Effects of Repeated Slash Removal in Thinned Stands on Soil Chemistry and Understorey Vegetation

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The increased interest in harvesting logging residues as a source of bio-energy has led to concerns about the potentially adverse long-term impact of the practice on site productivity. The aim of this study was to examine the effects on soil chemistry (pH, C, N and AL-extractable P, K, Ca and Mg) in three different soil layers (FH, 0–5 cm and 5–10 cm mineral soil) and understorey vegetation after the second removal of logging residues in whole-tree thinned stands. The study was performed at four different sites, established in the period 1984–87, representing a range of different climatic and soil conditions: a very fertile Norway spruce (*Picea abies* (L.) Karst.) site in south-western Sweden and three Scots pine (*Pinus sylvestris* L.) sites located in south, south-central and central Sweden. The effects of whole-tree thinning on soil chemistry and understorey vegetation were generally minor and variable. Across all sites the concentrations of Ca and Mg were significantly lower when slash was removed.

Keywords base cations, carbon, nitrogen, soil chemistry, understorey vegetation, whole-tree harvesting, thinning
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1 Introduction

Since the mid-1980s increasing interest in logging residues (slash) as a source of bio-energy has led to forests being more intensively harvested at many sites in Sweden (Jacobson et al. 1996). The removal of slash after clear felling has caused pools of exchangeable cations and pH to be lower, especially in the organic layer, than in comparable stands subjected to conventional harvesting (Nykvist and Rosén 1985, Olsson et al. 1996a). Several authors have expressed fears that slash removal may lead to depletion of nutrients (both N and base cations) and that this could adversely affect long-term site productivity (e.g. Mälkönen 1976, Kimmins 1977, Hendrickson et al. 1989, Sverdrup and Rosén 1998). In thinnings, the removal of slash could be expected to reduce the soil pools of N and base cations to a lesser extent than whole-tree harvesting in clear fellings. However, according to model calculations based on soil C and N by Rolff and Ågren (1999), whole-tree harvest in thinnings may cause a greater reduction in tree growth than the same practice in clear fellings. A number of studies have reported reductions in tree-growth following whole-tree harvesting in both thinnings and clear fellings in Fennoscandia (e.g. Egnell et al. 1998) and various other parts of the world (e.g. Sterba 1988, Compton and Cole 1990, Proe et al. 1996). Jacobson et al. (2000) found that reductions in tree growth started to become measurable about four years after whole-tree thinning, and that effects were still detectable ten years after the thinning. However, although reductions in growth were found after whole-tree thinning, only minor negative effects were detected in the soil pools of exchangeable base cations after five years (Olsson 1999). A conclusion of Jacobson et al. (2000) was that the decreased rates of tree growth that followed whole-tree thinning were due to reductions in N supply.

In a long-term study, 15–16 years after clear felling, Olsson et al. (1996b) did not find any clear effects of harvesting at a range of intensities on soil C and N pools. However, in a meta-analysis, Johnson and Curtis (2001) found that pool sizes of both C and N tended to be greater following conventional harvesting and lower following whole-tree harvesting compared to unharvested controls. The additional nutrient removal caused by whole-tree harvesting may be counteracted to some extent by the higher nutrient losses that appear to occur when the logging residues are left on site (Rosén and Lundmark-Thelin 1987, Stevens and Hornung 1990, Staaf and Olsson 1994), probably due to enhanced mineralization of the soil organic layer and increased nitrification rates (Rosén and Lundmark-Thelin 1987, Emmett et al. 1991). Reductions in nutrient uptake by plants may also contribute to the higher rates of leaching that follow conventional harvesting, since the remaining slash may suppress revegetation by shading and/or acting as a physical barrier (Fahey et al. 1991b). However, such physical barriers will be temporary, and disappear as the residues decompose (Olsson and Staaf 1995).

A number of studies have indicated that leaving logging residues on site may increase the concentrations of nutrients, thus favouring nutrient-demanding species such as *Rubus idaeus* L. and *Chamaenerion angustifolium* (L.) Scop. (Fahey et al. 1991b, Olsson and Staaf 1995, Bråkenhielm and Liu 1998). In a study by Fahey et al. (1991b) the understorey vegetation biomass increased twice as fast after whole-tree harvesting than after conventional harvesting, mainly because the residues suppressed plant expansion in the latter case. Olsson and Staaf (1995) found that these suppressive effects remained for at least eight years after harvesting. After a further 8-year period no such effects could be detected. Bråkenhielm and Liu (1998) found that the abundance of nitrogen-demanding species was higher in conventionally harvested stands than in whole-tree harvested stands 10 years after final felling.

