



# Long-term effects of repeated urea fertilization in Douglas-fir stands on forest floor nitrogen pools and nitrogen mineralization

Jörg Prietzel\*, Gage L. Wagoner, Robert B. Harrison

College of Forest Resources, University of Washington, Box 352100, Seattle, WA 98125, USA

Received 12 October 2003; received in revised form 2 December 2003; accepted 1 February 2004

## Abstract

In six Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stands in the Puget Sound Region in Western Washington/USA, forest floor C and N pools were quantified on control plots and on plots that had been fertilized repeatedly with urea 8–30 years ago (total amount of applied N 0.9–1.1 Mg ha<sup>-1</sup>). Additionally, net N mineralization and nitrification rates were assessed in field and laboratory incubation experiments. Forest floor C/N ratios were decreased on the fertilized plots of all sites compared to the respective control plots. The decreases were particularly strong at sites with initial C/N ratios larger than 30. On sites with low productivity (site index at age 50: <33 m), N fertilization resulted in considerable increases in forest floor N pools. Net N mineralization and nitrification during 12-week field incubation was negligible for the unfertilized and fertilized plots of all except one site (Pack Forest), where the stand had been clear-cut 2 years ago. The increases in N mineralization rates during 12-week laboratory incubation induced by repeated N fertilization showed an inverse relationship to the time elapsed since the last fertilizer application, and were generally larger at sites with initial forest floor C/N ratios >30. For the investigated sites, fertilization effects on net N mineralization sustained for at least 11 years after the last fertilizer application. Nitrification correlated strongly with the forest floor pH; significant formation of NO<sub>3</sub><sup>-</sup> was observed only for O layers with a pH (H<sub>2</sub>O) higher than 4.5.

© 2004 Elsevier B.V. All rights reserved.

**Keywords:** Forest floor; N availability; N fertilization; N mineralization; N pools; *Pseudotsuga menziesii*

## 1. Introduction

Forest growth in the Pacific Northwest of the USA is often limited by the supply with plant-available nitrogen (N). Consequently, forest fertilization with N, applied as ammonium salt, urea, or biosolids, at

many sites results in considerable growth increases (e.g. Gessel and Walker, 1956; Edmonds and Hsiang, 1987; Stegemoeller and Chappell, 1990), and increased foliar N contents (Heilman and Gessel, 1963; Turner, 1977; Pang et al., 1987). In contrast to the reports of Binkley (1986) and Miller (1988), beneficial effects of N fertilization in N-limited forest ecosystems on N availability and stand growth occasionally seem to sustain over a period longer than 5–10 years (Binkley and Reid, 1985; Strader and Binkley, 1989; Prescott et al., 1995; Priha and Smolander,

\* Corresponding author. Present address: Technische Universität München, Am Hochanger 2, D-85354 Freising, Germany.  
Tel.: +49-8161-71-4734; fax: +49-8161-71-4466.  
E-mail address: prietzel@wzw.tum.de (J. Prietzel).

1995; Smolander et al., 1998; Nohrstedt et al., 2000) and may even affect the subsequent stand generation.

In the coastal area of the State of Washington/USA, Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] plantations are of significant economic relevance for the local forest industry, and N fertilization is a widely accepted tool to increase the productivity of these stands. Up to now, however, no information is available (i) how long N fertilization effects on soil fertility and stand productivity last in Douglas-fir plantations in that area and (ii) how the period over which N fertilization is effective depends on site conditions. This paper describes long-term (8–15 years) effects of urea fertilization on forest floor C and N pools, N mineralization, and nitrification in six Douglas-fir plantations at different sites in Western Washington. In particular, the following questions were addressed:

- How long after urea application can fertilization effects on forest floor C and N pools, C/N ratios as

well as on N mineralization and nitrification be noticed?

- Are the intensity and duration of N fertilization effects dependent on site properties, as e.g. the a priori N status of the forest floor?

## 2. Material and methods

### 2.1. Study sites

The study sites (Fig. 1) are located in the Puget Sound Area of Western Washington/USA. All belong to the *Tsuga heterophylla* (Raf.) Sarg. zone described by Franklin and Durness (1988). This zone is characterized by a wet, mild maritime climate, with moderate moisture stress during summer. Mean annual air temperatures average 9–10 °C. Depending on the topographic situation, annual precipitation for the study sites ranges between 1000 and 2900 mm (Table 1).

