8.9 (−19.3%)	−9.6 (−20.9%)
Average abatement costs and tax payments in CHF per NO_3^- mg/l[a]		17.9	17.2	16.7	**15.1**	15.6	17.0
Changes in the nitrogen pool in final year of the planning horizon in g/tons (g/ton of soil) with respect to initial value of 8,364 g/ton	−136	−212	−289	−351	**−408**	−433	−496

[a]The stated values are the average values over the entire planning horizon of 30 years.

Table 4. Average crop rotation plan (hectares per type of land-use) over time for the case of a tax on the nitrogen content of mineral fertiliser with no substitution by organic fertiliser

Type of land-use	Tax on the nitrogen content of mineral fertiliser						
	0	40%	80%	120%	**145%**	160%	200%
Maize (conventional tillage, mineral fertiliser)	6.0	6.0	6.0	6.0	**6.0**	6.0	6.0
Pasture (mineral fertiliser)	4.0	4.0	4.0	4.0	**4.0**	4.0	4.0
Winter wheat (conventional tillage, mineral fertiliser)	10.0	10.0	10.0	10.0	**10.0**	10.0	10.0

Figure 3a shows that the average amount of fertiliser over the entire planning horizon decreases from approximately 110 kg/ha to 58 kg/ha with the introduction of the nitrogen tax. Finally, Figure 3b demonstrates the development of the nitrate concentration of the groundwater over time given a nitrogen tax of 40 per cent and one of 200 per cent.

The introduction of water treatment costs of 0.36 CHF reduces the average nitrate concentration in the groundwater by 8.5 mg/l. As a consequence, the average social net benefits of farming per hectare decrease by 144.3 CHF. The same reduction in the average nitrate concentration in the groundwater can be achieved by an N-tax of 145 per cent, which is accompanied by a decrease in the farm net benefit of 128.4 CHF. Thus, off-site abatement or *ex post* remediation in the form of water treatment is far less cost-efficient than on-site abatement or *ex ante* prevention in the form of an N-tax. Moreover, when subtracting the water treatment cost of 105.7 CHF and the tax payments of 99.6 CHF per hectare from the corresponding social or farm net benefits, we obtain the farmer's abatement cost for each policy. These calculations show that the farmer's average abatement costs per hectare of $144.3 - 105.7 = 38.6$ CHF for water treatment are clearly higher than the farmer's average abatement costs of an N-tax, given by $128.4 - 99.6 = 28.8$ CHF.

5.3. Land-use tax and N-tax

As an alternative to a tax on the nitrogen content of mineral fertiliser, land-use taxes have been proposed (Pan and Hodge, 1994). In contrast to a tax on mineral fertiliser, land-use taxes could be spatially differentiated, i.e. targeted according to the characteristics of each location. Moreover, the tax base of land-use taxes can be easily observed as its elements consist in the cultivated crop, the location of the crop, and the cultivation technique employed. However, land-use taxes only control the extensive margin and not the intensive margin. Thus, an increase in the amount of applied fertiliser could

