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Effect of conventional and whole-tree clear-cutting on concentrations of some micronutrients in coniferous forest soil and plants

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Abstract. Increasingly intensive and mechanized clear-cutting may deplete the forest ecosystem of essential nutrients. A clear-cut area near Växjö, southern Sweden, was investigated for changes in Mn, Cu and Zn in soil (NH_4NO_3 extractable and HNO_3 soluble) and wavy hair grass (*Deschampsia flexuosa*) after conventional (CC) and whole-tree clear-cutting (WTC). The soil samples were mostly iron podzols. The area consisted of four clear-cut sites, respectively 2, 4, 6 and 8 years old, and an uncut forest reference stand. Each of the clear-cuts was split in two parts representing WTC and CC sites. Manganese showed the most definite trends after clear-cutting, exhibiting higher extractable concentrations in Oe, Oa and E horizons (4–8 years after clear-cutting) and B horizons (6–8 years after clear-cutting). The increase of exchangeable Mn in the E (2–8 years) and B (4–8 years) horizons was particularly strong. Zn concentrations tended to fluctuate with time. There was a tendency to higher Mn and Zn concentrations in the humus layer especially 2 years after CC-treatment compared with WTC, whereas the opposite trend was apparent for Cu. Mn, Cu and Zn concentrations decreased in *Deschampsia flexuosa* 2 years after clear-cutting, possibly due to increased soil pH.

Key words: whole-tree clear-cutting, conventional clear-cutting, *Deschampsia flexuosa*, soil, micronutrients.

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Introduction

Whole-tree clear-cutting (WTC) can deplete the forest ecosystem of important nutrients (Kimmins, 1977; Hornbeck & Kropelin, 1982; Johnson *et al*., 1982; Olsson *et al*., 1996). Disturbances of nutrient balances following WTC have been addressed e.g. by Nykvist & Rosén (1985), Staaf & Olsson (1991, 1994), and Olsson *et al.* (1996). In Swedish forestry WTC has to some extent replaced conventional clear-cutting (CC) due to the use of slash for bioenergy. Negative effects due to WTC in Sweden have been suggested to be of greater concern in the southern part due to higher acid deposition (Falkengren-Grerup *et al*., 1987), and therefore an increased risk of depleting nutrients. Practical experiments in Sweden show that WTC affects stem basal area growth of Norway spruce and Scots pine (e.g. Egnell *et al*., 1998). Height growth

of Scots pine was not affected by WTC (Staaf & Björkroth, 1980; Egnell *et al.*, 1998). Survival of planted Scot pine is usually higher after WTC, which might compensate for production losses. Egnell *et al.* (1998) suggest that the negative effect on basal growth after WTC is due to less available nitrogen as normally released from logging residues. Thus, the importance of slash left at the clear-cut areas is due to its contribution to nutrient supply in the soil, and it also has a significant effect on the development of the field vegetation layer.

Reduced input of needles together with increased decomposition of organic matter has shown to yield a decreased thickness of the humus layer following clear-cutting (Sartz & Huttinger, 1950; Covington, 1981; Løbersli, 1981; Berthelsen & Steinnes, 1995). The reduction of the organic layer is caused by higher rates of decomposition due to increased soil temperature, higher moisture content and more available NH_4^+ (Tamm *et al.*, 1974; Vitousek *et al.*, 1979; Keeney, 1980; Jansson, 1987). Clear-cutting reduces the evapotranspiration, causing an increase of the water percolation through the soil. Slash covered plots in Central Sweden were 1–2 °C colder and had a 3–6% higher water content the first year after clear-cutting compared with clear-cut areas where slash had been removed (Jansson, 1987).

Mineral nutrients are lost from forested areas by biomass removal (Weetman & Webber, 1972; Bormann & Likens, 1979) and WTC might affect leaching but could both increase and decrease loss of elements (Mann *et al.*, 1988; Hendrickson *et al.*, 1989; Westling *et al.*, 2004). Both CC and WTC lead to increased mineralization of organic material and reduced uptake of nutrients in the plant biomass, which increases the risk of leaching of important nutrients to nearby streams (Bormann & Likens, 1979). In a study from two watersheds in a coniferous forest area in central Sweden, clear-cutting resulted in an increased runoff of 119 and 75%, respectively. No differences between WTC and CC were detected, probably due to natural variations between the two areas (Rosén, 1984). Changes in algae concentrations and composition in nearby forest brooks after clear-cutting in Finland indicated that increased runoff and nutrient supply had a crucial influence on the biological balance in these brooks (Holopainen & Huttunen, 1992).