Slash removal has given variable results with respect to vascular plant cover. Olsson and Staaf (1995) found that the cover of most vascular plants declined after whole-tree harvesting, whereas Kardell (1992) found that cover of several species increased after this treatment. One species for which cover increased in at least two studies following the removal of slash is *Vaccinium myrtillus* L. (Kardell and Eriksson 1990, Olsson and Staaf 1995). Bryophytes for which cover has increased following whole-tree harvesting include *Hylocomium splendens* (Hedw.) Schimp., *Dicranum* spp. and *Polytrichum commune* (Hedw.), whereas the cover of *Pleurozium schreberi* (Brid.) Mitt. has declined (Kardell 1992, Olsson and Staaf 1995).

Previously performed studies have mostly examined the effects of whole-tree harvesting at clear felled sites. The aim of this study was to examine the effects of whole-tree harvesting on soil chemistry and vegetation cover after repeated removal of logging residues in thinned stands.

2 Materials and Methods

2.1 Experimental Sites

The studied sites represent a range of climatic conditions (Table 1). Three experimental sites (Munkfors, Åmot and Vetlanda) were established

Table 1. Characteristics of the studied sites. Data from Jacobson et al. (1996), Jacobson et al. (2000).

	Site			
	181 Örsås	184 Vetlanda	193 Munkfors	219 Åmot
Location	57°23´N,13°05´E	57°25´N,15°18´E	59°51´N,13°47´E	61°02´N,16°12´E
Altitude (m asl)	170	145	220	350
Mean annual temp. (°C) [a]	6.0	6.1	4.2	3.8
Precipitation (mm yr^{-1}) [a]	1000	680	670	750
Forest type	Mesic dwarf-shrub with low herbs	Mesic dry dwarf-shrub	Mesic dwarf-shrub	Mesic dwarf-shrub
Tree species	*Picea abies*	*Pinus sylvestris*	*Pinus sylvestris*	*Pinus sylvestris*
Site index (H100, m) [b]	G 36	T 26	T 26	T 27
Stand age	46	53	48	44
Study period [c]	16/4	17/4	17/4	17/4
Soil type	Podsol	Podsol	Podsol	Podsol
Soil texture	Silty-sandy till	Sandy-silty till	Sandy till	Sandy-silty till
Humus type	Mor-moder	Mor	Mor	Mor

[a] Data from nearest climate station according to Alexandersson et al. (1991).
[b] Tree height at the age of 100 years (Hägglund, 1973, 1974).
[c] Number of growing seasons between first and second (x/x) thinnings and the latest measurement.

in Scots pine (*Pinus sylvestris* L.) stands with similar levels of fertility, and one (Örsås) was established in a very fertile Norway spruce (*Picea abies* (L.) Karst.) stand (Table 1).

The experimental sites were established between the years 1984 to 1987 in stands that had just reached the first thinning stage in order to investigate the effects of whole-tree thinning on subsequent stem growth. The second thinning was performed in 1997. The thinning grade on individual plots was not allowed to differ by more than 1% from the average grade within the block (Jacobson et al. 1996). The amount of nutrients in the slash was approximately twice as high in the Norway spruce site compared to the Scots pine sites (Jacobson et al. 1996). The slash was evenly distributed within plots. Five treatments were applied in a randomised block design with three replicates at each of the four sites. Each plot was 30 m × 30 m in size, and surrounded by a 5 m border strip. Further general information about the stands and sites can be found in Jacobson et al. (1996, 2000). In this study two treatments were included: conventional thinning (control) where logging residues were left on site; and whole-tree thinning with repeated removal of all logging residues.

