Does geography matter in nutrient abatement? Bioeconomic model of heteregoneus farm nutrient loads

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1 Introduction

Eutrophication of the water bodies has proven to be a persistent environmental problem. For many watersheds the main contributor of excess nitrogen and phosphorus is agriculture [Aertebjerg, 2001, Johansson, 2004, Ekholm and Mitikka, 2006]. As nutrients enter streams by various pathways from extensive land areas, measuring and monitoring the emissions poses high costs. Such problem of non-point pollution renders many control measures infeasible [Griffin and Bromley, 1982]. Sustainable solution to this problem has been a research topic for decades, but the complexity of the underlying environmental and human interactions have lead to variety of models with different scales, angles and policy recommendations [Dunn and Shortle, 1988, Russel and Shogren, 1993, Schou *et al.*, 1998, Romstad, 2003, Gren *et al.*, 1997, Vatn *et al.*, 1999, Brady, 2003, Johansson, 2004, Lehtonen *et al.*, 2007]. In terms of past modeling efforts, it is possibly to distinguish between process oriented environmental models which include a set of management options specified as exogenous parameters and economic optimization models, which describe the management choices endogenously, but have limited description of the environmental processes. Naturally, there have been several studies, which describe some form of hybrid approach. Besides building the bridges between different fields of science and institutions, hybrid models pose several challenges in spatial and temporal scaling [Vatn *et al.*, 1999]. However, accounting for spatial variation has been argued to promote more efficient environmental policies [Wu and Babcock, 1996, Carpentier *et al.*, 1998, Ribaudo *et al.*, 1999, Qiu and Prato, 1999, Canton *et al.*, 2009]. Thus, it seems that the understanding of spatial distribution of environmental characteristics of inter-linked nutrients is required for meaningful policy design. Many agent-based models such as GEOLP [Lant *et al.*, 2005], which have sufficient spatial detail to assess environmental systems more accurately suffer from the drawback of being linear. Linear formulation of the farmer's abatement problem can for example lead to larger losses in yields than what would be expected from agronomic studies and hence obscure the most efficient methods of abament. To assess the potential of different types of abatement measures geographically explicit information needs to be conjoined with appropriate mathematical models, which capture the nonlinearity both in economic and environmental responses. Thus, the contribution of this study is to determine the significance of spatial analysis for Finnish nutrient abatement policies. We extend earlier non-linear Finnish models [Lankoski, 2003, Helin *et al.*, 2006] to account for watershed specific variation in plant cover, slope and soil. The formal model description is followed by the application at the Kalajoki watershed, which contains the scaling between data, environmental process model and the economic frame. The results show how spatial variation in the environmental model and data are captured in the economic analysis. We conclude that without spatially explicit soil and slope description in agro-economic models, the abatement costs for nutrients are likely to be overestimated

2 Theory

Consider a region where agricultural production of crops j takes place on soil s and slope l with k tillage practices. The farmers are risk neutral profit-maximizers who base their farming decisions on the known characteristics of land $X_{j,k,s,l}$ and expect the weather to follow long-term average patterns. The characteristics of arable land of the region are fixed and the farming capital is given. The field work is hired and incurs a tillage specific variable cost c_k. Arable land produces yield $y_{j,k}$ as a function of tillage and fertilizers given constant phosphorus stock $\bar{P}_{j,k,s,l}$ in soil . The fertilizer costs are given for nitrogen $N_{j,k,s,l}$ and phosphorus $P_{j,k,s,l}$ by multiplying them with respective prices p_N and p_P. While the importance of the animal production in terms of nutrient abatement is recognized, let us assume for sake of simplicity that the more direct abatement measures at fields are more efficient than changes in the animal diet, numbers or manure management [Helin, 2007]. Hence, the effect on animal operations is captured only in the silage demand. Formally for the profit maximization problem of a representative crop producing farm (1)-(2)

$$\max_{X_{j,k,s,l}, N_{j,k,s,l}, P_{j,k,s,l}} \pi \left(X_{j,k,s,l}, N_{j,k,s,l}, P_{j,k,s,l}\right) \tag{1}$$

$$= \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{l=1}^{L} \left\{ p_j y_{j,k} \left(N_{j,k,s,l}, P_{j,k,s,l}, \bar{P}_{j,k,s,l}\right) - c_k - p_P P_{j,k,s,l} - p_N N_{j,k,s,l} + u_j \right\} X_{j,k,s,l} \tag{2}$$

$$s.t. \quad \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{l=1}^{L} r_{i,j,k,s,l} X_{j,k,s,l} \leq \bar{R_i}, \quad \forall i \tag{3}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} X_{j,k,s,l} = \omega_{s,l}, \quad \forall s, l \tag{4}$$

