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The effect of decreasing fertilization on agricultural nitrogen leaching: a model study

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In Finland, the use of agricultural nitrogen (N) fertilizers has decreased since the beginning of the 1990's but there is not yet any clear response in observed water quality in the monitored agricultural catchments and river basins. It is therefore important to analyse how the reduction in N fertilization affects N leaching at the root zone scale. In this study the nutrient leaching model ICECREAM was used to demonstrate the effects of climatic conditions and decreased N input on N leaching. Ten years (1991–2000) of climatic input data from five stations located in different parts of the country were used as input to simulate nitrate N (NO_3-N) leaching from barley cultivation with i) constant N fertilization (*Baseline* simulation, 90 kg N ha^{-1}) and ii) decreasing N fertilization (*N Reduction Scenario* simulation: annual linear decrease from 110 to 90 kg N ha^{-1}). The annual and regional variation of simulated N leaching was considerable in both the *Baseline* and *N Reduction Scenario* simulations. In the *Baseline* simulation the average annual NO_3-N leaching was 24% of the N fertilization amount. From 1991 to 2000, the annual N leaching decreased close to *Baseline* leaching values in the *N Reduction Scenario* simulations, but the decrease was not linear due to high variability in N losses caused by changes in annual weather conditions. The model results indicate that it is possible to achieve a reduction in root zone N leaching by adjusting the fertilizer levels.

Key-words: agriculture, nitrogen, fertilizer, model, leaching, climate

Introduction

Agricultural nitrogen (N) loading is still among the major environmental problems in many countries with intensive agricultural production (e.g. U.S. Environment Protection Agency 2000, European Environment Agency 2005). Nitrogen is readily lost to surface and groundwaters from the agricul-

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tural system and it is therefore important to avoid excessive N fertilization. Nitrogen surpluses are common in intensive agricultural production: within the EU-15 (year 1997), regions with high mineral N fertilizer application rates were located in the Netherlands, Belgium, Germany and France. Application of livestock manure, the second major source of N, was highest in the Netherlands and Belgium. As a result, N surpluses, defined as the difference between the annual total amount of N entering the agricultural soil and the amount leaving the soil, were high in these areas (e.g. 256 kg N ha^{-1} in the Netherlands) (Hansen 2000). Mitigation of harmful consequences of agriculture, such as eutrophication of surface waters and deterioration of groundwater quality, is a key issue in environmental policy within the EU and elsewhere (U.S. Environment Protection Agency 2000, European Environment Agency 2005).

In the Nordic-Baltic region the long-term trends in agricultural N loading have been analysed by using monitoring data of water quality in streams, lakes and coastal waters (e.g. Vuorenmaa et al. 2002, Räike et al. 2003, Stålnacke et al. 2003, Kronvang et al. 2005, Kyllmar et al. 2006, Ulen and Fölster 2006). In Sweden, nutrient discharge data from 27 small agricultural catchments revealed significant downward trends of monthly nitrate N load in seven catchments and an increasing trend in one catchment (Kyllmar et al. 2006). Decreasing trends of reactive inorganic N concentrations were also found in five out of twelve large agriculturally loaded rivers studied in Sweden (Ulen and Fölster 2006). In Denmark, trend analysis of total N concentrations in streams draining dominantly agricultural catchments showed a significant downward trend in 48 streams during 1989–2002. Over the same period, considerable changes in agricultural practice resulted in a 41% reduction (from 136 to 88 kg N ha^{-1}) in the annual N surplus applied to agricultural land (Kronvang et al. 2005).