2.2 Soil Sampling

Soil sampling was carried out from May through June 2001 four years after the second thinning was performed. Within each experimental plot 20 humus (FH) samples were taken with a 50 mm auger and 40 samples of the mineral soil (0–5 and 5–10 cm) with a 27 mm auger in a systematic pattern for all sites. For each experimental plot, samples were pooled by layer. The samples were then stored at 5 °C until sieving and chemical analysis. The humus samples were sieved through a 6 mm mesh net and the mineral soil through a 4 mm mesh net. The fresh material was dried at 85 °C for 24 h to determine dry matter. The pH of soil suspensions (16.5 ml fresh soil and 33.5 ml water) was then measured using a PHM 82 Standard pH-meter equipped with a combination electrode (GK2401C) after shaking for 30 minutes, leaving them to stand overnight at room temperature, repeating the shaking and allowing them to stand once more for at least 30 minutes. Potassium (K) and phosphorus (P) as phosphate were measured with an Auto Analyzer II (Technicon) after extracting 5 g fresh material in 100 ml 0.1 M ammonium lactate (pH 3.75) for 1.5 h and filtering the resulting suspension through pleated filters (00A, 125 mm). P was analyzed using a colorimetric method (ammonium molybdateascorbic acid, abs. 660 nm) and K using a flame photometer. The same extract was used when analysing calcium (Ca) and magnesium (Mg), but these cations were measured with an inductively coupled plasma optical emission spectrometer (ICP) (Optima 300 DV, Perkin-Elmer). Total C and N concentrations of air-dried soil samples (0.5 g humus and 1.0 g mineral soil) were analysed by combustion at 1250 °C with a LECO 2000 analyzer (LECO Equipment Corp.).

The amounts of extractable base cations, total N and total C per unit area in the organic horizon were calculated by multiplying the dry weight of the sieved organic layers per plot ($n = 20$ per plot) by the derived nutrient concentrations per unit dry mass. Similar calculations were made regarding the mineral soil, but based on mean values of the sieved amount of dry material per unit area for each site and soil layer ($n = 240$: 40 samples × 3 blocks × 2 treatments).

2.3 Understorey Vegetation

Understorey vegetation data were gathered at the experimental plots at Vetlanda and Örsås in June, and at Åmot and Munkfors in the beginning of September. Within each experimental plot, 12 quadrats (0.5 m × 0.5 m) were laid out in a systematic pattern. The cover was estimated by the naked eye, as projected onto the ground, to the nearest one per cent. Cover was estimated for stone, mineral soil, humus, litter, root, field layer, bottom layer and individual species. When the field and bottom layers were estimated separately, the total cover could exceed 100%. Species with less than 1% cover were recorded as '< 1' in the vegetation registrations, and in order to include their occurrence in calculations, a nominal figure of 0.1 was used. Nomenclature regarding vascular plants follows Lid (1985), while bryophyte nomenclature follows Söderström and Hedenäs (1998).

2.4 Statistics

Effects of whole-tree thinning on soil chemistry were analysed for each layer. In the statistical calculations regarding vegetation cover, mean values of the cover in field and bottom layer species exceeding 1% per plot were analysed.

The model used (nested ANOVA), included the following variables: Site, Block(Site), Treatment and Site × Treatment, using the general linear model (GLM) procedure (SAS, 1997). The need for transformation was judged by the Shapiro-Wilk test, visual examination of the data for kurtosis or skewness and visual interpretations of the residuals in normal-probability plots. Paired t-tests were used to evaluate the significance of differences ($p < 0.05$) between treatments.

3 Results

3.1 Treatment Effects on Soil Chemistry

No statistically significant treatment effects were detected on pH, dry weight (for which only the FH layer was included in the analysis) or concentrations and pools of C and N (Table 2). However, there was a general tendency for dry weight and pools of C and N to be lower in the FH layer after whole-tree thinning than in conventionally thinned plots. Generally, there seemed to be higher C and N concentrations and pools in the mineral soil layers at the Vetlanda and Örsås sites in southern Sweden. The C/N ratios differed between sites, with lower mean values being found at the spruce site compared to the less fertile pine sites ($p < 0.03$).

Analyses across all sites revealed that ammonium-lactate extractable concentrations of Ca and Mg in the FH layer were lower in the whole-tree thinned plots than in control plots ($p = 0.039$ and $p = 0.047$, respectively) (Table 3). At Munkfors, the concentrations of Ca in the 0–5 cm mineral soil layer and Mg in the humus layer were significantly lower in the whole-tree thinned plots ($p = 0.003$ and $p = 0.038$, respectively). Regardless of treatment, the Ca and Mg concentrations in the FH layer differed between tree species, with higher mean values of Ca at the pine sites ($p < 0.03$) and lower mean values of Mg ($p < 0.01$). At one pine site (Åmot) the ammonium-lactate extractable concentration of P in the FH layer was significantly higher in the whole-tree thinned plots ($p = 0.006$).

