Effect of clear-cutting and the amount of logging residue on chemical composition of percolation water in spruce stands on glaciofluvial sandy soils in southern Finland

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The relationship between the amount of logging residue and element leaching from forest ecosystems to watercourses is not fully understood. We hypothesized that if the amount of logging residue in slash piles increases, this will be reflected as elevated N, DOC, base cation and PO_4-P concentrations in soil percolation water after clear-cut of spruce stands at site types with homogenous sandy material. Percolation water (depth 40 cm) was collected from small experimental sample plots by soil column lysimeters at two sites. The treatments were 0, 10 and 40 kg m^{-2} of logging residue. The highest NO_3-N concentrations (mean > 15 mg l^{-1}) were associated with the highest amount of logging residue left at the site. The NO_3-N concentrations were < 1 mg l^{-1} in the third year after clear-cut in the treatments 0 and 10 kg m^{-2} of logging residue. DON, DOC and PO_4 did not leach markedly, but higher base cation concentrations were associated with the highest amount of logging residue.

Introduction

Nitrogen (N) leaching from forest ecosystems was studied intensively during the past two decades. In particular, N leaching in soil percolation water to ground and surface waters was investigated in relation to N deposition (Gundersen 1995, MacDonald *et al.* 2002, Mustajärvi *et al.* 2008, Gundersen *et al.* 2009, Iost *et al.* 2012), as well as in relation to forest management practices, such as clear-cutting (e.g. Rósen and Lundmark-Thelin 1987, Mann *et al.* 1988, Kubin 1998, Piirainen *et al.* 2002, Wall 2008). High N leaching amounts or N concentrations in soil water have been found to coincide with high N deposition (Gundersen 1995, Iost *et al.* 2012). N leaching is, however, a complex process that is not strictly controlled by the N input to the forest soil but also by the N status of the whole forest ecosystem (Aber *et al.* 1989). For example, clear-cuttings have also been found to increase N leaching (e.g. Rósen and Lundmark-Thelin 1987) that lasted for a few years (Mann *et al.* 1988) to even decades (Kubin 1998). The soil C/N ratio has been proposed as an important parameter indicating an increased risk of N leaching (Gundersen *et al.* 1998). However, the N leaching response was extremely variable, depending on stand, site or soil conditions; in some cases harvesting with clear-cutting resulted in only minor

increases in N leaching (Piirainen *et al*. 2002), whereas in other cases the high N concentrations indicated elevated N leaching (Smolander *et al*. 1995). More specifically, quality, amount and distribution of logging residue may affect N leaching. For example, Rósen and Lundmark-Thelin (1987) reported that slash piles left on a clear-felled area caused increased N leaching from the soil below the piles (also Wall 2008). The effect of clear-cutting on nutrients and elements (base cations, organic carbon, phosphorus) other than N has also been studied in some areas and conditions in boreal forests. For example, Piirainen (2002) found that clear-cutting did not cause significant leaching of DOC, PO_4-P and base cations in mixed forest stands in eastern Finland. According to Morris (2009), after harvest with clear-cutting, DOC and DON fluxes increased in the second year but decreased after that. Chipper debris was considered to be an important source of the DOC and DON at these upland sites in Canada (Morris 2009).

During recent years, there has been an increasing interest in utilization of forest bioenergy in Finland (Peltola 2009) as well as in other countries (e.g. Löfgren *et al*. 2009). Considerable amounts of nutrients are removed from forest ecosystems when logging residue is harvested, because it, especially needles, contains large amounts of nutrients (Mälkönen *et al*. 2001). Nutrient concentrations in the soil solution and leaching to watercourses after clear-cutting are probably also affected by the amount of logging residue. The removal of logging residue may lead to lower nutrient concentrations in the soil percolation water and decreased leaching amounts. The role of the logging residue in element leaching is still not fully understood although some information on the general pattern of nutrient leaching after harvests with clear-cutting is already available (e.g. Rósen and Lundmark-Thelin 1987, Piirainen 2002). We hypothesized that if the amount of logging residue in slash piles increases, this will be reflected as elevated N, DOC, base cations and PO_4-P concentrations in the soil percolation water below large logging-residue accumulations in clear-cut Norway spruce stands growing on homogenous sandy material. Logging residue is a potential source of nutrients or it may favour soil pro-

cesses below the piles that lead to increased leaching. These "hotpots" would probably be important pathways for nutrient leaching within the stand.

Material and methods

Nutrient concentrations and leached amounts (fluxes) in the soil percolation water were studied in clear-cut spruce stands located on homogenous sand material (glaciofluvial sandy soils). The experiments in this study were carried out in two areas which were chosen to be as similar as possible with regard to the soil properties (soil texture, taxonomic classification of the soil, horizon thickness), climate, stand attributes and forest cutting operations. Those sites were located in Evo (61°N, 25°E) and Lapinjärvi (60°N, 26°E), both in southern Finland. The soil type at those sites was Haplic Arenosol (IUSS Working Group WRB 2006), being poorly podzolized. According to the Finnish forest-site type classification, both sites were of *Myrtillus* type (Cajander 1949). Before clear-cutting, the main tree species was the Norway spruce, and the age of the stands was ca. 70 years.