$$X_{j,k,s,l} \geq 0, N_{j,k,s,l} \geq 0, P_{j,k,s,l} \geq 0 \tag{5}$$

where u_j is the crop specific subsidy per hectare of arable land. Including the crop hectare based subsidy in farmer's profit maximizing problem reflects Common Agricultural Policy (CAP) of the European Union on the reference year 2003. Various biological, technical and political limitations in crop farming can be represented with a constraint function (3), where $\bar{R_i}$ is the resource maximum for the given criteria. The farmer's inability to change the basic land characteristics is described by the equation 4 where $\omega_{s,l}$ is the fixed land distribution. It is assumed that there is no feasible way for the farmer to remove land or nutrients from it (e.g. non-negativity constraints 5).

To derive the nutrient loads and abatement costs the complex environmental processes are described with a metamodel for each nutrient in equations (6) to (9).

$$\bar{N}^L = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{l=1}^{L}\left[\phi_{j,k,s,l}\exp\left[\gamma_{j,k,s,l}N_{j,k,s,l}\right]\right]X_{j,k,s,l}. \tag{6}$$

$$\bar{P}^{TP} = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{l=1}^{L}\left[P^{DR}_{j,k,s,l}\left(P_{j,k,s,l},\bar{P}_{j,k,s,l}\right) + \eta P^{P}_{j,k,s,l}\left(P_{j,k,s,l},\bar{P}_{j,k,s,l}\right)\right]X_{j,k,s,l} \tag{7}$$

$$P^{DR}_{j,k,s,l} = \left[\theta_{j,k,s,l}[2(\bar{P}_{j,k,s,l} + 0.01(P_{j,k,s,l}) - 1.5]\right] * 10^{-4} \tag{8}$$

$$P^{P}_{j,k,s,l} = \left[\Delta_{j,k,s,l}\left[250\ln\left[\bar{P}_{j,k,s,l} + 0.01(P_{j,k,s,l})\right] - 150\right] * 10^{-6}\right] \tag{9}$$

The total annual nitrogen load $\bar{N}^L$ is a function of fertilization $N_{j,k,s,l}$. The differences between the crops, slopes and tillage methods are captured in the parameters $\phi_{j,k,s,l}$. and $\gamma_{j,k,s,l}$. Phosphorus enters the water ways via two mechanisms which are represented by functions (8) and (9). Dissolved reactive form of nutrient P^{DR} is determined by the amount of runoff $\theta_{j,k,s,l}$ in the equation (8) of [Uusitalo and Jansson, 2002]. Some of the phosphorus load consists of phosphorus still bound to the eroded soil particles $\Delta_{j,k,s,l}$ as it reaches the receiving water body[Uusitalo and Ekholm, 2003, Uusitalo, 2004]. It is assumed that runoff ($mm\ ha^{-1}\ a^{-1}$) and erosion ($kg\ ha^{-1}\ a^{-1}$) are independent of the soil P status ($mg\ l^{-1}$) and annual P fertilization rates ($kg\ ha^{-1}a^{-1}$). The total algal phosphorus load P^{TP} is determined by these flows by adding them up in equation (7). However, the total load itself is higher as the equation (9) predicts the algae available form, which is a share of P^{TP}. To convert the load estimates back to the total phosphorus a constant coefficient η is used. The equations (2) to (9) are used to derive the abatement costs for nitrogen and phosphorus. The status quo nutrient loads are given by solving the profit-maximizing problem specified above and consequently $\bar{P}^{TP}$ and $\bar{N}^L$ refer to the baseline levels of the respective loads. By introducing the equations (6) to (9) as constraints of the farmer's profit-maximizing problem and reducing the load from the baseline by $\tau\bar{P}^{TP}$ or $\tau\bar{N}^L$ for $0 < \tau < 1$, constrained profit solutions are given for both of the nutrients. Thus, the abatement costs C^{TP} and C^N are given by the difference between the baseline profits π and the constrained profits π^N or π^{TP} depending on which nutrient we are dealing with in equations (10) - (11).

$$C^N = \pi - \pi^N\left(\tau\bar{N}^L\right) \tag{10}$$

$$C^{TP} = \pi - \pi^{TP}\left(\tau\bar{P}^{TP}\right) \tag{11}$$

3 Research methodology

Operationalizing even such a simple theoretical approach on a scale of the watershed demands considerable amount of data. In Finland, the empirical efforts in nutrient modeling have focused on southern parts of the country with different dominant soils and steeper slopes. Hence, the calibration of this model will need to rely on the results of other studies and models. While using model results as data hinders the validation of the overall results, the more comprehensive description of a new research area offers more insight on the design of environmental policy and answers why some of the recommendations of the Finnish environmental subsidy system fail to produce concrete results in nutrient abatement. The mathematical model described in the equations (1)-(11) along with the calibration of the parameters is programmed as non-linear mathematical programme in GAMS [Brooke *et al.*, 1998].