In Finland, the implementation of the Agri-Environmental Program (AEP) in 1995 (when joining the EU) contributed widely to the adoption of environmentally sound management practices (Ministry of Agriculture and Forestry 2004). For example, the use of N fertilizers decreased from an average of 101 kg N ha^{-1} in 1990–1995 to 86 kg N ha^{-1} in 1996-2000, and accordingly the N soil surface balances decreased from 75 to 59 kg N ha^{-1} (Salo et al. 2007). Even so, the long-term data of N export from small agricultural catchments and agricultural river basins show very little or no decrease (Vuorenmaa et al. 2002, Granlund et al. 2005, Ekholm et al. 2007). The question arises whether the existing agricultural measures included in the AEP have been ineffective. On the other hand, from the 1970s onwards there has been a rapid increase in temperature especially during wintertime (Tuomenvirta 2004). Such mild winter conditions may have enhanced nutrient leaching, thus possibly masking the positive effects of adopted measures (Puustinen et al. 2006).

In addition to monitoring of actual water quality in agriculturally loaded streams, rivers and lakes, mathematical modelling of N leaching is commonly used as a method to estimate potential effects of management practices. In this study, the field scale nutrient leaching model ICECREAM (Tattari et al. 2001, Yli-Halla et al. 2005) was used to estimate potential effects of the observed decrease in N fertilization levels on root zone N leaching in barley cultivation. Ten years of climatic input data from five stations located in different parts of the country and representing different Rural Centres (a basic administrative unit for reporting e.g. annual agricultural statistics) were used as input to simulate NO_3-N leaching with i) constant N fertilization (*Baseline* simulation, 90 kg N ha^{-1}) and ii) linearly decreasing N fertilization (*N reduction Scenario* simulation: annual decrease from 110 to 90 kg N ha^{-1}). Targeted fertilizing is one of the key measures in the AEP (90 kg N ha^{-1} for fodder cereals). The aim of this study was (i) to analyse the effectiveness of this measure and (ii) to demonstrate the effect of climatic variability on N leaching.

Material and methods

Description of the ICECREAM model

ICECREAM (Tattari et al. 2001, Yli-Halla et al. 2005) is a simulation model predicting transport of water, eroded soil, phosphorus (P) and N at the edge of a field parcel and out of the root zone. It is an extension of the CREAMS/GLEAMS models (Knisel 1980, Knisel et al. 1995) originally developed in the U.S. to assess and compare the impact of different management practices on soil and nutrient losses. The hydrology, crop growth, and partly also the erosion calculations have been further developed, to better account for Finnish conditions (Rekolainen and Posch 1993, Tattari et al. 2001, Yli-Halla et al. 2005). In this study, the most recent model version was used (version 1106, November 2006).

The hydrology component of ICECREAM simulates daily runoff using a modification of the SCS Curve Number method (USDA-SCS 1972), which relates to soil texture and structure, land use and management practice. The matrix flow in soil is described by a simple 'tipping bucket' system using the user-defined hydraulic conductivity and pF-curve values for porosity, field capacity and wilting point. Evapotranspiration is calculated according to the Penman-Monteith method (Monteith and Unsworth 1990). Erosion is computed using the modified Universal Soil Loss Equation, MUSLE (Foster et al. 1977).

The submodels for P and N transformation and transport are mainly based on the GLEAMS model with several modifications, especially for P (Yli-Halla et al. 2005), in order to achieve a better fit to local conditions. The N submodel includes the key pools and flows of the N cycle in soil (Fig. 1). Nitrate (NO_3^-) and ammonium (NH_4^+) constitute the plant-available inorganic N. Plant uptake of N (total uptake of the crop) is calculated on the basis of biomass demand and supply. Nutrient status of soil can limit N uptake, but in practice, the typical fertilizer amounts used do not affect actual N uptake. The N pools are connected by processes such as mineralisation and immobilisation. Nitrogen can be transported from the soil either in dissolved form or as attached to soil particles (Fig. 1). Gaseous losses include volatilization of ammonia and denitrification. Most of the nutrient reactions are controlled by the moisture content and temperature of soil layers. Inorganic and organic fertilizers as well as atmospheric deposition constitute the input of nutrients to the model. In this model application the N fertilizer was assumed to be injected at a depth of 8 cm as dissolved ions (30% NO_3-N and 70% NH_4-N).