We tried to minimize the variation in soil properties between the sites and treatments as much as possible by selecting homogenous parts of the sand deposit within each site, and placing small experimental sample plots side by side in those parts of the deposit. Because forest operations can cause large variation in the topsoil conditions after harvesting, lysimeters were installed where the soil surface had remained undisturbed. The selected parts of the sand deposit were stoneless and no stumps were located in the immediate vicinity. The soil characteristics were measured from a soil pit, and a composite soil sample was taken from the wall of the soil pit (ca. 6-m long) located along one side of the experimental sample plots. Sub-samples were taken along the whole length of the soil pit by horizons, and combined into one composite sample per layer and site. The soil material, on which the experimental plots were located, was composed of sorted sand, and the thickness of the O horizon (Mor) was 5 cm. The E horizon was poorly developed (thickness < 5 cm), and
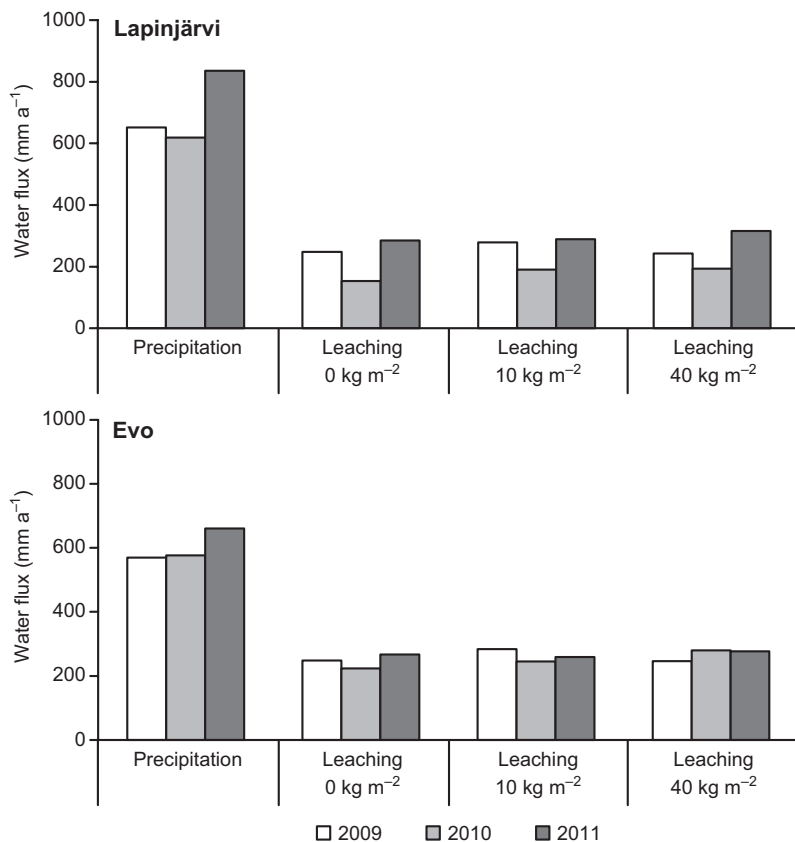
Fig. 1. Precipitation amount and leaching fluxes of water during 2009–2011 at the Lapinjärvi and Evo sites for the treatments 0, 10 and 40 kg m^{-2} of logging residue.

the B horizon was 25–30 cm thick (Table 1). The soil parent material was composed of granitic rocks and gneisses. At the Lapinjärvi site, the mean annual precipitation varied between 619 and 836 mm during 2009–2011, and between 278 and 426 mm during the growing seasons (May–October) in the same period (measured at the nearest ICP Forests Level II site located in Luumäki ca. 20 km away) (Fig. 1). At the Evo site, the mean annual precipitation was between 570 and 661 mm during 2009–2011, and between 268 and 367 mm (May–October) in the same period (measured at the nearest ICP Forests Level II site located at Evo ca. 0.5 km away) (Fig. 1). In southern Finland, the mean annual temperature is about +5 °C.

Table 1. Soil characteristics of the areas where the treatment plots were located.

Experimental site	Soil horizon	Thickness (cm)	Organic matter (%)	Bulk density (kg dm^{-3})	Silt + clay (wt%)	Sand (wt%)	Stoniness (vol%)
Lapinjärvi	O	5					
	E	< 5	1.1	1.28			
	B	30	1.7	1.34			
	C		0.8	1.46	1	99	< 0.5
Evo	O	5					
	E	< 5	7.1	0.89			
	B	25	3.5	1.19			
	C		1.0	1.44	1	99	< 0.5

Clear-cutting of the sites was done in 2008, and the leaching experiments were started in May 2009, when the logging-residue piles were placed on the experimental plots. Soil percolation water was collected during 2009–2011 from small (1 m^2) sample plots, which were located side by side (ca. 0.5–1 m apart). There were three sample plots at the Evo site: (1) one plot for the treatment 'no logging residue', (2) one plot for '10 kg m^{-2} logging residue', and (3) one plot for '40 kg m^{-2} logging residue' of fresh spruce branches and needles. The Lapinjärvi site had a corresponding experimental setup. Water percolating in the soil profile was collected by a zero-tension lysimeter (surface area 1 m^2, depth 40 cm) installed next to the 6-meter-long soil pit used for soil sampling. The soil profile (1 × 1 m) was carefully removed from the location where the treatment plot was situated, and the plastic sheet with one outlet was inserted into the soil after which the soil profile was returned to its original place. Percolation water was collected from a depth of 40 cm below the ground surface into polyethylene containers located in the dark and cool conditions at the bottom of the soil pits to prevent algae growth (no chemicals were used). Water samples were collected during the snow-free period at 4–6-week intervals. The collection containers were washed with distilled water after each sampling occasion. The experimental sites were located in commercially-utilized forests, and therefore only a restricted part of the sites could be used for the lysimeter installations.

On each sampling occasion, first pH of the collected water was measured (pH meter: Denver, Model 20) according to the standard SFS 3021 (accredited method), and then the samples were filtered through a 0.45 μm membrane filter (Pall Supor-450, Life Sciences, hydrophilic polyethersulfone). The total N (N_{tot}) and NH_4-N were determined with a flow injection analyzer (Lachat Quikchem 8000 FIA analyzer, A83200, Zellweger Analytics, Milwaukee, USA) according to the standards SFS-EN ISO 11905 and SFS-EN ISO 11732 (accredited methods), but the N_{tot} concentration in the samples collected in 2010–2011 was determined using TOC/TN analyzer (TOC-VCPH/N analyzer, Shimadzu Corporation, Kyoto, Japan) according to the standard SFS-EN 12260 (accredited method). The NO_3-N

and PO_4-P concentrations were determined by ion chromatography (Dionex DX 120, 98120636, Dionex corporation, Sunnyvale, California, USA) according to the standard SFS-EN ISO 10304-1 (accredited method). The dissolved organic N (DON) was calculated by subtracting NH_4-N and NO_3-N from N_{tot}. The dissolved organic carbon (DOC) was determined using a TOC/TN analyzer (TOC-VCPH/N analyzer, Shimadzu Corporation, Kyoto, Japan) according to the standard SFS-EN 1484 (accredited method). The Ca, Mg and K concentrations were determined by an inductively coupled plasma atomic emission spectrophotometer (iCAP 6500 Duo analyzer, Thermo Scientific, Cambridge, United Kingdom) according to the standard SFS-EN ISO 11885 (accredited method).

