Simulated nitrogen leaching patterns and adaptation to climate change in two Finnish river basins with contrasting land use and climatic conditions

Katri Rankinen, Pirkko Valpasvuo-Jaatinen, Anni Karhunen, Kaarle Kenttämies, Suvi Nenonen and Ilona Bärlund

ABSTRACT

Inorganic nitrogen (N) loading was simulated by the catchment scale INCA-N model from two large river basins with contrasting land use. The main aim was to analyze the timing and origin of inorganic N loading and the effectiveness of different water protection methods. Predicted changes in precipitation and temperature increases the nutrient load from catchments to water bodies in future climate. The total inorganic N load from the forested Simojoki river basin located in northern Finland was about 5% of that from the Loimijoki river basin in south western Finland. In the Loimijoki river basin agriculture dominated inorganic N loading. When applying realistic water protection methods (limits on manure spreading) the simulated inorganic N load from the river basin decreased by 11%. With more drastic methods (no manure spreading + catch crop) a decrease up to 34% was achieved. In the Simojoki river basin there were several equally significant sources, so suitable combinations of different water protection measures would be the most efficient way to decrease the inorganic N load. As the inorganic N load may be composed of very different sources, depending on land use in the river basin, efficient allocation of water protection measures requires detailed analysis of different sources of loading.

Key words | adaptation to climate change, agriculture, catchment scale modeling, nitrogen leaching, water protection scenarios

Katri Rankinen (corresponding author)
Kaarle Kenttämies
Finnish Environment Institute,
P.O. Box 140, Helsinki FI-00251,
Finland
Tel.: +358 400 148832
E-mail: *katri.rankinen@ymparisto.fi*

Pirkko Valpasvuo-Jaatinen
Anni Karhunen
West Finland Regional Environment Centre,
P.O. Box 47, Turku FI-20801,
Finland

Suvi Nenonen
Lapland Regional Environment Centre,
P.O. Box 8060, Rovaniemi FI-96101,
Finland

Ilona Bärlund
Centre for Environmental Systems Research,
University of Kassel,
Kurt-Wolters-Strasse 3,
Kassel D-34125,
Germany

INTRODUCTION

Eutrophication of surface waters due to increased nutrient loading is one of the main environmental concerns in Finland. The EU Water Framework Directive sets new challenges for integrated river basin management, with levels of ecological and chemical parameters for surface waters to be achieved by 2015. In a recent evaluation it was found that most of the Finnish surface waters fulfills these standards (Anon 2008). Rivers in northern Finland are generally in an excellent or good ecological state. Those rivers whose status is classified as moderate or poor are located mainly in coastal regions of the southern and western parts of Finland. Further, inshore waters in the Gulf of Finland and the Archipelago Sea generally have a poor ecological status, although conditions further out in the archipelago tend to be moderate.

In Finland nutrient release from non-point sources (agriculture, forestry and scattered settlements) exceeds the industrial and municipal loads including peat mining and fish farming (Statistics Finland 2004). Räike *et al.* (2003) showed in the long-term analysis of nutrient concentration trends in Finnish rivers that the water purification of municipal and industrial waste had effectively decreased

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nutrient emissions from point sources, leading to improved water quality, whereas no clear effects of decreasing non-point loading were found.

Agriculture forms the greatest single source of nutrients to surface waters (Rekolainen *et al.* 1992; Vuorenmaa *et al.* 2002). In southern Finland the risk of nutrient leaching is highest outside the growing season due to high runoff which in spring is induced by snow melt (Lemola & Turtola 2000). In autumn the leaching is driven by high precipitation combined with low evaporation. Further, Wivstad *et al.* (2005) reported mineralization of soil organic matter to continue in agricultural soils outside the growing season.

On the basis of model estimations and observations, increases in precipitation and temperature will most probably increase N losses from agricultural areas to surface waters (Kallio *et al.* 1997). The latest climate change scenarios predict increasing temperature and precipitation in northern Europe and especially precipitation in autumn and winter is expected to increase (Räisänen *et al.* 2004). Nitrogen processes in soil are sensitive to both of them, so an increase in one or the other may increase N leaching from catchments to the Baltic Sea. In the eutrophic areas of the Baltic Sea, N is observed to be the growth-limiting nutrient either during summer months or throughout the whole growing season (Tamminen & Andersen 2007). Thus effective mitigation measures for eutrophication are needed to decrease the N load to the sea.

There are already several existing policy instruments on which adaptation measures to climate change can be based on. The implementation of the EU Nitrates Directive is one of the policy measures aimed at decreasing N and phosphorus (P) losses from agricultural sources (Mitikka & Britschgi 2005). It contains provisions on good agricultural practices, storage of manure, spreading and allowable quantities of fertilizers and silage effluent, and analysis and recording of N in fertilizers. It also sets the absolute, crop-specific upper limits on N fertilizers. The most important policy measure in Finland for controlling agricultural N and P loading is The Agri-Environmental Programme (AEP) (Valpasvuo-Jaatinen *et al.* 1997; Ministry of Agriculture and Forestry 2004*a*). In 2002 it covered about 92% of Finnish farms and 93% of the arable area (Ministry of Agriculture and Forestry 2004*b*). In general the maximum fertilization levels for different crops are lower in the AEP than in the Nitrate Directive, with certain exceptions in cases when farmers are allowed to adjust N fertilization according to estimated yield.

