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Assessing impacts of alternative agricultural land use scenarios on nitrogen leaching with the INCA-N model

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Abstract

The Integrated Nutrients Model for Catchments – Nitrogen (INCA-N) model was applied in Savijoki, a small (15.4 km^2) agricultural catchment, in order to analyse possibilities to achieve the targeted 50% reduction in agricultural nitrogen loading. The model was applied for the years 1995–1999, representing the first period of the Finnish Agri-Environmental Programme, a widely adapted policy measure for controlling environmental impacts of agriculture in Finland. Firstly, the model was applied to the present agricultural conditions and the results were compared with observed nitrogen loads (Baseline scenario). Secondly, six different scenarios of agricultural land use and management practices were analysed with the INCA-N model: afforestation of agricultural land, grass cultivation, cereal cultivation with direct sowing, cereal cultivation with stubble and reduced tillage, cereal cultivation with autumn ploughing and bare fallow. For the scenarios the calculated average NO_3-N loads varied from approximately 40 kg N km^{-2} a^{-1} (afforestation) to 740 kg N km^{-2} a^{-1} (bare fallow). The loads increased with increasing efficiency of agricultural soil manipulation and related decrease in winter vegetation cover. Methods in which the agricultural soil was assumed to remain undisturbed during winter (stubble and direct sowing) decreased NO_3-N export remarkably (34 and 56%, respectively) compared to the observed load.

1. Introduction

Agricultural production is the major source of diffuse nutrient loading to watercourses in Finland. Total nutrient load from catchments depends strongly on the proportion of agricultural land (Rekolainen 1989). To date, studies in Finnish agricultural catchments and river basins have indicated only minor reduction of nutrient loads, despite massive efforts towards environmentally sound management practices, e.g. introduction of the Finnish Agri-Environmental Programme in 1995 (FAEP, Valpasvuo-Jaatinen *et al*. 1997), a massive and widely adopted (more than 90% of the farms participating) policy measure for controlling nutrient losses from agriculture. Water protection policy has aimed at a significant, as high as 50% reduction of nutrient loads due to increased concern about water quality in inland waters and the Baltic Sea (Ministry of the Environment 1998).

In Finland, the Integrated Nitrogen Model for Catchments (INCA-N) (Whitehead *et al*. 1998; Wade *et al*. 2002) has been successfully tested and applied to the analysis of nitrogen leaching related to forestry and agricultural practices at catchment scale (e.g. Rankinen *et al*. 2002; Rankinen *et al*. 2004, Granlund *et al*. 2004). In order to analyse possibilities to achieve the proposed 50% reduction in agricultural nitrogen loading, the INCA-N model is being applied in Savijoki, a small (15.4 km^2) agricultural catchment which represents well the intensively cultivated areas of south-western Finland. The aim of this study was to use the calibrated INCA-N model (Granlund *et al*. 2004) to analyse nitrogen loading in the Savijoki catchment under changing agricultural land use conditions using five years of hydrological data (years 1995–1999) as input to the model. The selected years represent the first period of the FAEP. Firstly, the INCA-N model was run for present agricultural land use conditions and the simulated NO_3-N loads were compared with the observed loads for the years 1995–1999. Secondly, the model was run with six different agricultural land use and management scenarios representing different levels of field soil manipulation: afforestation of agricultural land, grass cultivation, cereal cultivation with direct sowing, cereal cultivation with stubble and reduced tillage, cereal cultivation with autumn ploughing and bare fallow. NO_3-N loading results from the different modeled cultivation scenarios were compared with observed values in order to analyse the effectiveness of the selected scenarios.

2. Material and methods

The Savijoki catchment is located in south-western Finland in the southern boreal zone, about 30 km northeast of the city of Turku (60°36', 22°40'). It is a small, agriculture-dominated sub-catchment (15.4 km^2) of the River Aurajoki that discharges to the Baltic Sea. Savijoki contains no lakes and belongs to the Finnish network of small representative catchments, originally established for hydrological research in 1957 (e.g. Seuna 1983). Agriculture is the main source of diffuse nutrient losses in the Savijoki catchment (Rekolainen 1989). Livestock density and the area of grassland are relatively low and spring cereals are the most common crops, which is typical in this part of the country.

