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The effect of forest cutting on the quality of groundwater in large aquifers in Finland

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The effects of forest cuttings on the level of the groundwater table and the quality of groundwater in large aquifers in Finland were studied by interpreting the long-term data from three groundwater monitoring stations together with information about the forest management history. Groundwater nitrate concentrations increased after clear-cuttings and thinnings for several years after the operations. However, the nitrate concentrations remained low (< 2 mg l^{-1}) even after the treatments. None of the changes in the groundwater level or in the other studied variables (electrical conductivity, alkalinity, pH, ammonium, chloride, sulphate, sodium, potassium, calcium and magnesium) could be attributed to the forestry operations.

Introduction

In Finland, forests cover ca. 86% of the land area and most of them are intensively managed (Peltola 2001). Annually thinning is carried out on 300 000–400 000 ha (1%–2% of the land area) and final cuttings on 150 000 ha. Soil preparation is often carried out before regeneration on final cut areas. Two thirds of the forests are growing on upland mineral soils and one third on peatlands. Of the upland mineral forest soils, 76% comprise glacial till and the other 24% glacial or postglacial sediments consisting mainly of gravel and sand. Many of these gravel and sand deposits are important groundwater recharge areas. The groundwater resources in Finland have been inventoried, and those which are potential sources of municipal water supply cover 9235 km^2 (Class I and II), i.e. 3.5% of the land area (Britschgi and Gustafson 1996). The forest management methods used on groundwater recharge areas do not differ from those in the other forest areas. Only intensive soil preparation methods and fertilization are avoided in order to diminish the risk of nutrient leaching into the groundwater. After cuttings more precipitation reaches the soil surface but, at the same time, dry deposition is reduced due to the removal of the tree canopies (Piirainen 2002, Piirainen *et al*. 2002). Total deposition of sulphur and base cations on the forest floor decreases, and that of ammonium and nitrate nitrogen increases, after coniferous forest is clear cut (Piirainen 2002, Piirainen *et al*. 2002). Growth in the coniferous forests of Fennoscandia is usually nitrogen limited, and nutrient cycling is efficient with minor losses (Tamm 1991). This efficient cycle can be disturbed by the removal of trees, which results in almost complete cessation of nutrient uptake. The logging residues left on the ground after harvesting start to decompose and the nutrients are released (Hyvönen *et al*. 2000). Higher soil moisture and temperature and the increased pH and availability of ammonium after harvesting can promote nitrification, which is usually at a low level in boreal forest soils (Martikainen 1984, Paavolainen and Smolander 1998, Smolander *et al*. 1988). These phenomena can result in the increased export of nutrients into the groundwater.

There are no systematic studies on the effects of forest cuttings on the level of the groundwater table or on the quality of groundwater in large aquifers in the boreal forest zone of Fennoscandia. However, a number of studies have focussed on the effects of clear cuttings on the depth of the groundwater table or on the quality of groundwater on peat or glacial till soils, where groundwater conductivity is usually low and groundwater is of little significance as a household water resource. The most pronounced effect of clear-cutting has been an increase in nitrate concentrations (Wiklander 1981, Wiklander *et al*. 1991, Kubin 1995, 1998). A positive relationship has also been found between the intensity of clear-cutting and the magnitude of the increase in the level of the groundwater table (Lundin 1979, Päivänen 1982). The conductivity of water in the vadose zone is higher in deposits of large aquifers consisting of sand and gravel than in glacial till or peat. Although this might facilitate the transport of water and elements into the groundwater, large groundwater reservoirs are better able to dilute any changes in element concentrations. The effects of thinning operations on the quality of groundwater have not been studied, but they are probably smaller than those of clear-cuttings due to the smaller reduction in tree nutrient uptake and transpiration and the absence of soil preparation.

The quality of groundwater in Finland is generally good as measured by the nitrate concentrations, which are usually below 5 mg l^{-1}. Although the nitrate concentrations in groundwater in some restricted areas can be as high as 20–30 mg l^{-1}, these levels are still well below the upper limit of 50 mg l^{-1} set for household water in Finland (Suomen säädöskokoelma 2000). Concentrations exceeding 15 mg l^{-1} indicate anthropogenic pollution and should be monitored (Finnish Water and Waste Water Works Association 2000).

The aim of this study was to investigate the effects of forest cuttings on the level of the groundwater table and on groundwater quality in large aquifers located in coniferous forest areas in Finland. This was carried out using data from the national monitoring programme carried out by the Finnish Environment Institute and the Regional Environment Centres for evaluating changes in the groundwater table and the quality of large aquifers together with forest cutting history information obtained from land owners.