In the AEP, an environmental subsidy is paid to farmers who undertake "basic" and "additional measures", such as preparing a farm environmental management plan, establishing filter strips along main ditches and water courses, and conforming to targeted levels of fertilizer and manure application. In animal husbandry reduction of ammonia emissions and treatment of dairy wastewater are supported. In turn, "special measures" require more efficient environmental protection, e.g. establishment and management of 15 m wide buffer zones, wetlands and sedimentation ponds.

In forestry buffer zones, wetlands and sedimentation ponds are recommended as voluntary measures against erosion and nutrient leaching caused by forestry practices, and the same measures are used to reduce suspended sediment and nutrient leaching from peat mining areas. Peat mining, like any other industrial production, needs an environmental permit in which limits to emissions are set. Further, at the beginning of 2004 a treaty came into operation aiming to prevent deterioration of water quality by setting minimum requirements for purification efficiency of private wastewater disposal systems. On-site waste water treatment in one-family houses should be improved to fulfill current standards by 2014.

The influence of the AEP on agricultural nutrient losses and quality of receiving waters was recently evaluated (Ekholm *et al.* 2007). In this evaluation monitoring data of nutrient and suspended sediment fluxes in agricultural catchments in 1990–2004 and water quality of agriculturally loaded rivers, lakes and estuaries in 1990–2005 was used. No clear effect on loading or improvement in water quality was detected. Simultaneous changes in agricultural production (e.g. regional specialization) and in climate may have counteracted the effects of agri-environmental measures. Also the actions to reduce agricultural loading might have been more successful if they had been focussed specifically on the areas and actions that contribute most to the loading. In particular, reducing N fluxes in a changing climate calls for special attention, because national N balance in Finland has decreased by 40 kg ha^{-1} a^{-1} since 1990 (Salo *et al.* 2007) without any detectable improvement in water quality.

The main aim of this study was to analyze the timing and origin of inorganic N loading and effectiveness of different water protection methods to plan adaptation measures to climate change. The INCA-N (Integrated Nutrients from CAtchments–Nitrogen) model was applied to two large river basins with contrasting land use and climate. INCA-N is a dynamic semi-distributed process-based model which calculates inorganic N loading from the terrestrial environment and in rivers. The INCA-N model was applied already in previous studies to Simojoki river basin in northern Finland where the main land use is boreal forest (Rankinen *et al.* 2006). In the Loimijoki river basin in south western Finland agriculture dominates land use.

METHODS

The river basins

The Loimijoki river basin (3,138 km^2) is located in south western Finland (Figure 1), where agricultural land use has

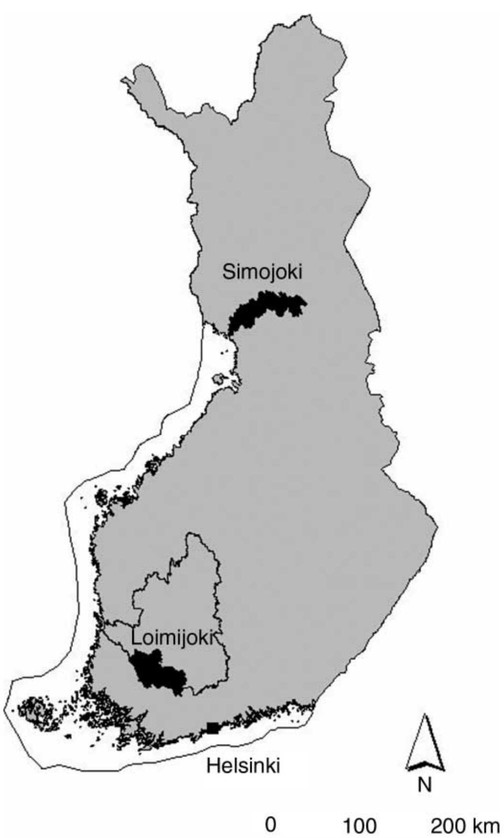

Figure 1 | Location of the Loimijoki and the Simojoki river basins in Finland (thin line shows territorial waters of Finland).

been traced back to the first century AD. The main soil type in the river basin is clay. Fields cover 38% of the catchment area, and the main crops are cereals (34%), grass ley (3%) and special crops, like sugar beet (1%). There are also some areas with small-scale industry and several small but relatively densely populated settlements in the river basin as well as cattle breeding farms. Pig and poultry farming has been intensified during the last decade.

Over the period 1961–1975, the mean annual precipitation in the area was 600 mm and the mean annual runoff 200–250 mm. The mean annual temperature was 3.5–4.5°C. The mean daily flow in the Loimijoki river was 24 m^3 s^{-1} during 1991–2000. The maximum discharge was 184 m^3 s^{-1} and the minimum discharge 2.3 m^3 s^{-1} during the same period.

