Cost-effective farm-level nitrogen abatement in the presence of environmental and economic risk

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Abstract

This paper evaluates the consequences of considering environmental and economic risk in the analysis of cost-effective nitrogen abatement options in crop production. A farm-level mathematical programming model incorporating nitrogen leaching variability, field time variability, yield variability, and output price variability is developed. The empirical results reveal that requiring a high reliability with respect to a desired abatement target can be extremely costly, due to the high variability of nitrogen emissions. It appears to be sufficient to reduce average nitrogen load in order to reduce the environmental risk associated with nitrogen leaching variability, since a change to crops with lower average load also results in lower variability of nitrogen emissions. A farmer's degree of risk aversion has some effect on the economically optimal choice of crop mix. However, it is more important to consider the utilisation of machinery and labour resources and crop rotation effects, than considering risk aversion.

Keywords: nitrogen abatement, risk aversion, diversification, chance constraints, discrete stochastic programming

Introduction

Reducing nitrogen leaching from agriculture, in order to improve surface water quality, is an important social objective in many European and North American countries. The design of cost-effective abatement measures is complicated by the fact that flows of nitrogen from agricultural land cannot be monitored on a continuous and widespread basis with reasonable accuracy or at a reasonable cost (Shortle & Dunn, 1986). Further, nitrogen emissions are inherently stochastic. Due to the monitoring problem, it is necessary to focus abatement policies on farm management practices, rather than on controlling the amount of nitrogen emitted from individual farms or fields. While public policies so far mainly have focused on controlling average nitrogen runoff, the stochastic nature of nitrogen emissions is gaining increasing attention among researchers. McSweeny & Shortle (1990) point out that pollution control properly defined involves improving the distribution of emissions rather than reducing the mean value. In addition to the environmental risk associated with nitrogen leaching variability, the farm-level economic effects of water quality protection practices are subject to uncertainty. A survey of empirical studies provided by Bosch and Pease (2000) show that changes in production practices, in order to improve water quality, may increase or decrease economic risk, depending on type of practices and site characteristics.

The main purpose of this study is to investigate the consequences of considering environmental and economic risks when analysing nitrogen abatement options in crop

production. Considering these risks may have consequences for abatement costs as well as the socially optimal choice of farming practices. A hypothesis is that diversification of the crop mix may decrease the risk of high levels of nitrogen leaching in individual years (environmental risk), in the same way as diversification may contribute to reduced economic risk. While the latter problem has been extensively studied in the literature (see for example Dillon, 1999), the diversification effect on nitrogen leaching variability has not been given any attention. An analysis of the impacts of environmental and economic risks requires development of an economic model of the production system. In order to examine the consequences of considering environmental and economic risks, an empirical mathematical programming model incorporating the relevant farm-level management decisions is developed. The model incorporates four sources of risk: environmental risk (nitrogen leaching variability), crop yield risk, output price risk, and field time risk (weather variability affects time available for performing field operations). Economic risk is modelled using the direct expected utility maximising (DEMP) (Lambert and McCarl, 1985) framework. Environmental risk is modelled by imposing a probabilistic constraint on farm level nitrogen load to surface water, using the multiple realisation chance constrained programming (MRCCP) (Morgan, 1990; Morgan et al., 1993; Wagner and Gorelick, 1989) technique. The model features endogenous selection of cropping activities and scheduling of tillage and drilling operations, utilising the model framework developed by Ekman (2000). Discrete stochastic programming (DSP) (Cocks, 1968; Rae 1971) is employed to model the sequential nature of farm-level management decisions. Harvesting operations are not modelled in this study; contractor harvest is assumed. Contributions of this study, in comparison with previous studies of cost-effective control of stochastic pollution in agriculture, include:

- a richer representation of the production system, including scheduling of field operations given limited machinery capacity and field time risk;
- simultaneous modelling of yield risk, output price risk, field time risk and environmental risk;
- an analysis of whether a cost-effective reduction of environmental risk can be obtained by choosing a more diversified crop mix;
- an analysis of how a reduction of average nitrogen leaching affects environmental risk, compared with a reliability constrained abatement target.

Problem

In focus of this study is the problem of choosing farm-level land use to obtain a cost-effective reduction of environmental risk caused by stochastic nitrogen leaching. Land use includes choice of crop rotation, use of a catch crop that covers the soil after the main crop is harvested, tillage practices, and the possibility to idle land. Choosing the economically optimal land use is a matter of on-farm diversification. A number of reasons for diversifying land use are reported in the literature (e.g. Bosch and Pease, 2000; Dillon 1999; Hardaker et al., 1997):

- economic risk can be reduced by selecting a mixture of activities that have net returns with low or negative correlation;
- economic risk is reduced when an added enterprise has lower variance than the enterprise being partially replaced;
- labour and machinery requirements for a diversified crop mix will be more evenly spread throughout the year, using these resources more efficiently;

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- cultivation of different crops in sequence may improve soil structure and enhance crop insect and disease resistance, which affects crop yields positively (crop rotation effects).