Site and treatment interactions were found for P

Table 2. Mean values of soil pH, concentrations and pools of C and N, C to N ratio and dry weight, by layer for the two treatments at the sampled sites. The pools are calculated for the FH layer and the sum of the FH and mineral soil layers (FH + MS). P-values refer to the significance levels of the differences between treatments (n = 3).

	Soil layer	Munkfors (S.P)			Åmot (S.P)			Vetlanda (S.P)			Örsås (N.S)			S.P sites			S.P + N.S sites		
		CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p
pH	FH	4.3	4.23	*0.42*	4.4	4.6	*0.12*	4.2	4.2	*0.67*	4.2	4.2	*1.00*	4.3	4.3	*0.73*	4.3	4.3	*0.70*
(H_2O)	0–5 cm	4.4	4.23	*0.24*	4.5	4.5	*1.00*	4.6	4.5	*0.18*	4.2	4.2	*0.54*	4.5	4.4	*0.23*	4.4	4.4	*0.34*
	5–10 cm	4.7	4.70	*0.67*	5.0	4.9	*0.83*	5.0	4.8	*0.13*	4.4	4.5	*0.35*	4.9	4.8	*0.44*	4.7	4.7	*0.83*
C_{tot}	FH	394.8	392.2	*0.85*	358.3	347.5	*0.85*	382.0	381.0	*0.97*	374.1	361.6	*0.71*	378.4	373.5	*0.71*	377.3	370.3	*0.76*
mg g^{-1} dw	0–5 cm	21.9	21.4	*0.92*	29.6	23.7	*0.07*	57.2	68.2	*0.45*	36.8	38.6	*0.48*	36.2	37.7	*0.79*	36.3	38.0	*0.68*
	5–10 cm	9.4	18.7	*0.30*	13.4	12.9	*0.76*	37.9	44.3	*0.75*	26.4	25.7	*0.78*	20.2	25.3	*0.22*	21.8	25.4	*0.24*
C_{tot}	FH	16.8	15.7	*0.77*	20.3	11.3	*0.20*	10.7	11.1	*0.99*	19.8	13.8	*0.58*	15.9	12.7	*0.37*	16.9	12.9	*0.17*
Mg ha^{-1}	FH + MS	34.9	38.9	*0.22*	41.5	29.4	*0.12*	46.8	53.7	*0.45*	54.3	48.9	*0.49*	41.1	40.6	*0.95*	44.4	42.7	*0.73*
N_{tot}	FH	11.9	11.6	*0.71*	12.3	12.0	*0.76*	12.5	12.5	*1.00*	14.5	13.3	*0.69*	12.2	12.0	*0.62*	12.8	12.4	*0.37*
mg g^{-1} dw	0–5 cm	0.6	0.7	*0.85*	1.0	0.8	*0.18*	1.8	2.1	*0.10*	1.6	1.5	*0.69*	1.1	1.2	*0.66*	1.2	1.3	*0.78*
	5–10 cm	0.3	0.6	*0.40*	0.5	0.5	*0.95*	1.2	1.3	*0.59*	1.1	1.0	*0.24*	0.6	0.8	*0.25*	0.8	0.8	*0.40*
N_{tot}	FH	0.5	0.5	*0.74*	0.7	0.4	*0.20*	0.4	0.4	*0.91*	0.8	0.5	*0.64*	0.5	0.4	*0.38*	0.6	0.4	*0.20*
Mg ha^{-1}	FH + MS	1.0	1.2	*0.45*	1.4	1.0	*0.11*	1.5	1.6	*0.06*	2.2	1.9	*0.49*	1.3	1.3	*0.91*	1.5	1.4	*0.54*
C to N	FH	33.3	33.9	*0.25*	29.2	29.0	*0.91*	30.6	30.6	*0.95*	25.9	27.2	*0.80*	31.0	31.2	*0.48*	29.7	30.2	*0.24*
ratio	0–5 cm	36.7	32.6	*0.43*	30.9	28.2	*0.14*	31.2	32.5	*0.74*	23.7	25.8	*0.25*	33.0	31.1	*0.37*	30.7	29.8	*0.61*
	5–10 cm	33.1	32.2	*0.78*	28.1	27.4	*0.85*	32.2	34.1	*0.74*	24.7	26.1	*0.37*	31.1	31.2	*0.91*	29.5	30.0	*0.58*
dw	FH	4.2	4.0	*0.82*	5.6	3.2	*0.16*	2.8	2.9	*0.89*	5.3	3.8	*0.50*	4.2	3.4	*0.40*	4.5	3.5	*0.19*
kg m^{-2}	0–5 cm	57.5	57.5		47.8	47.8		34.7	34.7		53.4	53.4		46.7	46.7		48.4	48.4	
	5–10 cm	58.5	58.5		52.3	52.3		42.9	42.9		56.3	56.3		51.2	51.2		52.5	52.5	