Clear-cutting has shown to have an impact on microbiological activity in soil as well. Fungal biomass decreased after clear-cutting a pine forest in Sweden (Bååth, 1980). An increased level of viable counts of bacteria was found following clear-cutting in a spruce forest in Finland (Sundman *et al.*, 1978). Lundgren (1982) found that plots in a clear-cut pine forest in Sweden receiving slash contained greater amounts of bacteria than plots where slash was removed. Slash left on the ground did not affect the fungal biomass even though there was a greater amount of FDA-active fungal mycelium at sites where slash was left on the ground (Bååth, 1980).

Nitrogen mineralization and nitrification are normally increased immediately after clear-cutting due to increased soil temperature and short-term accumulation of NH_4^+ in the soil. Since nitrogen uptake in plants is reduced, elevated concentrations of ammonium and nitrate are frequently observed in the soil and soil water at clear-cut sites (Vitousek & Melillo, 1979, Högbom *et al.*, 2002; Westling *et al.*, 2004). Increased levels of nitrate have been observed in streams and groundwater after clear-cutting and at 50 cm depth. Örlander *et al.* (1996) demonstrated increased soil water concentrations of both NH_4-N and NO_3-N 4 years after clear-cutting. Maximum peaks were observed 3 years after forest clear-cutting. In a study from a fertile forest area in southern Sweden, Wiklander *et al.* (1991) showed a similar effect of clear-cutting on groundwater NO_3-N levels that lasted as long as 4 years. Using an *in vivo* nitrate reductase activity bioassay, Högbom *et al.* (2002) showed amplified

level of plant available nitrate more than 5 years after clear-cutting in the same area as investigated in the present study.

Previous literature on relations between different methods of forest clear-cutting and micronutrient distribution and mobilization in soils and field-layer plants is sparse. The objective of the present study was to examine the effects of WTC and CC on the behaviour of some micronutrients with time after clear-cutting through their vertical distribution in the soil and levels in a dominant grass species found on these clear-cuts. *Deschampsia flexuosa* dominates the field vegetation layer at clear-cut sites in Sweden (Bergkvist *et al*., 1999) and was an obvious choice for this investigation.

Material and Methods

Study sites and experimental design

The investigated sites were situated near Asa Forest Research station (57°10´N, 14°47´E), in southern Sweden in an area called Bråtarna. The species mixture ratio before clear-cutting at Bråtarna in volume % was 43:56 for *Pinus sylvestris* and *Picea abies* respectively (Nilsson & Örlander, 1999). The field vegetation layer in the original coniferous forest surrounding the clear-cut sites was dominated by bilberry (*Vaccinium myrtillus*). The clear-cut areas on the other hand were dominated by grasses, primarily wavy hair grass (*Deschampsia flexuosa*).

Altogether 9 sites were included in the present study and all were located in the same original stand. Four clear-cut areas being 2, 4, 6 and 8 years old had been split in to two equally sized areas. The 4, 6 and 8 years old clear-cuts were the same areas as described in detail by Nilsson & Örlander (1999). Approximately 80% of the slash was removed at one half of the clear-cut sites and each clear-cut was 1–4 ha in size. The slash had been removed using a forwarder. The 2-year old clear-cut was located close to the other clear-cut areas and had been treated in the same manner. An uncut area from the same stand was chosen as reference stand with the purpose to represent the conditions prior to clear-cutting.

The soils had rather variable depths and were quite shallow in some places, down to 10 cm total depth. The soil also exhibited some differences in stage of podzolisation, but most of the soils were iron podzols. Additional information about soils in study areas is available in Nilsson and Örlander (1999).