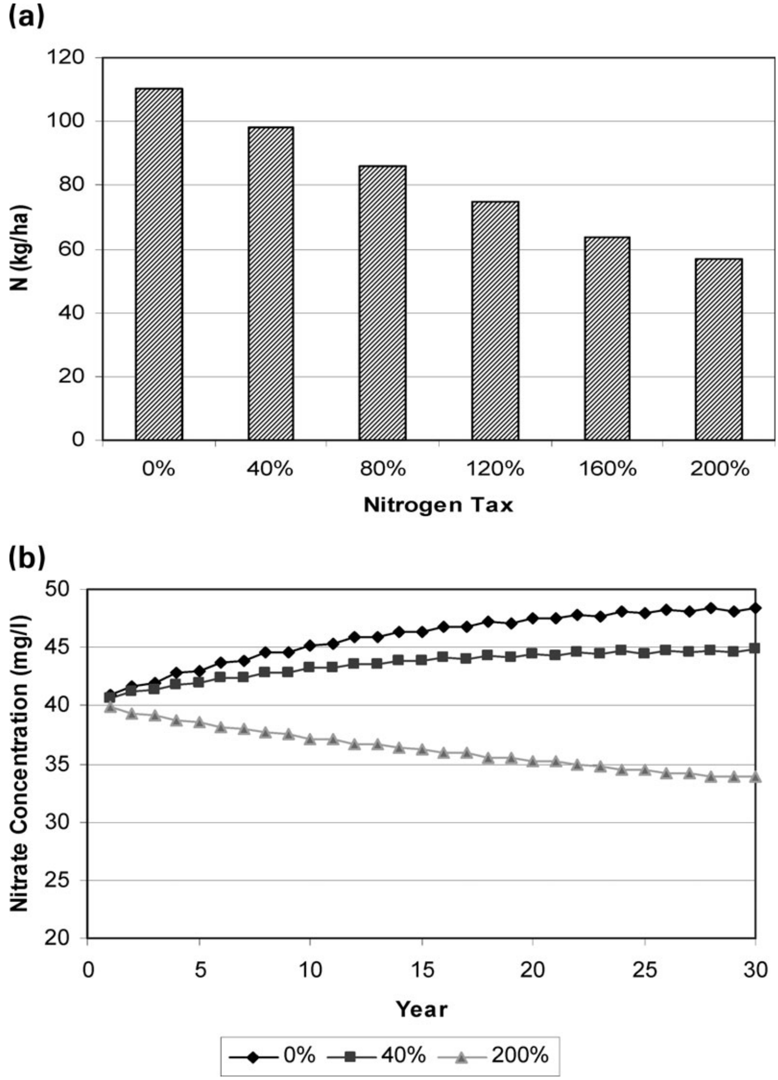

Figure 3. (a) Average fertiliser use over time for different nitrogen taxes. (b) Nitrate concentration of the groundwater over time with an input tax of 0, 40, and 200 per cent.

be expected if land-use taxes were implemented. The results of our calculations with spatially non-differentiated land-use taxes confirm this conjecture. The average use of mineral fertiliser increased from 103 to 113 kg/ha, and the average nitrate concentration in groundwater rose from 46 to nearly 48 mg/l. Because of these results, spatially non-differentiated land-use taxes alone were not considered for the comparison of second-best policies in the empirical part of the paper.

To control the intensive and extensive margin at the same time, we propose to combine land-use taxes with a nitrogen tax on mineral fertiliser. As our model does not allow for spatial differentiation, we considered only non-spatially differentiated instruments. To determine these two taxes, we initially defined a restriction that produces an average reduction in the NO_3 concentration in groundwater (8.5 mg/l). Thereafter, the resulting amount of mineral fertiliser and the resulting crop rotation were formulated as restrictions in a subsequent optimisation of the economic model. These restrictions produced shadow prices that establish the tax on the nitrogen content of mineral fertiliser and on land-use. In the case where the restriction on land-use is not binding, the inequality sign of the restriction is reversed, to produce a shadow price that establishes the corresponding land-use subsidy. The results of our optimisations are presented in Table 5.

The combination of land-use and nitrogen taxes leads to a decrease in the average nitrate concentration of 8.5 mg/l in the groundwater, and to a reduction in the average farm net benefits per hectare of 100.7 CHF. Subtracting the average tax/subsidy payments of 76.2 CHF per hectare from the corresponding farm net benefits, we obtain abatement costs of 24.5 CHF per hectare. Hence, the combination of land-use and nitrogen taxes leads to a decrease in the abatement costs of 4.3 CHF per hectare in comparison with an N-tax alone.

The resulting crop rotation plan, presented in Table 6, shows that the maize cultivation activity has to be reduced (land-use tax) and the activity of growing maize with a cover crop has to be extended (land-use subsidy) to replicate the crop rotation resulting from the optimisation where the concentration of nitrate in the groundwater is reduced on average by 8.5 mg/l.

Table 5. Outcomes in the case of a combination of a land-use tax and an N-input tax

Outcome	No taxes	Combined land-use and N-input taxes
Sum of the farm's net benefits of farming over 30 years (in 1,000 CHF/20 ha)	704	644
Changes in the average farm's net benefits of farming in CHF/ha (1,174 CHF/ha with no abatement and damage costs)[a]		−100.7
Average tax payments		76.2
Changes in the average NO_3^- concentration in the groundwater in mg/l (46 mg/l with no abatement and damage costs)		−8.5 (−18.5%)
Average abatement and tax payments in CHF per NO_3^- mg/l[a]		11.9
Changes in the nitrogen pool in the final year of the planning horizon in g/ton of soil with respect to the initial value of 8364 g/ton	259	−1063

[a]The stated values are the average values over the entire planning horizon of 30 years.