Material and methods

Study areas

The groundwater monitoring network was constructed in Finland in the beginning of the 1970s on aquifers where human impacts on the quantity and quality of groundwater were small (Soveri *et al*. 2001). The network consists of 53 groundwater observation stations representing different Quaternary formations and climatic and terrain conditions. Data covering a period of 22 years (1975–1997) in two areas located in Valkeala and Pyhäntä, and a period of 20 years (1975–1995) in Lammi, were used in the study (Fig. 1). The period for Valkeala had to be shortened because a housing estate, which could have had an effect on groundwater quality, was built in the area at the end of the 1990s. The area in Lammi is located on the Tullinkangas aquifer, the area in Valkeala on the Utti aquifer and the area in Pyhäntä on the Vörssinvaara–Järvienkangas aquifer. The total estimated yield of the Tullinkangas aquifer is about 5000 m^3 day^{-1} and the total groundwater recharge area 7.8 km^2. The corresponding values for the Utti aquifer are 12 600 m^3 day^{-1} and 15.4 km^2, and for the Vörssinvaara–Järvienkangas aquifer 3500 m^3 day^{-1} and 5.2 km^2 (National Board of Waters and Environment 1992, 1994, 1995).

The three study areas represent different types of large aquifers, where the Precambric bedrock is covered by layers of glacial and postglacial sediments, consisting mainly of sand and gravel. Two of the areas are located in ice marginal formations (Lammi and Valkeala) and one in a glaciofluvial esker (Pyhäntä). There were no large gravel-extraction sites, settlements or agriculture in the areas. Valkeala was the only area with a road with heavy traffic. Cuttings were the major human impacts in the study areas and cutting history was available for the period 1975–1997.

Groundwater flow and table

The level of the groundwater table was measured twice a month in 10–12 groundwater tubes in each area. The data were used to determine the direction of groundwater flow and the area supplying most of the water (immediate groundwater recharge zone) to the spring/weir where the water quality samples were taken with the Surfer 7.0 computer software (Figs. 2, 3 and 4).

The area of the immediate groundwater recharge zone of the spring investigated in Lammi is 0.5 km^2 and the yield of the spring 0.4 l s^{-1} (Soveri *et al*. 2001). According to the soil maps (1:20 000; Kukkonen *at al*. 1985) and soil sampling carried out at the time the groundwater tubes were installed, the soils in the vicinity of the spring are mainly sand and gravel and the main groundwater flow direction is from west to east. The groundwater table was, on average, 0.9–2.4 m below the soil surface. In Valkeala the area of the immediate groundwater recharge zone is 1.0 km^2 and the yield of the spring 10–15 l s^{-1} (Soveri *et al*. 2001). The groundwater table was 0.2–1.7 m below the soil surface. The sediments in the vicinity of the spring consist mainly of sand, silt and peat (Rainio *et al*. 1987). The main groundwater flow direction is from south to north. A major road runs through the southern parts of the immediate groundwater recharge zone. In Pyhäntä the area of the immediate groundwater recharge zone is 0.7 km^2 and the yield of the measuring weir 1.3 l s^{-1} (Soveri *et al*. 2001). The sediments in the vicinity of the spring consist mainly of sand and gravel, and include some finer material. The main groundwater flow direction is from southeast to northwest, and the groundwater table was 0.4–8.7 m below the soil surface.

Fig. 1. Location of the study areas.

Groundwater quality and the amount of atmospheric deposition

Groundwater was sampled from one spring or measuring weir in each area. The samples were taken at the same point throughout the whole observation period. During 1975–1979 the samples were taken once a month, and from 1980

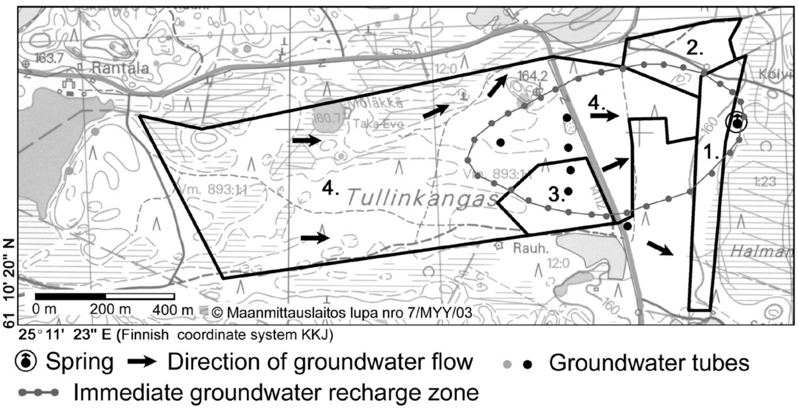

Fig. 2. Locations of the forest stand compartments, groundwater tubes, spring and the immediate groundwater recharge zone in the Lammi area. The number of forest stand compartments refers to Table 1.