In order to scale the results from the small experimental sample plots to the leaching fluxes per hectare, an assumption was made that the theoretical sites of 1 ha would be composed of homogenous sorted sand. Based on this assumption, the annual N leaching fluxes (kg ha^{-1} a^{-1}) were calculated by multiplying the mean concentrations of NH_4-N, NO_3-N and DON (mg l^{-1}) by the leaching flux of water (mm) for every sampling occasion, and the annual leaching flux was calculated by summing up these sampling occasion values. The water amount was weighted on every sampling occasion and the height (mm) of a water column in the collection container was measured. The annual precipitation amount and N deposition was taken from the nearest ICP Forests monitoring sites at Evo and Luumäki (near Lapinjärvi) (Lindroos *et al.* 2013). The N leaching fluxes were calculated for all the logging residue treatments, and the values were combined to represent a theoretical clear-cut area where, on average, 7 kg m^{-2} of fresh logging residue was left (Piirainen 2002). We assumed that 10%, 30% and 60% of the area were covered by piles of 40 kg m^{-2}, 10 kg m^{-2} and 0 kg m^{-2} of logging residue, respectively (*see* e.g. Rósen and Lundmark-Thelin 1987). The logging residue amount of 7 kg m^{-2} is close to 3–6 kg m^{-2} typically left on clear-cut spruce sites in Finland (Peltola *et al.* 2011).

In order to test if there were differences among the treatments in the percolation water quality, Friedman's non-parametric ANOVA was applied. This method assumes that the samples

are related and makes comparisons of the treatments by the sampling occasions, which were repeated during the growing season. Friedman's test was used for screening the possible effect of the treatments on the percolation water quality. The effects of the logging residue amounts on the water quality were tested using the Randomized Intervention Analysis (RIA) (Carpenter *et al.* 1989). This method, while making no assumption regarding data distribution, allows for testing whether the changes in tested parameters from one period to another at experimental and reference sites, respectively, differ significantly. In particular, we analysed the changes in the annual mean values from 2009 to 2010 and from 2009 to 2011, and compared the 10 and 40 kg m^{-2} logging-residue treatments with the control (no logging residue). The test statistic for the RIA was $d = D_y - D_{2009}$, where D_y is the mean of differences between treatment and control in the concentrations measured at the same sampling time in year y. The descriptive statistics and Friedman's test were computed using the SPSS Statistics 20.0 package, and the RIA was carried out in R (R Core Team 2014) using the package *boot* (Canty and Ripley 2014).

Results

Concentrations

The highest NO$_3$-N concentrations were found under the highest amounts of logging residue left at the sites, and this was reflected at the Lapinjärvi site as a significant increase in mean NO$_3$-N concentration from 2009 to 2011 ($p = 0.00$, RIA, Table 2), and to 2010 at the Evo site ($p = 0.00$, Table 3). Even at the end of 2011, i.e., three years after the experiment had begun, the NO$_3$-N concentrations were > 10 mg l^{-1} (Fig. 2). In the third year and in the 0 and 10 kg m^{-2} logging residue treatments, the NO$_3$-N concentrations decreased below 1 mg l^{-1}.

During 2009–2011 and at both sites, the annual median NH$_4$-N concentrations in the percolation water at the 40 cm depth were mostly below 1 mg l^{-1} in all logging residue treatments (Tables 2 and 3). The exceptions were the 40 and 10 kg m^{-2} logging residue treatments in the

second year (2010) at the Lapinjärvi site where the median concentrations were > 1.6 mg l^{-1} in both treatments; in those cases, the change from 2009 was significantly different when compared with that in the control ($p = 0.02$, RIA, Table 2).

The annual median DON concentrations were < 1 mg l^{-1} throughout the study period in all treatments and at both sites (Table 2 and 3), and the RIA did not reveal any significant ($p > 0.05$) differences. The annual median DOC concentrations were < 25 mg l^{-1} during the study period in all treatments (Tables 2 and 3); significantly elevated concentrations as compared with those in the control were found in the treatment 10 kg m^{-2} at the Evo site in 2010 ($p = 0.02$, RIA) and 2011 ($p = 0.00$, RIA).

The percolation water acidity (Tables 2 and 3) increased significantly with time at the Lapinjärvi site in the 40 kg m^{-2} logging-residue treatment as compared with the values in the two other treatments ($p = 0.02$, RIA, Table 2).

High Ca, Mg and K concentrations were associated with the logging residue treatment of 40 kg m^{-2} in 2011 at the Lapinjärvi site and 2010 at the Evo site ($p < 0.05$, RIA) (Tables 2 and 3, Figs. 3–5). The PO$_4$-P concentrations were low (median 0.07 mg l^{-1}) in all treatments at both sites (Table 2 and 3).

Water and N leaching fluxes

The mean annual water flux (mm a^{-1}) at the 40-cm depth was 34% of the mean precipitation at the Lapinjärvi site, and 43% at the Evo site (Fig. 1). The total annual N leaching flux from the clear-cut area containing on an average 7 kg m^{-2} logging residue (10%, 30% and 60% of the area covered with logging residue piles of 40 kg m^{-2}, 10 kg m^{-2} and 0 kg m^{-2}, respectively) was the highest during the third year of the experiment reaching 13 kg ha^{-1} a^{-1} at Lapinjärvi and 15 kg ha^{-1} a^{-1} at Evo (Fig. 6). The leaching flux was higher than that of the atmospheric deposition. Of the N forms, NO$_3$-N dominated the leaching flux.

Discussion

The elevated NO$_3$-N concentrations in the perco-

Table 2. Annual concentrations of nutrients and pH in the percolation water at 40 cm depth of the treatments 0, 10 and 40 kg m^{-2} logging residue during 2009–2011 at the Lapinjärvi site. SD is the standard deviation and n is the number of samples. If there were differences among treatments (Friedman's test: $p < 0.05$, or $p < 0.10$, if $n = 3$), the p and χ^2 values are given. For the years 2010 and 2011 and the 10 and 40 kg m^{-2} logging residue treatments, those means which according to the RIA indicate a significant change from 2009 as compared with the control are denoted with an asterisk (*). For those mean values, the estimated difference, RIA d, and p value (RIA p) are given. Friedman's test: difference among treatments. n is the lowest n for a year and parameter.