Reducing environmental risk may be another reason for diversification, when an added activity has lower leaching variability than the activity that is being partially replaced. Selecting a mixture of activities with low or negative leaching correlation can also reduce environmental risk. The answer to the question of how many crops, which crops and how much of each crop to cultivate is an empirical matter, determined by the interactions among the above forces. If a certain crop is extremely profitable and the gains from diversification are low, then it may be economically rational to grow only this crop and eventually idle some land to reduce environmental risk. On the other hand, it may be rational to choose a highly diversified crop mix if that contributes to low machinery and labour costs, high crop yields, low economic risk, and low environmental risk.

Previous research

In the literature there exist some empirical studies of cost-effective nitrogen abatement considering the stochastic nature of nitrogen emissions. Most empirical studies report that considering variability implies substantially higher abatement costs than when a restriction on average loading alone is considered. McSweeny and Shortle (1990) show that in general when pollution loadings are normally distributed, an increase in the desired probability of achieving a stated pollution reduction will result in a tighter restriction on a farm's activities and increased costs of water quality protection. Two methods are used for incorporating stochastic constraints on nitrogen loads into mathematical programming models. Byström et al. (2000), Elofsson (2000), Halstead et al. (1991) and McSweeny and Shortle (1990) use chance constrained programming (CCP) (Charnes and Cooper, 1956). Mapp (1999), Teague et al. (1995) and Qiu et al. (1998) use the environmental target MOTAD (ETM) technique, introduced by Teague et al. Using the CCP technique requires specification of a continuous probability distribution, while the ETM technique is based on discrete outcomes. The CCP constraint specifies the probability by which a certain abatement target must be fulfilled, while the constraints in the ETM formulation limits the total amount (the sum over all outcomes) by which the target may be violated.

Only one of the studies mentioned above considers economic, objective function risk; Qiu et al. (1998) incorporate yield risk using a Safety First approach. However, there exist several other studies that consider economic risk in the analysis of water quality protection measures in agriculture (but without considering environmental risk). Bosch and Pease (2000) provide an overview of such studies. A mathematical programming technique for considering economic risk (objective function risk) whose use is increasing is direct expected utility maximisation (DEMP) (Lambert and McCarl, 1985). With this technique, expected utility of wealth or income is maximised. One of the most widely used techniques to model economic risk is the expected value-variance (E-V) model (Freund, 1956; Markowitz, 1959). It can be viewed an approximation to expected utility maximisation, where only the first two moments of the distribution of outcomes are taken into account. Another technique that, at least historically, has been popular is the MOTAD (Hazel, 1971) formulation, which is a linear approximation to the E-V model. Further, there exist various safety-first formulations. These models seem to suffer from lack of theoretical underpinning and somewhat arbitrarily set critical values.

Variations in weather not only impact crop yields but also influence the time available for fieldwork (field time). As a consequence, the time when crops are drilled will vary between years. Delayed drilling in years with unfavourable weather conditions results in reduced crop yields in these years. Ignoring this randomness will typically overstate profits, not only in years with unfavourable weather conditions, but on average as well (Eytang et al., 1998). In addition, considering the randomness of resource levels for machinery capacity and labour has implications for the economically optimal choice of machinery system an crop rotation, as noted by Ekman (2000) and Eytang et al. (1998). Two techniques for considering stochastic machinery capacity and labour constraints are found in the literature. Chance constrained programming (CCP) is simplest to use. Given an assumption about the probability distribution for field time availability and a reliability level, the probabilistic constraint is converted into a deterministic equivalent. The problem with the CCP formulation is how to select the reliability level for the chance constraint; a problem discussed by Eytang et al. (1998). The alternative to CCP is to solve the true stochastic scheduling problem using discrete stochastic programming (DSP) (Cocks, 1968; Rae 1971). Using DSP it is possible to consider that drilling be delayed in years with unfavourable weather, which results in lower crop yields in these years. Studies where DSP is used are Ekman (2000) and Kaiser and Apland (1989).

Modelling framework

The complexity and empirical nature of the decision problem make mathematical programming a suitable tool for analysis. Given the reasons for diversifying land use identified above, it seems appropriate to model both crop mix selection and scheduling of field operations. Consequently, the areas of different cropping activities as well as various machinery operations are considered endogenous variables in the model developed. The method chosen to model economic, objective function, risk is DEMP. This technique has a solid foundation in expected utility theory and imposes fewer restrictions on the distribution of outcomes or the form of the utility function than E-V or MOTAD models. Multiple realisation chance constrained programming (MRCCP) (Morgan, 1990; Morgan et al., 1993; Wagner and Gorelick, 1989) is the method selected to model environmental risk in this study. MRCCP is the CCP technique adapted to a model with discrete outcomes instead of a continuous probability distribution. With MRCCP it is not necessary to make any assumptions about the joint probability distribution of nitrogen leaching from different cropping activities, since observed (or simulated) leaching data can be inserted directly into the model as discrete outcomes. Another reason for choosing a CCP-type of approach is that a percentage reliability level is easily communicated and understood.