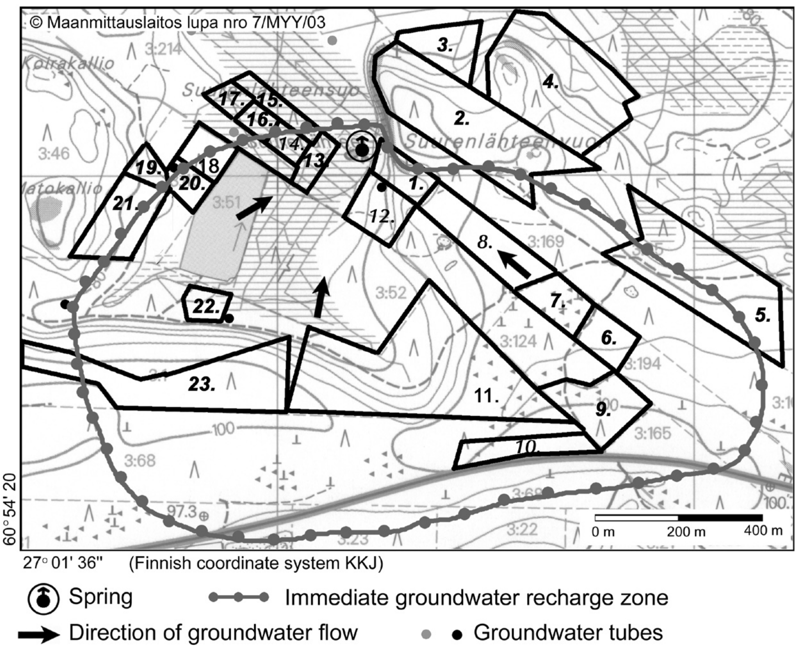

Fig. 3. Locations of the forest stand compartments, groundwater tubes, spring and the immediate groundwater recharge zone in the Valkeala area. The number of forest stand compartments refers to Table 1.

onwards every second month. The samples were analysed for electrical conductivity, alkalinity, pH, nitrate, ammonium, chloride, sulphate, sodium, potassium, calcium and magnesium in the laboratories of the Finnish Environment Institute or the Regional Environment Centres. Ammonium was determined spectrophotometrically, sulphate and chloride by ion chromatography, and base cations (calcium, magnesium, potassium, sodium) by atomic absorption spectrophotometry. The nitrate analysis methods changed during the observation period, but tests showed that this had no effect on the results. The sampling and chemical analyses were based on standard methods (Erkomaa and Mäkinen 1975, National Board of Waters 1981, Mäkelä *et. al.* 1992). The detection limit for nitrate was 5 μg l^{-1}. More details of the sampling and analysis methods are also given by Soveri *et al.* (2001).

The amount of bulk precipitation, evaporation and atmospheric deposition of nitrate in the areas were derived from the nearest atmospheric deposition monitoring station run by the Finnish Environment Institute (Hydrological yearbook 1972–1975, 1976–1977, 1978–1979, 1980, 1981–1983, 1984–1986, 1987–1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, Järvinen 1986, Järvinen and Vänni 1989–1999) In the Lammi area the nearest station was located at a distance of 13 km, in the Valkeala area 45 km, and in the Pyhäntä area 20 km.