Input data and parametrisation of the ICECREAM model

The ICECREAM model uses measured daily data on air temperature, precipitation and cloudiness (or

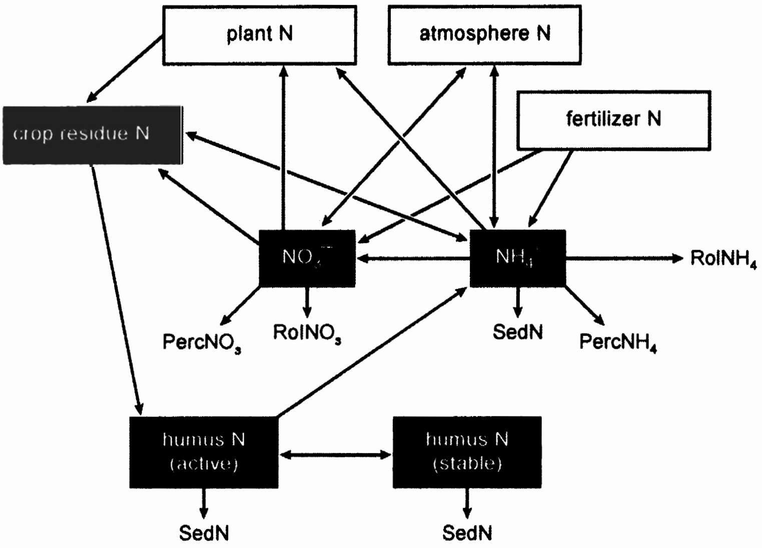

Fig. 1. Nitrogen submodel in ICECREAM. Boxes represent different N pools (soil pools: dark boxes). Arrows indicate N transformation processes and fluxes: inorganic N flux via surface runoff ($RolNH_4$, $RolNO_3$), inorganic N flux leached from the root zone ($PercNH_4$, $PercNO_3$) and flux of sediment-attached N (SedN).

solar radiation) as driving variables. Statistical data about N fertilization and N balance were available for the Rural Centres. Climate-induced hydrological conditions have a pronounced effect on N leaching. Adequate climate data was not available for all the Rural Centres. Therefore, N leaching was simulated using climate data from five stations operated by the Finnish Meteorological Institute. The selected stations represent Rural Centres in southern, central and eastern Finland (Fig. 2, Table 1). Ten years of climatic input data were used to simulate the period 1991–2000, which represents the period before the FAEP (years 1991–1994) and the first six years of the FAEP.

The distribution of soil types and the most common crops were analysed for the Rural Centres. The final ICECREAM simulations were made with barley grown in a sandy loam soil, a combination present in all selected Centres. The slope of the field was set to 1% and the profile thickness to 1 meter (to represent the root zone above the tile drains). According to Puustinen et al. (1994), the median slope of Finnish fields is 0.8%. In Finnish mineral agricultural soils, NO_3-N is typically the dominating fraction in N losses (Turtola and Paajanen 1995, Turtola and Kemppainen 1998, Lemola et al. 2000). Nitrate N is mostly transported in subsurface

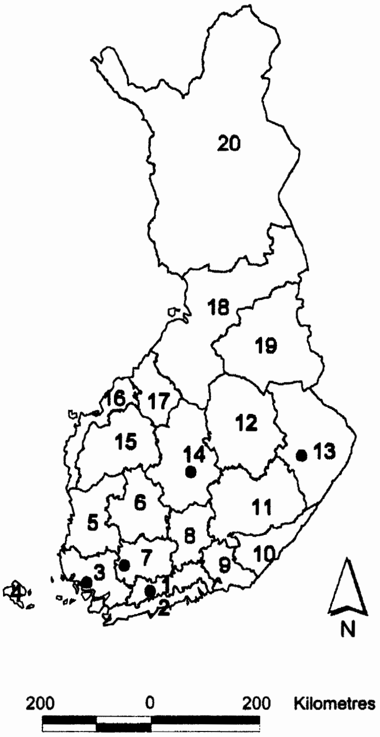

Fig. 2. Location of Rural Centres and meteorological observation stations for ICECREAM model applications. Names of the selected Rural Centres: 1 = Uusimaa, 3 = Farma, 7 = Häme, 13 = Pohjois-Karjala, 14 = Keski-Suomi.