The Simojoki river basin (3,160 km^2) is located in northern Finland (Figure 1), in the boreal vegetation zone. The River Simojoki is an unregulated Atlantic salmon river without any major sources of point pollution and the dominating human impacts in the area are forestry, peat mining, agriculture and scattered settlements. Forests cover 95% of the area. A large part of the river basin is covered by ground moraine, mainly sandy till. In the lower reaches there are also river deposits and some areas of clay. Almost one-third of the river basin is covered by peatlands which are mainly forested.

Over the period 1961–1975, the mean annual precipitation in the area was 650–750 mm and the mean annual runoff 350–450 mm. The mean annual temperature was 0.5–1.5°C. The mean daily flow at the outlet was 40 m^3 s^{-1} during 1965–2002. The maximum discharge was 730 m^3 s^{-1} and the minimum discharge 3 m^3 s^{-1} during the same period.

The INCA-N model

The dynamic INCA-N (Integrated Nutrients in Catchments–Nitrogen) model integrates hydrology and N processes (Whitehead *et al.* 1998; Wade *et al.* 2002; Wade 2004). The model is semi-distributed, meaning the land surface is not described in detail, but rather by the land-use classes in sub-basins. The sources of N include atmospheric deposition, leaching from the terrestrial environment and direct discharges. The terrestrial N fluxes are calculated in up to six user-defined land use classes.

The hydrologically effective rainfall (HER) is used to drive N through the catchment system and N can enter the river system by the lateral flow through the surface soil layers or by the vertical movement and transport through the groundwater zone. The hydrology within the sub-catchments is modelled using a simple two-box approach, with reservoirs of water in the reactive soil zone and in the deeper groundwater zone.

The mass balance equations for NO_3-N and NH_4-N in the soil and groundwater zones are solved simultaneously with the flow equations. The key N processes that are solved in the soil water zone are nitrification, denitrification, mineralization, immobilization, N fixation and plant uptake of inorganic N in six land use classes. It is assumed that no biochemical reactions occur in the groundwater zone. In the rivers the key N processes are nitrification and denitrification.

The river flow model is based on mass balance and uses a multi-reach description of the river system. Within each reach, the flow variation is determined by a nonlinear reservoir model. The point source inputs of N can be added as parameters when they are daily averages for the whole simulation period. The discharge, which varies with time, may be added as effluent time series which contain flow ($m^3\ s^{-1}$) and NO_3-N and NH_4-N concentrations ($mg\ l^{-1}$).

The model set-up to the Loimijoki river basin

The set-up of the INCA-N model for the Simojoki river basin is described in detail in Rankinen *et al.* (2006). The set-up of the model for the Loimijoki river basin followed the same schema so that the hydrological input to the model was taken from the operational Watershed Simulation and Forecasting System (Vehviläinen 1994). Input data from the years 1995–1999 and 2000–2004 were used in calibration and validation. These years covered the first and second program periods of the Agri-Environmental Programme.

Land use of the Loimijoki river basin was based on CORINE 2000 land cover data. The proportions of different crops was defined by interviewing local officials and agricultural advisers. The amount of cattle and other domestic animals was based on the annual statistics (Information Centre of the Ministry of Agriculture and Forestry 1997, 2004).

All the manure produced in the area was assumed to be applied to spring cereals only, which led to an average amount of 52 kg N $ha^{-1}\ a^{-1}$. The amount of manure applied in autumn was assumed to reach the maximum amount (e.g. 20 tonnes ha^{-1} cattle slurry or 15 tonnes ha^{-1} pig slurry) allowed according to the Nitrates Directive. This is a common practice because farmers empty manure storages before winter. Otherwise the fertilization followed the regulations of the AEP assuming only 50% of N in the manure applied in autumn would be usable for vegetation. The amount of N fertilizers followed regulations of the Nitrates Directive (Table 1), as this sets the absolute maximum limit allowed in Finland. Fertilization levels according to the AEP are typically lower (Table 1) but there are options to also use higher fertilization, depending on the contract type the farmer has signed.

Mineral fertilizers are assumed to decay with a rate of 0.15 d^{-1} (information from manufacturers). The INCA-N model does not simulate organic N processes in detail. Thus application of manure was assumed to increase the pool of ammonia (NH_4-N). That pool was assumed to nitrify rapidly (70% in 5 d). Further, manure was assumed to increase the mineralization potential on those fields where it was applied (Bergström & Kirchmann 2006). Catch crop was simulated as undersown crop by changing plant growth parameters so that N uptake continued after harvest to the end of the growing season.