The agricultural load within this metamodel is based on a field plot level process model ICECREAM, which has been developed for Finnish conditions from the GLEAMS/CREAMS model [Rekolainen and Posch, 1993, Tattari *et al.*, 2001]. For purposes of this study we have used ten year average weather conditions (1996-2006) for estimating the total annual load of the watersheds in ICECREAM. By ICECREAM simulations we obtain load, runoff and erosion estimates for combinations of 7 land use types, 7 fertilisation levels, 3 tillage types, 4 soils types and for 4 slope classes. This load parameter matrix, however is not comprehensive representation of the possible variation in the data. Hence, the lacking parameters have been interpolated from the simulation results as described below.

The load parameter matrix has been conjoined with heterogeneous field plot data which was obtained by spatial overlays of Agrifood Research Finland, National Land Survey of Finland, Ministry of Agriculture information service unit and Finnish Environmental Institute data. The sets j, k, l, s are defined below. The research area is illustrated in the Figure 1.

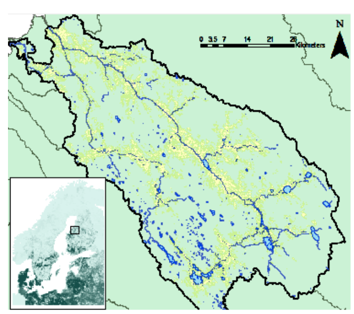


Figure 1: Kalajoki watershed

3.1 Farm systems

The climatic conditions in Finland generally lead to farming systems which rely on natural rainfall on artificially drained soil. The growing season is short, between 120-190 days and generally only single grain yield can be obtained annually. The majority of region's fields have small gradient and hence the effect of erosion control measures can be questioned. According to survey data on Kalajoki dominant method of tillage is conventional ploughing of soil, while cultivation and conservation tillage practices are rather marginal. As the change in tillage has implications for nutrient loads, all three types are considered in the model and presented in Table 3.1. However, the data was not sufficient to describe the existing distribution of tillage methods between the crop, soil and slope classes. Hence for all parcels, it is assume that the status quo distribution of tillage is constant over the slope and soil classes in the calibration of the nutrient load. The input and output prices are calculated from the statistics of year 2003.

Table 3.1. Different tillage types

k	tillage	share %
1	normal plough	86
2	cultivator	9
3	direct sowing	5

3.2 Land use and crop types

The land use data was obtained from the database of Information Centre of the Ministry of Agriculture and Forestry in Finland for the year 2003. Load parameters based on the ICECREAM model results of both of the study regions and both nitrogen and total phosphorus were available for barley, sugarbeet, grass and green fallow. In addition, nitrogen load parameters for winter wheat and oilseed and phosphorus load parameters for potato and rye were obtained for both regions. The parametrized crops cover approximately 75 % of the agricultural land on Kalajoki watershed. The share of most common crops from the total agricultural land is presented in the table 3.2.

Table 3.2. Common crops, their share of total arable land and nitrogen fertilization levels N $kg\ ha^{-1}\ a^{-1}$ for different soils recommended by the Finnish environmental subsidy system

Crop type	**share**			**Limits**
		clayey	**sandy**	**organic**
	%	kg	kg	kg
winter wheat	<1	120	110	70
spring wheat	3.3	120	110	70
spring rye	<1	120	100	40
winter rye	<1	120	100	40
barley	31	110	100	60
barley(malt)	<1	90	80	60
oats	11.5	110	90	60
mixed grain	1.7	120	110	70
peas	<1	50	50	40
potato	<1	60	60	60
potato(industrial)	<1	80	80	80
Sugarbeet	<1	120	120	120
spring rapeseed	<1	120	110	50
winter rapeseed	<1	120	110	50
silage, grass and hay	31.9	180	180	180

While majority of the existing agricultural crop cover could be represented with these parameters, the model reliability in both describing the existing system and the nutrient abatement options related to the crops, can be improved by having a broader crop set. Hence, some marginal land use classes were retained when their use or abandonment could have implications for the abatement of the nutrient loads and when the parameters could be estimated from other crops. The N-load parameters of potato were calculated from the sugarbeet parameters by using the differences between potato and sugarbeet in earlier nutrient load studies [Brady, 2003]. The missing cereal, protein and oilseed plant parameters are based on the parameters of barley. For oilseed plants, parameters were modified with the ratio from [Helin *et al.*, 2006]. The grass load parameters were used for all of the types of silage and hay. Missing parameters for winter and spring varieties were calculated so that N load of winter rye corresponds with winter wheat and P load of winter wheat corresponds with winter rye.