Table 1. The Rural Centres and representative climate stations selected for the ICECREAM simulations. Mean precipitation (P_{mean}) and temperature (T_{mean}) for the climate stations (Drebs et al. 2002). For location of the Rural Centres and climate stations see Fig. 2.

Rural centre	Climate station Number*	Location	P mean (mm)**	T mean (°C)**
Uusimaa	0309	60°25'N 24°24'E	626	4.5
Farma	1101	60°31'N 22°16'E	685***	5.2
Häme	1201	60°49'N 23°30'E	607	4.3
Pohjois-Karjala	2401	62°24'N 25°40'E	638	2.9
Keski-Suomi	3801	62°39'N 29°36'E	643	2.6

* National identification number (LPNN).

** Mean for the period 1971–2000.

*** Precipitation data from Liedonperä station located 25 km northeast from station number 1101.

drainage (Turtola and Paajanen 1995, Turtola and Kemppainen 1998). Therefore the main emphasis in this study was on the simulation of NO$_3$-N leached from the root zone.

Parametrisation of the ICECREAM model was similar to that in simulations carried out in a study of the environmental impacts of the Finnish Agri-Environmental Program (MYTVAS-study, Pyykkönen et al. 2004). Management dates and parameters related to cultivation techniques were kept unchanged during the simulation periods. Spring barley was sown and fertilized on 5 May and harvested on 15 August. The soil was ploughed in early September and was left bare during the winter.

In order to study the effect of decreasing N fertilizer amounts on N leaching, two sets of fertilizer scenarios were simulated. The first simulations (*Baseline* simulation) were made with a constant annual amount of fertilization (90 kg N ha^{-1}) for each Rural Centre and for each year. This set of simulations demonstrates the variation in N leaching due to differences in climatic conditions: in the Rural Centres the mean annual temperature varied from 2.6 to 5.2°C and the annual precipitation from 607 to 685 mm (Table 1). Secondly, the simulations were repeated by allowing the annual fertilizer amount to decrease linearly by 20 kg N ha^{-1} from 110 to 90 kg N ha^{-1} yr^{-1} (*N reduction Scenario*). These values were chosen based on the present recommended N fertilization rates for fodder cereal (basic measure of the AEP: 90 kg N ha^{-1} yr^{-1}) and the observed national decrease in average inorganic N fertilizer use from 112 to 84.6 kg N ha^{-1} yr^{-1} during 1991–2000 (Salo et al. 2007).

Results

The annual variation of simulated N leaching was considerable in both the *Baseline* and *N Reduction Scenario* simulations (Fig. 3). Annual N leaching was higher in all stations when a higher amount of fertilizer was used, but the difference became small towards the end of the simulation period. On average, 24% of the applied fertilizer amount was leached in the *Baseline* case. The mean annual leaching was lowest in Farma Rural Centre for both sets of simulations (*Baseline* 14.2 kg NO$_3$-N ha^{-1}yr^{-1} and *N Reduction Scenario* 20.4 kg NO$_3$-N ha^{-1}yr^{-1}) and highest in Pohjois-Karjala (*Baseline* 24.8 kg NO$_3$-N ha^{-1}yr^{-1} and *N Reduction Scenario* 33.9 kg NO$_3$-N ha^{-1}yr^{-1}). The changes in N process rates (e.g. mineralization) due to changes in fertilisation were insignificant. This was also true for N uptake and denitrification (Fig. 4), which together with NO$_{\_}$-N root zone leaching represent the highest N flows in ICECREAM. Higher root zone leaching in the *N Reduction Scenario* simulations was due to higher storage of mineral N in soil (Fig. 5a, b).

