Abatement costs for agricultural nitrogen and phosphorus loads: a case study of South-Western Finland

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Abstract

Designing efficient agri-environmental policies for agricultural nutrient load reductions calls for information on the costs of emission reduction measures. This study develops an empirical framework for estimating abatement costs for nutrient loading from agricultural land. Nitrogen abatement costs and the phosphorus load reductions associated with nitrogen abatement are derived for crop farming in southern Finland. The model is used to evaluate the effect of the Common Agricultural Policy reform currently underway on nutrient abatement costs. Results indicate that an efficiently designed policy aimed at a 50 % reduction in agricultural nitrogen load would cost € 25 to € 28 million, or € 1995 to € 2197 per farm.

1. Introduction

Excessive concentrations of nutrients that regulate phytoplankton growth cause eutrophication of marine and freshwater ecosystems. The most heavily loaded marine areas in Europe show symptoms of severe eutrophication (see for example Ærtebjerg et al., 2001). The Baltic Sea ecosystem has proved particularly vulnerable to nutrient pollution*.* Blooms of toxic blue-green algae occur during the warm summer months, and filamentous algae cover the seabed in coastal areas. Eutrophication results in significant damages through reduced value of fisheries and recreational activities (e.g. Gren et al. 1997, Kosenius 2004). Nutrient loading from land-based sources and the atmosphere builds up nutrient concentrations. The state of eutrophied water ecosystems can be improved by reducing nutrient loads from inland sources, which include agriculture, municipalities and industry. Agriculture has been identified as the major source of eutrophying nutrients in developed countries (see e,g, Shortle and Abler, 2001). For example in the Nordic countries, municipal and industrial nutrient loads have been reduced significantly during the last few decades, while agricultural nutrient loads remain substantial (HELCOM, 2005)

Linking nutrient load reductions with the costs of those reductions is essential for informed decision making. Abatement costs are relatively easy to assess in the case of municipal and industrial point-source pollution, whereas quantifying abatement costs for agricultural non-point pollution poses a challenge (see e.g. Russel and Shogren, 1993). Nutrient removal at municipal and industrial sources requires setting up wastewater treatment facilities, after which chemical or biological nutrient removal occurs at an approximately constant cost. Agricultural abatement instead takes place through changes in agricultural practices and through adopting abatement measures that move land away from production, for example buffer strips and wetlands. Nutrient loading is affected both by agricultural management practices, such as crop choice, fertiliser use, and tillage, and by environmental factors, such as climate, soil type and field slope. Abatement costs arise from forgoing agricultural profits as a result of constraining agricultural production and adopting abatement measures. Estimating agricultural abatement costs requires considerable information on the runoff process and a detailed description of the production technology.

The costs of agricultural nutrient load reductions have been addressed in numerous studies. Mattsson and Carlsson (1983) and Johnsson (1993) analyzed the effect of nitrogen fertilization on profits from crop production in Sweden using discrete fertilization intervals. Gren et al. (1995) constructed continuous cost functions for nitrogen and phosphorus fertilization reductions in Denmark, Finland and Sweden from estimated fertilizer demand. Accounting for the increased knowledge on the relationship between agricultural management practices and nutrient leaching, Brady (2001) modeled crop yield and nitrogen leaching as continuous nonlinear functions of fertilization, with different coefficients for each cropping alternative. In addition to fertilization reduction, Brady considered catch crops and delayed tillage as abatement measures. The model was applied to estimate an abatement cost function for crop farming in Southern Sweden. Berntsen et. al. (2003) evaluated the effect of four different nitrogen taxes on nitrate leaching and profits on Danish pig farms. Johansson (2004) derived phosphorus abatement cost functions for the Sand Creek basin in Minnesota using simulation data to describe the effects of 14 distinct sets of management practices on nutrient loads and profits. Johansson considered crop rotations, fertilizer application rates and methods, and conservation tillage as abatement measures. Turpin et. al. (2005) derived both the direct and indirect costs for three sets of agricultural management practices using national accounting data.

Grass buffer strips have been shown to be an effective means to reduce nutrient loads from arable land (see e.g. Magette et al. 1987, Dillaha and Inamdar 1997, Patty et al. 1997, Uusi-Kämppä et al. 2000, Uusi-Kämppä 2005). Recent results on the effect of tillage on nutrient loads suggest that no-till also significantly reduces nitrogen loads from arable land, although the effect on total phosphorus loads is ambiguous (Puustinen 2004). This paper presents a framework for deriving nitrogen abatement costs that includes both buffer strips and no-tillage as abatement measures. Furthermore, we account for the interdependence of reductions in nitrogen and phosphorus loads. We use an approach that is similar to Brady (2001) and Johansson (2004), but extend the model to consider buffer strips and depict both nitrogen and phosphorus loads as nonlinear functions of fertilization. We apply the model to derive an abatement cost function for crop production in the Uusimaa and Varsinais-Suomi provinces in Southern Finland. The model is used to evaluate the effect of the current agricultural income support policies on the cost of reducing agricultural nutrient loading.

The paper is constructed as follows: Section 2 describes a farm-level profit maximization model that links nitrogen abatement levels and costs. In section 3, we present an empirical framework for linking agricultural management practices and nitrogen and phosphorus loading from agricultural land. Section 4 describes the application, crop farming in South-Western Finland. Section 5 presents the results, and section 6 concludes.

2. Economic model

The abatement cost function represents the minimum cost of achieving any desired abatement level, where the abatement level is measured as the reduction in kilograms of nutrient discharges from the unconstrained level. Thus, the abatement cost function maps the cost-minimizing choice of abatement effort necessary to achieve any abatement target. This section outlines the link between farmers' production choices and nutrient discharges. We consider the case of cereal production. We adopt an integrated economic and natural science modelling approach: An economic model of farmers' decision making is combined with a biophysical model predicting the effect of farming practices on crop yield as well as nitrogen and phosphorus discharges. Similarly to Yiridoe and Weersink (1998), Brady (2001) and Johansson et al. (2004), we model abatement effort on the extensive and intensive margins. Extensive margin practices include for example crop selection and tillage method, and intensive margin practices fertilizer application rates and methods.

Formally, we consider the problem of maximizing profits from agricultural production, subject to a constraint on the allowed nitrogen discharges. The abatement cost function is obtained through varying the constraint and repeatedly solving the constrained optimization problem. By assumption, farmers use a compound fertilizer that contains nitrogen and phosphorus in fixed proportions and in the absence of constraints choose fertilizer application rates based on yield response to nitrogen application.[1] The abatement measures on the extensive margin affect both nitrogen and phosphorus discharges. Consequently, nitrogen and phosphorus discharges cannot be reduced independently. Given a constraint on the allowable nitrogen discharges, phosphorus discharges are determined through the phosphorus content of the compound fertilizer and phosphorus runoff functions.

Current environmental subsidies are not included in the analysis. The aim of the study is to determine the minimum cost for achieving any given load reduction target and thus provide guidelines for designing cost-effective agri-environmental policy. Including agricultural income subsidies means that the analysis is conducted in a second-best framework, which is not unusual for studies of the agricultural sector (see e.g. Antle and Just, 1991). The choice also reflects policies in the European Union (EU) in that the Common Agricultural Policy income support is decided upon at the EU level, while individual member countries are responsible for environmental policy design.

By assumption, farmers are perfectly competitive and risk-neutral. Agricultural profits are a function of the chosen farming practices. Farmers' objective is to maximize farm profits while complying with the load restriction. The constrained profit function $\pi\left(L^N\right)$ gives farm profits as a function of the allowed nitrogen load L^N when farming practices are chosen optimally. Agricultural profits in the absence of abatement are denoted by π^*. Formally, the constrained profit function $\pi\left(L^N\right)$ is defined by the solution to the maximization problem

$$\begin{aligned}\max_{X_{j,k},N_{j,k},B_{j,k}} \pi(X,N,B) = &\sum_{j=1}^{J}\sum_{k=1}^{K}\left[p_j f_{j,k}\left(N_{j,k}\right) - p_N N_{j,k} - c_{j,k} + s_{j,k}\right]\left(1-B_{j,k}\right)X_{j,k} \\ &+ \sum_{j=1}^{J}\sum_{k=1}^{K}\left[s_{B,j,k} - c_{B,j,k}\right]B_{j,k}X_{j,k}\end{aligned} \tag{1}$$

$$s.t. \sum_{j=1}^{J}\sum_{k=1}^{K} a_{i,j,k}X_{j,k} \le A_i, \quad \forall i \tag{2}$$

$$X_{j,k} \ge 0, \;\; N_{j,k} \ge 0 \tag{3}$$

$$N_{j,k} / P_{j,k} = F_j \tag{4}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} B_{j,k} = \overline{B} \tag{5}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} e_{j,k}\left(N_{j,k}, B_{j,k}\right)X_{j,k} \le L_N . \tag{6}$$

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[1] An interview study of Finnish farmers conducted as a part of the Finnish agri-environmental program evaluation indicated that Finnish cereal producers use predominantly compound fertilizers and choose the fertilizer application rate based on the nitrogen content of the fertilizer mix and yield response to nitrogen application. Phosphorus application rate follows from the phosphorus content of the compound fertilizer. (Sonja Pyykkönen, Finnish Environmental Institute, pers. comm.).