The technique chosen to model field time variability is DSP. Using this technique it is not necessary to make any distributional assumptions, since historical field time data can be used directly in the model. Considering field time variability results in a sequential decision problem. A two-stage DSP model is developed. Machinery investments and choice of crop rotation are decisions made in stage one, when the farm manager only has probabilistic knowledge of weather (field time) outcomes in individual years (Figure 1). Field operations in stage two need to be adjusted to actual weather conditions; i.e. field operations can only be performed in days with suitable weather and soil conditions. The farm manager has only probabilistic knowledge about crop yields and nitrogen leaching as stage one and stage two decisions are made (Figure 1). Machinery investments are not considered explicitly in the model, instead different machinery systems can be simulated to determine economically

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optimal machinery capacity. Considering farm-level machinery capacity is relevant because it may affect the gains from diversifying the crop mix. Farmers can make small adjustments to the crop rotation in years with extreme weather conditions, but that option is not considered in this study in order to simplify the analysis. Only the time when different field operations are performed varies between years in the model.
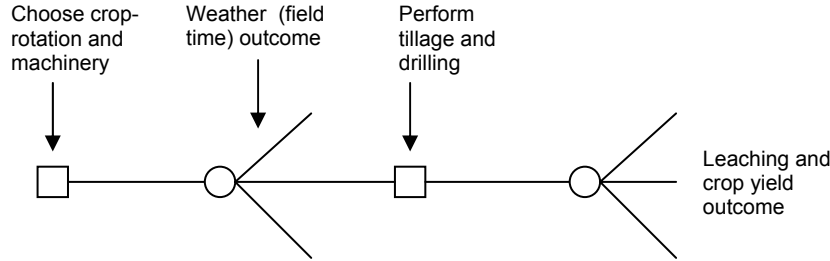

Figure 1. Decision tree; □, decision node; ○, event node.

Given the choice of modelling techniques and endogenous decision variables, a conceptual model can be formulated as:

$$\max_{x,y} \quad E[U(x,y)] \tag{1}$$

subject to

$$Pr[a_v x \leq b \quad \forall v] \geq \alpha \tag{2}$$

$$Ax \leq c \tag{3}$$

$$B_w x + C_w y_w \leq d_w \quad \forall w \tag{4}$$

where:
$E[U(\cdot)]$ is expected utility;
x is a vector of first stage decision variables (crops);
y is a vector of second stage decision variables (machinery operations);
$Pr[\cdot]$ is probability;
a_v is a set of vectors (one for each v) of leaching coefficients;
v is state of nature with respect to nitrogen leaching;
b is an upper limit on the farm level nitrogen load to watercourses;
$\forall$ means "for all elements in the set";
α is the required reliability level for b;
A is a matrix of technical coefficients in the first decision stage;
c is a vector of right hand side coefficients in stage one;
B_w is a set of matrices (one for each w) linking first and second stage activities;
w is state of nature with respect to field time;
C_w is a set of matrices (one for each w) of technical coefficients in the second decision stage;
d_w is a set of vectors (one for each w) of right hand side coefficients in stage two.

The objective function (equation 1) may include stochastic coefficients related to both first and second stage decision variables. Equation 2 is a generalised chance constrained programming problem. Equations 3 and 4 represent a general two stage DPS formulation where stage one decisions are made prior to the uncertainty regarding weather outcome is resolved and stage two decisions can be adjusted to actual weather outcome. In (1) a utility function needs to be defined, in order to account for the decision-maker's degree of risk aversion. Theoretical analyses of decision making under risk and empirical studies focusing on portfolio selection generally consider utility and risk aversion in terms of wealth. In this study utility of uncertain income is considered, as in many other applied studies in agricultural economics (e.g. Lien and Hardaker, 2001; Weersink et al. 1998). The motivation for considering utility of income, rather than utility of wealth, is that the decision-maker (the farmer) already has chosen invested a substantial part of his/her wealth in the farm business.

In the literature it is argued that the utility function should exhibit positive but decreasing absolute risk aversion (DARA) (Arrow, 1971; Pratt, 1964). However, empirical work shows no universal consensus (Saha, 1994). A utility function with intuitively plausible properties, such as DARA, is the constant relative risk aversion (CRRA) power utility function:

$$U(Z) = (1/(1-\rho)) Z^{(1-\rho)} \qquad (5)$$

where Z is income and ρ is the coefficient of relative risk aversion. For ρ approaching 1, equation 5 reduces to the logarithmic function. The CRRA property implies that if we multiply all payoffs by a positive constant, the choice between different risky prospects will be unchanged. Empirical findings on the nature of relative risk aversion have been mixed, ranging from decreasing to increasing relative risk aversion (Saha et al., 1994). However, the literature suggests that CRRA is a plausible property (e.g. Arrow 1971; Copeland and Weston, 1988). The method that will be used in this study to consider various levels of risk aversion is utility efficient programming (UEP) (Patten et al., 1988), which simply means that the model will be solved at different levels of risk aversion.