Discussion

In this study a modelling framework was set up to study the potential effect of decreasing N fertilization level on root zone N leaching. Due to the lack of climatic input data, only a selected set (five stations) of climatic conditions in southern, central and eastern Finland could be included in the simulations. The ICECREAM model set-up was kept as simple as possible in order to allow comparison between stations representing different climatic conditions. For example, all the crop, soil and cultivation parameters were constant for different stations and only mineral fertilization was used as N input. Therefore, the *Baseline* simulation results with constant annual N fertilization (90 kg N ha^{-1}) demonstrate the temporal and spatial variation in N losses resulting from varying climatic conditions.

It was not possible to calibrate the model system against actual observed leaching values, because the model set-up represents theoretical soil profiles and typical management conditions for cereals, aiming to demonstrate the effects of fertilizing and climatic conditions only. Moreover, in Finland, many field scale studies on nutrient leaching have focused on management practices rather than on fertilization amounts. However, the

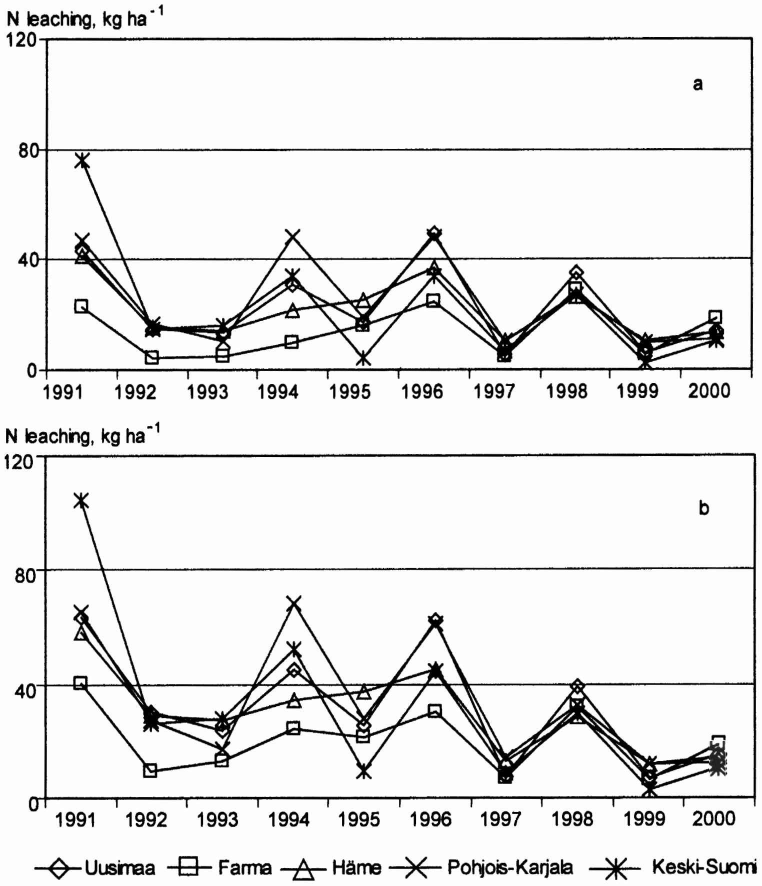

Fig. 3. ICECREAM model results for annual root zone leaching of NO_3-N from barley cultivation in five Rural Centres. (a) *Baseline* simulation with constant (90 kg N ha^{-1}) fertilizer application. (b) *N Reduction Scenario* simulation: decreasing N fertilization from 110 to 90 kg N ha^{-1}.