The INCA-N model was calibrated and validated successfully for the Loimijoki river basin. The simulated and observed discharge and the inorganic N concentrations are presented in Figure 2. For nitrate (NO_3-N) an R^2 value was used as a measure of the goodness of fit between simulated and observed values. The value of R^2 was 0.285 in the calibration period (years 1995–1999) and 0.268 in the validation period (years 2000–2004). For discharge the

Table 1 | Fertilization levels according to Finnish Agri-Environmental Programme (AEP) and The Nitrates Directive

	N fertilization (kg ha^{-1} yr^{-1})	
Crop	**AEP**	**Nitrates Directive**
Spring cereals	100	170
Winter cereals	120	200
Grass ley	180	250
Sugar beet	120	170

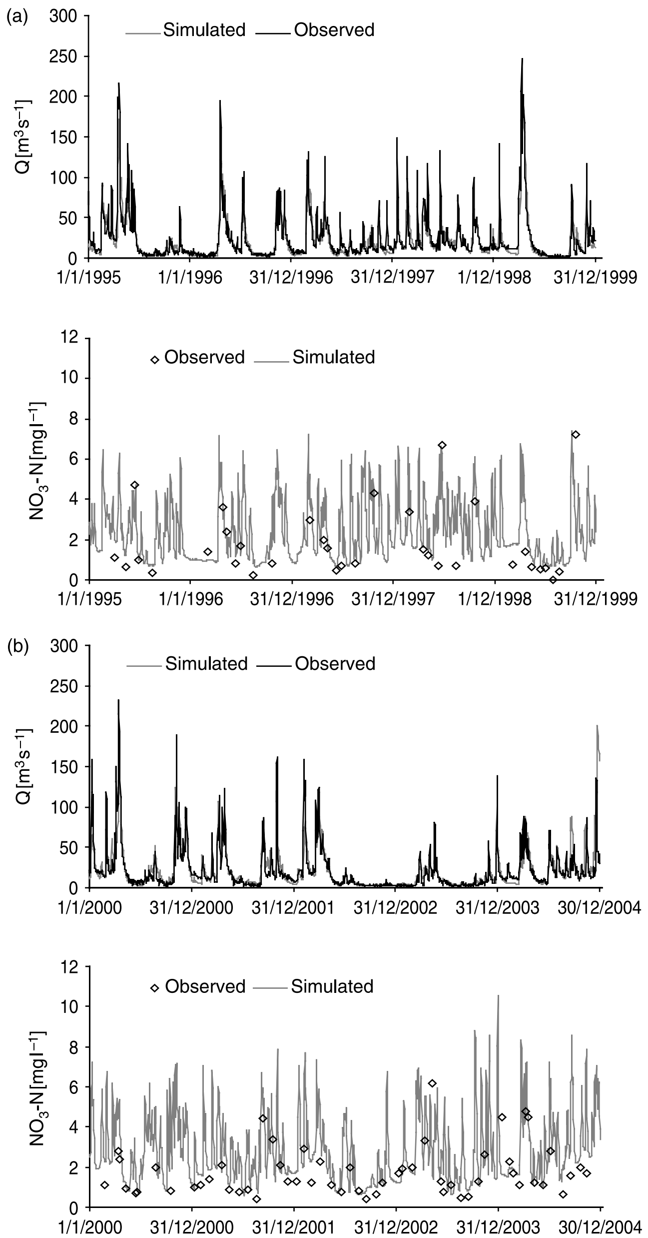

Figure 2 | The observed and simulated discharge and NO_3-N concentration in the River Loimijoki. (a) Calibration period 1995–1999, (b) validation period 2000–2004.

Nash–Sutcliffe efficiency (Nash & Sutcliffe 1970) was calculated, as it also took into account the timing of the peaks. For discharge the Nash–Sutcliffe efficiency was 0.79 in the calibration period and 0.72 in the validation period. The value of R^2 was 0.623 in the calibration period and 0.819 in the validation period when the daily NO_3-N load calculated from observations was compared to the simulated load (Figure 3). Daily simulated loads during the validation period were higher than loads calculated from observations. One reason may be that the years 2000–2004 covered the second program period of the AEP and there were several small changes in supported measures compared to the first program period (1995–1999).

RESULTS AND DISCUSSION

Origin and timing of N load from the river basins

In the Loimijoki river basin, agriculture was the main source of inorganic N loading, so that 74% of the total simulated load was from spring cereals (Figure 4). The level of N fertilization according to the Nitrates Directive might have been a slight overestimation, as some of the farmers are likely to follow the lower fertilization levels set in the AEP. Alternatively those levels of the AEP are not strictly mandatory as, when following additional measures of the AEP, farmers are allowed to adjust N fertilization according to estimated yield. The simulated inorganic N leaching from spring cereal fields was 39 kg N ha^{-1} a^{-1}, which corresponded with observed leaching from fields fertilized by manure (Niinioja 1993). The proportion of the inorganic N load from forests and from point pollution sources and scattered settlements together was approximately 5%. The proportion of NO_3-N in the total N load from the Loimijoki river basin was over 90%, also reflecting high loading from agriculture (Figure 5). N balance calculated for the whole river basin was clearly positive, so that anthropogenic inputs (deposition and fertilization) were 75 kg ha^{-1} yr^{-1} and vegetation uptake only 60 kg ha^{-1} yr^{-1}.