Equation 2 can not be incorporated directly into a mathematical programming model. Instead, a heuristic algorithm developed by Morgan et al. (1993) is used to solve the MRCCP problem. The solution procedure can be summarised as follows:
1. Begin with the highest reliability level (100%). The model to be solved contains the constraints associated with all the nitrogen leaching realisations or outcomes. There is one leaching constraint for each nitrogen leaching realisation, and all these constraints must hold. Solve the model.
2. Identify all realisations for which the nitrogen leaching constraint is binding. All leaching realisations that have a binding constraint are candidates for the most critical realisation at the next solution stage.
3. These candidates are alternatively dropped from the optimisation model by removing the leaching constraint associated with the particular candidate realisation. Now, there is one optimisation model for each realisation that is removed.
4. Solve the models created. The realisation whose elimination produces the highest objective function value is taken as the most critical realisation, and the solution to the corresponding model represents the optimal solution at this level of reliability.
5. Return to step 2 with the optimal solution, unless there are no more binding constraints.

The algorithm systematically follows all paths through decision space, from full reliability to no reliability, and selects the global optimum at each level (Morgan et al.,

1993). The reliability level at each stage is calculated as $\alpha = 1 - S/V$, where α is the nominal reliability, S is the number of realisations removed from the original model, and V is the total number of realisations in the original model (with 100% reliability). For details of the heuristic algorithm, the reader is referred to Morgan (1990) and Morgan et al. (1993).

Data

The model developed is applied to a 250-hectare hypothetical farm in Southern Sweden. The farm size is chosen in order to allow for some flexibility regarding choice of machinery capacity. Crop yield and nitrogen leaching data are obtained from a field trial on clay till soil (Hessel et al., 1998), which is a common soil type in the southernmost part of Sweden. Data are available for a period of 8 years, where each crop has been cultivated during all years. The field trial consists of two crop rotations. Leaching data are presented in Table 1; these data are used directly into the model assuming that each of the years represents equally likely states of nature (outcomes) with respect to nitrogen leaching. Hereby, the correlation between the different crops is automatically considered. In the analysis it is assumed that there are no second year effects of a crop on nitrogen leaching; leaching depends only on the crop grown and tillage operations after the crop. This allows for some additional flexibility in the choice of crop rotation when the data are used in the model. Permanent fallow is also considered in the analysis, in order to account for the possibility to idle land. Average leaching after fallow amounts to 5 kg nitrogen per hectare and year (Johnsson and Hoffman, 1997). It is assumed that leaching after permanent fallow follows the same variability pattern and has the same coefficient of variation as barley with catch crop (crop H in Table 1). In the analysis it is considered that tillage practices in the field trial differ depending on crops grown. Stubble cultivation is performed in the early autumn after all crops except sugarbeet and crops with an undersown catch crop. Mouldboard ploughing is performed in the early autumn if a crop is to be followed by a winter crop, otherwise in the late autumn.

Table 1. Nitrogen leaching after each crop in the field trial, kg per hectare

Year	Rotation 1						Rotation 2			
	Winter rape	Winter wheat	Triti-cale	Sugar-beet	Spring barley	Oats	Winter wheat	Barley + CC[a]	Sugar-beet[b]	Barley + CC[a]
	A	B	C	D	E	F	G	H	I	J
1993/94	72	51	38	37	72	38	35	18	24	31
1994/95	37	52	50	42	50	34	56	25	34	23
1995/96	13	6	11	9	8	6	8	8	7	8
1996/97	13	11	13	9	19	9	13	7	6	6
1997/98	39	19	30	27	28	14	25	16	20	16
1998/99	35	17	16	15	16	16	17	14	15	18
1999/00	25	15	26	20	13	11	19	11	18	13
2000/01	18	13	13	14	3	11	8	9.5	10.5	6.5
Mean	31.5	23.0	24.6	21.6	26.1	17.4	22.6	13.6	16.8	15.2
CV[c]	0.62	0.78	0.57	0.58	0.90	0.69	0.72	0.44	0.56	0.58

[a] CC = catch crop.
[b] Tops removed from the field.
[c] CV = coefficient of variation.

While Table 1 shows that leaching varies considerably between years, Table 2 indicates that nitrogen leaching from different crops is highly positively correlated. In most cases the correlation coefficient is between 0.8 and 1. Correlation coefficients for gross revenue from the crops considered are also calculated, based the discrete outcomes with respect to gross revenue used in the model. In general, gross revenues from the crops considered are less correlated than nitrogen leaching. Gross revenues for each crop in each state of nature are obtained by multiplying crop yields in the field trial each year by crop price each year. The crop prices (Swedish Board of Agriculture, 2001) are adjusted for trend by regressing observed prices against time. The residual from each year, for each crop, is then added to the predicted crop price in 2001, to construct a detrended series. The effect of preceding crop on crop yield is incorporated in the model, but no third year effects are considered.