Sampling and chemical analyses

Parts of the 4, 6, and 8 years old clear-cut areas had been treated with insecticide and herbicide in limited blocks (Nilsson & Örlander, 1999). Soil and plant samples to be investigated in the present study were selected randomly from plots at appreciable distance from the treated parts of these areas.

Ten samples of *Deschampsia flexuosa* at each clear-cut and reference area were obtained by randomised collection. The grass samples were air dried at room temperature and homogenized using a pair of steel scissors. The plant material was digested using a microwave oven technique. About 0.4 g of grass was digested in nitric acid (65%, 4 ml) using a special microwave program designed for plant material, followed by filtration and dilution of the solution to 10 ml with H_2O.

At each site 15 soil cores were randomly sampled using a hollow steel cylinder (10 cm diameter). Each core was sub-divided according to horizon. In some samples transition layers were apparent, and these layers were excluded from further analyses. Soil extracts were prepared by adding 3 g of air-dried, sifted (2 mm) soil in 100 ml polyethylene bottles. 30 ml NH_4NO_3 (1.0 M) was added to each bottle and after

shaking for 2 hours the samples were filtered. The filtrates were stored in a freezer until analysis. Nitric acid soluble element concentrations were determined by digestion of 2 g of soil in nitric acid (65%, 20 ml) at about 95 °C for approximately 18 hours. The samples were then filtered into acid-washed polyethylene bottles and diluted to 50 ml with H_2O.

All samples were analysed using a Perkin-Elmer flame atomic absorption spectrophotometer (AAS). Homogeneity in metal concentrations of the soil and plant samples was tested on a selection of the samples by extracting or digesting 10 sub-samples. The soil pH was measured in a 1:10 (v/v) soil/water suspension. Loss-on-ignition (L.O.I.) was determined by measuring the weight loss upon heating oven dry soil (105 °C for 12 hours) to 550 °C in a muffle furnace for 4 hours.

Parametric statistical analysis was used for comparison in each of the soil horizons between reference forest and each of the different years after clear-cutting and different clear-cutting methods using the general linear method (GLM) in SPSS 10.0. Tukey-Kramer test was performed choosing the Tukey test post-hoc option in GLM for each element.

Results

Table 1 shows concentrations of Mn, Zn, and Cu in *Deschampsia flexuosa* with standard errors and statistical differences between groups. Corresponding results on pH/L.O.I., Mn, Zn, and Cu concentrations in soil are summarised in Tables 2–5, respectively.

Changes in element concentrations in Deschampsia flexuosa following clear-cutting

The development of metal concentrations in *Deschampsia flexuosa* (Table 1) with time may be briefly described as follows:

Mn: Concentrations fluctuated over the period with the lowest values after 2 years. After 8 years the WTC level was significantly higher than that in CC.

Zn, Cu: These elements showed similar fluctuating trends with a drop to about 60% of the initial value after 2 years, followed by an increase the following 2 years, significantly greater for CC. Then a decrease was evident over the next 2 years to the same level as after 2 years, followed by a slight increase again after 8 years.

Table 1. Concentrations (ppm) of Mn, Zn and Cu in *Deschampsia flexuosa* in forest and clear-cut areas with associated standard errors (range). Values in rows followed by the same letter do not differ significantly at the 5% level. Bold numbers show significant differences between CC and WTC.

		Age of clear-cut areas					
Element		Forest	2	4	6	8	S.E. (range)
Mn	CC	ab 78	a 65	a 74	b 91	ab **77**	(1.6-2.7)
	WTC	a 78	b 52	ac 83	a 74	c **97**	(1.4-2.7)
Zn	CC	a 35.3	b 21.2	a **37.4**	b 22.8	b 25.4	(0.4-0.9)
	WTC	a 35.3	b 19.0	c **26.0**	bc 22.0	ac 31.4	(0.4-0.9)
Cu	CC	a 4.3	b 2.6	a **3.8**	b 2.8	a **3.7**	(0.0-0.1)
	WTC	a 4.3	b 2.5	b **3.1**	b 3.0	b **2.8**	(0.0-0.1)

Temporal trends in soil chemistry after clear-cutting

Soil pH and L.O.I.