The crop yields are modeled as additive non-linear functions of nitrogen and phosphorus fertilization. The nitrogen yield response follows [Lehtonen, 2001] and the phosphorus yield [Saarela, 1995]. The effect of tillage method on yields is modeled as in [Helin *et al.*, 2006]. Rapeseed pest control is represented by restricting its annual field area to 1/3 of the total arable area. Contractual sugarbeet and potato arrangements between farms and the food industry are constrained by setting an upper limit of 4% of total arable area. Fallow minimum according to CAP requirements of 2003 was 10% and maximum fallow entitled to subsidies was 50%. To enable subsidy eligible and non-eligible fallow, the fallow land is split in two classes. Further division is made between managed grass covered fallow and non-managed bare fallow.

The metamodel for nitrogen load is estimated from ICECREAM point data for fertilization levels 0,20,30,50,60,120,150,200. This range covers the allowed nitrogen fertilization amounts in the Finnish environmental subsidy scheme (table **3.2**).

3.3 Field slopes

Slope tool of ArcGIS spatial analyst was used in calculating the map of slopes based on the Digital Elevation Model (DEM) of the study region. For each given cell of the DEM grid, the altitude of neighboring cells are compared and the slope is calculated based on the maximum altitude difference between the cell and its neighbors. The effect of different tillage methods on different soils and slopes on runoff , erosion and total nitrogen was available from the ICECREAM model on slopes of 0.1 %,0.5%,1% and 3%. for the study region.

Table 3.3. Distribution of field slopes.

s	Slope class (%)	Share of arable area (%)
1	0-0,5	56.6
2	0.5-1	21.1
3	1-2	15.3
4	2-3	4.1
5	3-6	2.5
5	>6	0.4

The mean slope of the watershed is 1.06%.The slope of 0-3% cover majority of the arable land area of the Kalajoki watershed. However, on approximately 3% of the area the slopes are steeper. These areas are expected to cause more than 3% of the loads and demonstrate some abatement potential. For these steep fields the load parameters had to be extrapolated from the results of the ICECREAM model. As erosion prevention measures can be expected to decline in efficiency as slopes get very steep, the extrapolation was not extended to slopes steeper than 6%. The steeper areas were modeled as part of the 3-6% class. The effect of the slope on the nitrogen load was estimated as linear functions with OLS in GAMS for all the specified crops, tillage methods and soils. Similarly OLS regression was estimated for runoff volume and erosion, which are used to determine the total phosphorus load. The outcome of the OLS regressions are discussed further in the results section. The load for each slope class is calculated by the mean value of the class.

3.4 Soil

This study benefits from the recent work on top soil classification and cartography in Finland, which provides the opportunity for wide scale spatially explicit modeling of soil. Soil bodies have been classified according to the World Soil Reference Base from the Finnish soil classification types and maps. ICECREAM load parameters were available for four soil classes which follow the Finnish soil classification. Hence, the soil data and their load parameters do not correspond one to one and some extrapolation and generalization was required for a better spatial coverage of soil. For arenosol and podsol soils the parameters follow the Finnish soil class of coarse sand (0.06-0.2 mm). Regosol load parameters are based on the class of fine sand (0.02-0.06 mm) and cambisol-gleysol parameters on the Finnish class of silty clay, in which the silt particles constitute approximately 40% and clay 60%. The nutrient loads from histosol are not described by the ICECREAM parameters. In this study, the histosol load parameters are given by sandy clay, which simplifies the load parameter estimation considerably. Similar sandy clay parametrization of the remaining 2% of arable land follows from the gleye composition of these soils. The soil of land use classes is summarized in the table 3.4.The phosphorus stock parameter $\bar{P}$ is available on the municipal level [ViljavuuspalveluOy, 2007].