Table 2. Correlation coefficients for nitrogen leaching after each crop, as implied by the raw data used in the model

Crop	Crop									
	Winter rape A	Winter wheat B	Triti-cale C	Sugar-beet D	Spring barley E	Oats F	Winter wheat G	Barley + CC H	Sugar-beet I	Barley + CC J
A	1.00									
B	0.80	1.00								
C	0.68	0.91	1.00							
D	0.78	0.94	0.98	1.00						
E	0.89	0.93	0.82	0.86	1.00					
F	0.86	0.99	0.86	0.91	0.94	1.00				
G	0.61	0.92	0.97	0.94	0.80	0.87	1.00			
H	0.68	0.89	0.94	0.94	0.76	0.86	0.96	1.00		
I	0.68	0.89	0.97	0.97	0.75	0.84	0.96	0.97	1.00	
J	0.95	0.89	0.80	0.86	0.91	0.93	0.78	0.82	0.81	1.00

Table 3. Correlation coefficients for gross revenue from each crop, as implied by the gross revenue data used in the model

Crop	Crop									
	Winter rape A	Winter wheat B	Triti-cale C	Sugar-beet D	Spring barley E	Oats F	Winter wheat G	Barley + CC H	Sugar-beet I	Barley + CC J
A	1.00									
B	-0.81	1.00								
C	-0.69	0.49	1.00							
D	0.29	0.03	-0.08	1.00						
E	-0.94	0.92	0.54	-0.27	1.00					
F	-0.62	0.80	0.34	-0.13	0.82	1.00				
G	-0.85	0.94	0.66	-0.04	0.86	0.63	1.00			
H	-0.91	0.71	0.61	-0.51	0.90	0.75	0.70	1.00		
I	0.19	0.17	0.22	0.76	-0.11	0.25	0.10	-0.19	1.00	
J	-0.88	0.71	0.64	-0.45	0.87	0.76	0.71	0.99	-0.08	1.00

One may ask to what extent the variability data from the $962m^2$ plots in the field trial represent farm level variability for each crop. A comparison of yield variability in the field trial with farm level yield variability on Danish farms in a region with relatively similar soils (Rasmussen, 1997) reveal that the field plot data may be a reasonably good approximation of farm level variability in different crops. Coefficients of variation (CV) reported by Rasmussen are between 0.17 and 0.21, for the crops in this study, while CV

for yield based on the field trial data are in the range between 0.10 and 0.29. Comparing nitrogen leaching in the field trial with a 36 hectare observation field within the same region (Johansson et al., 1999) reveals that nitrogen leaching variability (measured as CV) in the field trial is somewhat higher than in the observation field. Based on 24 years of measurement, CV of nitrogen leaching in the observation field is 0.51, which can be compared with the data in Table 1.

Machinery and labour is considered in the analysis by scheduling field operations over 10-day periods. A yield coefficient, for each crop, with respect to sowing period is specified in the model, in order to account for the effect of drilling date on crop yields. Further, four different sets of machinery are tested using the model, in order to find the economically optimal machinery capacity. It is assumed that the labour force consists of one person who can work 8 hours per day with field operations, if weather is suitable for performing field operations. Field time variability is modelled by defining 8 states of nature with respect to field time. Field time in each period in each state of nature is calculated using precipitation data for the same sequence of years considered in the field trial.

The policy environment as of 2001 is considered in the analysis. Policies affecting the studied crop farm include EU direct income payments to cereal grain crops, oilseed crops and set-aside, as well as a Swedish subsidy to catch crops (SEK 900/ha). It is assumed that the farm's sugar quota allows for sugarbeet on at most 20 per cent of the farm area. Set-aside payments cannot be obtained for a larger area than the area of cereal grain and oilseed crops together, but it is possible to idle more land without receiving the set-aside payment for all the land idled. In this study it is assumed that idle land consists of permanent fallow. Eventual mandatory set-aside is not taken into account, since the mandatory set-aside requirement has varied from one year to another.

Results

Farm-level nitrogen leaching is maximised to 15 kg per hectare and year in the analysis. Three risk aversion levels are analysed; risk neutral and risk averse with a coefficient of relative risk aversion of 1 and 4. Higher risk aversion levels were also tested, but the resulting crop rotations did not seem to be consistent with observed farmer behaviour (large areas of set-aside). Figure 1 shows that requiring 100 per cent reliability with respect to the 15-kg leaching target is extremely costly. On the other hand, requiring 75 per cent reliability results in relatively low abatement costs. No abatement measures are necessary if the required reliability level for the 15-kg target is less than 50 per cent. The 50 per cent reliability level corresponds to an abatement target focusing on average nitrogen load, if nitrogen emissions are normally distributed. The farmer's level of risk aversion has very little effect on the abatement cost; it is marginally lower with high risk aversion than with low. (A more risk-averse decision-maker selects a more conservative production plan, so the profitability level is lower to start with.)