The notation in (1) to (6) is as follows. Subscript *j* denotes crop and *k* tillage method. The options for tillage method depend on the measures suitable for each particular crop. Variable $X_{j,k}$ denotes the land in hectares allocated to crop *j* and tillage *k,* $N_{j,k}$ the per hectare nitrogen application rate*,* and $B_{j,k}$ the proportion of land left uncultivated as buffer zone*.* In the profit expression p_j denotes the average price per kilogram for crop *j,* $f_{j,k}(N_{j,k})$ is crop yield as a function of nitrogen application for crop *j* and tillage *k*, $s_{j,k}$ represents area based subsidies (excluding environmental subsidies), $c_{j,k}$ the per hectare cost, and p_N is the variable cost of applying a kilogram of nitrogen fertilizer, Possible subsidies to buffer zones (again environmental subsidies excluded) are given by $s_{B,j,k}$, and $c_{B,j,k}$ denotes the cost of establishing and maintaining buffers. In constraint (2), $a_{i,j,k}$ represents the amount of resource *i* required to farm one hectare of crop *j* using tillage *k,* and A_i is the total quantity of resource *i* available*.* The constraint states that the amount of resource *i* used in production may not exceed the total quantity of resource *i* available. Constraint (3) ensures that fertilizer application rates and land allocated to each crop and tillage are nonnegative. Constraint (4) represents the ratio of nitrogen and phosphorus in the compound fertilizer for crop *j.* Average nitrogen discharge for crop *j* and tillage *k* is given by $e_{j,k}(N_{j,k}, B_{j,k})$. Finally, constraint (6) implements the restriction on allowable nitrogen discharges.

Having outlined the economic model, we now turn to the sub-models describing the agro-environmental system.

3. Empirical specifications for crop yield and nutrient runoff functions

3.1 Crop Yield

Per hectare crop yield is modelled as a function of nitrogen fertilization. Following Lehtonen (2001), the yield function for turnip rape, silage and sugarbeet is assumed to have the quadratic form

$$Y_{j,k} = f_{j,k}(N_{j,k}) = a_{j,k} + b_{j,k}N_{j,k} + c_{j,k}N_{j,k}^2 \qquad (7)$$

where $Y_{j,k}$ is crop yield and $N_{j,k}$ is nitrogen application rate, both in kg per hectare. Lehtonen (2001) estimated the parameters in (7) for conventional tillage. The crop yield parameters for reduced tillage and no till were obtained by adjusting the crop yield for conventional technology in Lehtonen (2001) by yield coefficients reduced tillage and no till reported in Ekman (2000).

The crop yield function for spring wheat, barley, oats and winter wheat is assumed to follow the Mitcherlich form

$$Y_{j,k} = m_{j,k}(1 - l_{j,k}e^{-q_{j,k}N_{j,k}}) \qquad (8)$$

The parameters of (8) for spring wheat, barley and oats were obtained from Uusitalo and Eriksson (2004). The parameters for winter wheat were calibrated assuming that the average yield for winter wheat is 1.05 times that for spring wheat**.** The crop yield functions in (7) and (8) can be interpreted as average yield responses to nitrogen fertilizer application.

3.2 Nitrogen load

Nitrogen discharges are determined by the concentration of mineral nitrogen in the soil and the quantity of water percolating through the soil. The choice of agricultural practices affects both soil nitrogen concentration and percolation. Nitrogen fertilization increases soil nitrogen concentration and has a direct impact on nitrogen leaching (see e.g. Simmelsgaard, 1991, Simmelsgaard and Djurhuus, 1998). Nitrogen discharges can be controlled through the fertilizer application rate, crop choice, and tillage method. No-till and reduced tillage are emerging as effective ways to reduce the runoffs of nitrogen and particulate phosphorus (see e.g. Soileau et al., 1994, Stonehouse, 1997, Puustinen, 2004). Runoffs can also be reduced by leaving buffer strips (see e.g. Uusi-Kämppä and Yläranta, 1992, Uusi-Kämppä and Yläranta, 1996, Uusi-Kämppä and Kilpinen, 2000).

Average nitrogen discharge per hectare is given by $e_{j,k}\left(N_{j,k}, B_{j,k}\right)$, where $N_{j,k}$ is the fertilization rate and $B_{j,k}$ buffer strip area. Simmelsgaard (1991) and Simmelsgaard and Djurhus (1998) estimated the effect of fertilization intensity on nitrogen runoff from sandy-loam soil to be

$$e_{j,k}\left(N_{j,k}, 0\right) = \phi_{j,k} e^{0.71\left(N_{j,k}/\overline{N}_{j,k}-1\right)}, \tag{9}$$

where $\phi_{j,k}$ is the average leaching in kilograms per hectare, and $e^{0.71\left(N_{j,k}/\overline{N}_{j,k}-1\right)}$ is the fertilization factor defined in terms of the actual fertilization rate $N_{j,k}$ relative to the yield maximizing fertilization rate $\overline{N}_{j,k}$.

Buffer strips reduce nitrogen runoff through two channels, the nitrogen uptake by buffer strips and a reduction in the amount of fertilizer applied:

$$e_{j,k}\left(N_{j,k}, B_{j,k}\right) = (1 - B_{j,k}^{0.2})\phi_{j,k} \exp\left[0.71\left(\frac{(1-B_{j,k})N - \overline{N}}{\overline{N}}\right)\right] \tag{10}$$

The first term on the right hand side of (10) gives nitrogen uptake by buffer strips, where $B_{j,k}$ denotes the share of land allocated to buffer strips. The second term on the right hand side of (10) accounts for the reduction in fertilizer applied. The parameterization in (11) follows Lankoski et al. (2004), who calibrated the model to data from Finnish experimental studies on grass buffer strips (Uusi-Kämppä and Yläranta 1992, Uusi-Kämppä and Yläranta 1996, Uusi-Kämppä and Kilpinen 2000).

The total nitrogen runoff given crop choice, tillage practices and buffer strips is

$$\overline{L}^{N} = \sum_{j=1}^{J}\sum_{k=1}^{K} e_{j,k}\left(N_{j,k}, B_{j,k}\right) X_{j,k}. \tag{11}$$

3.3 Phosphorus load

Phosphorus is transported from agricultural land to surface water in two forms: (i) dissolved reactive phosphorus (DRP) and (ii) particulate phosphorus (PP). Discharges of both DRP and PP are affected by the fertilizer application rate, crop choice, and tillage method. The runoff processes for dissolved and particulate phosphorus are described below. Phosphorus runoffs are modelled following Lankoski et al. (2004), who used results from Finnish studies on grass buffer strips (Uusi-Kämppä and Kilpinen 2000) and DRP runoffs (Uusitalo and Jansson 2002), and long-term fertilizer trials (Saarela et al., 1995, Saarela et al., 2003) to construct phosphorus runoff functions incorporating the effect of buffer strips.

The surface runoffs of dissolved reactive phosphorus and particulate phosphorus in kg/ha are given by

$$L^{DRP} = \left(1 - B_{j,k}^{1..3}\right)\sigma_{j,k}\left[0.02\left(\theta + 0.01\left(\left(1 - B_{j,k}\right)P_{j,k}\right)\right) - 0.015\right]/100 \, , \qquad (12)$$

$$L^{PP} = \left(1 - B_{j,k}^{0.3}\right)\left[\Delta_{j,k}\left[250\ln\left[\theta + 0.01\left(1 - B_{j,k}\right)P_{j,k}\right] - 150\right] * 10^{-6}\right]. \qquad (13)$$

The term $\left(1 - B_{j,k}^{1.3}\right)$ captures phosphorus uptake by buffer strips. Parameter $\sigma_{j,k}$ describes the effect of crop choice *j* and tillage *k* on DRP runoff*,* θ is the soil phosphorus status (mg/l) [2], $P_{j,k}$ represents the phosphorus fertilizer application rate (kg/ha), and $\Delta_{j,k}$ is average erosion for crop *j* and tillage *k*. Fertilizer is not applied on the buffer strip area $B_{j,k}$.