Agricultural areas cover 2.5% of the Simojoki river basin area but, according to simulation results, the share of the inorganic N loading was about 15% (Rankinen *et al.* 2006). About 40% of the simulated inorganic load was from forested areas. The largest single anthropogenic source of inorganic N, 28% of the total load, was scattered settlements. The total inorganic N load from the Simojoki river basin was about 5% of that from the Loimijoki river basin. N balance calculated for the whole river basin was very close to that of natural forests, so that anthropogenic input (mainly atmospheric deposition) was very low (<5 kg ha^{-1} a^{-1}). Forest vegetation uptake (28 kg ha^{-1} a^{-1}) was covered

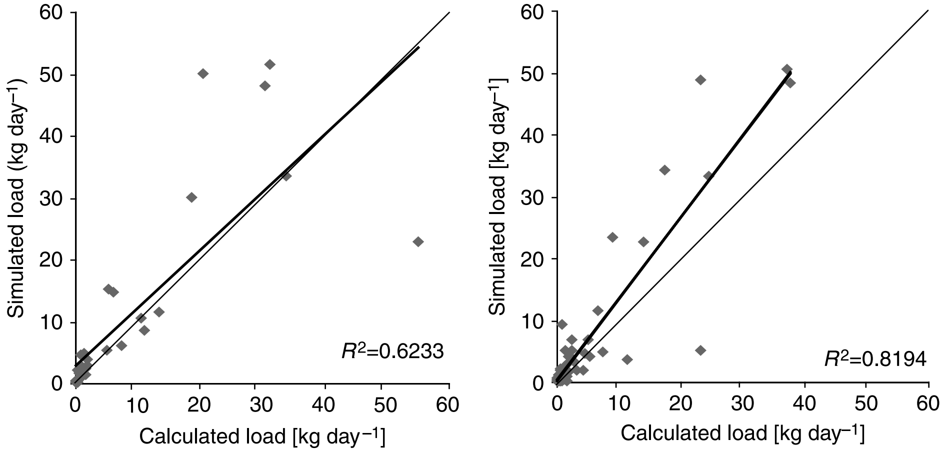

Figure 3 | The simulated and calculated daily loads in the Loimijoki river basin. (a) Calibration period 1995–1999, (b) validation period 2000–2004.

mainly by mineralization, i.e. N release from soil organic matter (24 kg ha^{-1} a^{-1}). Thus leaching of inorganic N was low (<1 kg ha^{-1} a^{-1}).

The proportion of inorganic N in the total N load calculated by a statistical method used as a standard in Finland was about 20%, the rest being organic N. Though the inorganic load from the Simojoki river basin was very low compared to that from the Loimijoki river basin the role of terrestrial organic N in the total N load to the sea is an interesting question. According to the latest studies chromophoric dissolved organic matter decomposes in coastal waters mainly due to photodegradation (Vähätalo & Wetzel 2004; Vähätalo & Zepp 2005). In this way organic N may become available to food chains in seas with a scarcity of N.

The inorganic N loading from both of the river basins was concentrated around snow-melting in spring representing 30–50% of the total annual inorganic N load. In the Simojoki river basin inorganic N concentrations increased during winter due to over-winter mineralization in soils (Rankinen *et al.* 2004). Snow-melting clearly dominated annual discharge and early winter was a low-flow period (Rankinen *et al.* 2006). These annual patterns were not so obvious in the Loimijoki river basin where, in some winters, several early snow-melting periods occurred. On average 75% of inorganic N loading occurred between October and April, outside the main growing season.

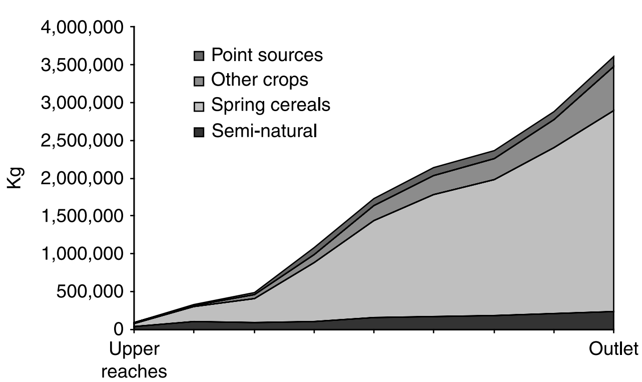

Figure 4 | The share of different sources on inorganic N load along the River Loimijoki.

Effectiveness of the water protection measures

As the inorganic N loading from the Loimijoki river basin was dominated by one source only, the water protection measures were designed for spring cereals. Positive N balance indicated a need to either decrease N fertilization or increase vegetation uptake. As fertilization levels were set in the Nitrate Directives and the AEP the planned water protection scenarios concentrated on increasing vegetation uptake.

