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Phosphorus retention properties of forest humus layer in buffer zones and clear-cut areas in southern Finland

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Hydrological losses of phosphorus (P) from forested areas have been reported to increase after harvesting operations. An efficient method of decreasing P losses has been to leave unmanaged buffer zones along forest brooks, streams and lakes. However, the processes controlling P retention by buffer zones are still not fully understood. To assess the importance of forest humus layer in P retention a small-scale survey was carried out at three buffer zones and adjoining clear-cut areas in southern Finland. In general, the humus layer in the buffer zones adsorbed more P than in clear-cut areas and the P adsorption was strongly related to the contents of oxalate extractable iron and aluminium. However, there were indications that the P retention capacity of the humus may decrease with the length of time the clear-cut area or buffer zone has been under the impacts of clear-cutting. There may be significant seasonal changes in humus P retention, but further studies are needed for a critical evaluation of the changes in humus P adsorption between seasons and years. Nevertheless, when compared with the increase in P release after harvest in a boreal forest, the maximum P retention capacity of the humus layer was small. Therefore, the role of the forest humus layer in P retention in clear-cut areas and buffer zones may be insignificant.

Introduction

In the northern boreal region, eutrophication of surface waters is attributed to an excess supply of nutrients, especially phosphorus (P) (Pietiläinen and Räike 1999). Hydrological losses of P from forested areas are generally low (Kortelainen and Saukkonen 1998, Mattsson *et al*. 2003), but after tree harvest operations leaching may increase (Ahtiainen and Huttunen 1999, Nieminen 2003). To prevent P from leaching to recipient water courses, it is recommended that riparian areas should be left unmanaged as buffer zones (Metsähallitus 1997).

Previous studies have shown that correctly designed and dimensioned buffer zones effectively reduce P losses (Ahtiainen and Huttunen 1999, Kubin *et al*. 2000, Silvan *et al*. 2005) although the processes that control P retention are not yet fully understood. P is mainly removed from the water passing through the buffer zone by biological uptake and adsorption by the soil matrix. However, in the northern boreal region the biological P uptake may be of low importance during critical loadings. In these regions with a distinct winter period, nearly half of the annual runoff generally occurs during a short snow-melt period in early spring (Kortelainen and Saukkonen 1998). Consequently, a significant proportion of the annual P load may enter the buffer zones during conditions when the biological P uptake is limited. Under such conditions, the adsorption of P by the surface soil of a buffer zone is the major sink for through-flow water P (Väänänen *et al*. 2006).

Phosphorus retention in soils and sediments is related to the amounts of iron (Fe) and aluminium (Al) oxides and hydroxides (e.g. Sample *et al*. 1980, Hartikainen 1982, Borggaard *et al*. 1990, Yuan and Lavkulich 1994, Li *et al*. 1999). These are abundant especially in upland forest soils with podzolized B horizons. The high P retention capacity of the B horizon is reflected in the concentrations of P in percolate water, which are generally much lower below the B horizon than above it (Piirainen *et al*. 2004). Therefore, under the conditions where the main direction of water flow is vertical the risk of P leaching from upland forests to recipient water bodies is low. However, during the snow-melt period, frost in the subsurface soil combined with high runoff may cause a significant proportion of water to flow horizontally in contact with only the shallow organic soil layer above the mineral soil, the humus layer. Under these early spring conditions the humus layer may be an important sink for P, but for critical evaluation of its contribution in P retention, the data collected so far are insufficient.

The retention of P in humus is mainly regulated by biological processes as uptake by plants and micro-organisms (Wood *et al*. 1984) whereas chemical retention, like in mineral soil, is related to the contents of Al and Fe (Giesler *et al*. 2002). As compared with the amounts of Fe and Al in the underlying mineral soil, these are generally low in the forest humus layer (Tamminen and Starr 1990, Westman 1990, Tyler 2004). This suggests that the forest humus layer may not be a considerable sink for P. However, because Al and Fe are often enriched in the surface soils of river banks and other groundwater-discharge areas (Giesler *et al*. 2002, Pellerin *et al*. 2002, Norrström 1995), the humus layer of buffer zones may adsorb more P than that in the other forest sites.