WTC gave lower L.O.I. values (Table 2) in the humus layer (Oe and Oa) after 6 years while the opposite trend was apparent in the E horizon with a 2- to 3-fold increase in L.O.I. 4 years after CC. Although a relatively clear increase in the soil pH after clear-cutting in the Oe and Oa horizon is indicated in Table 2, soil pH was not tested statistically because too few samples had enough soil left for pH measurement.

As shown in Table 2 the organic matter content (Oa horizon) following clear-cutting was significantly lower in CC than in WTC. Six years after clear-cutting an opposite trend was evident with higher L.O.I. in soil from CC. Also in the E horizon there was a tendency to higher L.O.I. at CC starting four years after clear-cutting.

Table 2. Soil pH and L.O.I. (%) in Oe, Oa, E and B horizons in forest and clear-cut areas. Means in rows followed by the same letter do not differ significantly at the 5% level. Bold numbers show significant differences between CC and WTC. Values are arithmetic means and errors are given as a range of standard errors (S.E.). N.d.-not determined.

Analytical method	Soil	Clear-cutting method	Age of clear-cut areas					
			Forest	2	4	6	8	S.E. (range)
pH	Oe	CC	3.27	3.51	3.78	3.88	3.95	N.d.
		WTC	3.27	3.68	3.85	3.57	3.96	N.d.
	Oa	CC	3.23	3.51	3.53	3.52	3.60	N.d.
		WTC	3.23	3.64	3.63	3.52	3.61	N.d.
	E	CC	3.68	3.70	3.82	3.62	3.85	N.d.
		WTC	3.68	3.86	3.79	3.83	3.87	N.d.
	B	CC	3.91	3.86	3.88	3.95	4.00	N.d.
		WTC	3.91	4.16	4.01	4.11	4.07	N.d.
L.O.I.	Oe	CC	a 95.5	a 93.7	a 92.9	a 91.8	a 86.8	(0.2-1.7)
		WTC	a 95.5	a 92.0	a 86.6	b 86.1	b 87.3	(0.3-2.6)
	Oa	CC	a 87.6	a **78.4**	a 87.2	a **84.1**	a 80.3	(0.7-2.9)
		WTC	a 87.6	a **90.0**	a 88.5	b **70.4**	b 72.4	(0.7-2.2)
	E	CC	a 11.8	a 10.9	b **33.6**	b 29.4	b 27.1	(0.4-2.3)
		WTC	a 11.8	a 26.7	a **20.9**	a 18.3	a 20.6	(0.4-9.5)
	B	CC	a 8.0	a 9.4	a 8.8	a 8.8	a 7.6	(0.2-0.8)
		WTC	a 8.0	a 7.7	a 8.0	b 10.9	a 8.8	(0.1-0.9)

Mn, Zn and Cu in soil

Clear-cutting resulted in a significantly higher level in the Oe, Oa and E horizons of both ammonium nitrate extractable and nitric acid soluble Mn concentrations just 4 years after clear-cutting. At the 6 year-old clear-cut there was a significant increase in the B horizon as well. There were as much as 15–30 times higher exchangeable Mn concentrations (Table 3) in the E and B horizons after 8 years following clear-cutting compared with the forest reference soil, whereas in the same horizons there was only 2–2.5 times increase of nitric acid soluble Mn concentrations (Table 3). In the Oe and Oa horizons, there was an increase of about 3–7 times both for ammonium nitrate extractable and nitric acid soluble Mn after 8 years following clear-cutting. There was a significantly increased level of both ammonium nitrate extractable and nitric acid soluble Mn in the Oe and Oa horizon 2 years after clear-cutting but also noticeable are higher Mn concentrations in the Oe horizon 8 years following CC.

Table 3. Significant differences between forest and clear-cuts for exchangeable and nitric acid soluble manganese (mg kg^{-1}) in different soil horizons and with different clear-cutting methods. Errors are given as a range of standard error (S.E.) values. Means in rows followed by the same letter do not differ significantly at the 5% level. Bold numbers show significant differences between CC and WTC. Values are arithmetic means.