		2009				2010				2011			
		40	10	0	p/χ^2	40	10	0	p/χ^2	40	10	0	p/χ^2
NO$_3$-N	mean	2.87	3.16	2.76		17.04	8.08	1.66	0.018/8.0	27.73*	1.22	0.24	0.006/10.3
(mg l^{-1})	median	2.22	2.10	2.18		14.88	5.36	1.44		25.73	0.66	0.16	
	SD	2.45	2.22	1.09		13.94	5.68	0.57		6.95	1.91	0.26	
	n	7	7	7		6	6	4		8	7	6	
	RIA d									28.37			
	RIA p									0.00			
NH$_4$-N	mean	0.28	0.29	0.76		1.92*	1.82*	0.48	0.050/6.0	0.88	0.41	0.27	0.036/6.6
(mg l^{-1})	median	0.25	0.18	0.52		1.64	1.63	0.52		0.96	0.33	0.08	
	SD	0.24	0.29	0.60		1.46	1.87	0.33		0.65	0.40	0.31	
	n	6	7	7		6	6	4		8	7	5	
	RIA d					1.36	0.79						
	RIA p					0.02	0.02						
DON	mean	0.10	0.09	0.06	0.0019/7.9	0.33	0.30	0.03		0.23	0.17	0.12	
(mg l^{-1})	median	0.10	0.06	0.00		0.27	0.17	0.02		0.05	0.14	0.12	
	SD	0.07	0.08	0.16		0.35	0.42	0.03		0.32	0.14	0.09	
	n	6	7	7		6	6	4		8	7	5	
	RIA d												
	RIA p												
DOC	mean	7.25	2.49	2.54	0.006/10.1	7.05	4.55	2.35	0.039/6.5	7.66	4.39	4.27	0.032/6.9
(mg l^{-1})	median	6.35	2.40	2.10		6.30	2.40	2.25		7.70	3.00	3.00	
	SD	2.84	0.43	1.14		2.57	5.39	0.40		1.19	3.65	3.47	
	n	6	7	7		6	6	4		8	7	6	
	RIA d												
	RIA p												
Ca	mean	3.02	2.90	1.47	0.011/9.0	8.45	5.06	1.26	0.018/8.0	6.47	1.37	0.80	0.022/7.6
(mg l^{-1})	median	2.91	2.37	1.27		7.20	4.80	1.29		5.55	0.83	0.77	
	SD	1.24	1.41	0.43		6.31	2.59	0.16		3.19	1.32	0.13	
	n	6	7	7		6	6	4		8	7	5	
	RIA d												
	RIA p												
K	mean	5.42	4.18	1.69	0.011/9.0	17.58	9.16	1.81	0.018/8.0	31.34*	3.25	1.15	0.007/10.0
(mg l^{-1})	median	5.31	4.44	1.59		18.45	7.02	1.64		31.45	3.23	1.20	
	SD	0.83	2.00	0.34		9.42	6.27	0.57		3.17	1.00	0.25	
	n	6	7	7		6	6	4		8	7	5	
	RIA d									27.42			
	RIA p									0.00			
Mg	mean	0.72	0.75	0.53		1.37	0.94	0.37	0.039/6.5	1.40*	0.23	0.19	0.015/8.4
(mg l^{-1})	median	0.69	0.63	0.53		1.03	0.66	0.37		1.33	0.12	0.16	
	SD	0.21	0.28	0.12		1.13	0.60	0.03		0.44	0.19	0.06	
	n	6	7	7		6	6	4		8	7	5	
	RIA d									1.22			
	RIA p									0.03			
PO$_4$-P	mean	0.16	0.07	0.08		0.07	0.39	0.07		0.07*	0.08	0.22	
(mg l^{-1})	median	0.07	0.07	0.07		0.07	0.07	0.07		0.07	0.07	0.07	
	SD	0.25	0.00	0.05		0.00	0.78	0.00		0.00	0.04	0.38	
	n	7	7	7		6	6	4		8	7	6	
	RIA d									−0.14			
	RIA p									0.00			
pH	mean	5.58	5.78	5.57		5.10	5.53	5.82		4.22*	5.55	5.35	0.022/7.6
	median	5.45	5.68	5.01		4.77	5.54	5.76		4.22	5.63	5.28	
	SD	0.60	0.58	0.73		0.90	0.35	0.50		0.08	0.30	0.27	
	n	6	7	7		6	6	4		8	7	5	
	RIA d									−1.25			
	RIA p									0.02			

Table 3. Annual concentrations of nutrients and pH in the percolation water at 40 cm depth of the treatments 0, 10 and 40 kg m^{-2} logging residue during 2009–2011 at the Evo site. SD is the standard deviation and *n* is the number of samples. If there were differences among treatments (Friedman's test: $p < 0.05$, or $p < 0.10$, if $n = 3$), the *p* and χ^2 values are given. For the years 2010 and 2011 and the 10 and 40 kg m^{-2} logging residue treatments, those means which according to the RIA indicate a significant change from 2009 as compared with the control are denoted with an asterisk (*). For those mean values, the estimated difference, RIA *d*, and *p* value (RIA *p*) is given. Friedman's test: difference among treatments. *n* is the lowest *n* for a year and parameter.