Figure 3 depicts maximal and average annual nitrogen load to watercourses. Maximal load is the worst outcome over the eight leaching states of nature included in the model. Figure 3 shows that the maximal load is about twice the average load, which explains the high costs of requiring high reliability. Results are only displayed for two risk aversion levels in Figure 3 and in the following figures. The reason is that model results are almost identical for the risk neutral case and the case with a coefficient of relative risk aversion equal to one. The case when the coefficient of relative risk aversion equals four is labelled "very risk averse". It can be seen in Figure 3 that the

difference in average and maximal load between the risk neutral case and the very risk averse case is small.
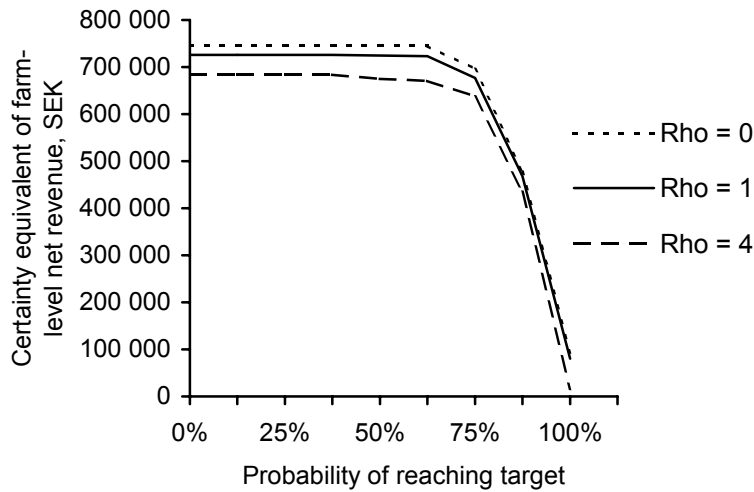

Figure 2. Certainty equivalent of farm-level net revenue depending on required reliability level with respect to the 15-kg N per hectare leaching target. Rho is the coefficient if relative risk aversion.
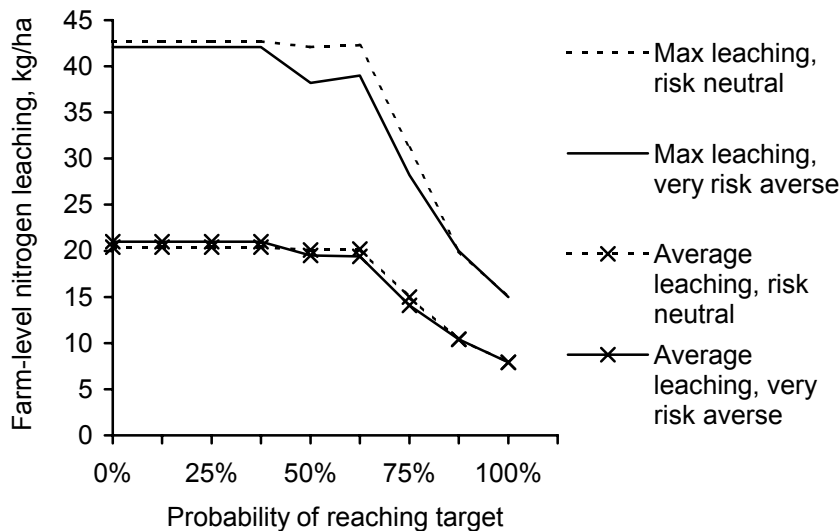

Figure 3. Maximal and average annual nitrogen leaching per hectare, depending on risk aversion level and required reliability level with respect to the 15-kg N per hectare leaching target.

While the level of risk aversion has almost negligible effects on abatement costs and nitrogen loads, there are some differences in optimal crop mix. As expected, the crop mix is more diversified if the farmer is very risk averse than if the farmer is risk neutral (Figure 4 and 5). A hypothesis set out in the beginning of this article was that considering environmental risk would lead to a more diversified crop mix. However, Figure 4 and 5 show that this is not the case. Imposing a probabilistic restriction on nitrogen leaching appears to result in a focus on few crops and idling of land, rather than a more diversified crop mix. This result can be explained by the high positive