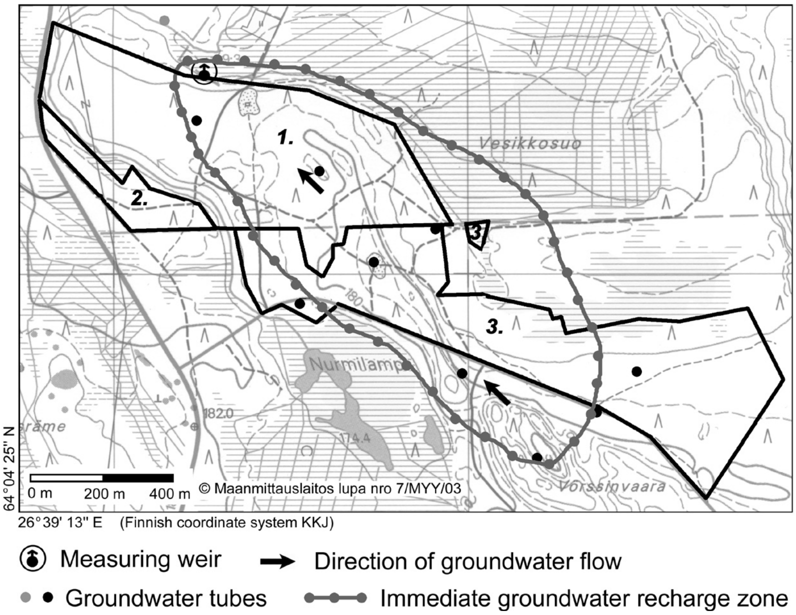

Fig. 4. Locations of the forest stand compartments, groundwater tubes, spring and the immediate groundwater recharge zone in the Pyhäntä area. The number of forest stand compartments refers to Table 1.

Table 1. Forest stand compartments and their area in the Lammi, Valkeala and Pyhäntä areas during 1975–1996 (1975–1995 in Lammi).

Forest cutting operation and the year implemented	Number of forest stand compartments	Total area of forest operation (ha)	Percentage of the immediate groundwater recharge zone
Lammi			
Clear-cutting and harrowing 1980	1	7	10
Clear-cutting and harrowing 1980	4	65	56
Clear-cutting and harrowing 1992	3	6	13
Clear-cutting and harrowing 1993	2	5	5
Valkeala			
Clear-cutting 1980	7	2	1
Clear-cutting 1980	8	4	3
Clear-cutting 1980	12	2	1
Clear-cutting 1982	13	0.5	0.6
Natural regeneration 1982	16	0.6	0.7
Thinning 1984	18	0.6	0.7
Natural regeneration 1983	11	7	10
Natural regeneration 1984	23	0.8	0.6
Clear-cutting 1984–1985	3	2	–
Clear-cutting 1984–1985	4	8	–
Clear-cutting 1985–1987	5	8	2
Clear-cutting and harrowing 1985–1987	2	8	0.7
Natural regeneration 1985	21	2	0.6
Clear-cutting 1987	10	1	2
Natural regeneration 1987 and harrowing 1988	1	2	1
Natural regeneration and harrowing 1987	6	1	1
Natural regeneration 1993	9	2	2
Pyhäntä			
Thinning 1984–1985	1	39	35
Thinning 1995	2	5	–
Thinning 1996	3	40	29

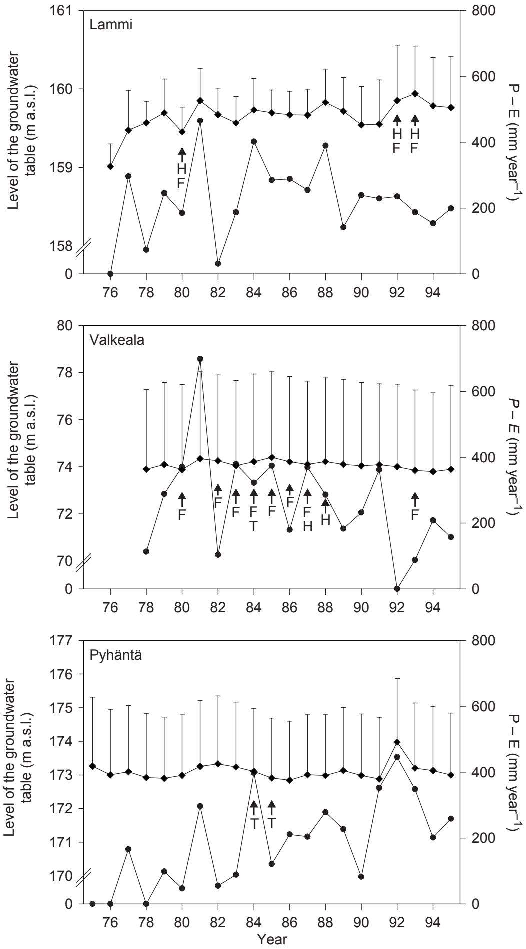

Fig. 5. The annual average level of the groundwater table (upper line) and the difference between precipitation and evaporation (*P* – *E*) (lower line) at the nearest monitoring station in the Lammi, Valkeala and Pyhäntä areas. F = Final cutting = Clear-cutting or natural regeneration, H = Harrowing, T = Thinning. Standard deviations of the level of the groundwater table are indicated above the lines.