Buffer strips only reduce the nutrient runoff via surface flow. Denoting the proportions of surface flow and drainage flow by s_s and s_d, the total runoffs of dissolved reactive phosphorus and particulate phosphorus into surface water are

$$\overline{L}^{DRP} = \sum_{j=1}^{J}\sum_{k=1}^{K}\left[\left(1 - B_{j,k}^{1.3}\right)s_s + s_d\right] \cdot \left[\sigma_{j,k}\left[0.02\left(\theta + 0.01\left(\left(1 - B_{j,k}\right)P_{j,k}\right)\right) - 0.015\right]/100\right]X_{j,k} \qquad (14)$$

$$\overline{L}^{PP} = \sum_{j=1}^{J}\sum_{k=1}^{K}\left[\left(1 - B_{j,k}^{0.3}\right)s_s + s_d\right] \cdot \left[\Delta_{j,k}\left[250\ln\left[\theta + 0.01\left(1 - B_{j,k}\right)P_{j,k}\right] - 150\right] \cdot 10^{-6}\right]X_{j,k}. \qquad (15)$$

3.4 Optimal agricultural abatement

The optimization problem in equation (1) is solved using nonlinear programming. The Lagrance function is specified as

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[2] The parameterization obtains when soil phosphorus status θ is between 9 and 13 mg/l.

$$
\begin{aligned}
&\max L\left(X_{j,k}, N_{j,k}, B_{j,k}\right) \\
&= \sum_{j=1}^{J}\sum_{k=1}^{K}\left[p_j f_{j,k}\left(N_{j,k}\right) + s_{j,k} - c_{j,k} - p_N N_{j,k}\right](1-B_{j,k})X_{j,k} \\
&+ \sum_{j=1}^{J}\sum_{k=1}^{K}\left[s_{B,j,k} - c_{B,j,k}\right]B_{j,k}X_{j,k} \\
&+ \sum_{i=1}^{I}\mu_i\left(A_i -. \sum_{j=1}^{J}\sum_{k=1}^{K}a_{i,j,k}X_{j,k}\right) \\
&+ \lambda\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\overline{L}^N - e_{j,k}\left(N_{j,k}, B_{j,k}\right)X_{j,k}\right) \\
&+ \eta\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\overline{B} - B_{j,k}\right)
\end{aligned}
\tag{16}
$$

The Kuhn-Tucker conditions for the problem in (16) are

$$
\begin{aligned}
&\frac{\partial L}{\partial N_{j,k}} = \left[p_j f'_{j,k}\left(N_{j,k}\right) - p_N\right](1-B_{j,k})X_{j,k} - \lambda\frac{\partial}{\partial N_{j,k}}e_{j,k}\left(N_{j,k}, B_{j,k}\right)X_{j,k} \le 0 \quad \forall j,k \\
&\qquad (= 0 \text{ if } N_{j,k} > 0)
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
&\frac{\partial L}{\partial B_{j,k}} = -\left[p_j f_{j,k}\left(N_{j,k}\right) + s_{j,k} - c_{j,k} - p_N N_{j,k}\right]X_{j,k} + + \sum_{j=1}^{J}\sum_{k=1}^{K}\left[s_{B,j,k} - c_{B,j,k}\right]X_{j,k} \\
&- \lambda\frac{\partial}{\partial B_{j,k}}e_{j,k}\left(N_{j,k}, B_{j,k}\right) - \eta \le 0 \quad \forall j,k \qquad (= 0 \text{ if } B_{j,k} > 0)
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
&\frac{\partial L}{\partial \mu_i} = \sum_{j=1}^{J}\sum_{k=1}^{K}a_{i,j,k}X_{j,k} - A_i \ge 0 \;\; \forall i \\
&\qquad (= 0 \text{ if } \mu_i > 0)
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
&\frac{\partial L}{\partial \lambda} = \sum_{j=1}^{J}\sum_{k=1}^{K}\left(\overline{L}^N - e_{j,k}\left(N_{j,k}, m_{j,k}\right)X_{j,k}\right) \ge 0 \\
&\qquad (= 0 \text{ if } \lambda > 0)
\end{aligned}
\tag{20}
$$

$$
\begin{aligned}
&\frac{\partial L}{\partial \eta} = \sum_{j=1}^{J}\sum_{k=1}^{K}\left(\overline{B} - B_{j,k}\right) \ge 0 \\
&\qquad (= 0 \text{ if } \eta > 0)
\end{aligned}
\tag{21}
$$

In addition, $X_{j,k}$ and $N_{j,k}$ have to satisfy the non-negativity constraints in (3). The solution to the problem in (16) consists of the values of $X_{j,k}$, $N_{j,k}$, and $B_{j,k}$ and the associated Lagrance multipliers that satisfy the Kuhn-Tucker conditions in (17) to (21). The Lagrance multipliers μ_i express the shadow price of the resource constraints A_i. The multiplier λ represents the shadow cost of the restriction on nitrogen discharges: the value of λ shows how much farm profits will fall if the load restriction is tightened by an additional kilogram. That is, the marginal cost of reducing agricultural nitrogen discharges is embedded in λ. The multiplier η gives the shadow value of buffer strips.

Solving the constrained optimization model in (16) for all possible values of the maximum allowable nitrogen load $\overline{L}^N$ yields the abatement costs as a function of $\overline{L}^N$. The abatement cost associated with a nitrogen load restriction $\overline{L}^N$ is the difference between the maximum profits from farming in the absence of load restrictions, π^*, and the maximum profits subject to the load constraint $\overline{L}^N$, denoted by $\pi\left(\overline{L}^N\right)$. Thus, the abatement cost function can be written as

$$C\left(\overline{L}^N\right) = \pi^* - \pi\left(\overline{L}^N\right). \tag{22}$$

Given the nitrogen fertilizer application rate, crop and tillage choice, and share of buffer strips associated with each level of the nitrogen load constraint $\overline{L}^N$, the loads of dissolved reactive phosphorus and particulate phosphorus are determined by the ratio of nitrogen and phosphorus in the compound fertilizer in (4), and by the phosphorus runoff functions in (14) and (15).

Reducing nitrogen fertilization and allocating land to buffer strips will unequivocally reduce yields, and consequently agricultural profits. The effect of reduced tillage or no-till on profits cannot be determined a priori, as reduced yields are accompanied with cost savings that may outweigh the effect of reduced yield on profits (see e.g. Lankoski et al., 2004).

4. Agriculture in Southern Finland

We utilize data from the Uusimaa and Varsinais-Suomi provinces in Southern Finland to estimate the abatement cost function. Agricultural runoffs from southern Finland constitute the largest anthropogenic nutrient source in the Finnish coastal waters of the Gulf of Finland, which is the most eutrophied sub-basin of the Baltic Sea. The shallow coastal waters are particularly prone to eutrophication, and toxic algae blooms frequently occur during the warm summer months. The Helsinki Commission has called for more effort to reduce the nutrient loads to the Baltic Sea, especially from agriculture (HELCOM). In Finland, agricultural nutrient abatement is the single most important investment under the Water Protection Target Programme (HELCOM, 2003). The main objective of Finnish Agro-Environmental Subsidy Programme is the reduction of nutrient loads to waterways (Turtola and Lemola, 2004). Besides the Baltic Sea, these priorities relate to the majority of Finnish lakes, which are shallow and hence vulnerable to nutrient pollution. Despite past efforts to reduce nutrient loads from arable land, the nutrient levels have not been decreasing (Ekholm et al., 2004, Räike and Granlund 2004, Granlund et al., 2005).

The research area covers the Uusimaa and Varsinais-Suomi provinces in southern Finland. Figure 1 depicts the study area and the catchments that approximately correspond to the provinces included in the study. Economic data pertain to the regional economic and employment development centres, while the ecological data come from the catchment area.

The area of cultivated agricultural land in the region was 481 500 hectares in 2003. This represents approximately 20 % of cultivated land in Finland. The climate is seasonal and the thermal growing season lasts for 160-190 days. The predominant soil type is clay (Kähäri et al. 1987). The average farm size in 2003 was 38 ha. Agriculture in the region is predominantly cereal farming: in 2003 the crops that took up the highest percentage of cultivated land were barley (24 %), spring wheat (22 %), and oats (13 %). Other commonly grown crops were turnip rape (6 %), winter wheat (5 %), silage (5 %), and sugar beet (3 %). (Yearbook of Farm Statistics 2003). We included these seven crops and fallow as land use choices in our model.