Table 3.4. Soil classes and parametrization

l	FAO class	load parameter	Particle size[1)] (mm)
1	Eutric Regosol	HHt	0.02-0.06
2	Anthrosol	HHt	0.02-0.06
3	Eutric Cambisol 1	HsS	<0.002
4	Eutric Cambisol 2	HsS	<0.002
5	Vertic Cambisol	HsS	<0.002
6	Umbric Gleysol 1	HsS	<0.002
7	Umbric Gleysol 2	HHt	0.02-0.06
8	Dystric Gleysol	Hts	<0.002
9	Haplic Podzol 1	KHt	0.06-0.2
10	Haplic Podzol 2	KHt	0.06-0.2
11	Gleyic Podzol 1	KHt	0.06-0.2
12	Gleyic Podzol 2	KHt	0.06-0.2
13	Dystric Leptosol	KHt	0.06-0.2
14	Lithic Leptosol 1	KHt	0.06-0.2
15	Lithic Leptosol 2	KHt	0.06-0.2
16	Fibric/Terric Histosol 1	Hts	<0.002
17	Fibric/Terric Histosol 2	Hts	<0.002
18	Fibric/Terric Histosol 3	Hts	<0.002

1). Dominant particle size of the load parameter class

4 Results

4.1 Land allocation

The base line allocation of land use is derived from the solution to the farmers's profit maximizing problem. The large difference between the baseline and the observed land use results from the influence of the animal husbandry. The price of silage[1] is not high enough to push it in the profit maximizing combination without the due consideration of the value added in the animal production. Instead, the dominant crop type in the baseline optimal allocation is barley. Given the assumptions on animal production, prices and yields the malting variety will give larger profit than the fodder barley. The sugarbeet and potato are the most profitable crop types and stay at their respective upper bounds despite the abatement of either of the nutrients.

4.2 Nutrient loads on steeper fields

Nitrogen load, erosion and runoff for the slopes between 3 and 6% were estimated with OLS regression models described in equations (12)-(14). Nitrogen loads for the steeper fields are given as functions of the slope in figure 2 for barley.

[1] calculated by estimating its energy value as fodder per kilogram and deriving the price from the price and energy value of fodder barley

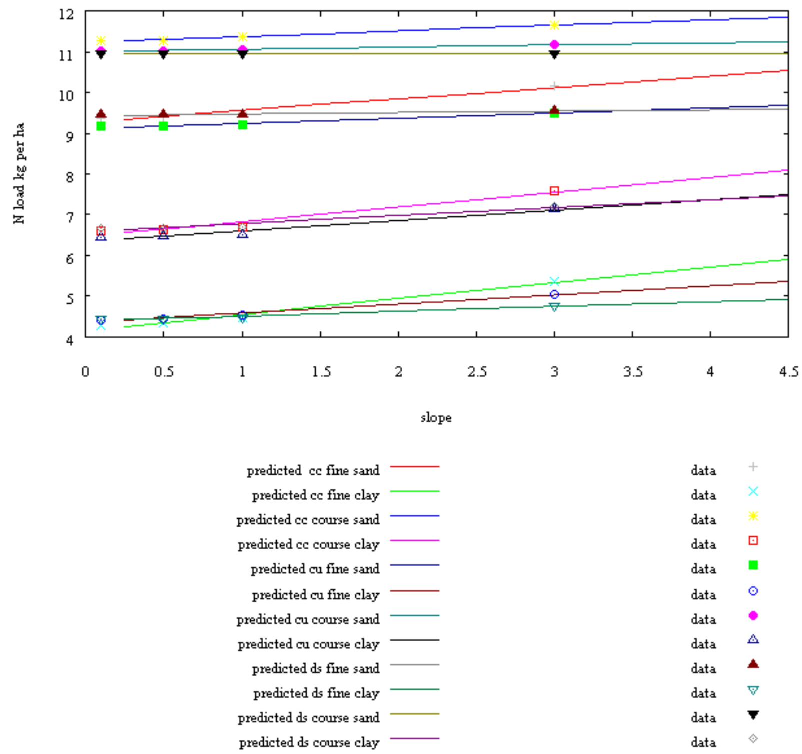


Figure 2: Nitrogen load as function of slope

The parameter values for rest of the crops are in appendix 1. Linear regression seems appropriate from the simulated data points. The estimated functions are plotted with lines from the mean values of the slope classes.

The results for barley demonstrate distinct differences in nitrogen loads between the soil types. Highest total nitrogen load occurs on the course sand. Steeper slopes lead to increased nitrogen load, but the magnitude of the effect is small compared to differences between soils. .

$$\bar{N}^L_{j,k,l,s} = \beta^N_{j,k,l} S_{j,k,l} + \alpha^N_{j,k,l} + \varepsilon_{j,k,l} \qquad (12)$$

$$\theta_{j,k,l,s} = \beta^R_{j,k,l} + \alpha^R_{j,k,l} + \varepsilon_{j,k,l} \qquad (13)$$

$$\Delta_{j,k,l,s} = \beta^E_{j,k,l} \left(S_{j,k,l}\right)^2 + \alpha^E_{j,k,l} + \varepsilon_{j,k,l} \qquad (14)$$