The changes in environmental conditions induced by harvesting may decrease humus P retention. One mechanism may be the increase in the supply of soluble P to the soil water (Palviainen *et al*. 2004, Piirainen *et al*. 2004). Moreover, harvesting increases the supply of organic and inorganic anions that compete with P for sorption sites (Larsen *et al*. 1959, Giesler *et al*. 2005). In the northern boreal region a decrease in the P retention capacity after harvesting may also occur because harvesting generally leads to a significant rise in the ground water table. During spring snowmelt a high ground water table that is stagnant for long periods is often observed in the buffer zones and other areas in the lowest parts of the catchments. Due to the reduction and redistribution of Fe, such waterlogged conditions could decrease retention of P (Mahapatra and Patrick 1969, Jensen *et al*. 1999).

Our aim was to quantify P adsorption in forest humus layer in the buffer zones and clear-cut areas at three small forested catchments, and determine the variations in P adsorption capacity between different seasons and years. The effect of the chemical properties of the humus layer on the P retention capacity was also assessed. Our hypothesis was that the adsorption by forest humus layer would be a relatively small sink for P and that the changes in environmental conditions caused by harvesting would further decrease the P retention efficiency of the humus layer.

Material and methods

Site description and sampling

The study was conducted at Janakkala (61°00´N, 24°43´E, 130 m a.s.l.) and Kuru (61°52´N, 23°41´E, 130 m a.s.l.) in southern Finland. The long-term (1961–1990) mean temperature at Janakkala is –6.1 °C in January and +16.4 °C in June and mean annual precipitation is 650 mm (Finnish Meteorol. Inst. 2002), approximately 200 mm of which falls as snow (National Board of Survey and Geographical Society of Finland 1987). Corresponding climatic data for the Kuru region is –7.3 °C, +15.5 °C, 680 mm and 250 mm.

One catchment area (C1) was selected at Janakkala and two areas (C2 and C3) at Kuru (Fig. 1 and Table 1). According to a Finnish forest site type classification (Cajander 1926), the catchment C1 is moderately fertile *Vaccinium myrtillus* (MT) type and the catchments C2 and C3 comprised sites belonging to both the MT-type and the less fertile *Vaccinium vitis-idaea* (VT) site type. Approximately 30% of the forest area in Finland belongs to the MT type and 32% to the VT type (Finnish For. Res. Inst. 2004).

The clear-cuttings were carried out using conventional stem-only harvesting, by which only stems down to a diameter limit of seven cm were removed. The harvested areas were prepared for planting by scarification and Norway spruce seedlings were planted one (C2 and C3) and two (C1) years after harvesting. At each area, a buffer zone was left along the main outlet ditch or brook. The width of the buffer strip was 10–35 m at C1, about 10 m at C2, and 20 m at C3.

The humus layer samples were taken along two sampling lines at C2 and one line at C1 and C3 (Fig. 1). At each sampling line, three 10 m × 10 m plots were located systematically: one at the highest elevation of the clear-cut area, one 10 m uphill from the border between the clear-cut area and the buffer zone, and one in the middle of the buffer zone. At each plot, the forest humus samples were taken from an undisturbed humus layer from five systematically located sampling spots using a cylindrical core sampler (diameter 5.7 cm). The samples were taken from the 0–6 cm layer, or if the humus layer was less than 6 cm, to the underlying mineral soil. Living plants, coarse litter and mineral soil particles were removed from the samples. The samples