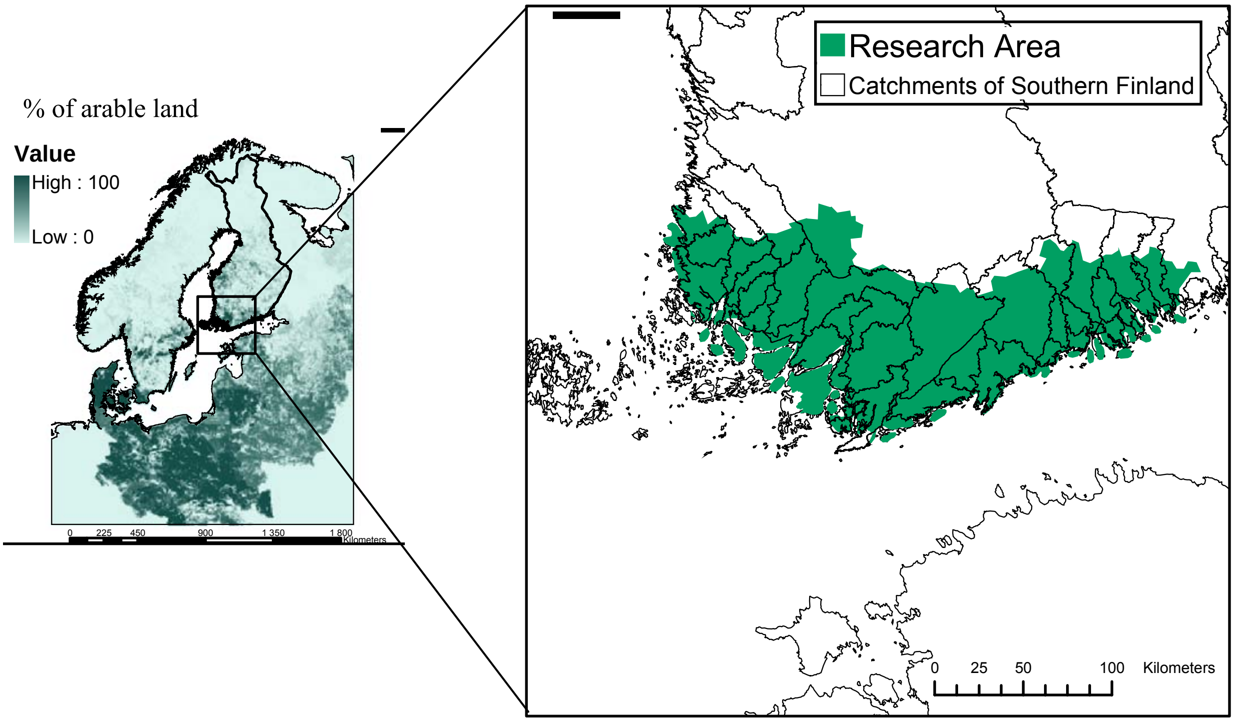


Figure 1 – Baltic Sea drainage bay and the research area. Source: Baltic Sea GIS, 1993;

We analyse the farming decisions at the level of a single representative farm, and scale up the farm to represent the entire region. The representative farm is constructed so that its characteristics – size, soil phosphorus status, and field area suitable for buffer strips - correspond to the statistical averages for the region. The agricultural commodity prices and fertilizer prices are the annual averages for 2003 from Finnish Agricultural Statistics (Table 1). The yield parameters are shown in Tables 2 and 3. The per hectare costs include fuel and labour costs, machinery, and harvest, while grain drying costs are yield dependent. The costs are displayed in Table 4.

Table 1. Commodity and fertilizer prices, EUR/kg[a]

Commodity prices	
Spring wheat	0,127
Barley	0,108
Oats	0,099
Winter wheat	0,127
Turnip rape	0,260
Silage	0,034
Sugar beet	0,054
Fertilizer prices	
Spring cereal composite fertilizer [b]	1,20
Winter cereal composite fertilizer [b]	1,10
Root vegetable composite fertilizer [b]	1,56

[a] Yearbook of Farm Statistics 2004.

[b] The fertilizer price was computed as the price of one kg of nitrogen assuming that a fertilizer mix appropriate for each crop type is applied. Spring cereal mix is applied to spring wheat, barley, oats, and turnip rape. Winter cereal mix is applied to winter wheat, and root vegetable mix to sugar beet.

Table 2. Crop yield parameters for Mitcherlich form[a]

Crop	Conventional tillage			Chisel plough			No till		
	m	k	b	m	k	b	m	k	b
Spring wheat	4871.0	0.7623	0.0104	4747.2	0.7623	0.0104	3937.3	0.7623	0.0104
Barley	5309.6	0.8280	0.0168	5421.2	0.8280	0.0168	5105.1	0.8280	0.0168
Oats	5659.1	0.7075	0.0197	5677.0	0.7075	0.0197	5368.4	0.7075	0.0197
Winter wheat	5114,55	0.7623	0.0104	4984,56	0.7623	0.0104	4134,17	0.7623	0.0104

[a]From Uusitalo and Eriksson (2004). Winter wheat yield parameters for each tillage method were obtained by increasing parameter *m* for spring wheat by 5 %, which corresponds to the average yield difference between spring wheat and winter wheat on Finnish bookkeeping farms in years 1995-2003.

Table 3. Crop yield parameters quadratic form[a]

Crop	Conventional tillage			Chisel plough			No till		
	a	b	c	a	b	c	a	b	c
Turnip rape	1096.1	9.82	-0.0354	1052,26	9.82	-0.0354	986,49	9.82	-0.0354
Silage	1182.9	24.24	-0.0394	Not applicable					
Sugarbeet	23630.0	53.21	-0.083						

[a] For conventional technology, the parameters are from Lehtonen (2001). The parameters for chisel plough and no till have been obtained by adjusting the crop yield parameters in Lehtonen (2001) by yield coefficients for chisel plough and no till reported in Ekman (2000).

Table 4. Crop production costs.

Fixed cost, EUR/ha[a]

Crop	Conventional tillage		Chisel plough		No till	
	Capital cost	Operation cost	Capital cost	Operation cost	Capital cost	Operation cost
Spring wheat	323	113	320	113	314	109
Winter wheat	323	113	320	113	314	109
Barley	323	113	320	113	314	109
Oats	323	113	320	113	314	109
Turnip rape	323	113	320	113	314	109
Silage	235	148	n.a.	n.a.	n.a.	n.a.
Sugar beet	384	327	n.a.	n.a.	n.a.	n.a.
Green fallow	109	68	108	68	91	40
Buffer zone	109	133	108	133	91	105
Grain drying costs, EUR/kg[b]						
Spring wheat, winter wheat, barley, oats	0,01 for all tillage practices					

[a] Calculated for the representative farm (38 ha) using Pentti (2003) and Enroth (2004). The buffer zone costs consist of the fixed costs of fallow, and a cost of ,65 eur/ha/a for removing plant residue at the end of the growing season.

[b] From http://www.maaseutukeskus.fi/julkaisut/s_julkaisut.htm

We consider short run farming decisions and consider farm capital to be given. By assumption, equipment can be rented, so that all technologies (conventional, reduced tillage, and no-till) are available. Labour is not constrained. The area of land allocated to different crops is restricted by farm size, 38 hectares. The model calculations are based on the use of compound fertilizers that contain nitrogen and phosphorus in a fixed ratio. We considered fertilizer mixes that are predominant in the production of each crop type in Finland. The nutrient ratios are given in Table 5. Nutrient discharges can be reduced through reduced tillage and no-till, through establishing buffer strips, and through reducing fertilization. In 2003, conventional tillage was predominant in the region.

Table 5. Ratio of phosphorus and nitrogen in the fertilizer mix applicable to each crop[a]

Spring wheat	0,15
Barley	0,15
Oats	0,15
Winter wheat	0,12
Turnip rape	0,15
Silage	0,14

Sugar beet	0,11
Green fallow	n. a.

[a] From http://www.maaseutukeskus.fi/julkaisut/s_julkaisut.htm.

Buffer strips that are at the maximum 3 meters wide are eligible for the EU Common Agricultural Policy (CAP) area subsidies. The buffer strip potential was estimated based on GIS data of field edges next to water ways and main ditches (TIKE, 2003). The upper limit of buffer strip area was 0,58% or 0.22 ha for a 38 ha farm. Further buffer capacity can be obtained by adoption of wider buffer zones, which have not been entitled to CAP subsidies. The regional environmental administration has estimated that 1-3% of the arable land area would benefit from buffer zones (Penttilä, 2003). The upper limit was set at 3 %, which corresponds to 1.14 ha for a 38 ha farm.