Forest cutting history

The forest cutting history information was obtained from the landowners, the Regional Forest Centres, the Finnish Forest and Park Service and the Forest Management Associations. They included the location, type, area and the year of the forest cutting, and the location, area and the year of soil preparation if used (Table 1). Field surveys were also carried out on the areas. In the Lammi area clear-cutting, followed by soil preparation, covered 66% of the immediate groundwater recharge zone in 1980, but during 1992–1995 the cuttings were carried out on a smaller area. In Valkeala clear-cuttings and thinnings were made throughout the whole study period. They covered a total of 27% of the immediate groundwater zone, and the largest cutting (10% of the area) was made in 1983. In Pyhäntä forest thinnings were made in 1984, 1985 and 1996. The thinnings in the 1980s covered 35%, and those in 1996 29% of the immediate groundwater recharge zone.

Analysis of the results

Changes in groundwater quality and level were compared with the timing of forestry operations. The level of the groundwater table was also compared with the difference between precipitation and evaporation, and the changes in nitrate concentrations of the groundwater to the changes in the amount of nitrate deposition.

Results

The data did not indicate any clear effects of cuttings on the level of the groundwater table at any of the sites (Fig. 5).

We studied the changes in groundwater electrical conductivity, alkalinity, pH, nitrate, ammonium, chloride, sulphate, sodium, potassium, calcium and magnesium (data not shown), but found that only the changes in nitrate concentrations could be attributed to forest cuttings. The mean annual nitrate concentration of the groundwater was 0.25 mg l^{-1} in Lammi, 0.38 mg l^{-1} in Valkeala and 0.12 mg l^{-1} in Pyhäntä during the study period. In Lammi the groundwater nitrate concentrations increased after clear cutting in 1980, and returned to the level before cutting within 6–7 years (Fig. 6). The increase in the annual maximum groundwater nitrate concentrations was greater than that in the mean annual nitrate concentrations. In Valkeala the cuttings, which covered 17% of the immediate groundwater recharge area during 1980–1983, were followed by an increase in the groundwater nitrate concentrations (Fig. 6). The concentrations started to decrease from the year 1985 onwards, even though several small cuttings were made during 1984–1989. The changes in the annual maximum nitrate concentrations followed those in the mean annual concentrations. In Pyhäntä the thinnings were carried out during 1984–1985 on 35% of the immediate groundwater recharge area (Table 1). The groundwater nitrate concentrations increased 3–4 years after thinnings, and were still at a higher level at the end of the study period (Fig. 6). Changes in the nitrate concentration in groundwater did not follow the changes in the amount of atmospheric nitrate deposition in Lammi and Pyhäntä, whereas in Valkeala there was a significant positive correlation (0.66, $p = 0.003$) between these two variables.