		2009				2010				2011			
		40	10	0	p/χ²	40	10	0	p/χ²	40	10	0	p/χ²
NO$_3$-N	mean	5.98	1.64	0.88		36.75*	1.15	0.53	0.009/9.5	24.69	0.32	0.17	0.097/4.7
(mg l^{-1})	median	5.14	1.32	0.72		32.41	1.04	0.15		24.94	0.41	0.00	
	SD	5.27	0.89	0.75		11.40	1.20	0.70		9.83	0.26	0.29	
	n	4	5	3		8	6	6		4	3	3	
	RIA *d*					31.54							
	RIA *p*					0.00							
NH$_4$-N	mean	2.31	0.63	0.57		1.68	0.52	0.13		1.09	0.32	2.68	
(mg l^{-1})	median	0.39	0.22	0.55		0.78	0.11	0.09		0.39	0.08	0.81	
	SD	4.30	1.06	0.37		1.93	0.75	0.11		1.67	0.46	3.92	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*												
	RIA *p*												
DON	mean	0.18	0.38	0.38		0.82	0.60	0.32	0.042/6.3	0.38	0.82	0.63	
(mg l^{-1})	median	0.17	0.41	0.36		0.70	0.59	0.35		0.37	0.81	0.47	
	SD	0.19	0.07	0.10		0.78	0.14	0.07		0.31	0.10	0.39	
	n	4	5	3		8	6	6		4	3	3	
	RIA *d*												
	RIA *p*												
DOC	mean	9.90	14.1	10.6	0.097/4.7	5.84	21.6*	11.2	0.02/12.0	6.28	27.3*	13.8	0.050/6.0
(mg l^{-1})	median	9.60	14.7	11.1		5.50	22.0	10.9		6.30	24.9	12.8	
	SD	3.65	1.29	2.98		1.43	3.15	1.17		0.40	4.10	2.89	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*					6.45				9.47			
	RIA *p*					0.02				0.00			
Ca	mean	2.25	1.14	1.03		15.87*	0.95	1.01	0.011/9.0	16.73	0.75	1.10	0.097/4.7
(mg l^{-1})	median	2.69	1.15	0.84		12.65	1.00	0.93		17.45	0.69	1.13	
	SD	1.15	0.27	0.42		7.76	0.31	0.17		4.79	0.17	0.26	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*					14.62							
	RIA *p*					0.02							
K	mean	1.86	2.72	2.41	0.097/4.7	3.41*	2.62	1.28	0.042/6.3	5.08	3.67	2.12	0.097/4.7
(mg l^{-1})	median	1.20	3.06	1.93		3.21	2.35	0.81		4.77	3.87	1.19	
	SD	1.48	0.96	1.55		1.32	1.17	1.16		1.56	0.92	2.11	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*					3.24							
	RIA *p*					0.05							
Mg	mean	4.02	1.57	0.77	0.050/6.0	19.31*	1.16	0.72	0.002/12	8.68	0.67	0.63	0.097/4.7
(mg l^{-1})	median	3.40	1.54	0.65		17.9	1.06	0.67		8.67	0.65	0.65	
	SD	2.17	0.30	0.33		3.87	0.59	0.13		4.3	0.11	0.08	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*					15.19							
	RIA *p*					0.00							
PO$_4$-P	mean	0.54	0.09	0.12		0.15	0.20	0.07		0.07	0.10	0.46	
(mg l^{-1})	median	0.07	0.07	0.07		0.07	0.07	0.07		0.07	0.07	0.07	
	SD	1.07	0.04	0.10		0.14	0.22	0.00		0.00	0.06	0.69	
	n	5	5	3		8	6	6		4	3	3	
	RIA *d*												
	RIA *p*												
pH	mean	6.21	6.27	6.4		5.99	5.98	6.18		6.02	6.25	6.42	
	median	6.27	6.20	6.19		6.22	6.02	6.20		5.77	6.44	6.70	
	SD	0.14	0.28	0.56		0.62	0.27	0.33		0.62	0.42	0.76	
	n	4	5	3		8	6	6		4	3	3	
	RIA *d*												
	RIA *p*												

Fig. 2. Changes in the NO_3-N concentrations in the percolation water of the (**a**) 40, (**b**) 10 and (**c**) 0 kg m^{-2} of logging-residue treatments in 2009–2011.

lation water below the rooting zone were clearly related to the amount of logging residue left on the site. This was evident especially in the 40 kg m^{-2} logging-residue treatment. In Finland, the typical amount of logging residue left on the site in stem-only harvesting of Norway spruce stands correspond to 30–70 Mg ha^{-1}, i.e. 3–7