The parameters $\varphi_{j,k}$, $\sigma_{j,k}$ and $\Delta_{j,k}$ of the runoff functions for nitrogen, dissolved reactive phosphorus and particulate phosphorus were calibrated so that at the calibrated values the nitrogen and phosphorus loads predicted by the runoff functions (11) to (13) correspond to the observed loads in 2003. The calibrated parameters are presented in Table 6. In the calibration land allocation was as in 2003, and fertilizer use conformed to current environmental regulations. The ratio of loads from different crops was held fixed, given the tillage method. For nitrogen, the relative loads for the different crops were based on field experiments in South-Western Finland (Tapio Salo, Agrifood Research Finland, pers. comm.). For phosphorus, the relative loads were based on simulations from the IceCream model (Tattari et al., 2001). Soil phosphorus status θ was fixed at 10.6 mg/l, which is the average for Finnish Farm Accountancy Data Network farms situated in southern and South-Western Finland (Myyrä et al., 2003). The ratio of surface flow and drainage flow was assumed to be 0.5. The normal nitrogen fertilization doses used to compute the nitrogen load are shown in Table 7.

Table 6. Technology-based differences in nutrient loads[a]

Crop	Conventional tillage			Chisel plough			No till		
	φ	σ	Δ	φ	σ	Δ	φ	σ	Δ
Spring wheat	21	326	212	20	362	92	20	354	127
Winter wheat	18	355	204	18	361	201	18	368	202
Barley	18	316	198	17	347	78	18	326	114
Oats	10	323	202	10	352	82	11	352	117
Turnip rape	22	329	220	21	362	100	21	345	135
Silage	11	629	52	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sugar beet	17	362	264	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Green fallow	10	197	8	10	197	8	10	197	8

[a] Calibrated so that the nitrogen and phosphorus loads predicted by the runoff functions (11) to (13) correspond to observed loads when land allocation is as in 2003, and fertilizer use conforms to current environmental regulations.

Table 7. Normal nitrogen fertilization dose, kg/ha[a]

Spring wheat	100
Barley	90
Oats	90
Winter wheat	120
Turnip rape	100
Silage	180
Sugar beet	120
Green fallow	0

[a] The amounts of nitrogen recommended by the Finnish Agri-Environmental support program. Source: Valtioneuvoston asetus luonnonhaittakorvauksista ja maatalouden ympäristötuesta 29.6.2000/644. http://www.finlex.fi/fi/laki/smur/2000/20000644.

Agricultural policy in terms of area based income subsidies is taken as given. The EU Common Agricultural Policy (CAP) provides farmers with direct subsidy payments for crops planted. Reforms of the system are currently underway. According to the European Commission, the CAP reform agreed upon in June 2003 is geared towards consumers and taxpayers and linked to the respect of environmental, food safety and animal welfare standard (European Commission, 2005). In practice, the reform levels the CAP hectare subsidy for different crop types and fallow. In Finland, the reform comes into force in 2006. In order to examine how the reform affects the cost of agricultural nutrient abatement, we considered two subsidy regimes: the one that prevailed in 2003 (BASE 2003) and the subsidy regime in place after the reform (CAP 2006). In order to eliminate the effects of year-to-year fluctuation, in both scenarios the commodity prices and costs were held at their 2003 levels. However, the price of sugar is decreased in the CAP 2006 scenario due to changes in the EU sugar policy. The level of subsidies for 2006 is prediction based on the arable land area and subsidies of 2003 (Heikki Lehtonen, Agrifood Research Finland, pers. comm.). The subsidies under the two CAP systems are displayed in Tables 8 and 9. Table 10 summarizes the EU regulatory constraints.

Table 8. Subsidies in 2003, EUR/ha[a]

Crop	CAP payments	LFA support	National support	Total subsidies
Spring wheat	279	150	105	534
Winter wheat	279	150	105	0
Barley	279	150	84	513
Oats	279	150	9	438
Silage	214	150	0	364
Turnip rape	247	150	143	540
Sugar beet	0	150	202	352
Fallow	214	150	0	364
Buffer, width 3 to 15 m	0	150	0	150
Buffer, width below 3 m	Same as main crop	150	Same as main crop	

[a] Niemi, J. and Ahlstedt, J. (2003).

Table 9. Subsidies in 2006, EUR/ha

Crop	CAP payments[a]	LFA support[b]	National support[b]	Total subsidies
Spring wheat	293	170	105	568
Winter wheat	293	170	105	568
Barley	293	170	84	547
Oats	293	170	6	469
Silage	293	170	129	364
Turnip rape	293	170	129	540
Sugar beet	293	170	129	352
Fallow	293	170	0	364
Buffer, width 3 to 15 m	0	170	0	150
Buffer, width below 3 m	Same as main crop	170	Same as main crop	

[a] Heikki Lehtonen, Agrifood Research Finland, pers. comm.

[b] The Ministry of Agriculture and Forestry. 2006

Table 10. Resource and EU regulatory constraints

Total land on representative farm	38 ha
Maximum turnip rape area (agronomic constraint)	9.5 ha
Maximum fallow (*EU* regulatory constraint)	19 ha
Minimum fallow (*EU* regulatory constraint)	3.8 ha
Maximum sugarbeet area (from Finland’s sugar quota)	0,5 ha
Maximum buffer strip area	0,22 ha
Maximum buffer zone area	1,14 ha

To solve the constrained optimization problem for a series of nitrogen load restrictions, the model was translated into the General Algebraic Modelling System (GAMS) language (Brooke and Kendrick 1998). The resulting nonlinear mathematical program was solved using the CONOPT3 optimisation algorithm, which searches for local optima by various methods (Drud, 2004). The model was first solved without the load constraint. The unconstrained solution was then used as the baseline for a series of tightening load restrictions. We considered nitrogen load reductions between 0 and 60 %, with each one of the 30 iterations reducing the allowed load by 2%. The results from the previous iteration were used as initial variable values for the following iteration. A quadratic abatement cost function was fitted based on these points to the cost projections produced by the s 30 iterations using ordinary least squares (OLS) regression.

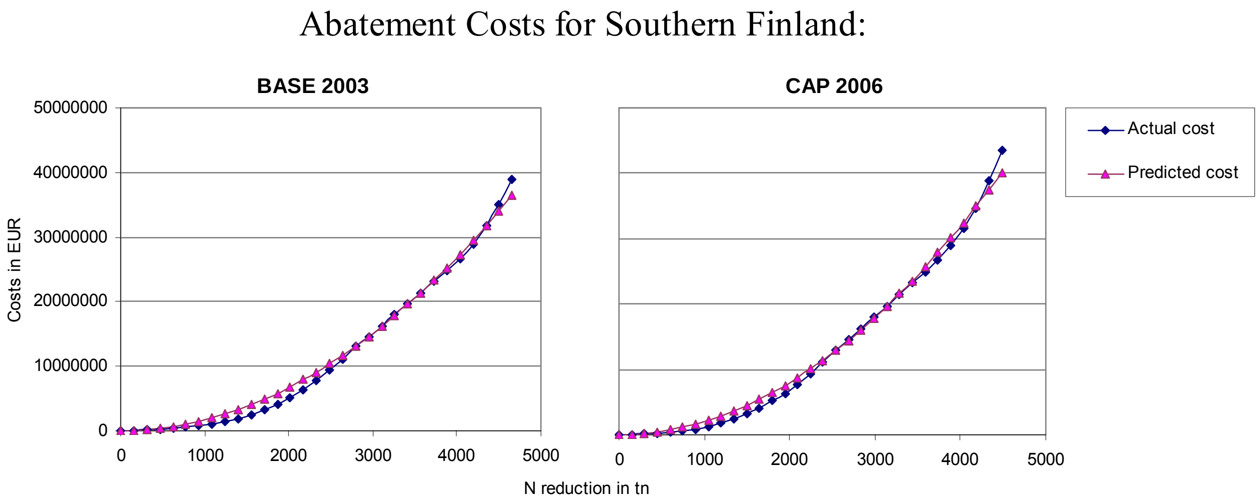
5. Results

We estimated abatement costs functions under the 2003 CAP subsidy regime and under the reformed CAP system that enters into force in 2006. The resulting cost functions are depicted in Figure 2. The estimated cost functions for the BASE 2003 system and the CAP 2006 system are

$$C_{2003}\left(A_N\right) = 1.68 A_N^2 \qquad (23)$$

$$C_{2006}\left(A_N\right) = 1.99 A_N^2 \qquad (24)$$

where A_N is the reduction in agricultural nitrogen load relative to unconstrained load. The unconstrained nitrogen load was 7764 tn per annum for BASE 2003 and 7473 tn for CAP 2006. The estimated phosphorus load reduction associated with a given nitrogen load reduction is $A_P = 0.0039A_N$ for BASE 2003, and $A_P = 0.0049A_N$ for CAP 2006, with the unconstrained loads 522 tn per annum for BASE 2003 and 548 tn for CAP 2006.