Mn extraction method	Soil	Clear-cutting method	Age of clear-cut areas					S.E. (range)
			Forest	2	4	6	8	
Nitric acid soluble	Oe	CC	a 150	ab **251**	b 369	b 389	c **791**	(5.2-19)
		WTC	a 150	a **124**	b 406	b 343	b **472**	(6.2-13)
	Oa	CC	a 80	b **179**	bc 233	cd 320	d 392	(4.0-14)
		WTC	a 80	a **98**	b 263	b 266	b 334	(4.0-6.3)
	E	CC	ab 64	a 68	bc 116	c 143	c 154	(2.1-10)
		WTC	a 64	a 79	ab 96	bc 138	c 162	(2.6-11)
	B	CC	a 90	a 80	a 118	a **118**	b 210	(2.7-7.2)
		WTC	a 90	a 114	a 105	b **196**	ab 149	(4.6-13)
Ammonium nitrate extractable	Oe	CC	a 99	a **163**	b 254	b **305**	c **386**	(3.0-8.7)
		WTC	a 99	a **69**	b 271	b **205**	b **269**	(3.4-8.1)
	Oa	CC	a 35	b **105**	c 144	c 188	d 244	(1.7-5.6)
		WTC	a 35	a **39**	b 169	b 168	b 210	(1.7-4.9)
	E	CC	a 2.0	a 7.4	b 41	c **77**	bc 60	(0.2-5.5)
		WTC	a 2.0	ac 9.1	bc 30	b **54**	b 44	(0.2-5.8)
	B	CC	ab 1.5	a 1.4	ab 8.7	b 10	c 23	(0.1-1.6)
		WTC	a 1.5	a 3.1	ab 8.8	b 16	b 20	(0.1-2.4)

Zn concentrations in Oa horizon (Table 4) were back to approximately the initial level 8 years following clear-cutting after a reduction in both nitric acid soluble and exchangeable Zn concentrations 2 years after WTC. There was an approximate doubling of the ammonium nitrate extractable and the nitric acid soluble Zn concentrations 6 and 8 after clear-cutting in the E and B horizon. There were only few significant differences in Zn between the two clear-cutting methods in the soil even though there were significantly higher levels of ammonium nitrate extractable Zn at CC compared with WTC in the Oa horizon after 2 and 4 years, followed by a significantly higher level of Zn in the E horizon after 6 years.

Eight years after clear-cutting all soil depths showed increased levels of Cu following CC and/or WTC with sporadically higher concentrations in 4 to 6 years after clear-cutting in the Oa, E and B horizons (Table 5). Cu showed few significant differences between the two types of clear-cutting, but higher nitric acid soluble Cu concentrations were observed in WTC compared with CC 2 and 4 years following clear-cutting in the Oa and the B horizon respectively.

Discussion

Changes in element concentrations in wavy hair grass following clear-cutting

Clear-cutting involves quite extensive changes in the underlying soil, both regarding the soil solution chemistry and the character of the humus layer. Due to enhanced mineral nutrient availability clear-cutting creates a favourable environment for growth of a large number of plant species. This prevents nutrient leaching to a great extent (c.f. Nilsson & Örlander, 1999). The field vegetation layer also goes through substantial changes after clear-cutting (Bergkvist *et al.*, 1999). *Deschampsia flexuosa* is a common and important grass widespread in acid boreal forest, and is believed to

Table 4. Significant differences between forest and clear-cuts for exchangeable and nitric acid soluble zinc (mg kg^{-1}) at different soil horizons and clear-cutting methods. Errors are specified as a range of standard errors (S.E.). Means in rows followed by the same letter do not differ significantly at the 5% level. Bold numbers show significant differences between CC and WTC. Values are arithmetic means.