Table 6. Average crop rotation plan over time for the case of a combination of a land-use tax and an N-input tax

Type of land-use	Hectares per type of land-use
Maize with a cover crop (conventional tillage, organic fertiliser)	2.5
Maize (conventional tillage, organic fertiliser)	3.5
Pasture (mineral fertiliser)	4
Winter wheat (conventional tillage, mineral fertiliser)	10

6. Summary and conclusions

The current literature on second-best policies for regulating pollution has paid little attention to the effect that regulation of the intensive margin has upon the extensive margin. This article shows that regulation of the intensive margin must be accompanied by regulation of the extensive margin. Whereas the former is always in the form of a tax, the latter is in the form of either a tax or a subsidy. It is in the form of a subsidy if the pollution elasticity with respect to nitrogen fertiliser is greater than one. If the pollution elasticity is less than one, the regulation of the extensive margin leads to a proper tax. If the pollution elasticity is equal to one, no regulation at the extensive margin is necessary. When the pollution elasticity is not known, the curvature of the pollution function together with information about the background loads allow us to determine whether the extensive margin should be regulated by a tax or a subsidy.

The economic model used is dynamic not only because nitrate is stored and released from the nitrogen pool of the soil and finally accumulated at the aquifer, but also because the choice of crop is modelled as a true decision variable. The results of our empirical study demonstrate that a combination of input and land-use taxes is about 18 per cent more cost efficient than an input tax alone and 58 per cent more cost efficient than an off-site abatement in the form of water treatment.

The introduction of a land-use tax to complement an input tax not only allows the cost efficiency to be raised, but would also allow a more site-specific environmental policy to be designed, as the land-use tax could in principle be observed easily by the regulator. It may be interesting in future research to evaluate the proposed combination of land-use and input taxes with respect to site-specific targeting or with respect to transaction, administration, control, and enforcement costs not considered in this analysis.

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Appendix

A1. First-order conditions of the social decision problem

The first-order conditions of the social decision problem yield

$$L_{x_{ij}} = \left((p_i f_{ij_x} - a_j - c_i f_{ij_x}) + \lambda g_{ij_x} + \left(\frac{\mu \phi_{ij_x}}{\sum_i^I \sum_j^2 y_{ij}} \right) \right) y_{ij} \leq 0 \tag{12}$$

$$L_{y_{ij}} = (p_i f_{ij} - a_j x_{ij} - c_i f_{ij} - k_{ij}) + \lambda g_{ij} + \left(\frac{\mu \phi_{ij}}{\sum_i^I \sum_j^2 y_{ij}} \right) + \mu \phi_{ij}(-y_{ij}(t)) \left(\sum_i^I \sum_j^2 y_{ij} \right)^{-2} \leq 0 \tag{13}$$

$$\dot{s} = \sum_{i=1}^I \sum_{j=1}^2 g_{ij}(x_{ij}, n) y_{ij}, \quad s(0) = s_0 \tag{14}$$

$$\dot{n} = \frac{\sum_{i=1}^I \sum_{j=1}^2 (\phi_{ij}(x_{ij}, n)) y_{ij}}{\sum_{i=1}^I \sum_{j=1}^2 y_{ij}}, \quad n(0) = n_0 \tag{15}$$

$$\dot{\lambda} = \delta\lambda + \psi'(s) \tag{16}$$

$$\dot{\mu} = \delta\mu - \left[\sum_i^I \sum_j^2 ((p_i - c_i) f_{ij_n}) y_{ij} + \lambda \sum_i^I \sum_j^2 g_{ij_n} y_{ij} + \frac{\mu \sum_i^I \sum_j^2 \phi_{ij_n} y_{ij}}{\sum_i^I \sum_j^2 y_{ij}} \right] \tag{17}$$

and the transversality conditions are given by

$$\mu(T) = e^{-\delta T} \zeta_n(n^*(T), s^*(T)), \quad \lambda(T) = -e^{-\delta T} \zeta_s(n^*(T), s^*(T)). \tag{18}$$

In the case of an interior solution, equation (12) states that the value of the marginal product of an increase in the application rate of fertiliser should equal its marginal cost. The first term in parenthesis captures these values in terms of market values. As shown in equation (8), λ is negative, and therefore the second term in parenthesis presents the marginal shadow cost of nitrate leaching. Unfortunately, the sign of μ cannot be determined analytically. However, empirical work shows that, if the nitrogen pool is small, an increase in the amount of nitrogen will predominantly favour crop growth and not nitrogen leaching (Schmid, 2001). On the contrary, if the nitrogen pool is large, an increase in nitrogen will favour nitrogen leaching and not crop growth. Thus, it is expected that μ is positive if the nitrogen pool is small and negative if the nitrogen pool is large. Given the changing sign of μ, the third term in parenthesis either presents the shadow marginal cost or the shadow value of the marginal product of a change in nitrogen of the nitrogen pool in the soil.