modelled leaching values in the *Baseline* case were comparable to existing data concerning N leaching under similar field conditions in barley cultivation (Yläranta et al. 1993, Turtola and Paajanen 1995, Salo and Turtola 2006). In a Swedish plot study, nitrate leaching was moderate in cereal cultivation when 100 kg N ha yr^{-1} was applied, but increased substantially with increasing fertilization (Bergström and Brink 1986). In a field study reported by Salo and Turtola (2006), N leaching averaged 15 kg N ha^{-1} yr^{-1} (range 4–46 kg N ha^{-1} yr^{-1}) for barley cultivation in clay soil in southern Finland. In ICECREAM, the fertilizer amounts used in this study do not limit crop growth and yield. A yield-response function presented by Hilden et al. (2007), based on field trials in barley cultivation, suggested only minor changes for yield levels when 90–110 kg N ha^{-1} yr^{-1} was used. Moreover, long term statistical data on soil surface N balances from the Rural Centres showed that harvested N has not decreased although net input of N decreased from 160 to 120 kg N $ha^{-1}yr^{-1}$during the period 1990–2004 (Salo et al. 2007).

The strong variability in N losses resulting from varying hydrometeorological conditions has been reported in many Nordic-Baltic field and modelling studies. Vuorenmaa et al. (2002) concluded, based on long-term data (1981–1997) from monitored agricultural catchments and river basins that weather-driven fluctuation in discharge was usually the main reason for changes in nutrient losses, and little or no impact of changes in agricultural production or management practices was observed. Vagstad et al. (2004) analysed diffuse N losses from 35 Nordic

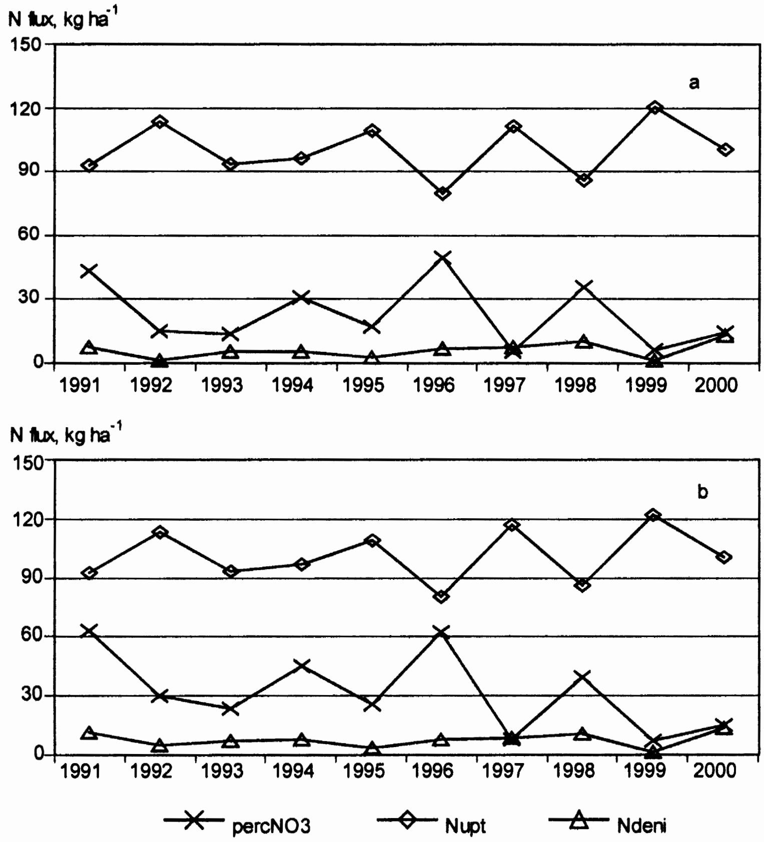

Fig. 4. Modelled annual N fluxes in a barley field in Uusimaa Rural Centre. (a) *Baseline* simulation with constant (90 kg N ha^{-1}) fertilizer application. (b) *N Reduction Scenario* simulation: decreasing N fertilization from 110 to 90 kg N ha^{-1}. PercNO3: NO_3-N leached from the root zone, Nupt: N uptake of the whole plant, Ndeni: N denitrification.

and Baltic catchments for the period 1994–1997. N losses were characterized by significant within-country and interannual variations. Differences in the hydrological processes and pathways (surface runoff, percolation through soil matrix to drainage systems and ground water flow) appeared to play an important role for N losses. According to Vagstad et al. (2004), a probable reason for the substantial variability of N losses in seven studied Norwegian catchments was the wide range of climatic and hydrometeorological conditions, e.g. the average annual precipitation ranged from 585 mm to 1230 mm. In an Estonian catchment, milder winters and a change in the precipitation pattern have influenced the mean annual water discharge, resulting in more intensive material flow (organic matter and nutrients) during colder seasons and decreased water runoff in summer (Mander et al. 2000).