correlation of nitrogen leaching from different crops. A crop with low average nitrogen leaching is also favourable from an environmental risk perspective. It can be concluded that crop rotation effects and the utilisation of machinery and labour resources are more important in determining the economically optimal crop mix than economic or environmental risk.
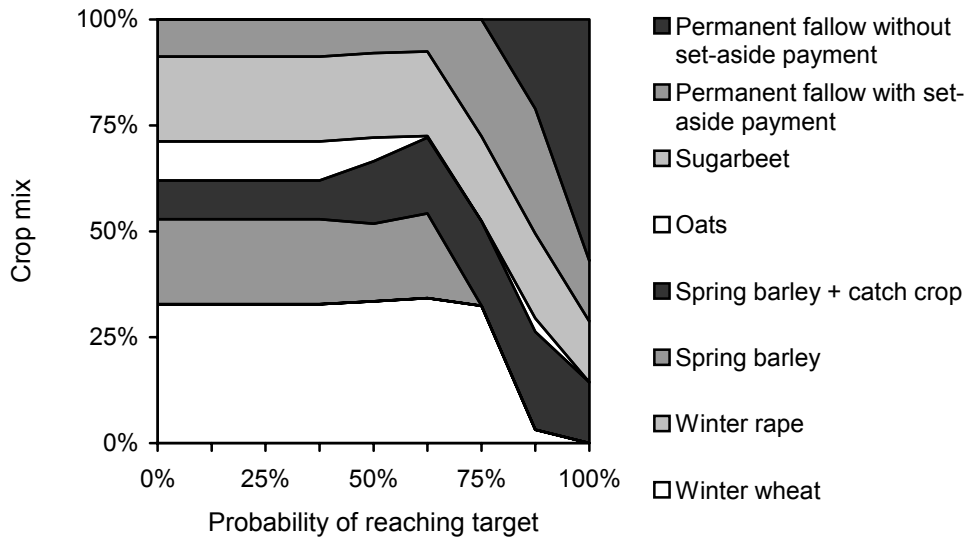

Figure 4. Optimal crop mix for farmers who are risk neutral, depending on required reliability level with respect to the 15-kg N per hectare leaching target.
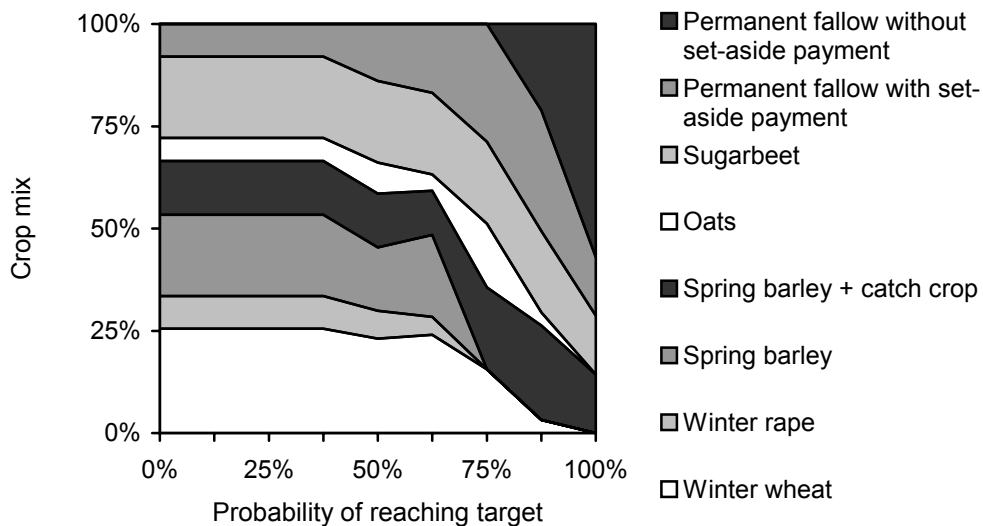
Figure 5. Optimal crop mix for farmers who are very risk averse, depending on required reliability level with respect to the 15-kg N per hectare leaching target.

Since many studies of cost-effective nitrogen abatement measures are focusing on average nitrogen load, it is motivated to investigate how effective an average load target is in reducing environmental risk. In fact, given a certain average load, maximal annual load is not lower when a chance constraint is imposed on annual farm level nitrogen load, than when average nitrogen load is constrained (Figure 6). The economically

optimal land use is almost exactly the same with the chance-constrained model and the restricted average leaching model. The conclusion is that it is sufficient to focus on average load when designing abatement policies to reduce environmental risk associated with nitrogen leaching variability. Results regarding the average load target are obtained by constructing a model where average nitrogen load is constrained, while the data for the chance constrained case are results from the analysis above where the reliability level for the 15-kg abatement target is varied.
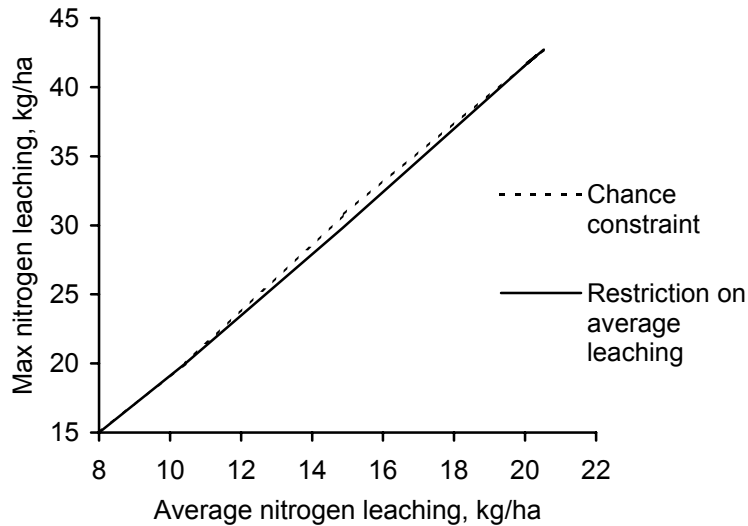