Figures 2a & 2b – Predicted and simulated costs for the research area.

Given the 50 % uniform load reduction target that the Helsinki Convention has set for Finnish agriculture, we computed the cost of reducing nitrogen loading in the study region by 50 %. The resulting abatement costs for the study region are € 25 million under **BASE 2003**. This is approximately € 3.3 per kg, or € 52 per ha. The cost to a typical farm in southern Finland would be € 1995. The costs are the equivalent of 49 % of the environmental subsidies received by the typical farm in the region in 2003. The reduction in phosphorus loading associated with the 50 % reduction in nitrogen loading would a mere 2 %. Under the reformed CAP regime the cost of a 50 % reduction in nitrogen loading would be € 28 million (€ 3.7 per kg, € 58 per ha or € 2197 for the typical farm) and the associated reduction in phosphorus loading again only 2 %.

Gren et al. 1995 found the abatement cost range for Finnish agriculture to be €6-24 for kilogram of nitrogen and €24-662 for kilogram of phosphorus. Gren et al. estimated the abatement costs based of fertilizer demand, using catch crops, energy forests and green fallow as abatement measures. Finnish data were used to derive the fertilizer demand in Finnish study region, while the costs of abatement measures in were assumed to be the same as in the Swedish Bothian Bay catchment. The lowest cost abatement measure in Gren et al. was the reduction of fertilizer inputs. Our results favour buffer strips, which strips were not included in the Gren et al. study. As several model assumptions different in the two studies, comparisons between results can only be indicative. The same caveat applies to comparing our results to those in Brady (2001, 2003). Nevertheless, our results support Hart & Brady (2002), who found that significant, reductions in nitrogen losses, for example 30%, can be obtained by relatively small decrease in gross profits.

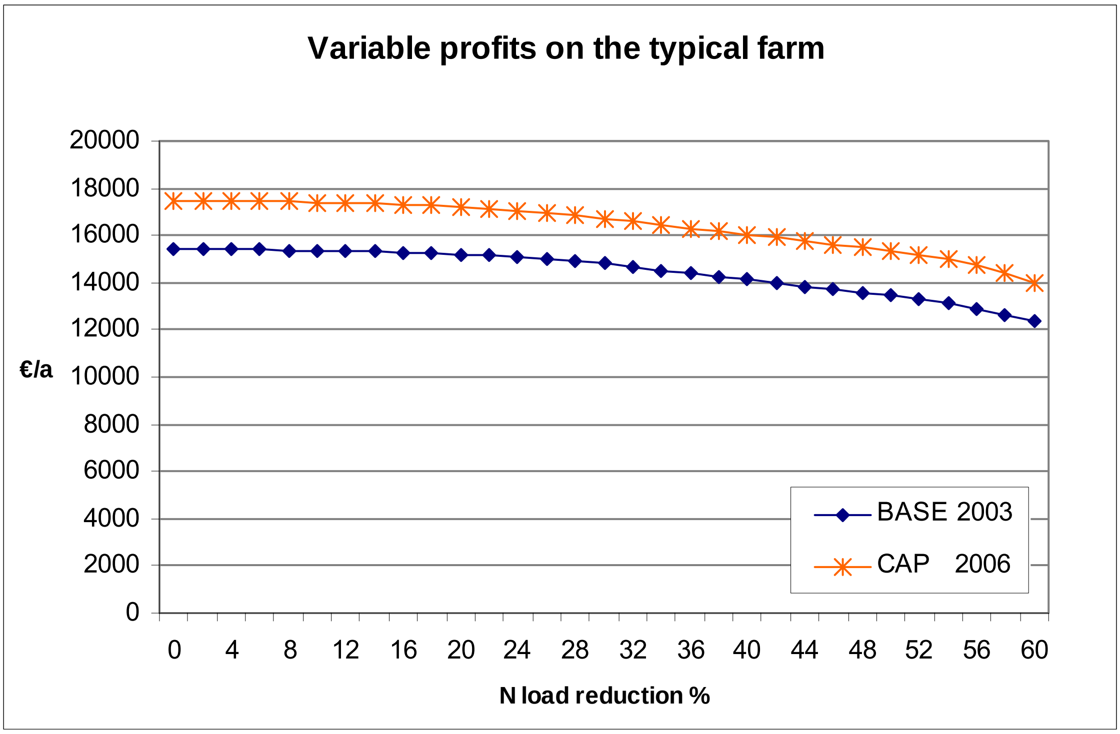
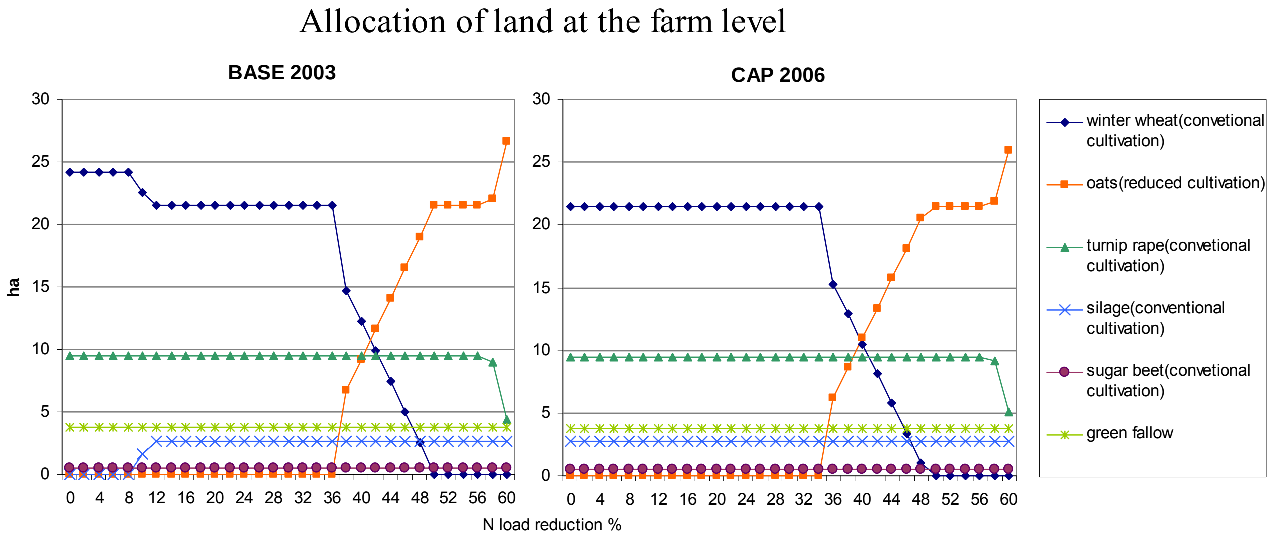


Figure 3. The effect of load restrictions on farm profits. The profits under CAP 2006 are approximately 13% higher than under the old CAP regime.

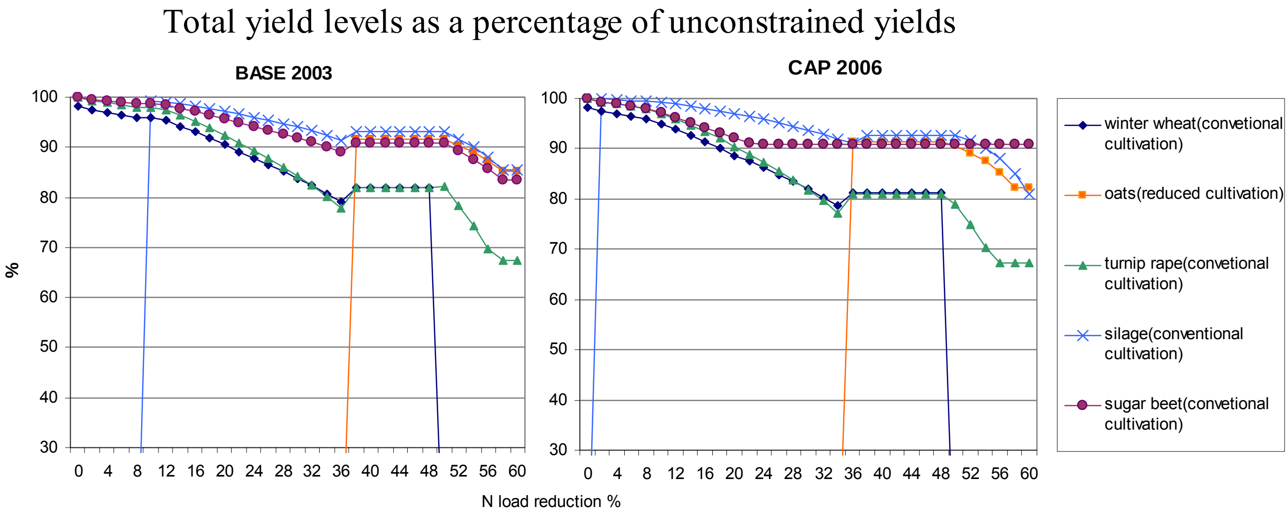
Figure 3 illustrates the effect of load restrictions on farm profits. We considered variable profits alone. Thus, fixed costs on capital were not included in the analysis. As the load restriction is tightened the profits decrease. The CAP reform increases the total revenue from the base 2003 level. The reform foresees a 36% reduction in the sugar price which is taken into account, but as the Finnish domestic sugar subsidy has not been determined yet, we have not included any support measures beyond the current frame for sugar. The EU and national area subsidies form a significant share of farm profits, which smoothes the effect of tighter load restrictions on the profits. Fixed costs and subsidies affect the allocation of land between different crop types, but do not affect the choice of fertilizer application rate or the width of buffer strip once the crop choice has been made.