CT = conventional thinning, WTT = whole-tree thinning
S.P = Scots pine, N.S = Norway spruce

Table 3. Effects of whole-tree harvesting four years after second thinning on exchangeable (AL-extracted) phosphorus and base cations at different sites and layers. The pools are calculated for the FH layer and the sum of the FH and mineral soil layers (FH + MS). Mean value (n = 3) and p-values of treatment effects are shown.

	Soil layer	Munkfors (S.P)			Åmot (S.P)			Vetlanda (S.P)			Örsås (N.S)			S.P sites			S.P + N.S sites		
		CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p	CT	WTT	p
P	FH	54.3	61.2	0.12	56.1	64.4	<0.01	49.4	44.8	0.59	47.4	41.7	0.36	53.2	56.9	0.46	51.7	53.2	0.70
µg g^{-1} dw	0–5 cm	9.8	14.2	0.39	6.8	5.1	0.51	15.9	19.0	0.82	14.7	4.6	0.51	10.9	12.9	0.43	11.8	10.8	0.78
	5–10 cm	6.7	13.3	0.42	8.9	2.8	0.42	13.2	14.6	0.72	15.7	3.7	0.53	9.6	10.2	0.87	11.1	8.7	0.59
P	FH	2.2	2.4	0.59	3.0	2.0	0.18	1.4	1.3	0.85	2.4	1.6	0.21	2.2	1.9	0.50	2.3	1.8	0.24
kg ha^{-1}	FH + MS	11.8	18.4	0.31	10.9	5.9	0.33	12.6	14.2	0.86	19.1	6.1	0.50	11.8	12.8	0.78	13.6	11.1	0.60
K	FH	352.5	375.56	0.33	337.2	403.4	0.06	332.1	300.6	0.11	269.2	300.4	0.74	340.7	359.8	0.57	32.3	34.5	0.35
µg g^{-1} dw	0–5 cm	28.2	24.96	0.19	42.7	44.6	0.79	46.9	43.4	0.27	27.8	33.5	0.45	39.2	37.7	0.48	36.3	36.7	0.89
	5–10 cm	15.5	16.60	0.23	26.5	22.3	0.77	25.3	25.7	0.87	16.3	16.2	0.93	22.3	21.6	0.68	20.8	20.3	0.70
K	FH	14.7	15.1	0.91	17.6	12.5	0.14	9.3	8.7	0.66	14.0	11.5	0.41	13.9	12.1	0.41	13.9	12.0	0.21
kg ha^{-1}	FH + MS	40.0	39.2	0.87	51.8	45.5	0.43	36.4	34.8	0.48	38.0	38.5	0.80	42.7	39.8	0.23	41.6	39.5	0.26
Ca	FH	1623.8	1528.3	0.19	2241.6	1869.8	0.46	1902.5	1756.7	0.20	1174.0	917.7	0.66	1922.7	1718.3	0.14	1735.4	1518.1	0.04
µg g^{-1} dw	0–5 cm	108.4	74.8	<0.01	309.2	203.8	0.39	200.1	173.9	0.63	52.1	33.2	0.59	205.8	150.8	0.16	167.3	121.4	0.11
	5–10 cm	38.6	24.7	0.06	106.5	81.2	0.39	116.7	87.2	0.55	24.4	36.2	0.20	87.3	64.3	0.14	71.6	57.3	0.23
Ca	FH	67.4	61.7	0.66	126.9	58.5	0.27	54.1	50.6	0.75	61.6	35.3	0.49	82.8	57.0	0.35	77.5	51.6	0.18
kg ha^{-1}	FH + MS	152.4	119.2	0.12	330.3	198.4	0.28	173.5	148.4	0.46	103.1	73.5	0.58	218.7	155.3	0.21	189.8	134.9	0.12
Mg	FH	173.6	167.0	0.04	222.0	181.7	0.38	259.1	232.6	0.19	343.4	325.3	0.95	218.2	193.8	0.13	249.6	226.6	<0.05
µg g^{-1} dw	0–5 cm	8.0	6.3	0.44	21.1	12.8	0.12	23.7	24.4	0.88	15.5	13.3	0.51	17.7	14.4	0.37	17.2	14.2	0.23
	5–10 cm	2.7	2.9	0.18	6.6	4.9	0.23	9.7	11.9	0.56	6.2	6.1	0.74	6.2	6.6	0.82	6.3	6.4	0.87
Mg	FH	7.3	6.8	0.74	12.5	5.8	0.31	7.3	6.7	0.67	18.0	12.5	0.49	9.0	6.4	0.33	11.3	7.9	0.13
kg ha^{-1}	FH + MS	13.5	12.1	0.30	26.0	14.4	0.19	19.7	20.3	0.83	29.7	23.0	0.53	19.7	15.6	0.39	22.2	17.4	0.18