Figure 6. Average and maximal annual nitrogen leaching with chance constrained nitrogen leaching, and maximal nitrogen leaching with a restriction on average leaching.
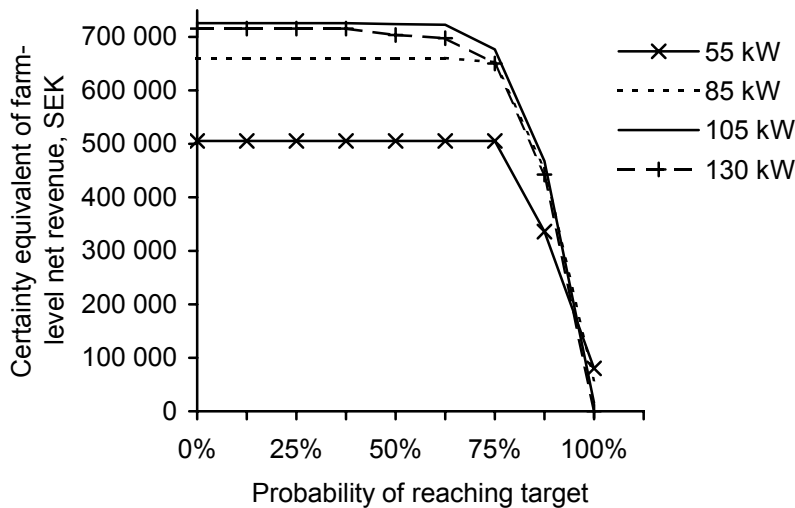

Figure 7. Certainty equivalent of farm-level net revenue, depending on machinery system and required reliability level for the 15-kg N per hectare leaching target.

Economically optimal machinery capacity at each reliability level and risk aversion level considered in the analysis is obtained by running the model with four different sets of machinery. A machinery system based on one 105 kW tractor is the economically rational choice in all cases except when 100 per cent reliability with respect to the 15-kg leaching target is required. A 55 kW tractor is chosen in the latter case. Evidently, the

choice of machinery capacity is quite as insensitive to the required level of nitrogen abatement and the level of risk aversion. Figure 7 depicts certainty equivalent of farm-level net revenue for the machinery systems considered in this study, given that the coefficient of relative risk aversion equals one. It can be seen that the error in estimated abatement costs is relatively low as long as machinery capacity is close to the optimal, but abatement costs are underestimated if the machinery system considered in the analysis is far from the economically optimal.

Conclusions

This study aims at investigating the consequences of considering environmental and economic risk in the analysis of cost-effective nitrogen abatement in crop production. It is noted that economic as well as environmental risk may affect the economically optimal degree of diversification of land use on an individual farm. A mathematical programming model is developed to select cropping activities and scheduling of field operations on a crop farm. The model considers environmental risk in the form of variations in the annual farm-level nitrogen load to surface water. Economic risks considered are field time risk, yield risk and output price risk.

Empirical analyses are performed for a hypothetical crop farm in Southern Sweden. The results show that requiring a high reliability level with respect to a desired abatement target can be extremely costly, in comparison with a low required reliability level. This result is due to a high degree of variability of nitrogen emissions. While the required reliability level greatly affects abatement costs and the associated choice of production practices at the farm level, it seems sufficient to reduce average nitrogen load in order to reduce environmental risk. If average load is reduced, peak loads are reduced as well. The reason is that nitrogen leaching from different crops is highly correlated. High correlation implies that the distribution of farm-level nitrogen emissions hardly can be affected by a diversification of land use. Instead it is necessary to focus on crops with low average nitrogen emissions in order to reduce environmental risk, as illustrated by the empirical results. The implication of the above results is that cost-effective adjustment of production practices to a certain abatement target can be found without considering environmental risk explicitly in the analysis. Instead, the analysis can be based on the average effect on nitrogen leaching of the various production practices available to farmers. The abatement target can be determined by considering the close relationship between average annual load and maximal annual load.

A farmer's degree of risk aversion influences the economically optimal choice of crop mix, as expected. However, the diversification effect of risk aversion is moderate, according to the empirical results. Crop rotation effects and the utilisation of machinery and labour resources are more important factors in determining the economically optimal land use pattern. As a result, abatement costs are almost similar when the farmer is risk neutral and when the farmer is very risk averse Related to the utilisation of machinery and labour resources is the choice of machinery system at the farm level. The results indicate that the economically optimal choice of machinery capacity is relatively insensitive to changes in land use. However, abatement costs will be underestimated if the machinery system considered in the analysis is far from the optimal. It can be concluded that it is more important to consider scheduling of field operations, field time variability and crop rotation effects than considering risk aversion when analysing nitrogen abatement options in crop production.

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