Figures 4a & 4b depict the effect of load restriction on the choice of crop under different subsidy regimes. The decoupling of CAP from crop type favours silage production, which receives significantly greater subsidies than earlier[3]. As the amount of available land is assumed constant, wheat production is replaced by silage production. The effect is limited by a constraint on the silage production. By assumption, the region retains its grain production emphasis while animal husbandry remains at its 2003 level, which limits silage production. As illustrated in Figures 4a and 4b, tightening the load restriction converts conventionally cultivated winter wheat area to silage under the BASE 2003 system as well. Further restrictions convert winter wheat and turnip rape cultivation to oats farmed with reduced tillage. The hectare allocation of the most profitable crop, sugar beet is constrained by the EU sugar quota and does not change from the constrained levels as a result of the CAP reform or tighter load restrictions. Also, The share of green fallow also remains constant at the minimum level of the EU set aside regulations.



Figures 4a & 4b. Allocation of land between different crop types and tillage methods.

Load restrictions lead to decreased yield levels. Figures 5a & 5b depict yields for each crop as a percentage of the yield in the unconstrained solution. Wheat yields are reduced to zero as the load restrictions reach 50%. Turnip rape yields are affected second to wheat. The kink point follows from a change in the crop choice and tillage practice which allows a slight increase in the fertilization levels.



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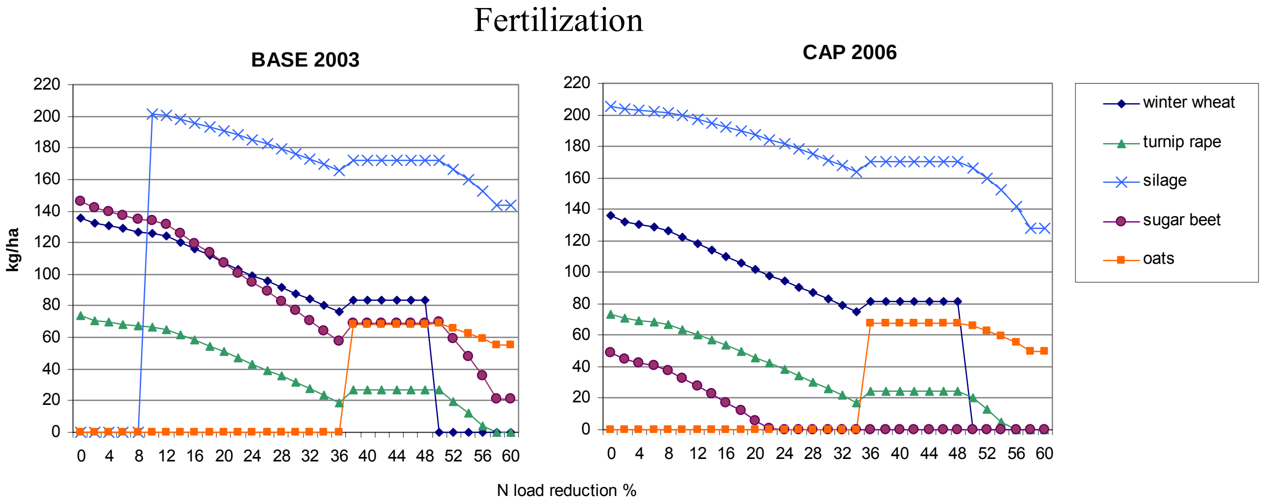
[3] National subsidies for silage were only paid to farms classified as animal husbandry farms

Figures 5a & 5b. Effects of nitrogen abatement on total yields. The vertical axis gives the constrained yield as a percentage of the yield in the private, unconstrained optimum. Sugar beet and turnip rape yields level as their fertilization is discontinued[4]. Fertilization levels are presented in Figures 6a & 6b. The decline in the sugar price is reflected in decreased fertilizer application, which explains the different sugar beet yield levels under the two CAP regimes. Further fertilizer reductions are borne by wheat and silage.



Figures 6a & 6b. Fertilization levels

The use of buffer strips as a load reduction measure is illustrated in Figure 7. The maximum buffer area eligible for CAP hectare subsidies was 0.22 ha for the 38 ha model farm, whereas the maximum buffer potential estimated to yield environmental benefits is 1.14 ha. Under both the BASE 2003 and CAP 2006 systems, the buffer area exceed the area eligible for CAP support. However, the maximum capacity for buffer zones is not reached. The strictest abatement targets are met by switching to reduced tillage cultivation of oats rather than by further increasing the buffer area. The switch to reduced tillage of oats also explains the slight decline in buffer area at load restrictions between 40 and 52 %.

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[4] The positive constant terms in the sugar beet and turnip rape yield functions retain farming the crops profitable at zero fertilization. While yield levels are likely to remain positive, the yield response function may be inaccurate at zero fertilization.

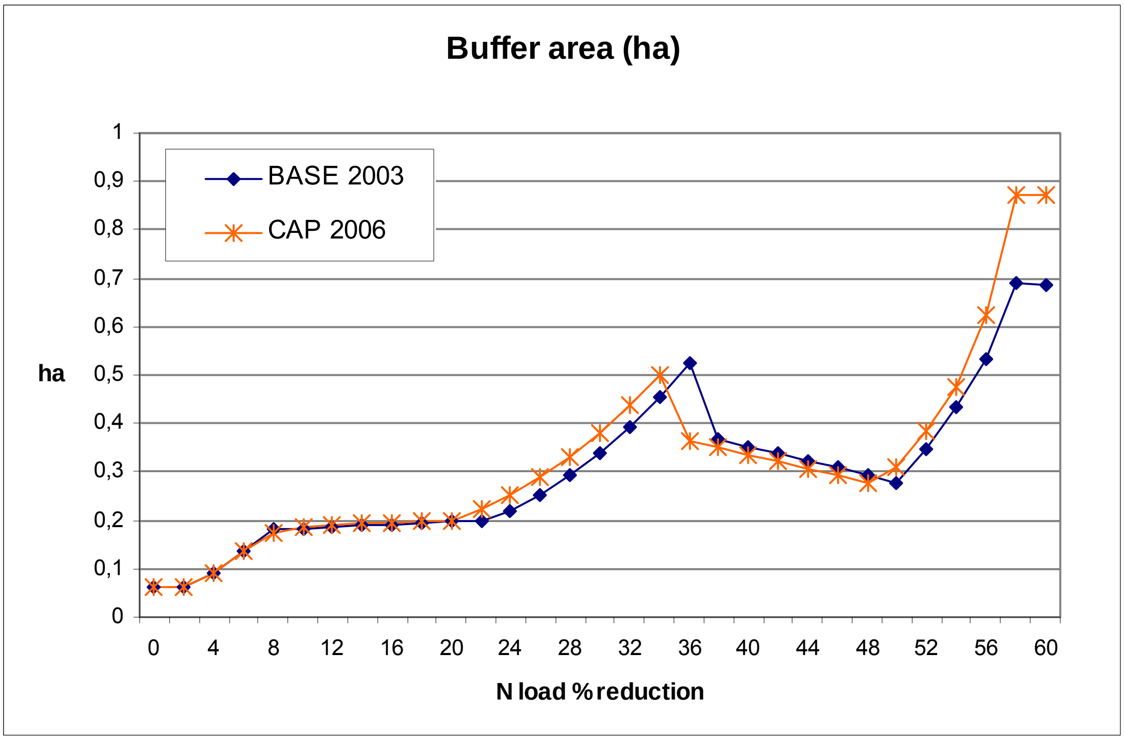

Figure 7. Buffer area as a function of load reduction target. The buffer strip area is constrained from above by

As can be seen from figures 4-7, a combination of different abatement measures is used to achieve least cost abatement. Moderate load restrictions are met by reducing fertilization and introducing buffer strips. Large load reductions are obtained through decreasing fertilization further and through conversion to reduced tillage cultivation of oats. Switching of tillage method did not occur for other crops. However, both the tillage method and crop choice were sensitive to the initial values provided. Thus, the absence of switching may be partly due to the treatment of initial values in the optimization algorithm. Variables with an initial level of zero are undesirable for non-linear optimization, as they appear to have no effect on the profit function (Drud, 2004). This effect hampers the switch between the tillage practices, which do not have large dissimilarities in the parameter values. Assigning arbitrary initial values instead of the values obtained from the previous solution leads to solutions which are local optima but produce lower profits, although tillage method switching occurs frequently.