CT = conventional thinning, WTT = whole-tree thinning
S.P = Scots pine, N.S = Norway spruce

Table 4. Mean coverage of field and bottom layers and mean number of species in the two different vegetation layers (n = 3). Significant treatment effects are marked with an asterisk (*).

	Field layer (%)		Bottom layer [a)] (%)		No. spec. field		No. spec. bottom [a)]	
	CT	WTT	CT	WTT	CT	WTT	CT	WTT
Munkfors (S.P)	19.2	26.4*	24.9	37.2	5.3	8.0	5.7	6.0
Åmot (S.P)	38.9	31.0	17.4	29.4	10.7	10.3	6.7	5.7
Vetlanda (S.P)	44.0	41.1	80.7	77.4	9.7	10.0	3.3	3.3
Örsås (N.S)	6.4	3.0	33.1	38.0	4.0	2.0	11.0	11.0
S.P sites	34.0	32.8	41.0	48.0	8.6	9.4	5.2	5.0
All sites	27.1	25.4	39.0	45.5	7.4	7.6	6.7	6.5

[a)] Bryophytes
CT = conventional thinning, WTT = whole-tree thinning
S.P = Scots pine, N.S = Norway spruce
*p = 0.03

and K concentrations in the organic layer ($p = 0.05$ and $p = 0.04$, respectively). However, the low statistical significance at individual sites prevents further interpretations of the data (Table 3).

The total pools (kg ha^{-1} in FH + 0–10 cm mineral soil) of extractable base cations and P did not show any significant treatment effects (Table 3).

3.2 Effects on Understorey Vegetation

The dominant field layer species at the pine sites (Munkfors, Vetlanda and Åmot) were *Vaccinium myrtillus* (Vm) and *Deschampsia flexuosa* (Df). Other field layer species for which cover was low but greater than 1% included *Vaccinium vitis-idaea* (Vv), *Maianthemum bifolium* (Mb) and *Calluna vulgaris* (Cv). The bottom layer at the pine sites was dominated by *Pleurozium schreberi* (Ps), *Hylocomium splendens* (Hs) and *Dicranum polysetum* (Dp) (Table 4). At the spruce site (Örsås), Df dominated in the field layer and the bottom layer was dominated by Ps and *Dicranum majus* (Dm). The cover of the bryophytes *Hypnum cupressiforme* (Hc), *Eurhynchium* spp. (Eu) and *Polytrichum commune* (Pc) found at the spruce site was low, but exceeded the chosen threshold of 1% for single species.

When treatments across all sites or when all pine sites were included in the model, no statistically significant treatment effects were found. However, the field layer mean cover was lower but not significantly different in the whole-tree thinned plots compared to the conventionally thinned plots in three of the four studied sites, whereas the opposite was found in the bottom layer (Table 4). Regardless of layer, no treatment effects on the number of species were detected. Neither was there any significant treatment effect on cover of single species within each site.