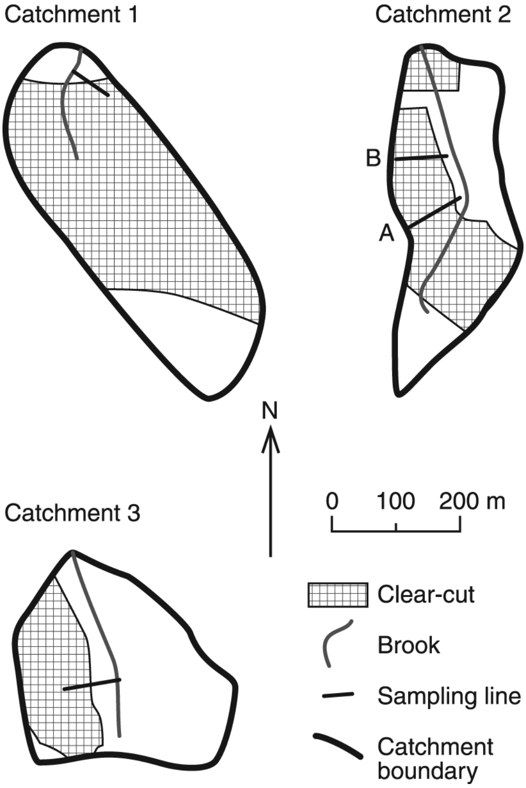

Fig. 1. The studied catchments and the sampling lines in Janakkala (Catchment 1) and in Kuru (Catchments 2 and 3).

Table 1. Basic information about the catchment areas.

	Catchment 1	Catchment 2	Catchment 3
Site type[a]	MT	VT/MT	VT/MT
Area (ha)	7.1	5.2	7.2
Buffer zone area (ha)	0.15	0.16	0.46
Stand volume (m^3 ha^{-1})	172	109	138
Pinus sylvestris (% of volume)	0	57	85
Picea abies (% of volume)	98	41	12
Betula spp. (% of volume)	2	2	2
Time of harvesting	Autumn 1997	Winter 1997–1998	Winter 1996–1997
Harvested area (ha)	5.4	2.1	2.8
Harvested volume (m^3 ha^{-1})	197	234	301

[a] According to Cajander (1926).

from the different sampling spots and plots were combined to one sample from the buffer zone and one from the clear-cut area from each catchment, besides at C2, where the samples from the two buffer zone plots were analysed separately.

The humus layer at the buffer zones differed from that at the surrounding upland soils in that the layer was thicker and had peat-like features, including residues of *Spahgnum* spp. In the Finnish peatland site type classification, where no minimum value for the thickness of the organic soil layer above the mineral soil is defined (Paavilainen and Päivänen 1995), the buffer strips at C2 and C3 would have been classified as shallow-peated mires and consequently the organic layer above the mineral soil would have been peat and not humus. However, in many other countries a minimum value for peat thickness is a criterion to separate peatlands from mineral soils (and peat from humus) (Paavilainen and Päivänen 1995 and references therein). In the present study, the organic soil surface down to the depth of –6 cm is referred to as humus no matter whether it was underlain by mineral soil or a shallow organic soil layer.

The first humus layer samples were collected in the first autumn after harvesting in 1997 in C1 and 1998 in C2 and C3. The sampling was repeated in 2001 from the same plots as in the first sampling. To study the seasonal changes in P adsorption properties, three samples from each plot were taken at different times in 2001: early spring samples on 25 April, mid-summer samples on 17 July, and late autumn samples on 1 October.

Laboratory analyses

The samples were frozen (–18 °C) until analysed in the laboratory. The P desorption-adsorption isotherms were determined according to the procedure described by Heikkinen *et al.* (1995). Samples of moist humus material (equivalent to 1 g dry weight) were added to bottles containing solutions (40 ml) with 0.0, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 or 10 mg l^{-1} of P. The bottles were shaken on a reciprocating shaker at 180 rpm for one hour and then left to equilibrate for 23 hours at 20 °C, after which the suspensions were shaken again for 5 min at 120 rpm. The suspensions were filtered through glass-fibre filters (Whatman GF/C) and a 0.2 μm membrane filter (Schleicher & Schuell GmbH ME 24) and the concentration of PO_4-P remaining in the filtrate determined colorimetrically using the molybdenum blue acid-reducing method and autoanalyser (LaChat Quickchem 8000).