Condition (13) determines the optimal size of the area cultivated with crop i and fertiliser j. As the Lagrangian function is linear in y_{ij}, boundary solutions at the upper and lower limits of y_{ij} are optimal. Equations (14) and (15) already form part of the original problem and are stated here only for completeness of the necessary conditions. Equation (16) states that at the optimum the inter-temporal change of the shadow cost of the nitrate in the groundwater should be equal to the sum of the interest forgone, if the water were not polluted, and the marginal monetary damage. Likewise, equation (17) shows that the inter-temporal change of the shadow cost of the amount of nitrogen in the nitrogen pool in the soil has to be equal to the sum of the interest forgone if the nitrogen were not extracted ($\mu > 0$) or the interest forgone if the nitrogen were not applied ($\mu < 0$), and of the marginal values of the change in the amount of nitrogen with respect to production, leaching and the nitrogen pool.

A2. First-order conditions of the private decision problem

The first-order conditions of the social decision problem read as

$$L^p_{x_{ij}} = \left((p_i f_{ij_x} - a_j - c_i f_{ij_x}) - \tau_{ij} + \frac{\mu \phi_{ij_x}}{\sum_i^I \sum_j^2 y_{ij}} \right) y_{ij} \leq 0 \tag{19}$$

$$L^p_{y_{ij}} = (p_i f_{ij} - a_j x_{ij} - c_i f_{ij} - k_{ij}) - \tau_{ij} x_{ij} - \sigma_{ij} + \left(\frac{\mu \phi_{ij}}{\sum_i^I \sum_j^2 y_{ij}} \left(1 - \frac{y_{ij}}{\sum_i^I \sum_j^2 y_{ij}} \right) \right) \leq 0 \tag{20}$$

$$\dot{n} = \frac{\sum_{i=1}^I \sum_{j=1}^2 (\phi_{ij}(x_{ij}, n)) y_{ij}}{\sum_{i=1}^I \sum_{j=1}^2 y_{ij}}, \qquad n(0) = n_0 \tag{21}$$

$$\dot{\mu} = \delta\mu - \left[\sum_i^{13} \sum_j^{2} ((p_i - c_i) f_{ij_n}) y_{ij} + \frac{\mu \sum_i^{13} \sum_j^2 \phi_{ij_n} y_{ij}}{\sum_i^{13} \sum_j^2 y_{ij}} \right]. \tag{22}$$

A3. Proof of Proposition 1

According to the mean value theorem for $0 < \tilde{x}_{ij} < x_{ij}^*$, we can say that

$$g_{ij}(x_{ij}^*, n^*) - g_{ij}(0, n^*) = \nabla_{ij}(\tilde{x}_{ij}, n^*) \cdot \left(\begin{pmatrix} x_{ij}^* \\ n^* \end{pmatrix} - \begin{pmatrix} 0 \\ n^* \end{pmatrix} \right)$$

where the symbol ∇ indicates the gradient of the function g_{ij}. Hence, we obtain that

$$g_{ij}(x_{ij}^*, n^*) - g_{ij}(0, n^*) = \frac{\partial g_{ij}(\tilde{x}_{ij}, n^*)}{\partial x_{ij}} x_{ij}^* \Longrightarrow 1 - \frac{g_{ij}(0, n^*)}{g_{ij}(x_{ij}^*, n^*)}$$
$$= \frac{\partial g_{ij}(\tilde{x}_{ij}, n^*)}{\partial x_{ij}} \frac{x_{ij}^*}{g_{ij}(x_{ij}^*, n^*)}.$$

If the pollution function is strictly convex, $g_{xx} > 0$, i.e. g_x increases with x, and replacing $\tilde{x}_{ij}$ by x_{ij}^* it holds that

$$1 - \frac{g_{ij}(0, n^*)}{g_{ij}(x_{ij}^*, n^*)} < \frac{\partial g_{ij}(x_{ij}^*, n^*)}{\partial x_{ij}} \frac{x_{ij}^*}{g_{ij}(x_{ij}^*, n^*)} \equiv \varepsilon_x^{g_{ij}}. \tag{23}$$

If the leaching function is strictly concave, $g_{xx} < 0$, or linear, $g_{xx} = 0$, the inequality sign in equation (23) is reversed, or replaced by an equality sign, respectively. According to equation (11), the land-use tax σ_{ij} is a subsidy ($\sigma_{ij} < 0$) if $\varepsilon_x^{g_{ij}} > 1$. From equation (23) it is clear that this condition is satisfied if the pollution function is strictly convex in x_{ij}, and if $g_{ij}(0, n^*) = 0$. Thus, we have verified part (a) of Proposition 1. According to equation (11), the land-use tax σ_{ij} is a tax ($\sigma_{ij} > 0$) if $\varepsilon_x^{g_{ij}} < 1$. Equation (23), but with the inequality sign reversed, shows that this condition is satisfied if the leaching function is strictly concave in x_{ij}. Similarly, one can prove part (c) of Proposition 1.