kg m^{-2}, ranging from 0 to 36.5 kg m^{-2} (Saksa *et al*. 2002). Our largest logging-residue treatment represents a considerable accumulation of logging residue (Peltola *et al*. 2011). It is not possible to draw far reaching conclusions about the NO_3-N leaching from the clear-cut areas as a whole, based on the results of the 40 kg m^{-2}
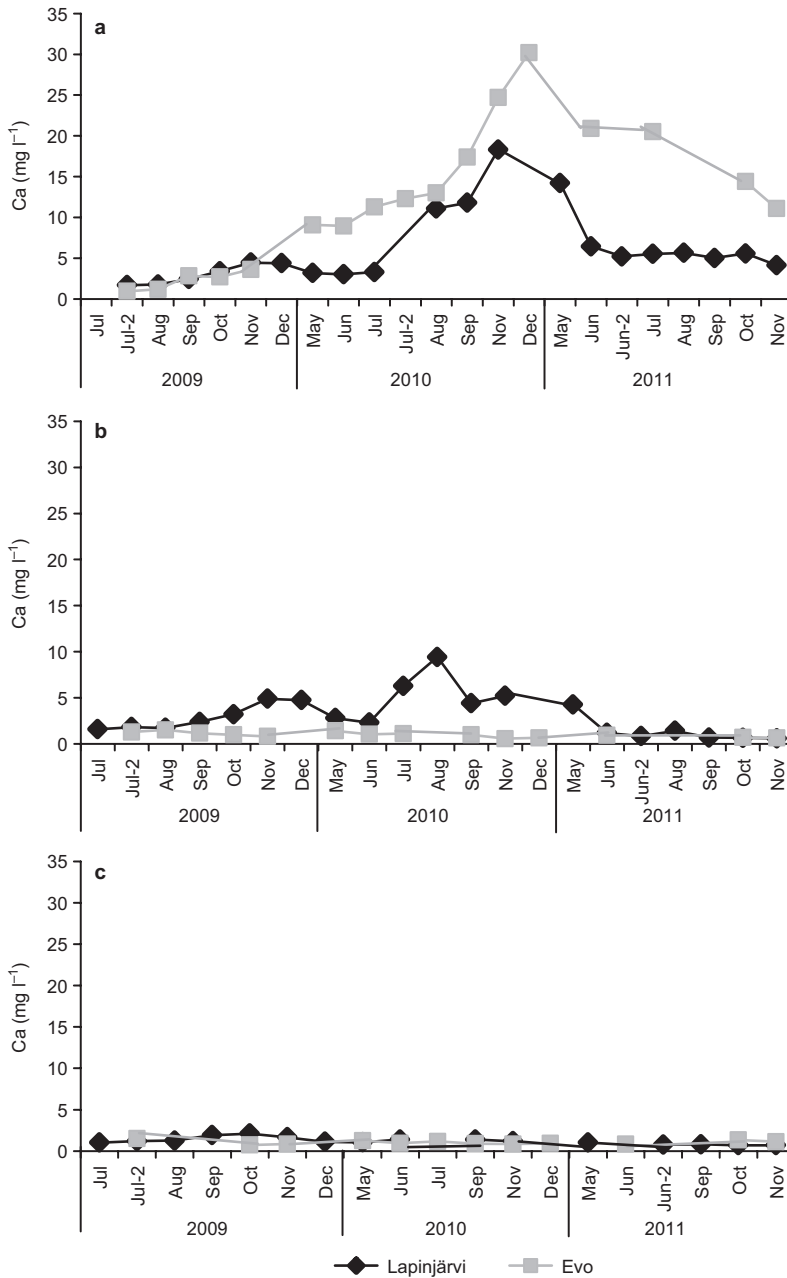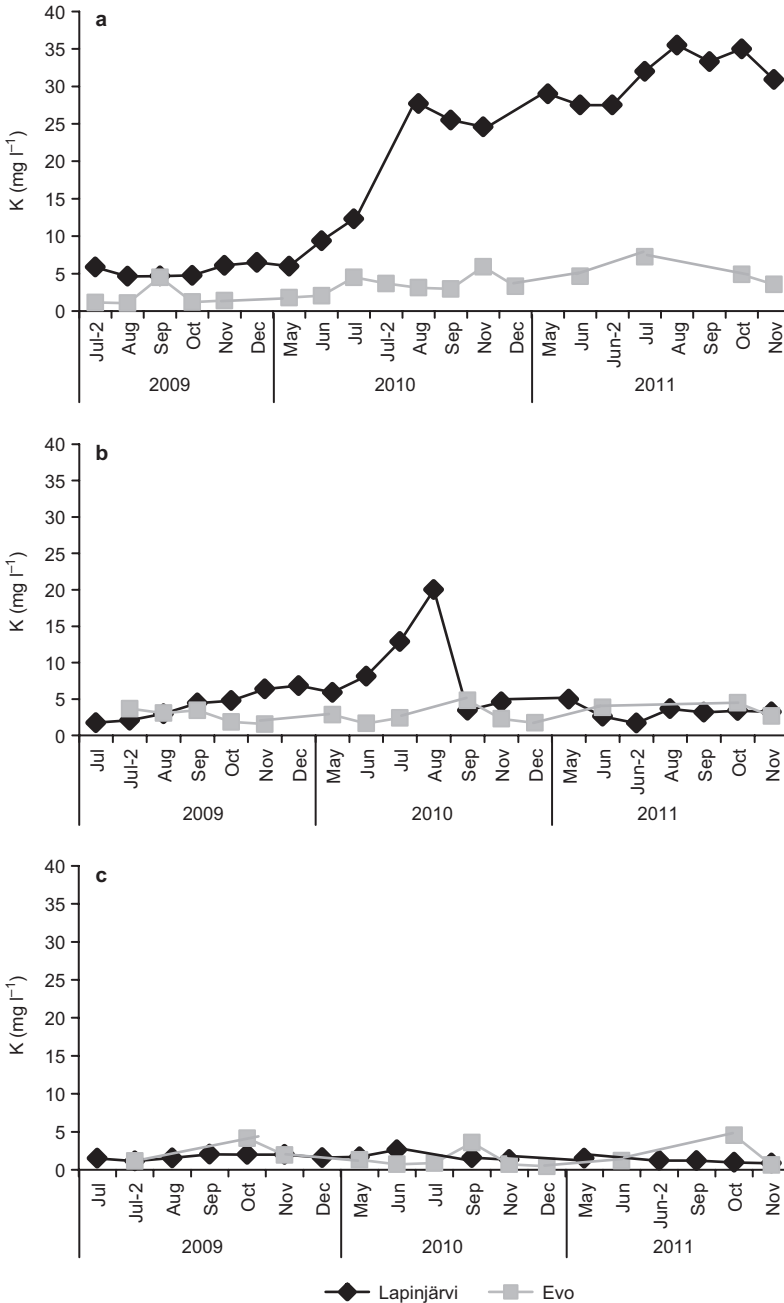
Fig. 3. Changes in the Ca concentrations in the percolation water of the treatments (**a**) 40, (**b**) 10 and (**c**) 0 kg m^{-2} of logging residue treatments in 2009–2011.

logging-residue treatment. However, it is known that relatively large accumulations of logging residue may occur in clear-cut areas, and our results show that these large piles of logging residue can cause unwanted changes in the soil solution beneath them. The effects of no logging residue or 10 kg m^{-2} of logging residue left on the site on the NO_3-N concentrations agreed with the results from earlier studies (e.g. Rósen and Lundmark-Thelin 1987, Smolander *et al.* 1995). In our study, the duration of the elevated NO_3-N concentrations associated with the treatments 0 or 10 kg m^{-2} was short, since the concentrations decreased below the concentrations of the first year in the third year after clear-cutting. On the other hand, the concentrations in the 40 kg m^{-2}
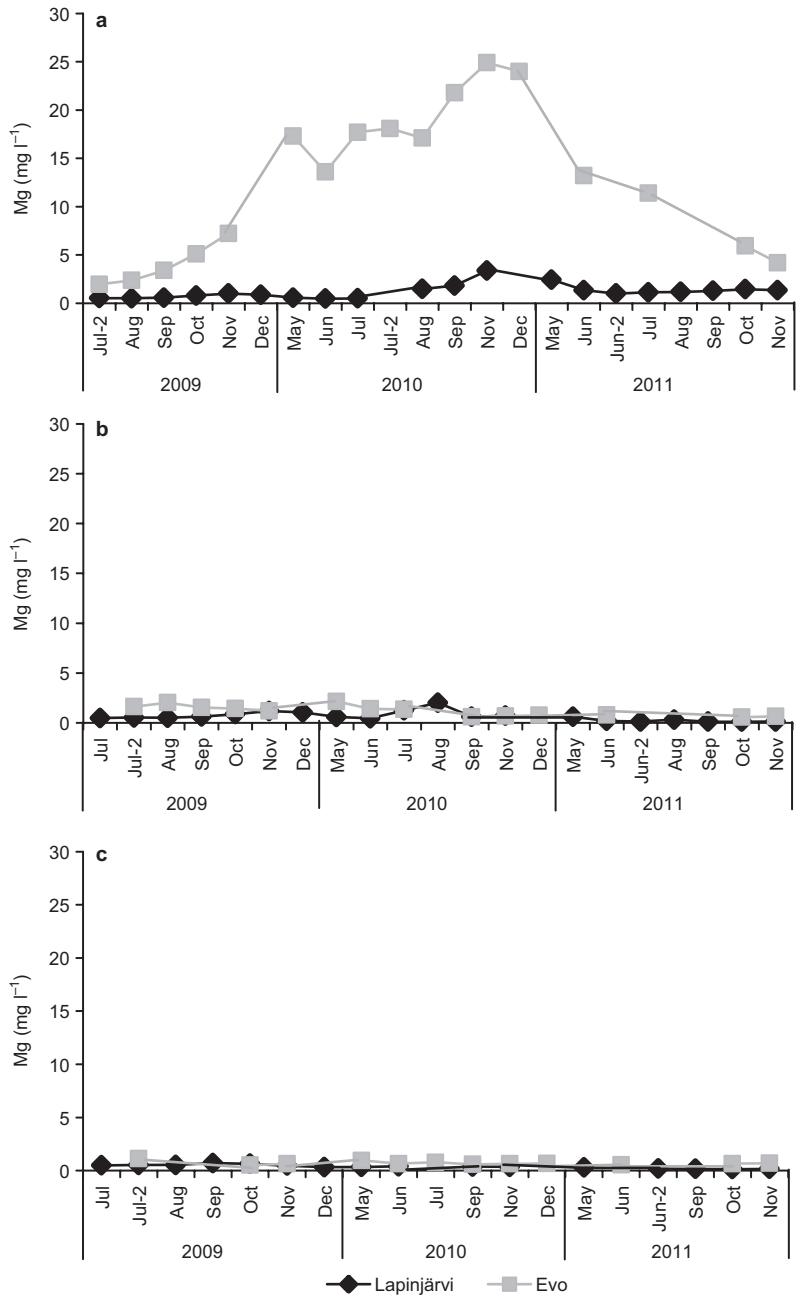
Fig. 4. Changes in the Mg concentrations in the percolation water of the treatments (**a**) 40, (**b**) 10 and (**c**) 0 kg m^{-2} of logging residue treatments in 2009–2011.