For total phosphorus load the effects of soil and slope are represented in runoff and erosion parameters of functions (8) and (9). Linear functional form

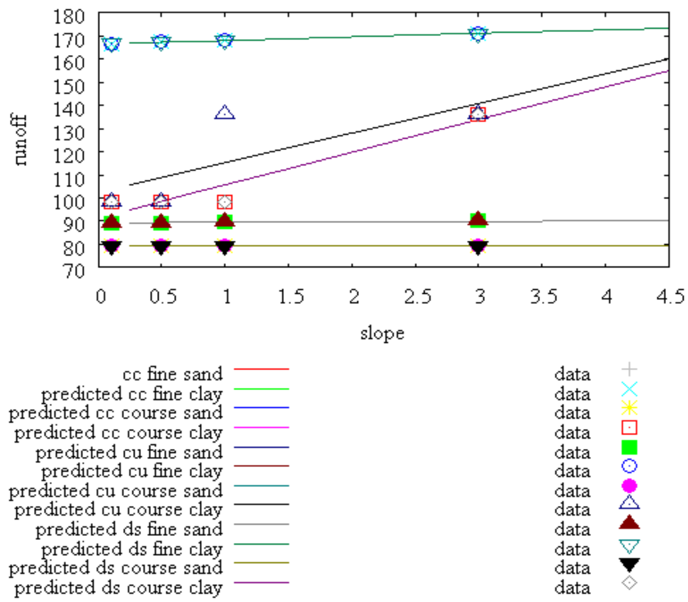


Figure 3: Runoff as a function of slope

provides a reasonable estimate for runoff on the steeper slopes (13). Erosion for the steeper fields is estimated from fitting quadratic functions with OLS (14). The parameters for the steepest slope class (3-6%) retain the differences resulting from soil, tillage and crop choice. The results for barley are shown in figures 3 & 4 correspondingly.

Runoff levels show a considerably variation over the soil and tillage types. For more porous soils the effect of slope is not significant while more solid soil structure and conservation tillage methods tend to increase runoff and lead to a pronounced slope effect. The quadratic functional form of erosion as a function of slope leads to high erosion estimates on the steepest fields.

4.3 Nutrient loads

The nitrogen load $\bar{N}^L_{j,k,l,s}$ is parametrised for all the model dimensions as a function of fertilization $N_{j,k,s,l}$. This regression model of N-load builds on the earlier regression between nitrogen and the slope in equation (12). The effect of the annual nitrogen application on the simulated load is presented in figure 5 for barley. The estimated values for parameters $\phi_{j,k,s,l}$ and $\gamma_{j,k,s,l}$ for all crops, can be found in the appendix 2.