4 Discussion

Regardless of site fertility, climate or tree species, repeated removal of logging residues after thinning did not result in any significant differences with respect to soil pH or soil contents of C or N compared to conventional thinning. These results were not unexpected since previous studies of the effects of whole-tree harvesting and conventional harvesting in clear felling on C and N have not given any clear results (e.g. Hendrickson et al. 1989, Olsson et al. 1996b, Johnson and Curtis 2001). However, the findings by Jacobson et al. (2000) that whole-tree thinning reduced tree growth by 7–17% during the first 10 years after first thinning at the sites included in the present study indicate that treatment-associated differences in nutrient availability occurred. Apart from affecting the release of nutrients from decomposing needles and twigs, the conventional thinning treatment may stimulate mineralization in the organic layer beneath the slash (cf. Rosén and Lundmark-Thelin 1987, Emmett et al. 1991). The resulting improvements in nutrient status have likely led to continuously increased rates of nutrient incorporation in the trees at the conventionally thinned plots. According to Fahey et al. (1991b) an alternative explanation of a lower growth rate of trees after whole-tree thinning could be due to a greater development of field vegetation, thereby reducing nutrient availability for trees. However, the general result from our study, indicating similar cover in conventionally thinned and whole-tree thinned plots, was not in agreement with the finding by Fahey et al. (1991b).

The removal of slash did not significantly affect the amount of dry matter in the FH layer (Table 2), partly because of the relatively small slash volumes and partly because of the sampling technique used here, which excluded litter. Furthermore, the slash left after the second thinning has probably only affected the litter layer. In a longer term perspective it is possible that the differences in dry matter in the FH layer will increase due to further decomposition of needles and coarser fractions, such as branches (cf. Hyvönen et al. 2000). In support of this hypothesis, 34 years after final felling and subsequent thinnings in a fertile Norway spruce stand, Mahmood et al. (1999) found a thicker humus layer in conventionally harvested plots compared to whole-tree harvested plots.

The expected decrease in pH due to whole-tree harvesting (Nykvist and Rosen 1985, Staaf and Olsson 1991) did not appear after repeated removal of slash in thinnings. However, the lower concentrations of exchangeable base cations (Ca and Mg) may lead to a decreased capacity to buffer acidity in the whole-tree thinned plots.

In the analysis across all sites, no significant treatment effects regarding concentrations and soil pools of P and K were found. However, the concentrations of Ca and Mg did show significant treatment effects in the humus layer, with higher levels in the conventionally thinned than in the whole-tree thinned plots (Table 3). This is in accordance with data gathered by Hendrickson et al. (1989) three years after clear felling. The calculated soil pools of exchangeable Ca and Mg did not show any general significant treatment effects (Table 3), which is in accordance with an earlier study five years after first thinning at the same sites reported by Olsson (1999). However, due to differences in the extraction methods used, the results cannot be directly compared.

A possible explanation for the lack of treatment effects on P, in contrast to the increases in Ca and Mg concentrations detected in the FH layer in the conventionally thinned plots, is that a major proportion of the Ca and Mg within needles is released within four years of decomposition, whereas the amount of P is almost unaffected (Berg and Staaf 1980, Staaf and Berg 1982, Berg and Lundmark 1985, Fahey 1991a). In the present study no general treatment effect on the K concentration was detected, although K is released relatively quickly from decomposing needles (see, for instance, Staaf and Berg 1982). This was also found by Olsson et al. (1996a) and may be explained by the much greater mobility of the K^+ ion compared with Ca^{2+} and Mg^{2+}, which may lead to losses through leaching (Staaf and Olsson 1994), or increased uptake of K^+ by plants.

Repeated removal of residues did not have any clear, general effect on the cover of vascular plants or bryophytes four years after the second removal of thinning slash. This finding is not surprising since earlier studies have reported both increases and decreases in cover due to slash removal after clear felling (Kardell 1992, Olsson and Staaf 1995). In thinnings, the remaining trees will probably compete with the understorey vegetation for nutrients released from the slash or possibly from increased mineralization in the organic layer (cf. Fahey et al. 1991b, Rolff and Ågren 1999). Furthermore, the nutrient contents and the suppressive effect of slash generated in thinnings, as in this study, will be much lower than after clear fellings (cf. Fahey et al. 1991a, Kardell 1992, Olsson and Staaf 1995).

In conclusion, the observed effects on soil chemistry and understorey vegetation of repeated whole-tree thinning were generally minor and somewhat inconsistent. Yet, in the organic layer the concentrations of exchangeable Ca and Mg were significantly lower in the repeatedly whole-tree thinned plots across all sites.

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