Subsamples from the first sampling occasion were oven-dried (105 °C) and an acid (pH 3.0) ammonium oxalate buffer solution (0.2 M) was used to extract poorly crystalline compounds of iron (Fe_{ox}) and aluminum (Al_{ox}) (Wang 1981). The soil samples were shaken in the dark with the oxalate solution (1/25 d.w/v) for 4 h and filtered with paper filters (Schleicher & Schuell GmbH 589^3 Blue ribbon). Fe_{ox} and Al_{ox} were measured using an atomic absorption spectrophotometer (AAS Perkin Elmer 5100 PC). To characterize the general properties of humus in our study sites, oven-dried samples were used to calculate the bulk density (BD) and analyze basic chemical properties (Table 1). Total carbon (C) and nitrogen (N) was measured with the combustion method (Leco CNS 1000). The cation exchange capacity (CEC) was measured by extracting 1 g (d.w.) of humus sample with 50 ml of 0.1 M $BaCl_2$ solution. The bottles were shaken on a reciprocating shaker at 130 rpm for an hour and the suspensions were filtered with 0.2 μm membrane filter (Schleicher & Schuell GmbH ME 24). $BaCl_2$-exchangeable cations (Al_e, Fe_e, Mg_e, Ca_e, Mn_e, K_e) were then measured using inductively coupled plasma mass spectrometer (ICP-MS ELAN 6000). Soil pH was measured from an aliquot of the $BaCl_2$ extraction solution.

Calculations and statistical analyses

Two single-value adsorption indices were used to study the relationship between humus P adsorption and humus chemical properties, the differences in humus P retention between buffer zones and clear-cut areas and between the different sampling occasions. The P desorbed at 0 mg P l^{-1} addition level was used as the maximum desorption (P_0) and the P adsorbed or desorbed at 10 mg P l^{-1} level was referred to as the maximum P adsorption (P_{10}). The relationships between

Table 2. Characteristics of the humus layer in the studied catchments C1, C2 and C3. Bz = Buffer zone, Cc = Clear-cut area.

	C1		C2		C3	
	Bz	Cc	Bz	Cc	Bz	Cc
Al_{ox} (g kg^{-1})	3.5	1.4	4.9	1.2	1.1	0.8
Fe_{ox} (g kg^{-1})	5.2	1.9	7.9	1.5	2.7	0.9
BD (g dm^{-3})	65	146	70	115	54	95
C (%)	34	32	43	41	49	41
N (%)	1.7	1.4	2.0	1.3	2.0	1.3
CEC (mmol kg^{-1})	249	273	321	240	356	285
Al_e (mmol kg^{-1})	81	20	138	26	26	8
Fe_e (mmol kg^{-1})	12	4	19	4	12	2
Mg_e (mmol kg^{-1})	20	20	23	26	84	39
Ca_e (mmol kg^{-1})	94	173	90	101	173	177
Mn_e (mmol kg^{-1})	1	15	5	8	1	9
K_e (mmol kg^{-1})	11	13	12	21	23	22
pH	3.22	3.27	3.18	3.00	3.12	3.26

P_0 and P_{10} and the humus chemical properties were tested using the data from the first sampling occasion with simple Pearson correlation analysis. The P_0 and P_{10} data were also tested with a repeated measures ANOVA (Wilks' Lambda test) using sampling site within catchment (buffer zone *versus* clear-cut area) as the grouping factor and sampling time as the repeated or within factor. Two repeated measures tests were calculated: first, the between-year differences were tested by comparing the autumn data of 1997–1998 with that of 2001; and secondly, the seasonal variation was tested using the spring, summer and autumn data of 2001 (buffer zones $n = 4$, clear-cut areas $n = 3$).

Results

The humus layer at C1 had a slightly higher bulk density and lower carbon content than at the other two catchments (Table 2). At all three catchments, the N, Al and Fe contents were higher in buffer zones than in the clear-cut areas, but the contents of Mn were very low in the buffer zones, especially at catchments C1 and C3.

The humus P adsorption capacity was higher in the buffer zones than in the clear-cut areas (Figs. 2 and 3). The maximum adsorption (P_{10}) was significantly higher in the buffer zones than in the clear cut areas ($p = 0.006$) but there was no difference in the maximum desorption (P_0) between the buffer zones and clear cuts ($p = 0.238$). The correlations between P_{10} and the chemical and physical characteristics of the humus indicated that the variation in humus maximum P adsorption (P_{10}) mainly was explained by the variation in Al and Fe contents (Table 3). There were significant positive correlations between P_{10} and both oxalate and $BaCl_2$ extractable Al and Fe contents ($p < 0.05$). Other positive correlations between humus P retention properties and humus chemical parameters were between P_0 and N ($r = 0.673$; $p = 0.017$), and between P_{10} and K_e ($r = -0.584$; $p = 0.046$).