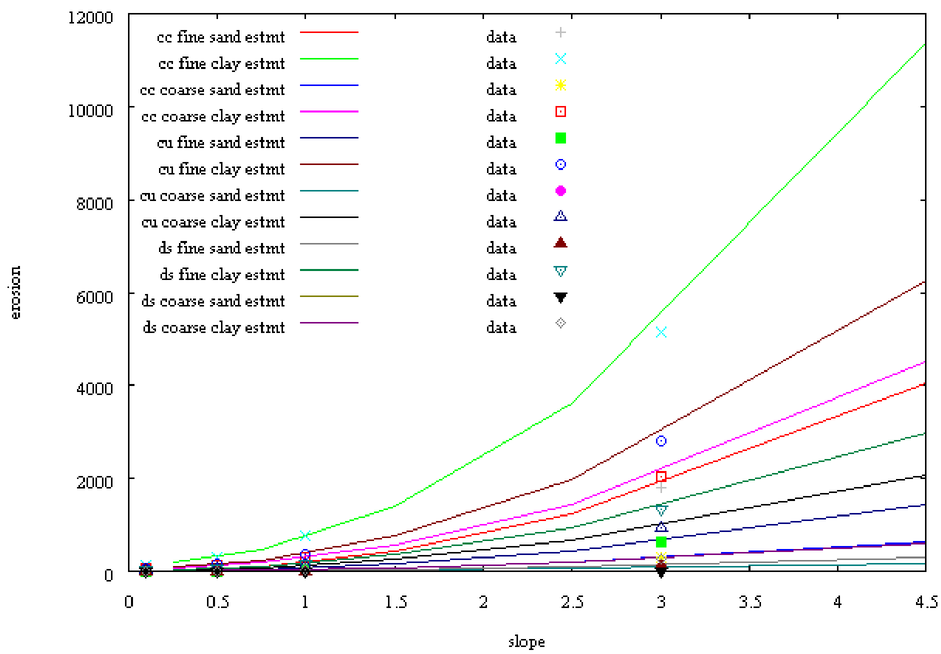


Figure 4: Erosion as a function of slope

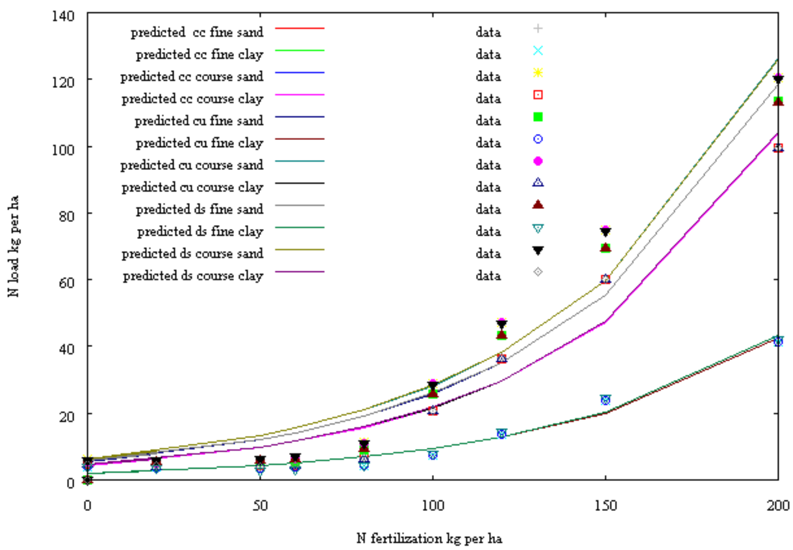


Figure 5: Nitrogen load as a function of fertilization

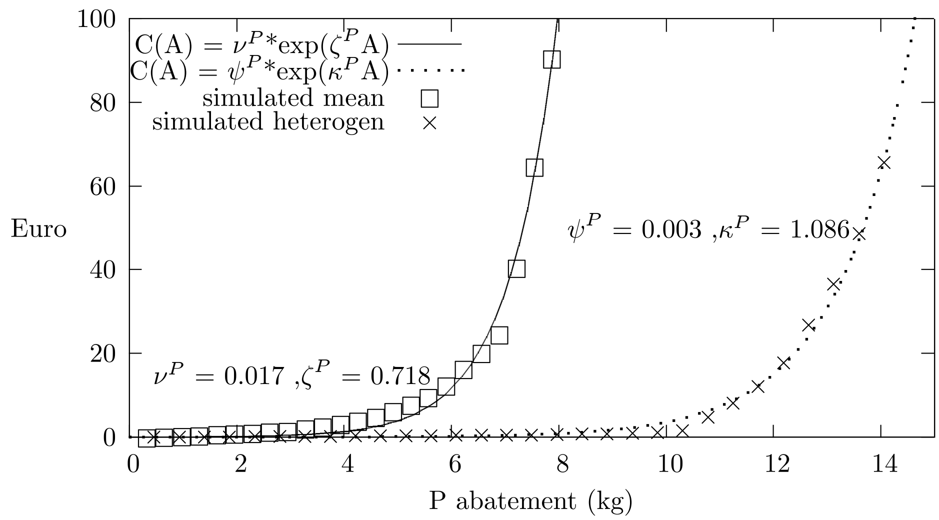
$$\bar{N}^L_{j,k,l,s} = \left[\phi_{j,k,s,l} \exp\left[\gamma_{j,k,s,l} N_{j,k,s,l}\right]\right] + \varepsilon_{j,k,l} \tag{15}$$

The baseline total nitrogen load is larger than the results reported by the environmental administration in Finland. The total phosphorus loads are smaller than the previous estimates. There are several reasons for this discrepancy. Land use and fertilisation levels should be normalised to calibrate the model for further use. However, by assuming that relative loads do not change by the calibration procedure, it is possible to estabslish abatement cost estimates without bias.

4.4 Abatement costs & methods

Given the bioeconomic model formulation, it is possible and interesting to see the economic implications of adopting averages in environmental policy models. The difference between the mean model approach, given distributionally weighted average parameters of soil and slope types, and the heterogeneous formulation, is illustrated with the abatement cost curves. In Figure 6, annual abatement costs are plotted against reduced kilogrammes of phosphorus for a representative farm.