Zn Extraction method	Soil	Clear-cutting method	Age of clear-cut areas: Forest	2	4	6	8	S.E. (range)
	Oe	CC	a 58.1	a 66.5	a 69.7	a 67.9	b **84.5**	(0.7-1.7)
		WTC	a 58.1	a 54.3	a 61.8	a 62.6	a **59.2**	(0.7-1.3)
	Oa	CC	ab 68.0	b **64.1**	ab **75.6**	ab 75.3	a 78.1	(0.8-1.2)
Nitric acid		WTC	a 68.0	bc **52.1**	ac **64.0**	a 65.6	a 76.3	(0.8-1.2)
soluble	E	CC	a 13.6	a 14.6	a 18.7	b **39.0**	b 34.0	(0.4-2.3)
		WTC	a 13.6	a 15.1	a 18.9	ab **25.0**	bc 31.4	(0.4-2.4)
	B	CC	a 11.1	a **15.2**	b **16.9**	a 16.4	b 21.4	(0.3-1.0)
		WTC	a 11.1	a **12.0**	b **27.9**	b 18.2	b 18.8	(0.3-0.9)
	Oe	CC	a 29.9	a 31.1	a 30.4	a 31.5	a 31.8	(0.4-0.5)
		WTC	a 29.9	a 26.4	a 26.3	a 28.1	a 27.5	(0.3-0.9)
	Oa	CC	ab 37.9	a **32.9**	b **41.2**	a 33.3	ab 36.1	(0.5-0.9)
Ammonium		WTC	a 37.9	b **21.3**	c **29.1**	c 29.1	ac 33.1	(0.4-0.6)
nitrate	E	CC	a 6.7	a 7.2	a 9.2	b **21.9**	a 11.5	(0.5-1.2)
extractable		WTC	a 6.7	a 6.8	a 8.0	ac **11.6**	bc 14.4	(0.5-1.3)
	B	CC	a 2.2	ab 3.0	ab **3.5**	b 4.2	b 4.1	(0.1-0.2)
		WTC	a 2.2	a 1.8	a **1.8**	ac 3.3	bc 4.3	(0.1-0.3)

Table 5. Significant differences between forest and clear-cuts for nitric acid soluble copper (mg kg^{-1}) at different soil horizons and clear-cutting methods. Errors are given as a range of standard errors (S.E.). Means in rows followed by the same letter do not differ significantly at the 5% level. Bold numbers show significant differences between CC and WTC. Values are arithmetic means. Results from determination of exchangeable Cu in soil were in most cases below detection limits for flame AAS and are not reported.

Cu Extraction method	Soil	Clear-cutting method	Age of clear-cut areas: Forest	2	4	6	8	S.E. (range)
	Oe	CC	ab 8.4	ab 8.8	a 7.7	ab 8.4	b 9.7	(0.1-0.2)
		WTC	a 8.4	a 8.8	a 8.7	a 8.2	a 9.2	(0.1-0.2)
	Oa	CC	a 7.7	a **7.1**	a 7.5	a 8.3	b 9.8	(0.1-0.2)
Nitric acid		WTC	ac 7.7	bc **9.2**	ab 8.9	c 7.3	b 9.4	(0.8-1.2)
soluble	E	CC	a 2.1	a 2.3	ab 3.2	b 5.0	b 4.2	(0.4-2.3)
		WTC	a 2.1	ab 3.5	b 4.3	ab 3.3	b 4.3	(0.4-2.4)
	B	CC	a 2.0	a 2.2	a **2.6**	a 2.4	a 2.7	(0.3-1.0)
		WTC	a 2.0	a 2.4	b **4.0**	ac 2.5	c 3.1	(0.3-0.9)

be favoured relative to other field-layer species by anthropogenic nitrogen. This particular grass appears to grow strongly on clear-cuts in previous bilberry forests and might be a forestry problem since it interferes with growth of e.g. planted *Picea abies* seedlings (Odell & Stahl, 1998; Nilsson & Örlander, 1999).

Higher pH in the humus layer reduces the plant-available concentrations of the micronutrients Mn, Zn and Cu to various degrees (Marschner, 1995). The pH increase in soil after clear-cutting shown in previous studies (Løbersli, 1981; Nykvist & Rosén, 1985; Staaf & Olsson, 1991; Taylor *et al.*, 1991; Berthelsen & Steinnes 1995) and seem-

ingly confirmed in this work could for the most part explain reduced levels of these elements in *Deschampsia flexuosa* after 2 years following clear-cutting. But other factors as e.g. increased Ca as previously shown e.g by Løbersli (1981) and thereby increased competition could also contribute to the reduced levels of Zn, Cu and Mn following clear-cutting in *Deschampsia flexuosa*.