Table 3. Spearman correlation (r) between P_0 and P_{10}, and the chemical and physical properties of the humus. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

	P_0	P_{10}
Al_{ox}	0.445	0.794***
Fe_{ox}	0.518	0.840***
BD	–0.231	–0.431
C	–0.025	–0.160
N	0.673*	0.559
CEC	0.245	0.466
Al_e	0.473	0.762**
Fe_e	0.518	0.790**
Mg_e	–0.277	–0.310
Ca_e	0.049	–0.125
Mn_e	–0.466	–0.331
K_e	–0.350	–0.584*
pH	–0.035	0.331

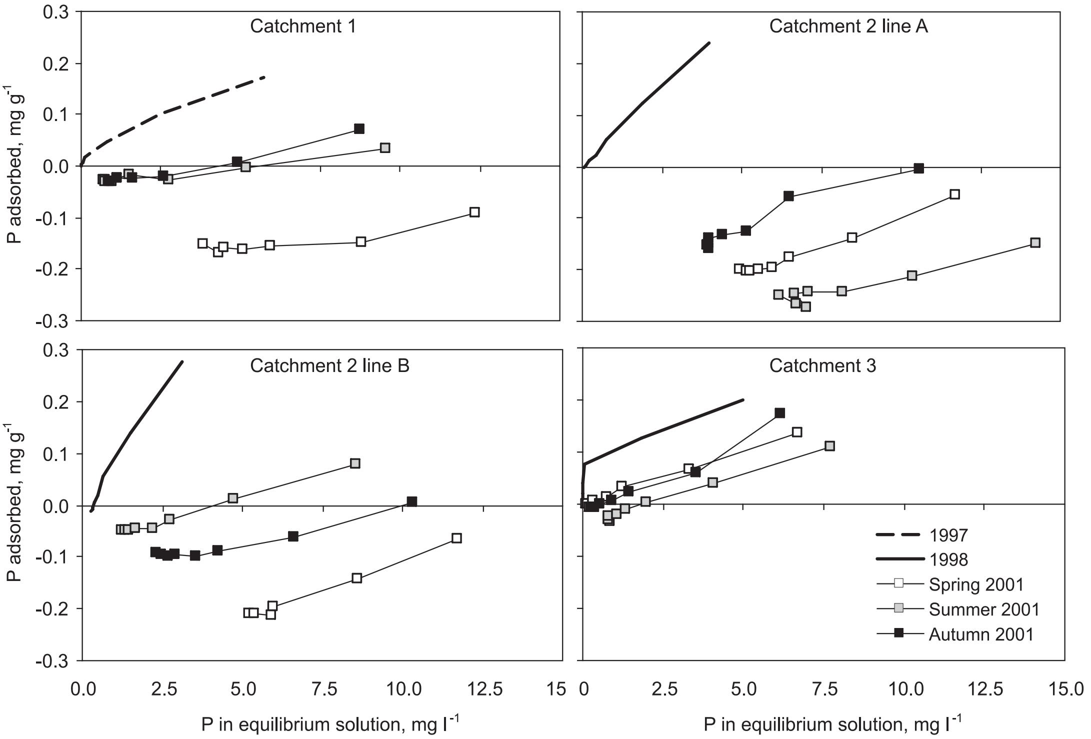

Fig. 2. Phosphorus desorption-adsorption isotherms of the humus in the buffer zones at the different times following harvesting.