In the first scenario a catch crop (which is defined as a crop taking nutrients when the ground would otherwise lie fallow or bare between two regular or main crops) was assumed on spring cereal fields. Several studies had shown that catch crops sown in autumn after the harvest of the main crop can take up large amounts of N (Lewan 1994; Lemola & Turtola 2000; Macdonald *et al.* 2005; Wivstad *et al.* 2005). For example, Lemola & Turtola (2000) observed 27–68% reduction of annual N leaching in lysimeters

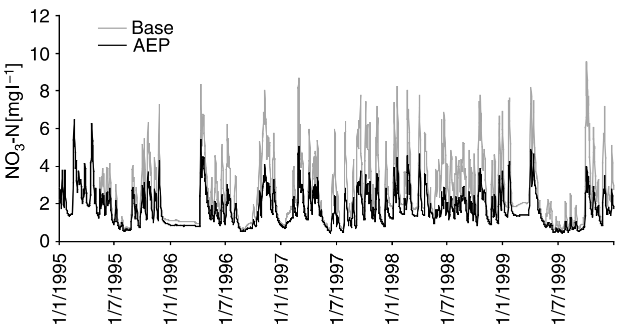

Figure 5 | NO_3-N concentration in the River Loimijoki when fertilization level is according to the Nitrates Directive (Base) or AgriEnvironmental Programme (AEP).

which were located in the Loimijoki river basin. In simulations applying catch crops led up to 5% decrease in N leaching (Table 2), which seemed to be low compared to the observed reduction. In this scenario manure spreding in autumn was allowed, which may have masked the positive effect of the catch crop.

In the second scenario application of manure in autumn was not allowed. The same amount of manure was applied to fields in spring only, when it benefited the growing crop. This led also to a decrease in the total amount (mineral + manure) of N fertilization, because in this case 100% of N in manure was assumed to be usable for vegetation (according to the AEP). This scenario led to a greater decrease in inorganic N leaching than the catch crop scenario (Table 2). In field-scale experiments Niinioja (1993) observed that N leaching from fields was clearly higher when manure was applied in autumn than in spring. Leaching of N depended very much on precipitation and rain periods in the autumn. When studying N leaching and crop uptake after pig slurry applications Bergström & Kirchmann (2006) noticed that leaching of total N increased with increasing slurry applications.

Together, the first two scenarios could decrease the inorganic N load from the Loimijoki river basin by up to 11%. The change was higher (5–18%) in the field scale from land use class "spring cereal" than in the river basin scale (4–11%). For example, Deelstra *et al.* (2004) measured about 28% lower agricultural N losses on the catchment than on the field scale. They assumed that one reason could be that the flow paths involved in groundwater generation at the catchment scale differ from those in the field scale. Further, Lemola & Turtola (2000) observed that N leaching measured in the field scale was 80% of that measured in the lysimeter scale. They assumed the reason to be a shorter period of soil frost and the absence of surface runoff in lysimeters. Thus more information about different retention processes in aquatic and terrestrial environments and flow processes in catchments is needed to be able to describe nutrient leaching from river basins in full.

In the third scenario fertilization levels were set according to the AEP (Table 1) and all fertilizers were assumed to be mineral fertilizers applied in spring. A second application was allowed to grass and winter cereals only. The undersown catch crop was assumed for barley fields. In this case the inorganic N load from the river basin decreased by 34% and in fields up to 38% (Table 2). The reduction target set in The Decision-of-Principle on Water Protection Targets to 2015 (Ministry of Environment 2007) for nutrient loading from the agricultural sector is one-third of that at the beginning of the 1990s.

This third scenario reduced effectively NO_3-N concentrations in the river so that the highest concentration peaks occurring in the autumn were halved (Figure 5). This corresponded with Lemola & Turtola (2000) who observed that undersowing reduced N concentrations by 54% in runoff waters. The highest simulated reduction by 45–48%

Table 2 | The effect of manure sreading and catch crop on N leaching in the Loimijoki river basin

Scenario	N leaching from spring cereals (kg N ha^{-1})	Change (%)	N load at outlet (t yr^{-1})	Change (%)
Manure in autumn	39	–	4,836	–
Catch crop	37	−5	4,654	−4
Manure in spring	33	−15	4,462	−8
Catch crop + manure in spring	32	−18	4,290	−11
AEP mineral fertilization + catch crop	25	−38	2,939	−34

of the inorganic N load occurred in autumn in August–October. As changing climate may increase N leaching, especially outside the growing season (Kallio *et al.* 1997; Wivstad *et al.* 2005), it is important to find measures which effectively decrease N leaching at that time. Thus, the third scenario can be an effective measure for adaptation to climate change.

Even though the third scenario is according to current legislation, it may be partly unrealistic because intensifying animal husbandry increases pressures to spread manure on the fields. Thus this scenario emphasizes the need to find sustainable solutions to use manure as fertilization. Further, in the AEP several other measures (e.g. stubble) to keep soil covered during the dormant season are supported, but the catch crop is not included. The catch crop decreases the risk for N losses due to soil N mineralization outside the growing season (Wivstadt *et al.* 2005), but it may also gradually increase the N mineralization potential of soils (Lewan 1994; Kirchmann *et al.* 2002; Macdonald *et al.* 2005; Wivstadt *et al.* 2005). Establishing the catch crop in spring by undersowing enables N uptake after harvest of the main crop. In this case the catch crop may also compete with the main crop and thus reduce the yield (Känkänen & Eriksson 2007).