Temporal trends in soil chemistry after clear-cutting

pH and L.O.I.

In several previous investigations (Løbersli, 1981; Nykvist & Rosén, 1985; Staaf & Olsson, 1991; Taylor *et al.*, 1991; Berthelsen & Steinnes, 1995) pH was observed to be higher in the humus layer during the first couple of years after clear-cutting and was shown to be continuously elevated over a period as long as ten years following clear-cutting procedures. Present results from 8 years after clear-cutting (Table 2) indicate a similar increase in pH (about 0.4–0.7 pH units). In contrast, Högbom *et al.* (2002), observed an increased soil pH level in the O horizon at the present investigated area only during the first year and no significant difference over the next three years following clear-cutting. This apparent inconsistency with the present investigation is not easily explained, but could possibly be related to the use of different analytical methods or experimental set-ups.

A number of factors could lead to increased soil pH following clear-cutting. Enhanced decomposition of organic material and transformation of humic substances might partly explain the observed increased pH after clear-cutting (Nilsson *et al.*, 1982; Nykvist & Rosén, 1985). Nitrogen mineralization is usually increased shortly after clear-cutting due to increased soil temperature and increased decomposition of organic material, but this effect is moderated by nitrification that is also normally higher following clear-cutting (Fuller *et al.*, 1988). Nitrogen uptake in plants is also reduced and elevated concentrations of ammonium and nitrate are frequently observed in the soil at clear-cut sites (Vitousek & Melillo, 1979). Reduced cation absorption by plant roots and subsequent lower release of H^+-ions from the roots during the first couple of years after clear-cutting (Binkley & Richter, 1987) and leakage of hydrogen ions together with nitrate into adjacent streams after clear-cutting (Fuller *et al.*, 1988) are also possible explanations of reduced H^+ concentration after clear-cutting. Moreover Staaf & Olsson (1991) observed substantially higher pH in the litter layer in grass-dominated clear-cut areas compared with areas with other types of vegetation.

Previous work (Staaf & Olsson, 1991) showed that the pH-value of the forest floor was 0.2–0.4 units higher after CC compared with WTC areas at four 7–9 years old forest sites in Sweden. These differences were not sustained in a study of the same areas 7 and 8 years later (Olsson *et al.*, 1996). It was not possible in the present study to show statistically possible pH differences between CC and WTC because only a few soil samples had sufficient material left for pH determination. In another study from Sweden both pH and base saturation (8% reduction) were lower in the humus layer after WTC compared with CC, presumably due to less contribution of base cations from slash left on the ground (Nykvist & Rosén, 1985). Since slash removal deprives the soil of important base cations as well of decomposable material, it contributes higher soil acidity (Staaf & Olsson, 1991).

Numerous investigations have shown that clear-cutting leads to increased decomposition of organic material (e.g. Sartz & Huttinger, 1950; Covington, 1981; Løbersli, 1981; Berthelsen & Steinnes, 1995). In the present study this was only evident 6–8 years following WTC in the Oe and Oa horizon. Increased mineralization previ-

ously shown after clear-cutting is thought to be due to increased microbial activity caused by higher soil temperatures and soil humidity (Vitousek *et al.*, 1979; Keeney, 1980), and is consistent with the increased downward transport of organic material observed after clear-cutting (Wright, 1957; Tyler, 1981; Bergkvist, 1986). This downward transfer of organic material may explain the increased levels of L.O.I. in the E horizon shown in Table 2. Complexing with organic material to a varying degree combined with vertical transport of organic material in the soil could have consequences for mobilization and redistribution of elements in the soil.

Mn, Zn and Cu

Plant accessible Mn in soil is usually derived from Mn incorporated in litter and decaying plant material and from Mn oxides (Heal, 2001). Pine needles have shown a substantial release of Mn ions during decomposition (Laskowski & Berg, 1993). Mn concentrations were markedly reduced where logging residues were removed after clear-cutting (Nykvist & Rosén, 1985; Olsson *et al.*, 1996). Lower Mn concentrations 2 years after WTC compared with CC as shown in Table 3 could indicate that a major part of increased Mn levels after clear-cutting is explained predominantly by an amplified contribution of Mn ions from needles left on the ground. The effect of the extra Mn ions in the needles seems to disappear just 4 years after clear-cutting. Increased decomposition of humus and reduced absorption of Mn ions during the first years after clear-cutting could also explain the 3-fold to 7-fold increase of Mn concentrations in the Oe and Oa horizons (Table 3).