The ICECREAM model cannot predict losses resulting from "catastrophies" during growth periods, such as low yields related to failures in germination or exceptional droughts. Therefore, the modelled yields or N uptake cannot be compared directly to observed statistical values. The *N reduction Scenario* simulations represent the N leaching response to decreasing fertilizer application rather than the effect of actual growth conditions during the study period. These simulations indicated that there is a potential to decrease N losses by decreasing the use of N fertilizers, although the response is not linear due to hydrometeorological variability. In a field-scale model study by Rankinen et al. (2007), the annual hydrology, as simulated on the basis of daily meteorological observations from Jokioinen climate station (Climate station nro 1201, also used in this

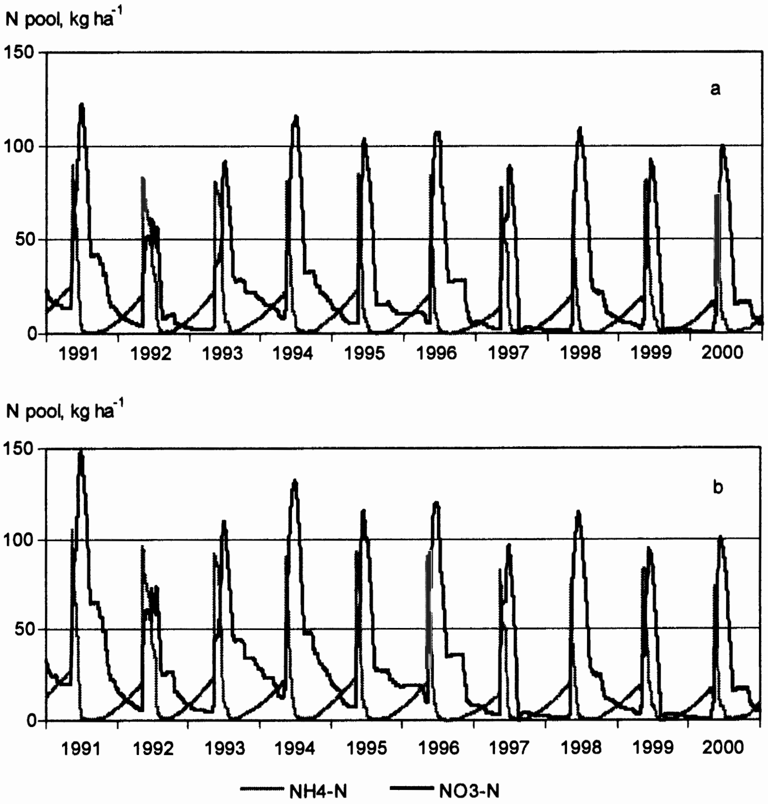

Fig. 5. Modelled NH_4-N and NO_3-N pools in soil used for barley cultivation in Uusimaa Rural Centre. (a) *Baseline* simulation with constant (90 kg N ha^{-1}) fertilizer application. (b) *N Reduction Scenario* simulation: decreasing N fertilization from 110 to 90 kg N ha^{-1}.

study to represent climatic conditions in Häme Rural Centre), strongly affected the simulated N leaching for different crops: inorganic N tended to accumulate in soil during dry periods and was washed away during rainy seasons. A decrease of 20% in fertilizer input was reflected in lower leaching losses.