A4. The hydrological model

For the empirical application of the theoretical model we decided to express the amount of nitrate in the groundwater in the form of mg/l as this is a standard measurement unit applied in policy formulation. EPIC considers the transport and transformation processes of nitrogen from the topsoil to the groundwater, and supplies the amount of nitrate that reaches the lower soil layers with the variable PRKN (mineral N loss in the percolate). Moreover, EPIC calculates the amount of gravitational water that feeds the aquifer as a function of the different crops. This information, therefore, allows the nitrate concentration of the gravitational water to be calculated. The hydrological model considered in our economic model is a single-cell aquifer where the pore volume is completely and homogeneously distributed and the water balance is constant. Thus, the amount of gravitational water, which is considered to be the only source of water that feeds the aquifer, is equal to the amount of water that is extracted or runs off.[9] According to Rohmann and Sontheimer (1985), these conditions allow us to write the water balance as

$$wl\hat{g}(c_g(t) - c_e(t)) = wlhn_f(\mathrm{d}c_e/\mathrm{d}t)$$

where w, l and h denote the width, length and height of the aquifer in mm, in that order. The variable $\hat{g}$ denotes gravitational water in mm per year (1 mm corresponds to 10,000 l/ha), n_f the available pore volume in the aquifer, and c_g and c_e the nitrate concentration of the gravitational water (mg/l) and extracted water (mg/l), respectively. Next, the water balance can be written in discrete form and resolved for $c_e(t+1)$, which yields

$$c_e(t+1) = \frac{\hat{g}^* c_g - c_e^*(\hat{g} - h^* n_f)}{h^* n_f}. \tag{24}$$

EPIC, however, provides nitrate losses in kg/ha and thus the function $g_{ij}(x_{ij}, n)$ in equation (2) has to be corrected by the factor 10^2 to obtain the nitrate concentration of the aquifer in mg/l.[10] Hence equation (2), written in discrete form and taking into consideration the hydrological model outlined above, results in

$$s(t+1) = \left(\sum_{i=1}^{14} \sum_{j=1}^{2} \frac{(10^2\, g_{ij}(x_{ij}(t), n(t-1))) - (s(t)(\hat{g} - hn_f))}{hn_f} y_{ij} \right) \Bigg/ \sum_{i=1}^{14} \sum_{j=1}^{2} y_{ij}(t) \tag{25}$$

where the nitrate emissions $g_{ij}(x_{ij}(t), n(t-1))$ into the groundwater are measured in kg per hectare, and the nitrate concentration in the groundwater $s(t)$ is now measured in mg per litre. Equation (25) can also be written as

$$s(t+1) = \frac{s(t) y_{ij}}{\sum_{i=1}^{13} \sum_{j=1}^{2} y_{ij}(t)} - \frac{s(t)\hat{g} y_{ij}}{hn_f \sum_{i=1}^{13} \sum_{j=1}^{2} y_{ij}(t)} + \sum_{i=1}^{13} \sum_{j=1}^{2} \frac{(10^2\, g_{ij}(x_{ij}(t), n(t-1))) - (s(t)(\hat{g} - hn_f))}{hn_f \sum_{i=1}^{13} \sum_{j=1}^{2} y_{ij}(t)} y_{ij} \tag{26}$$

9 Denitrification processes were not considered in our hydrological model as they depend on the existence of certain organic and inorganic compounds, which are irreversibly broken down in the process of nitrification. Thus, in the long run there will not be any denitrification (Weingarten, 1996).

10 1 mm of gravitational water per ha (10,000 l) with a concentration of 1 mg/l results in 10 g of nitrate/ha. Thus, the results of EPIC have to be multiplied by 10^2 in order to express kg/ha as mg/l.

showing that the average concentration of nitrate corresponding to 1 hectare in the next period is equal to the current average concentration of nitrate per hectare minus average diluting effect of the gravitational water per hectare plus the average nitrate emissions from farming per hectare.

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