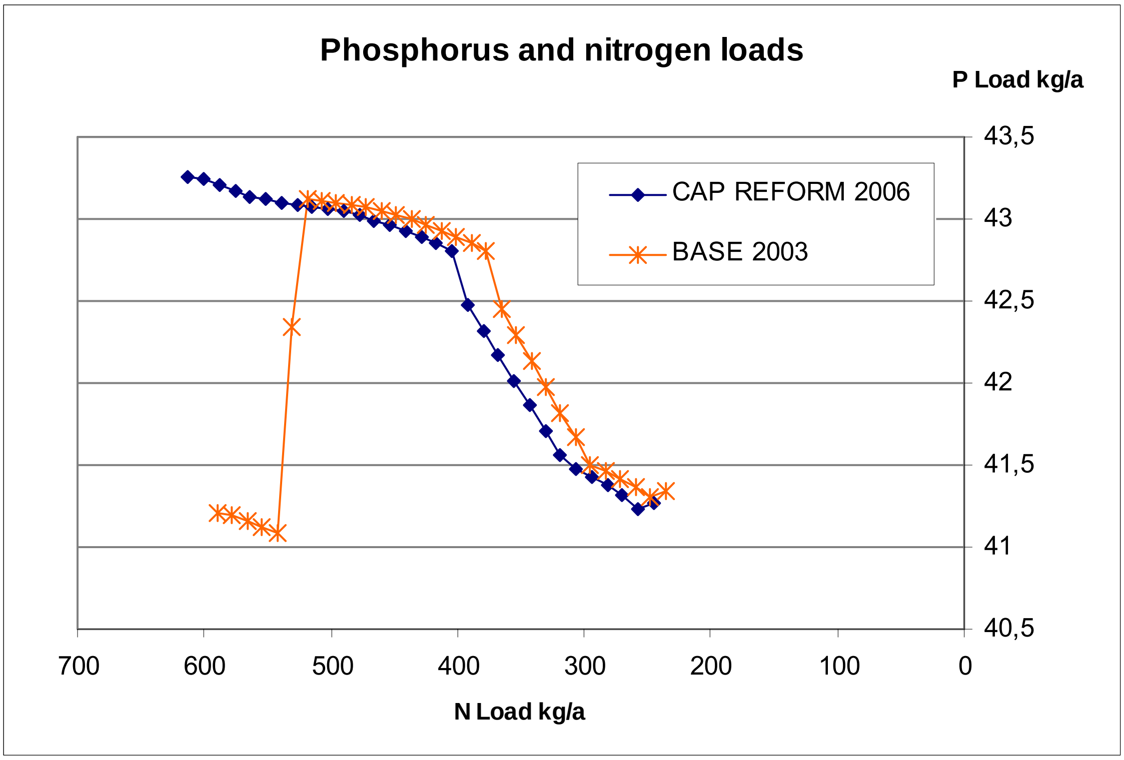

Figure 8 – Phosphorus load as a function of nitrogen load for the typical farm.

Reductions in nitrogen load lead to only modest reductions in phosphorus loads. Under the BASE 2003 regime, the phosphorus load actually increases at 10 % reduction target for nitrogen. The jump follows from part of the winter wheat production being replaced by silage, which produces markedly higher runoffs of dissolved reactive phosphorus than any of the other crops considered here (Table 6). The small changes in the phosphorus load are also due to the impact of soil phosphorus status on the load. Both dissolved reactive phosphorus and particulate phosphorus loads are largely determined by the soil phosphorus status (equations 14 and 15), which cannot be decreased by farmers in the short run. Accounting for the long run effect of nitrogen load restrictions or other water protection measures on phosphorus loads would require a dynamic model tracking changes in soil phosphorus status. Such analysis merits full attention in a separate future study. Our results indicate a higher average cost of phosphorus abatement than Gren et al. (1995) who, however, did not account for the effect of soil phosphorus status on phosphorus loads.

Brady (2001, 2003) obtained a broader selection of crops than the one arising from our analysis. He also found more changes in the land cultivation practises. The broader scope of crop choices may be due to the larger number of hectare constraints in Brady’s study. Adding modelling constraints is a trade-off between the description of the farmers’ adaptation possibilities, and the more detailed description of current farming practises. Furthermore, the possibility of establishing buffer strips, not considered in Brady (2003), provides farmers with an alternative way to reduce the nutrient load.

The sensitivity of the profit optima found by the optimization algorithm was tested by using different initial levels of the key variables. The crop choice and the tillage method were sensitive to the initial levels of hectares and nitrogen fertilization, while the maximum profit levels were not affected significantly. Sugar beet and turnip rape yields were relatively consistent at different initial values, but the choice of other crops, tillage, fertilizer use and buffer strip width were not conclusive. The third crop in all the results was wheat, although the type and tillage were switched as initial levels were changed.

The sensitivity is due to non-linearities in the production and load functions. The choice of plausible initial values and bounds is a normal part of non-linear optimisation problems. Initial levels for land were allocated based on the current regional distribution of crops (Yearbook of Farm Statistics 2003). Fertilizer use was initialised at the unconstrained profit maximising level. For each consequent iteration on the load constraint, the variable values from the previous iteration were used as starting values. This produced relatively smooth yield and profit curves.

6. Discussion and conclusions

We have studied the costs of agricultural nutrient abatement for crop farming in southwestern Finland. Our study area covered approximately 21 % of the Finnish arable lands. Compared to previous studies we have considered an extensive selection of crops and farming technologies and describe them by non-linear functional forms, which have been estimated from a large set of empirical data. We also modelled the loads of two nutrients simultaneously, where many studies have focused on a single nutrient and hence neglected the effect of reduction measures on the other. The modelling framework described here can be applied to other regions as well as in empirical studies and decision support systems tackling with optimal nutrient abatement strategies.

Empirical modelling of agricultural loads and the cost of abatement is a challenging task. Data requirements are vast. Whereas economic data are relatively easy to obtain and applicable to the entire region, data on crop yield and nutrient loads are specific to crop and the characteristics of each parcel of land, most notably the slope and soil type. Furthermore, climate affects both the farm yields and nutrient loads. We have abstracted from these considerations to approach a problem which is already a complex one without the stochastic elements. We focused on crop farming, which is predominant in the study region. The optimal solution favoured reduced fertilizer use and buffer strips as abatement measures. Switching between crops was also observed frequently, while reduced tillage was rare. Catch crops could also provide a low cost abatement alternative (Gren et al., 1995). As catch crops have not been common in Finland and no empirical data are available on their effect on nutrient loading in the study region, catch crops were not considered in this study. Naturally introduction of load restrictions could change farming practises in favour of catch cropping. The abatement costs may be somewhat over or underestimated due to leaving manure management and animal farms outside the analysis. Furthermore, homogenous treatment of soil types and other environmental factors, which in reality vary across regions, may overestimate the abatement costs (for an empirical example see Johansson 2004).

Subsidies are the key instrument of the Common Agricultural Policy (CAP) and there is a multitude of political motifs to retain them. The criticism on CAP presented in both developing and developed (e.g. Hill, 2000) countries has led to decoupling of production and subsidies. Decoupling is demonstrated to reduce environmental impacts of agriculture in the literature (Hofreither, 2003; Serra et al., 2004). Lankoski (2003) postulates that acreage subsidy leads to a switch towards more fertilization intensive crops. Our empirical results also support some changes for the design and implementation of further agri-environmental nutrient policies in Finland. Efficiency and enforcement issues should be taken seriously, as it is suggested that load reductions could be obtained by without entailing excessive costs or larger income transfers from tax payers to farmers. The CAP reform increases the costs of nutrient abatement and is contradictory with its environmental goals.

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