In reality, agricultural nutrient losses result from complex interactions between vegetation, climate, physical and biogeochemical soil processes and management practices. Further research is required in order to analyse actual long term response of the soil N cycle to changed environmental conditions, i.e. whether the soil will act more as a source or sink for N in future. For this, enhanced co-operation between process scientists and modellers is needed.

Actual improvement of water quality in rivers related to environmentally sound management practices is sometimes difficult to distinguish, at least in the short term. On the basis of a comprehensive review study in major European rivers, Grimvall et al. (2000) stated that the inertia of the systems controlling the loss of nutrients from land to sea was underestimated when the present goal of a 50% reduction of the input of nutrients to the Baltic Sea and the North Sea was adopted.

According to our model results, N leaching from the root zone can be decreased by decreasing the amount of N fertilizers, which therefore can be considered as an effective measure for the AEP. However, hydrological processes strongly control the annual variation in losses and consequently impede the judgement of surface water quality at least on an annual basis. According to Ekholm et al. (2007), long term monitoring data on N losses from small to meso-scale catchments showed that only NH_4-N losses (having a negligible contribution to total N losses) have decreased in many catchments, probably due to restrictions in spreading of manure during late autumn and winter. Among possible explanations for the lack of response to decreased N input at the catchment scale were the increased area of agricultural land and specialization and regional intensification of animal husbandry.

Conclusions

The field scale model results concerning agricultural N leaching indicated that it is possible to decrease N leaching by decreasing N fertilization. However, there was strong annual and regional variation in simulated N losses and therefore the average reduction in N losses did not show a linear response to N fertilizer reduction during the 10 year study period. The role of hydrological processes and the temporal and spatial variability of nutrient losses must be taken into account when evaluating the effects of fertilization on stream and river water quality.

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SELOSTUS

Lannoitustason vaikutus maatalousmaan typpihuuhtoumaan

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Typpilannoitteiden käyttö Suomessa on vähentynyt tuntuvasti, mutta laajat ja pitkäaikaiset vedenlaadun havaintoaineistot osoittavat, että selkeää alenemista tutkimusvaluma-alueiden ja jokivesistöjen typpikuormituksessa ei ole havaittavissa. Tästä syystä on tärkeää arvioida millaiseen juuristovyöhykkeestä tapahtuvaan typen huuhtoutumisen vähenemiseen todettu alentunut typpilannoitus voi potentiaalisesti johtaa. Tässä tutkimuksessa käytettiin ICECREAM-huuhtoumamallia arvioitaessa sääolojen ja alentuneen lannoitustason vaikutusta peltomaan nitraattityppihuuhtoumaan. Mallinnusten lähtöaineistona käytettiin säähavaintoja viideltä eri puolella Suomea sijaitsevalta ilmastoasemalta. Mallilla laskettiin typen huuhtouma jaksolla 1991–2000 ohrakasvustosta 1) vakiolannoitustasolla 90 kg N ha^{-1} ja 2) vuosittain lineaarisesti alenevalla (110–90 kg N ha^{-1}) lannoitustasolla.

Vakiolannoitustasolla keskimääräinen huuhtouma oli 24 prosenttia käytetyn lannoitteen määrästä. Huuhtouman vaihtelu oli huomattavaa eri vuosien ja alueiden välillä molemmissa simulointitilanteissa. Laskevaa lannoitustasoa käyttäen huuhtouma väheni kaikilla alueilla lähestyen peruslannoitustasoa vastaavaa huuhtoumaa, mutta väheneminen ei ollut lineaarista.

Mallinnustulokset osoittivat, että typpilannoituksen väheneminen voi vähentää myös typpihuuhtoumaa peltomaasta. Kymmenen vuoden tarkastelujaksolla huuhtouman pieneneminen ei kuitenkaan ollut lineaarista vaan vaihteli vuosittain voimakkaasti sääoloista riippuen. Tämä on syytä ottaa huomioon arvioitaessa lannoituksen vähenemisen vaikutuksia veden laatuun valuma-alueilla.