The Integrated Nutrients Model for Catchments – Nitrogen model (INCA-N) (Whitehead *et al*. 1998; Wade *et al*. 2002) is a process-based and semi-distributed model that integrates hydrology, catchment and river N processes to simulate daily concentrations of NO_3-N and NH_4-N in river systems. In the INCA-N model, hydrologically effective rainfall (HER) is the input to the soil water storage driving water flow and N fluxes through the catchment system (Whitehead *et al*., 1998). Catchment hydrology is modeled with a simple two-box approach, including reservoirs of water in the reactive soil zone and in the deeper groundwater zone. Nitrogen processes are modeled in the land phase for different land use classes (crop covers). Nitrogen processes in the river water include nitrification and denitrification.

Daily input data on HER for the years 1995–1999 was used to run the INCA-N model at the Savijoki catchment. In Savijoki almost all farms (29 out of 30 farms) were participating in the FAEP. Accordingly, it was assumed that environmentally sound management practices were adapted by all farmers already in 1995. In the baseline scenario simulation six land-use classes were defined for the Savijoki catchment, five of them representing the main crop types cultivated in the agricultural fields (barley and oats 17%, spring wheat 12%, oilseed 2%, grass 5%, green fallow (for set-aside) and others 3% of the catchment area, respectively) and one representing the managed forested area and the scattered settlement (61%). For agricultural area the crop-specific inorganic N fertilization rates set by the FAEP for the first period (1995–1999) were used as input.

Next, the model was run with six different agricultural land use and management scenarios representing different levels of field soil manipulation: afforestation of agricultural land (AF), grass cultivation (GL), spring cereal cultivation with direct sowing (DS), spring cereal cultivation with reduced tillage and stubble left on soil for winter (ST), spring cereal cultivation with normal autumn ploughing (NP) and bare fallow (BF). The scenarios GL, DS, ST and NP are included in the VIHMA model – a decision support system developed as a planning tool for allocation of mitigation measures against erosion and nutrient loading (Puustinen *et al*. 2005). The selected cultivation methods affect characteristics of the field surface in different ways, key factors being the date and intensity of tillage, vegetation cover during winter and the stability of the vegetation cover (Puustinen & Linjama 2005). The theoretical scenarios AF and GL were simulated to demonstrate model output in these extreme land use conditions.

Because INCA-N does not allow a direct simulation of all these effects, it was assumed that different cultivation practices change N mineralization rates in soil. Thus, mineralisation parameters were calibrated for each of the scenarios by comparing the simulated land use loads with observed ones found in the literature for similar conditions (BF and AF scenarios). For GL, DS, ST and NP scenarios, the specific land use loads were calibrated based on loading coefficients included in the VIHMA model.

3. Results and discussion

The observed annual exports of Tot-N, NO_3-N and NH_4-N varied considerably during 1995–1999. The mean Tot-N export was 858 kg N km^{-2} a^{-1}. On average 64 % of the annual Tot-N export was in the form of NO_3-N, whereas the relative contribution of NH_4-N was low (on average 4% of the annual Tot-N load).

The INCA-N model was able to simulate the overall concentration level of NO_3-N in the stream during 1995–1999 in the baseline conditions, although high concentration peaks were not predicted by the model. The simulation of annual export from the catchment was rather good for NO_3-N, except in year 1995. The high load in 1995 was probably due to a major change in land use: in south-western Finland the proportion of green set-aside, originally covering approximately 20% of field area on each farm, decreased in 1995 and fields were taken into cereal cultivation when implementing the Common Agricultural Policy of the EU. The average simulated NO_3-N export for five years was 438 kg N km^{-2} a^{-1} and the observed export was 556 kg N km^{-2} a^{-1}.