In the Simojoki river basin there were several equally significant sources of inorganic N. Water protection measures (buffer zones and wetlands established at agricultural fields, forest drainage combined with buffer zones, renewed subsurface disposal systems) would decrease the inorganic N load to the sea by up to 7% when acting individually (Table 3). Combination of the water protection measures both in agricultural and forestry areas and in areas of scattered settlement would decrease the load of inorganic N more effectively (about 18% of the total load) than when concentrating on one source only (Rankinen *et al.* 2006).

Table 3 | The effect of different water protection measures on N loading from the Simojoki river basin (Rankinen *et al.* 2006)

Scenarios of water protection measures	N load at outlet (t yr^{-1})	Change (%)
No water protection measures	208.6	–
Agriculture (buffer zones and wetlands)	186.1	−2.0
Forest ditching (buffer zones)	179.1	−5.6
Scattered settlements (subsurface disposal system)	177.4	−6.5
Altogether	155.6	−18.0

In the Simojoki river basin a large amount of total N is in the form of organic N. In the model the pool of organic N is unlimited and the long-term effects of manure application or the catch crop on the organic matter pool in soil is not defined. However, simulated reduction of N loading was close to what Rankinen *et al.* (2007) estimated to be (6–25%) on detailed field-scale modelling which included the organic pool when manure application was changed from autumn to spring.

There is no one effective adaptation measure to climate change in Finland. As the inorganic N load may be composed of very different sources depending on land use in the river basin, efficient allocation of the water protection measures requires detailed analysis of different sources of loading. There are still some effective water protection measures, like catch crop and effective handling of manure, which could improve the potential of the AEP to decrease N loading from river basins to the Baltic Sea.

CONCLUSIONS

The INCA-N model proved to be a suitable tool to explain inorganic N leaching not only from forested river basins but also from river basins where agricultural activities dominate river water quality. The efficiency of different relatively simple scenarios of fertilization and land use can be studied by the INCA-N model.

Modelling results indicate that the water protection measures carried out on agricultural areas could also decrease the leaching of inorganic N in the river basin scale, though the decrease in the field scale was higher. As the inorganic N load may be composed of very different sources depending on land use in the river basin, efficient allocation of the water protection measures requires detailed analysis of different sources of loading.

The potential of the AEP (Agri-Environmental Programme) to decrease the N load could be improved by introducing more site-specific water protection methods which can be focussed on the areas and actions that contribute most to the loading.

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REFERENCES

Anon 2008 http://www.ymparisto.fi/default.asp?contentid = 285385 &lan = en&clan = en Visited 18.6.2008.

Bergström, L. & Kirchmann, H. 2006 Leaching and crop uptake of nitrogen and phosphorus from pig slurry as affected by different application rates. *J. Environ. Qual.* **35**, 1803–1811.

Deelstra, J., Abramenko, K., Vagstad, N., Jansons, V., Sudars, R. & Dzalbe, I. 2004 Hydrological pathways, scale issues and nitrogen runoff: a case study in Latvian catchment. In: *Proc. XXIII Nordic Hydrological Conference, Tallinn, Estonia, 8–12 August*. NHP Report no. 48, 219–229.

Ekholm, P., Granlund, K., Kauppila, P., Mitikka, S., Niemi, J., Rankinen, K., Räike, A. & Räsänen, J. 2007 Influence of EU policy on agricultural nutrient losses and the state of receiving surface waters in Finland. *Agric. Food Sci.* **16**, 282–300.

Information Centre of the Ministry of Agriculture and Forestry 1997 *Maatilatilastollinen vuosikirja*. Yearbook of Farm Statistics, Helsinki.

Information Centre of the Ministry of Agriculture and Forestry 2004 *Maatilatilastollinen vuosikirja*. Yearbook of Farm Statistics, Helsinki.

Kallio, K., Rekolainen, S., Ekholm, P., Granlund, K., Laine, Y., Johnsson, H. & Hoffman, M. 1997 Impacts of climatic change on agricultural nutrient losses in Finland. *Boreal Environ. Res.* **2**, 33–52.

Känkänen, H. & Eriksson, C. 2007 Effects of undersown crops on soil mineral N and grain yield of spring barley. *Eur. J. Agron.* **27**, 25–34.

Kirchmann, H., Johnston, A. E. J. & Bergström, L. l. 2002 Possibilities for reducing nitrate leaching from agricultural land. *Ambio* **31**(5), 404–408.

Lemola, R. & Turtola, E. 2000 Undersowing Italian ryegrass diminishes nitrogen leaching from spring barley. *Agric. Food Sci. Finland* **9**, 201–215.

Lewan, E. 1994 Effects of catch crop on leaching of nitrogen from a sandy soil: simulations and measurements. *Plant Soil* **166**, 137–152.

Macdonald, A. J., Poulton, P. R., Howe, M. T., Goulding, K. W. T. & Powlson, D. S. 2005 The use of cover crops in cereal-based cropping systems to control nitrate leaching in SE England. *Plant Soil* **273**, 355–373.