logging-residue treatment remained high into the third year of the experiment.

The estimated N leaching flux (kg ha^{-1} a^{-1}) from a clear-cut area containing on an average 7 kg m^{-2} logging residue (Piirainen 2002, Saksa *et al*. 2002, Peltola *et al*. 2011) (results of the different treatments combined) was the highest in the third year. Leaching decreased consider-

ably in the treatments 0 and 10 kg m^{-2} logging residue in the third year, but in the treatment 40 kg m^{-2} the leaching was still high, although the concentrations were declining during the growing season. The output flux of N in the soil percolation water was much higher than that reaching the forest floor through atmospheric deposition, which is not normally the case in

Fig. 5. Changes in the K concentrations in the percolation water of the treatments (**a**) 40, (**b**) 10 and (**c**) 0 kg m^{-2} of logging residue treatments in 2009–2011.

the growing forests in Finland (Mustajärvi *et al.* 2008). Therefore, the measured N leaching is most probably a temporary phenomenon. Of the N forms, NO$_3$-N clearly dominated the leaching flux, accounting for ca. 75% of the total N leaching. The N leaching amounts of 6–15 kg ha^{-1} a^{-1} are comparable to those measured in similar conditions in Sweden by Rósen and Lundmark-The-

lin (1987). Our estimated values are much higher than those measured by Piirainen *et al.* (2002) in eastern Finland in a mixed forest located on till soil. However, the water fluxes were much lower in their study as compared with our values.

Based on our measurements from the 40 cm depth, it is not possible to judge whether NO$_3$-N originates from the logging residue or the soil
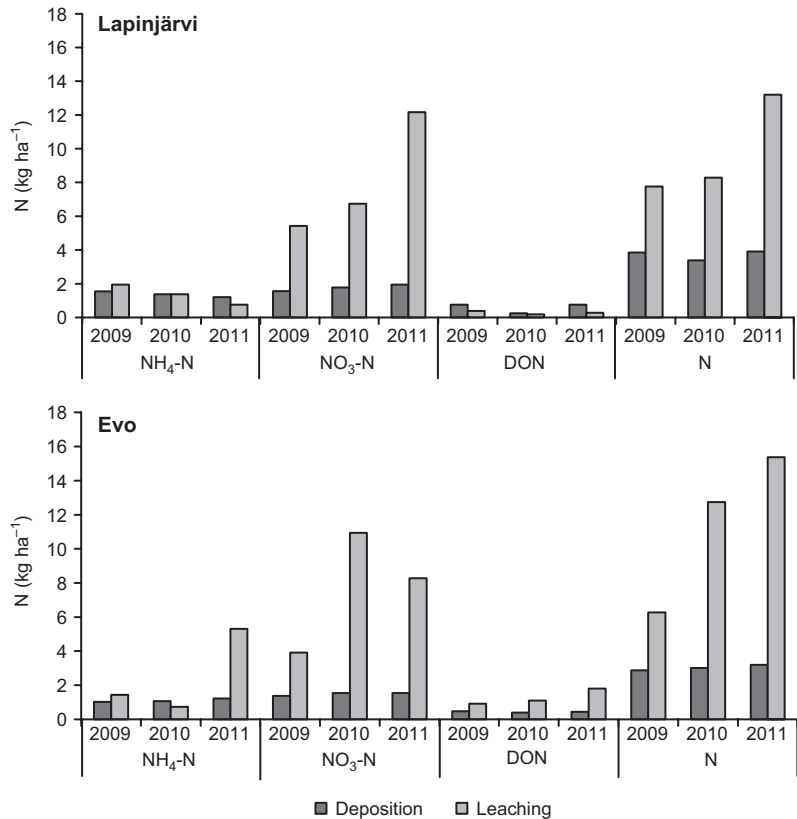
Fig. 6. Mean N deposition and leaching fluxes (kg ha^{-1} a^{-1}) during 2009–2011 at the Lapinjärvi and Evo sites (N deposition, Lindroos *et al.* 2013). The leaching fluxes were calculated for a clear-cut area containing on average 7 kg m^{-2} of logging residue (10%, 30% and 60% of the area covered with logging residue piles of 40 kg m^{-2}, 10 kg m^{-2} and 0 kg m^{-2}, respectively).