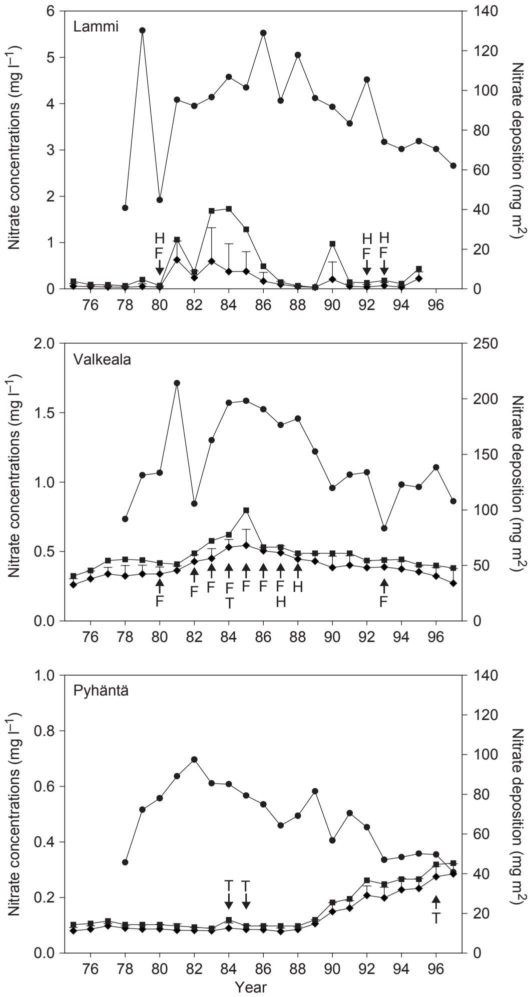

Fig. 6. Annual average and maximum nitrate concentrations in groundwater (two lowest lines) and the amount of atmospheric nitrate deposition (uppermost line) at the nearest monitoring station in the Lammi, Valkeala and Pyhäntä areas. F = Final cutting = Clear-cutting or natural regeneration, H = Harrowing, T = Thinning. Standard deviations of the groundwater nitrate concentrations are indicated above the lines.

Discussion

We utilised long-term monitoring data from groundwater monitoring stations and interpreted it together with forest management history information from areas in which atmospheric deposition and forest cuttings and soil preparation were the only major human impacts. This approach causes some problems in analysing the results. The lack of control areas with no cuttings, sampling from only one point in each area, and the fact that we did not have any information about the forestry measures carried out before the study period, were the weaknesses of the study. However, we were not able to devise any other explanations for the observed changes. The forestry measures were carried out according to the normal practices of the landowners, and we did not control their timing. The cuttings in 1980 in Lammi and those in 1984–1985 in Pyhäntä covered a significant proportion of the groundwater recharge zone, 66% and 35%, respectively. In the Valkeala area some operations were carried out in almost all the study years, which made it difficult to connect the changes to the forestry operations.

We could not detect any effects of cutting operations on the level of the groundwater table. Removal of the forest canopy increases the input of precipitation to the ground and decreases the transpiration, both of which can increase the groundwater recharge. However, these changes were probably so small compared to the volume of the aquifers that it was not possible to detect any such changes with the methods employed here. On peatlands and glacial till soils, where the groundwater table is closer to the soil surface and the vadose zone is narrower than in sand and gravel deposits, a clear increase has been observed in the groundwater table after cuttings (Lundin 1979, Päivänen 1982).

The increase in nitrate concentrations in Lammi and Pyhäntä most probably resulted from the cutting operations, whereas in Valkeala this was not as clear. In Valkeala the cuttings were carried out almost every year in the area, which makes it difficult to link the changes with forestry operations. The nitrate concentrations in groundwater were higher in Valkeala than in the other two areas throughout the study period. They also followed the changes in nitrate deposition, which was higher than that in the other areas. This might indicate that the forestry operations promoted a constantly increased input of nitrate of atmospheric origin into the groundwater. In Lammi the changes in the annual maximum nitrate concentrations after cuttings were much higher than those in the other two areas in nitrate concentrations. This could probably be due to the smaller groundwater recharge zone of the sampled spring. Our results indicating that the groundwater nitrate concentrations change for several years are in agreement with earlier findings from glacial till soils (Tamm *et al*. 1974, Wiklander 1981, Kubin 1995, 1998, Ahtiainen and Huttunen 1999, Wiklander *et al*. 1991). The effects of final cutting and soil preparation on the nutrient cycling of forest ecosystems are greater than those of thinnings, since only a small proportion of the trees are removed and no soil preparation is carried out in connection with thinnings. However, our results indicate that both treatments can affect groundwater nitrate concentrations.

In all the study areas the groundwater nitrate concentrations remained low after the forestry operations compared to the average concentrations in groundwater in Finland (0.96 mg l^{-1}) (Soveri *et al*. 2001), and also far below the critical values set for household water. In southern Sweden, where the level of nitrogen deposition of is much higher than that in our areas, the groundwater nitrate concentrations have increased from 2–14 mg l^{-1} to 20–30 mg l^{-1} after cuttings (Wiklander *et al*. 1991). We did not find any changes in other element concentrations in the groundwater after cuttings, as was the case in the boreal forest areas studied by Kubin (1995).

Conclusions

The effects of forestry operations on the level and quality of groundwater are difficult to detect on the basis of monitoring data with no control areas and no control on the timing and extent of the operations. However, since our knowledge on the effects of forest cuttings on the groundwater of large aquifers, which are important for the supply of household water, is very limited, these results are of considerable importance until the results from controlled experiments become available. Our results indicate that forest cuttings can increase groundwater nitrate concentrations for several years. They also show that groundwater nitrate concentrations on forested aquifers in low nitrate deposition areas remain very low even after the temporary changes caused by cuttings.

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