Ministry of Agriculture and Forestry 2004*a Agricultural Support*. Available at: http://www.mmm.fi/english/agriculture/support.htm

Ministry of Agriculture and Forestry 2004*b Mid-term Evaluation of the Horizontal Rural Development Programme*. Publications of the Ministry of Agriculture and Forestry 1/2004, Finland, In Finnish with English summary.

Ministry of the Environment 2007 *Vesiensuojelun suuntaviivat vuoteen 2015. Valtioneuvoston periaatepäätös*. Finnish Government Decision-in-Principle on Water Protection Policy Outlines to 2015. Suomen ympäristö 10.

Mitikka, S. & Britschgi, R. 2005 *Report on the Implementation of the Nitrates Directive in Finland 2004*. The Finnish Environment 741.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptional models. 1. A discussion of principles. *J. Hydrol.* **10**, 282–290.

Niinioja, R. 1993 *Lietelannan levitys ja ravinteiden huuhtoutuminen*. Vesi- ja ympäristöhallinnon julkaisuja–sarja A 150.

Räike, A., Pietiläinen, O.-P., Rekolainen, S., Kauppila, P., Pitkänen, H., Niemi, J., Raateland, A. & Vuorenmaa, J. 2003 Trends of phosphorus, nitrogen and clorophyll a concentrations in Finnish rivers and lakes in 1975-2000. *Sci. Total Environ.* **310**, 47–59.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P., Jones, C., Meier, H. E. M., Samuelsson, P. & Willén, U. 2004 European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Climate Dyn.* **22**, 13–31.

Rankinen, K., Granlund, K. & Bärlund, I. 2004 Modelling of seasonal effects of soil processes on N leaching in northern latitudes. *Nord. Hydrol.* **35**, 347–357.

Rankinen, K., Kenttämies, K., Lehtonen, H. & Nenonen, S. 2006 Nitrogen load predictions under land management scenarios for a boreal river basin in northern Finland. *Boreal Environ. Res.* **11**, 213–228.

Rankinen, K., Salo, T., Granlund, K. & Rita, H. 2007 Simulated nitrogen leaching, nitrogen mass field balances and their correlation on four farms in south-western Finland during the period 2000-2005. *Agric. Food Sci.* **16**, 407–420.

Rekolainen, S., Kauppi, L. & Turtola, E. 1992 Maatalous ja vesien tila. MAVEROn loppuraportti. *Luonnonvarajulkaisuja 15. Luonnonvarainneuvosto*. Maa- ja metsätalousministeriö, Helsinki.

Salo, T., Lemola, R. & Esala, M. 2007 National and regional net nitrogen balances in Finland in 1990-2005. *Agric. Food Sci.* **16**, 366–375.

Statistics Finland 2004 *Statistical Yearbook of Finland 2004*.

Tamminen, T. & Andersen, T. 2007 Seasonal phytoplankton nutrient limitation patterns as revealed by bioassays over Baltic Sea gradients of salinity and utrophication. *Marine Ecol-Prog. Ser.* **340**, 121–138.

Vähätalo, A. V. & Wetzel, R. G. 2004 Photochemical and microbial decomposition of chromophoric dissolved organic matter during long (months-years) exposures. *Marine Chem.* **89**, 313–326.

Vähätalo, A. V. & Zepp, R. G. 2005 Photochemical mineralization of dissolved organic nitrogen to ammonium in the Baltic Sea. *Environ. Sci. Technol.* **39**, 6985–6992.

Valpasvuo-Jaatinen, P., Rekolainen, S. & Latostenmaa, H. 1997 Finnish agriculture and its sustainability: environmental impacts. *Ambio* **26**(7), 448–455.

Vehviläinen, B. 1994 *The Watershed Simulation and Forecasting System in the National Board of Water and the Environment*, (**Vol. 17**). Publications of Water and Environment Research Institute, Helsinki, pp. 3–16.

Vuorenmaa, J., Rekolainen, S., Lepistö, A., Kenttämies, K. & Kauppila, P. 2002 Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. *Environ. Monit. Assess.* **76**, 213–248.

Wade, A., Durand, P., Beaujoan, V., Wessels, W., Raat, K., Whitehead, P. G., Butterfield, D., Rankinen, K. & Lepistö, A. 2002 Towards a generic nitrogen model of European ecosystems: New model structure and equations. *Hydrol. Earth Syst. Sci.* **6**, 559–582.

Wade, A. J. 2004 Errata in INCA-N equations to simulate nitrogen storage and transport in river systems. *Hydrol. Earth Syst. Sci.* **8**, 858–859.

Whitehead, P. G., Wilson, E. J. & Butterfield, D. 1998 A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): part I-model structure and process equations. *Sci. Total Environ.* **210-211**, 547–558.

Wivstad, M., Dahlin, A. S. & Grant, C. 2005 Perspectives on nutrient management in arable farming systems. *Soil Use Mngmnt.* **21**, 113–121.

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