below the piles of logging residue, or both. Rósen and Lundmark-Thelin (1987) found that slash piles left on a clear-felled site caused increased inorganic N leaching from the soil. They concluded that slash piles favoured mineralization and nitrification processes in the soil below the slash piles and N leaching directly from the slash piles likely played a minor role. Also Palviainen *et al.* (2004) concluded that logging residue is not necessarily a net source of N soon after clear-cutting carried out in a mixed boreal forest. Large piles of logging residue undoubtedly increase the moisture content and mineralization in the soil below logging residue (Rósen and Lundmark-Thelin 1987). The piles also change the soil temperature which together with elevated pH related to clear-cutting and substrate ammonium concentration, can favour nitrification in the soil (Tietema *et al.* 1992, Paavolainen *et al.* 2000a, Paavolainen *et al.* 2000b). In our study, the NO$_3$-N concentrations were very high, which indicates that large piles of logging residue themselves are probably also

a source of N. Nitrate production is an acidifying process, and this was evidenced by the decrease in percolating-water pH and elevated nitrate concentrations in the 40 kg m^{-2} treatment in 2011 at the Lapinjärvi site. This was not observed at the Evo site where the buffering capacity of the soil was presumably higher due to a higher content of biotite (*see* below).

Glaciofluvial sandy soils were efficient in retaining DON and DOC released from the logging residue. The DON and DOC values at the 40 cm depth under the logging residue were low and in all treatments comparable to those measured at Norway spruce sites of ages of > 65 years in different parts of Finland (Derome *et al.* 2002).

The Ca, Mg and K concentrations were elevated when large amounts of logging residue was left on the forest floor. The Mg and K concentrations behaved differently at the two sites in the presence of the highest amount of logging residue. This is maybe due to the fact that the soil at Evo contained more biotite than that at

in Lapinjärvi although otherwise the soils were comparable (based on the grain counting of the 0.06–2 mm soil material; A.-J. Lindroos unpubl. data). Biotite is an easily-weathering source of Mg and K and form secondary clay minerals which probably absorbed K. The higher Mg concentrations in the soil percolation water at Evo are probably caused by the fact that the soil is already saturated with Mg due to high weathering input which was not the case in Lapinjärvi. At Evo the K concentrations in the percolation water were lower than at Lapinjärvi, indicating retention of K. However, at both sites the Mg and K concentrations were elevated in the treatment with the largest amount of logging residue, as compared with the values in the other two treatments.

The PO_4-P concentrations were low in the percolation water at the 40 cm depth in all treatments, and this finding agrees with the results of Väänänen *et al.* (2008) who reported that the risk for phosphorus leaching is negligible when water percolates through the B horizon, as was also the case in our study.

Installation of the lysimeters undoubtedly caused some disturbance to the soil which could partly favour elevated concentrations especially during the first year. However, in the treatments with low amounts of logging residue, N concentrations as well as pH and DOC values were comparable with those obtained in other studies where N leaching was studied using lysimeters (e.g. Rósen and Lundmark-Thelin 1987, Smolander *et al.* 1995). The differences between the treatments became evident in the second or third year. In addition, because our main aim was to compare logging-residue treatments with the treatment without logging residue, the possible effects of lysimeters would have been similar in all treatments. Further, a disturbance to the soil is quite normal in many cases in clear-cutting operations and subsequent forest management practices (i.e. site preparation) although this disturbance is restricted only to the topmost part of the soil and does not normally reach 40 cm depth.

Although, the experiment was carried out on homogenous sand material and provided an opportunity to compare the treatments on this material, it should be kept in mind that forest-soil properties are generally known to vary consider-

ably within the stands in terms of texture, coarse fragment content, bulk density, porosity, density and configuration of root channels. Therefore, our results should be generalized with care, since our experimental design mainly provides a possibility to compare the treatments on similar sand material. However, Liski (1995) studied the variation in soil properties in stands located on glaciofluvial sorted sand deposits in southern Finland, and he found that most of the variation in the soil properties can be found within a circumference of a few meters around the sampling point. Therefore, one relatively large-volume soil-column lysimeter can probably be expected to cover at least some of the natural spatial variation in the forest soil on sorted sand deposits.

Direct measurements of the water amounts collected by the zero-tension lysimeters may in some cases be unreliable in the estimation of the annual water amount in Finnish conditions due to the problems in collecting water under a snow cover, during the snow-melting season and when temperatures below 0 °C occur. In spite of this, in this study we used direct measurements because the results of the hydrological modelling for Finnish forest soils justify this approach. The annual leaching flux of water has been estimated to be ca. 40% of the annual precipitation in an open area based on hydrological modelling of the forest soil percolation water in Finnish coniferous forest soils (Lindroos *et al.* 2008, Ilvesniemi *et al.* 2010), and the measured water amounts in our study were quite close to this estimation.

Conclusions

In conclusion, the highest NO_3-N concentrations were associated with the highest amount of logging residue (40 kg m^{-2}) left on the site. The concentrations in this treatment were high at least three years after the experiment had started. In the treatments 0 and 10 kg m^{-2} of logging residue, the NO_3-N concentrations decreased rapidly to < 1 mg l^{-1} by the third year of the experiment. The NH_4-N concentrations were also somewhat higher when large amounts of logging residue were left on the site. The glaciofluvial sandy soils were efficient in retaining DON and

DOC released from the logging residue. PO_4 was not leached from the soils in any of the treatments, but higher base-cation concentrations in the percolation water were associated with the highest amount of logging residue, balancing the negative charge caused by the increased nitrate concentration. The total N leaching calculated by combining the results of the different treatments was the highest during the third year, reaching 14 kg ha^{-1} a^{-1}. However, during the growing season of the third year, the highest N concentrations levelled off. Of the N forms, NO_3-N dominated the leaching flux. It seems likely that logging residue harvesting will decrease nitrogen and base cation leaching from clear-cut sites to some extent at least on sorted soils. However, the timing of the logging residue harvesting may affect this strongly. If the needles fall from the logging residue, the nutrient removal from the site will be much smaller and leaching probably will occur from those parts of the site where extremely large slash piles were accumulated. In the logging residue harvesting, it is important to avoid upsetting the nutrient balance of the forest ecosystems. Therefore, from the point of view of nutrient leaching and balance the most beneficial practice would be to leave logging residue in piles of small or moderate sizes that are as evenly distributed on the site as possible. This would favour small leaching losses and the retention of the nutrients in the soil. Avoiding extremely large logging residue piles on the site is important both in conventional stem-only harvesting and whole tree harvesting.

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