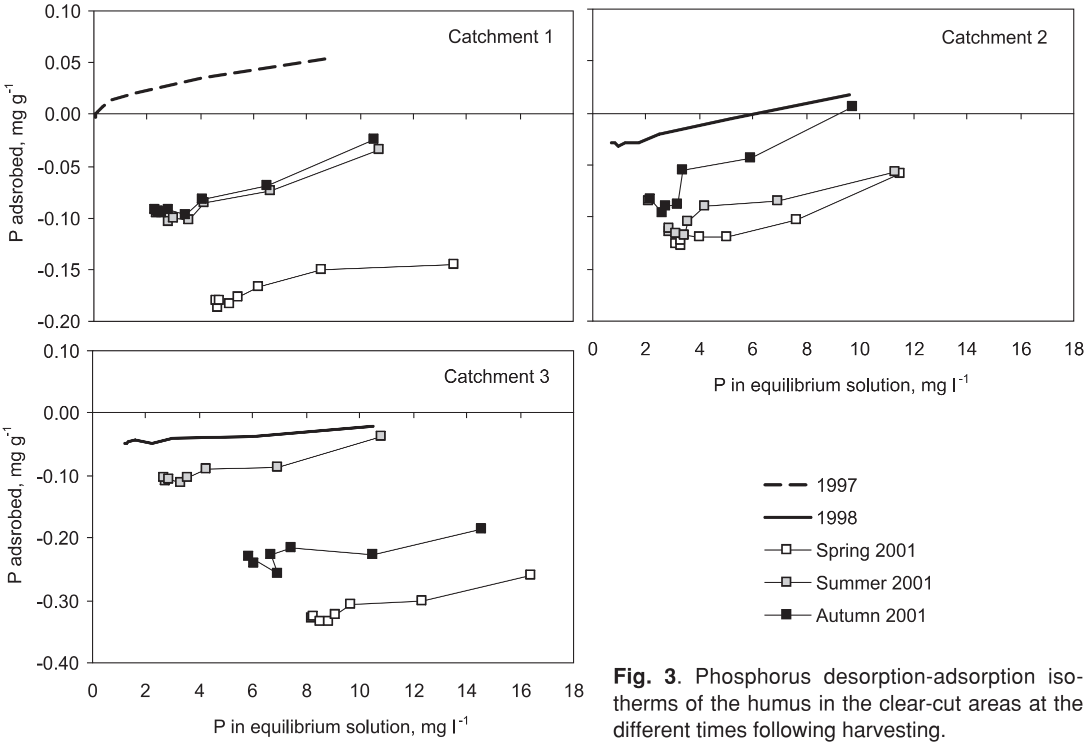

Fig. 3. Phosphorus desorption-adsorption isotherms of the humus in the clear-cut areas at the different times following harvesting.

Although the humus layer, especially in the buffer zones, had a noticeable P adsorption capacity in the first autumn after tree harvest (in 1997 or 1998), the capacity of the samples collected three to four years later, in 2001, was small. Both the P_0 and the P_{10} had decreased and the differences between the sample years were significant (P_0: $p = 0.018$ and P_{10}: $p = 0.024$). The differences between the spring, summer and autumn values of 2001 were also significant for both P_0 ($p = 0.050$) and P_{10} ($p = 0.036$).

Discussion

As suggested in our hypothesis, the P retention capacity of the forest humus layer was relatively low, and it resembled more the retention by peat (Kaila 1959, Cuttle 1983, Heikkinen *et al.* 1995, Nieminen and Jarva 1996, Väänänen *et al.* 2006) than by mineral soils rich in highly P sorptive Al and Fe compounds (Hartikainen 1982, Yuan and Lavkulich 1994, Li *et al.* 1999). The P sorption for the humus layer both in the buffer zones and clear-cut areas continued to increase gradually with increasing P concentration in the added solution and, typically for soils with low P retention capacity, a well-defined maximum adsorption level was not obtained. To overcome this problem, numerous adsorption indices and adsorption equations have been developed and applied to estimate the maximum adsorption (Bache and Williams 1971). By using the P_{10} value from the first autumn after harvest as an estimate for the maximum adsorption, the maximum P retention in the humus would have been 5–7 kg ha^{-1} for the three buffer zones and about 0–2 kg ha^{-1} for the clear-cut areas. As the increase in P supply from boreal forests after harvest may be 2–5 kg per harvested hectare annually (Palviainen *et al.* 2004, Piirainen *et al.* 2004), it is concluded that the forest humus layer in clear-cut areas and in the 5–20-m-wide buffer zones probably has little ability to retain P against leaching. During the first two years after the harvest were the hydrological losses of P from our study sites 0.07–0.13 kg ha^{-1} yr^{-1} (Haapanen *et al.* 2006). This suggests that the P that was mobilized after the harvest, and which was not adsorbed by the humus, was retained in the catchment by other processes. These processes, such as P accumulation by biota and adsorption by the Al- and Fe-rich B horizon, are probably more important sinks for P than the retention by the humus layer.