Heal (2001) summarized that conifer afforestation is associated with increased Mn in runoff from clear-cut areas. Manganese concentrations in water from streams draining clear-cuts were 3–4 times higher than equivalent values from uncut adjacent forest areas (Fuller *et al.*, 1988) indicating that Mn ions could be mobile following clear-cutting. Increased levels in the present work of Mn in the E and B horizons 4–6 years following clear-cutting could indicate that Mn ions have migrated downward and are redistributed inside the surface soil.

Lower Zn content was observed in the Oa horizon of a clear-cut area compared to an adjacent forest area in the southern part of Norway (Berthelsen & Steinnes, 1995). This is consistent with results from Table 4 showing lower nitric acid soluble Zn in the Oa horizon 2 years after WTC. However, the change is temporary and 4 years after clear-cutting no changes in the Zn concentrations in the Oa horizon are observed any longer. Olsson *et al.* (1996) showed that WTC at four coniferous forest soils in Sweden generally resulted in lower pools of exchangeable Zn compared with CC. This is in accordance with the higher concentrations of both nitric acid soluble and ammonium nitrate extractable Zn 2 years after CC compared to WTC as seen in Table 4. This is presumably mainly due to the contribution from decomposing needles, but could also be affected by less competition for bonding sites at the higher pH normally observed the first years following clear-cutting at CC compared to WTC (Staaf & Olsson, 1991).

Zn ions are quite weakly bound to organic material and they are relatively mobile at aerobic and acidic soil conditions (Tyler, 1978). Weak binding of Zn ions in humus probably explains the redistribution observed in the present work resulting in increased Zn concentrations in the E and B horizons 6–8 years after clear-cutting.

Increased Cu concentrations in the E horizons following clear-cutting as shown in Table 5 are consistent with results from a pine-forested area in southern Norway (Berthelsen & Steinnes, 1995), where the authors explained the increased Cu concentrations in the E horizon by increased weathering rather than increased input from

the humus layer following clear-cutting. Results from Table 2 indicate that a reduction of the organic content in Oe and Oa horizon and the following increased concentrations of organic material in the E horizon might partly explain the higher levels of Cu in the E horizon (Table 5) observed in the present work. Scott *et al.* (2000) found no change of Cu concentrations within months following harvest of northeast deciduous forest in New Hampshire. Even though there are numerous differences e.g. in tree species and geology between Scott *et al.* (2000) and the present investigation the similarity in results confirms that Cu has quite low mobility after clear-cutting.

Cu is rather effectively retained by humus (Tyler, 1978). The significantly higher level of L.O.I. in the Oa horizon following WTC compared with CC (Table 2) can therefore to a great extent explain the higher concentrations of Cu in Oa 2 years following clear-cutting when branches were removed.

Conclusions

The present investigation shows that the behaviour of the studied micronutrients is markedly affected by clear-cutting. Mn was most strongly affected by clear-cutting with higher extractable concentrations in Oe, Oa, and E horizons (4–8 years after clear-cutting) and B (6–8 years after clear-cutting. In the case of Zn, the reduced levels in Oa horizon 2 years after WTC (Table 4) were back to approximately the initial level 8 years following clear-cutting. All three metals showed increased concentrations in the mineral soil just 4–6 years after clear-cutting, probably due to a redistribution of these ions in the surface soil.

Noticeable was the higher concentrations of Zn and Mn in the humus layer 2 years after CC compared with WTC, thought to be an effect of contribution of these ions from decomposing needles and humus. In contrast Cu concentrations in the Oa were significantly higher 2 years following WTC compared with CC. All three metals were also reduced in *Deschampsia flexuosa* 2 years following clear-cutting, possibly due to increased soil pH. Based on the effect of the two different clear-cutting on the selected micronutrients in the present work, we are not able to recommend one clear-cutting *method* in preference to the other.

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