The selected agricultural scenarios represented typical cultivation methods, changing gradually from intensive autumn tillage (scenario NP) to permanent grass cover (scenario GL). Additionally, two theoretical land use conditions were used to demonstrate nitrogen losses in extreme conditions: bare fallow (scenario BF) and afforestation (scenario AF) for agricultural land. As would be expected, the modeled average NO_3-N export from the catchment was highest for bare fallow conditions (743 kg N km^{-2} a^{-1}) and lowest for afforestation (40 kg N km^{-2} a^{-1}). Modeled NO_3-N export was 34% higher than the observed average for BF conditions and approximately 90% lower for AF conditions. If all agricultural land was under cereal production with normal autumn ploughing (scenario NP), NO_3-N export was of the same order or somewhat higher than the observed export during 1995–1999. All of the scenario simulations for NO_3-N export were lower than that observed in 1995. If all fields were under grass cultivation (scenario GL), the NO_3-N export was 30% of the observed average. Cereal cultivation with stubble (scenario ST) or direct sowing (scenario DS) approximately halved the NO_3-N export (66% and 44% of the observed average, respectively) (Fig. 1).

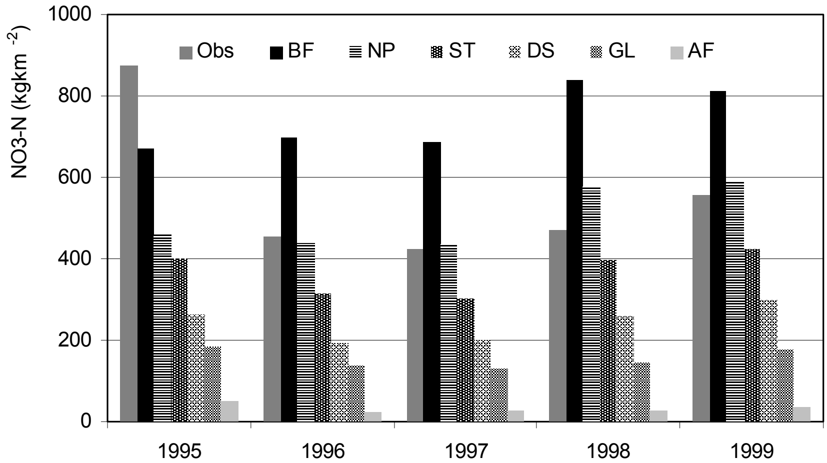

Figure 1. Observed and simulated annual exports of NO_3-N in Savijoki catchment during 1995–1999 for different land use and management scenarios: BF=bare fallow, NP=spring cereal with intensive autumn ploughing, ST=spring cereal leaving stubble on the field over winter, DS=spring cereal with direct sowing, GL=permanent grass ley cultivation, AF=afforestation of agricultural land.

The scenario simulations indicated that in the Savijoki catchment a remarkable reduction of nitrogen export can be achieved by introducing reduced tillage practices (direct sowing) and an increased amount of winter vegetation cover (grass cultivation or stubble left on soil) on agricultural land. These measures are already included in FAEP: environmental support is paid to farmers for undertaking them. Some of the measures had already been adopted since 1980 within the agri-environmental policy in Finland by means of guidance, education and voluntary compliance with good agricultural practices (Niemi and Ahlstedt, 2005). Direct sowing is becoming more popular in Finland, due to the shorter working time and lower cultivation costs. It has been estimated that more than 4.5% of the total area of cultivated land will be under direct sowing this year (Alakukku et al., 2004; Alakukku, 2005).

Today, grass cultivation is not very common in the Savijoki catchment (on average 11% of the agricultural area during 1999–2002), mostly due to the rather low number of cattle farms (3 farms in the year 2002). It is obvious that a monoculture of grass ley on all agricultural land in Savijoki is not probable, although it would provide a high reduction of nitrogen load. The scenarios for afforestation and bare fallow on agricultural land are most probably also realistic only in limited areas, but they were included in the simulations in order to provide some idea of the potential range in nitrogen export in extreme conditions.

4. Conclusions

The INCA-N model was applied in the Savijoki catchment to analyse possibilities to achieve the targeted 50% reduction in agricultural nitrogen loading. Six different scenarios of agricultural land use and management practices were simulated. The results indicated that a gradual change towards permanent vegetation cover is essential for achieving a remarkable reduction in nitrogen load. This is especially important in southern Finland, where the proportion of agricultural land in river basins is relatively high and conditions for nitrogen leaching during winter-time are favourable. So far, the differences between regions and farms have received minor attention in the environmental support. Permanent vegetation cover should be especially targeted in southern and coastal Finland when implementing the Water Framework Directive and when planning the new Agri-Environmental Programme for the coming years.

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