The results of this study agree with a number of earlier investigations which show that P retention is strongly related to the contents of Al and Fe also in organic soils (Kaila 1959, Cuttle 1983, Richardson 1985, Nieminen and Jarva 1996, Giesler *et al.* 2002). However, neither the acidity nor the carbon content of the humus layer correlated with the P retention. In unfertilized acid soils, an increase in the soil pH can reduce the P retention slightly if the pH is below 6.0 (Barrow 1984, Giesler *et al.* 2005). In the catchments of this study, the humus pH (determined from $BaCl_2$ extraction) was low in all samples (2.9–3.6; Md 3.1) and no systematic differences occurred between the samples with differing P adsorption capacity. The carbon content of the humus layer in the buffer zones (24%–50%, Md 47%) was slightly higher than in the clear-cut areas (16%–50%, Md 40%). In this study the main reason for measuring the carbon content was to obtain an estimate of how carefully the mineral soil particles had been removed from the samples. The low carbon contents in some samples indicated that the mineral soil particles had not been completely removed. However, when considering that there was no correlation between the humus carbon content and the P adsorption capacity, any effect of mineral soil particles on the P adsorption in the humus samples would have been negligible.

High concentration of Al has been reported in the organic surface soil of river banks and groundwater discharge areas (Mulder *et al.* 1991, Norrström 1993, Giesler *et al.* 2002, Pellerin *et al.* 2002) and indications of increased Fe has also been shown (Norrström 1995). It has been suggested that Al is transported by high flow events, like snowmelt, and precipitation occurs when the acidity of Al-containing surface flow is reduced by mixing with less acid baseflow (Norrström 1993, Pellerin *et al.* 2002). This mixing can occur in river banks and groundwater discharge areas where baseflow reaches surface (Pellerin *et al.* 2002). High Al and Fe content in organic surface soil create favourable conditions for P retention even to the extent of limiting plant growth (Giesler *et al*. 2002, 2005). The higher Al and Fe contents and higher P retention in buffer zones compared with the clear-cut sites in the present study may be because of the processes described above.

A number of changes in the environmental conditions caused by tree harvesting can explain the decrease in the P-retention capacity over time in the humus layer of both the clear-cut areas and the buffer zones. In the lowest parts of the catchments, such as the buffer zones, water-logged conditions may occur after harvesting. By increasing its solubility with increased anaerobiosis, Mn is one of the most sensitive elements (McBride 1994). The very low Mn concentrations in the buffer zones, especially at catchments C1 and C3, indicate that water-logged conditions may have occurred frequently. Due to water-logging, the reduction and redistribution of Fe would decrease the humus and soil P adsorption capacities (Mahapatra and Patrick 1969, Jensen *et al*. 1999). The explanation for the decrease in humus P sorption capacity may also be that the P sorption sites had been saturated with P. As discussed earlier, the maximum P sorption capacity of the humus is evidently lower than the increase in P supply after harvesting of boreal forests; thus the P supply would be sufficient to saturate the adsorption capacity. A decrease in P adsorption can also occur if the phosphate ions in the sorption sites are exchanged with inorganic and organic anions that compete with P for sorption sites. The supply of these anions may increase considerably as a result of harvesting (Lundin 1999, Nieminen 2004).

In conclusion, the forest humus layer in the clear-cut areas and buffer zones had low P adsorption capacity. Consequently, the humus layer alone in narrow buffer strips along brooks is of small importance in restricting the leaching losses of P from forest clear-cut sites in the northern boreal region. Larger buffer zone areas in relation to clear-cut could result in better P retention. Furthermore, the results of the present study indicated that the capacity of forest humus layer to retain P may decrease due to harvesting induced changes in the environmental conditions. In retaining leaching of P from forest clear-cut sites, biological P accumulation and adsorption of P by Al- and Fe-rich mineral soils may be more important processes than the P adsorption capacity of the humus.

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