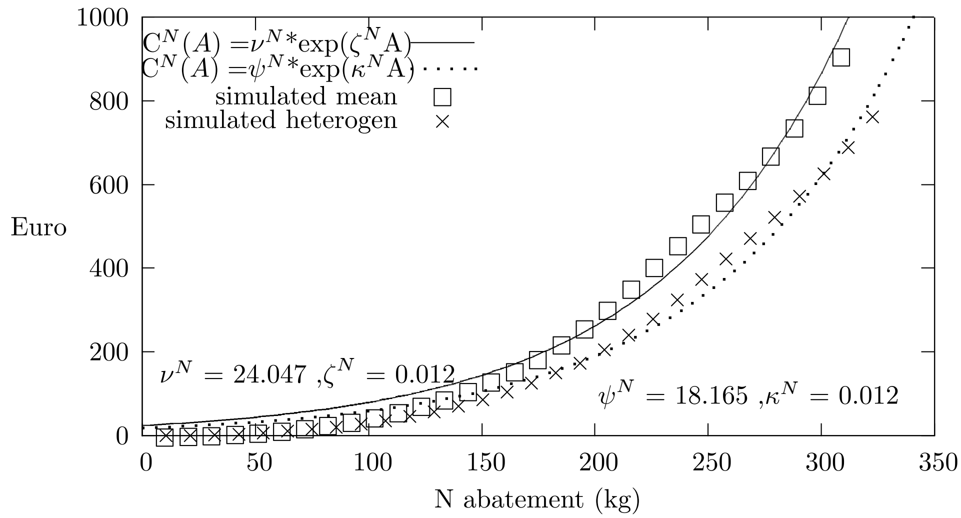
Figure 6: Phosphorus abatement cost



Cross symbols present the simulated results of abatement on heterogeneous land, while box symbols illustrate the simulations of abatement on mean soil. Correspondingly, solid and dashed lines are two-parameter exponential functions of the simulated points estimated with OLS regression method. As shown in the Figure 6, the mean value approach leads to significantly higher phosphorus abatement cost prediction than the heterogeneous specification of the problem.

Calculating the abatement costs from the mean parameters implies that the distribution of load over high and low load potential regions cannot be considered in the abatement set. Given, the heterogenous model specification, the spatial allocation of the abatement measures provides an efficient means of phosphorus abatement. Re-establishing the fallow land on steeper slopes from the flat areas and converting between bare fallow to green fallow on favorable locations are key abatement measures, which cannot be considered in the watershed average models. For nitrogen loads, as shown in the Figure 7, the heterogeneity would not seem to be as important and the mean model would seem to predict the abatement costs rather well.

Figure 7: Nitrogen abatement cost



Ambitious abatement targets cannot be reached cost-effectively only by relocating the farming activities. At higher reduction levels the abatement measures include changes in the tillage towards conservation practises and increasing the share of both productive grass and fallow land from the total farm area. The measures lead to higher percentage decrease in PP load than DRP load. However, according the results there is only limited scope for the PP abatement measures, which are most effective at steeper erosion prone slopes. Further abatement problems arise because at the steeper slopes the conservation tillage methods increase runoff, which lead to increasing the DRP load. As by definition the PP-load is less algae available than DRP, such trade-offs can defeat the purpose of the reduction measure, even though the total phosphorus load would be reduced. All in all it seems that the means to abate phosphorus in short-term e.g. before the national and EU targets set for 2015, are limited.

5 Conclusions

This study showed that reallocation of fallow land can be used to abate nutrient loads. Introducing slope and soil as parameters increased the model robustness, in the sense that the results are not as sensitive to a single mean parameter value. While conversion to fallow decreases the loads of both nitrogen and phosphorus, the efficient spatial distribution of the fallow land depends on which of the nutrients is targeted. As relocating the fallow on the farm land is part of the cost-efficient abatement set even on the relative flat watershed of Kalajoki, the soil and slope distribution should be modeled in further abatement cost and environmental policy studies. Furthermore, the results on the abatement costs showed that estimating the cost functions based on watershed average parameter can lead to considerable overestimation of the costs. Still considering the results, the abatement set for phosphorus is quite limited and would benefit from addition of further measures, even though they might not be part of the cost-efficient set at low reduction requirements. For measures such as wetlands and manure management cost efficiency estimates do already exist. However, the efficiency of these measures also depends on spatially variable economic and environmental circumstances. Considering the spatial distribution effect of such measures would require many changes and warrants a separate study. Future research efforts should also take account the heterogenous soil phosphorus levels within municipalities and yield heterogeneity. The bioeconomic framework presented in this study enables further consideration of implications of spatial variability, especially regarding the soil, with relative ease. Featuring soil characteristics as a part of the parametrization of the yield functions could be used to weed out unlikely farming combinations and to pinpoint regions where abatement targets lead to lesser economic losses.

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