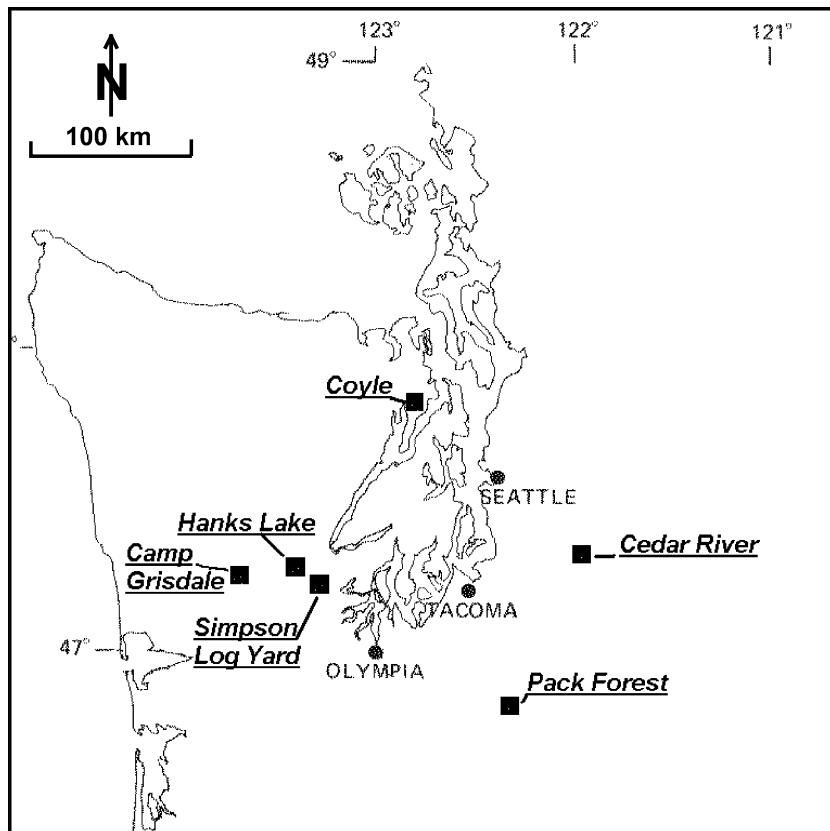


Fig. 1. Location of the study sites.

Table 1  
Description of the study sites<sup>a</sup>

	Pack Forest (134)	Coyle (156)	Simpson Log Yard (168)	Hank's Lake (167)	Camp Grisdale (53)	Cedar River (5)
Latitude	46°50'2"N	47°50'56"N	47°14'25"N	47°18'34"N	47°15'4"N	47°22'38"N
Longitude	122°17'38"W	122°45'25"W	123°15'50"W	123°16'54"W	123°35'31"W	121°54'29"W
Elevation (m)	548	189	152	177	420	274
Precipitation (mm per year)	1000	1000	1800	2000	2900	1800
Slope, aspect	40%, S	20%, SE	Flat	Flat	15%, W	10%, E
Bedrock	Colluvial andesite	Glacial outwash	Glacial outwash + tephra	Glacial outwash	Old alluvium, glacial drift	Gravelly glacial outwash
Soil type, texture	Ultic Haploxeralf, fine-loamy	Dystric Xerochrept, sandy, skeletal	Dystric Xerochrept, sandy, skeletal	Dystric Xerochrept, sandy, skeletal	Umbric Dystrochrept, fine-loamy	Dystric Xerochrept, sandy, skeletal
Stand establishment (year)	1930	1937	1923	1920	1941	1931
SI 50 (m, unfertilized plots)	30	33	29	20	38	31

<sup>a</sup> Stand Management Cooperative Installation numbers in parentheses.

The study sites differ considerably in elevation, slope, and aspect.

At four sites (Coyle, Hank's Lake, Simpson Log Yard, and Cedar River), the parent material is exclusively or predominantly glacial outwash. Soils are Dystric Xerochrepts of the Everett series with sandy-skeletal texture. At Pack Forest, where the parent material is andesite colluvium, the soil is a fine-loamy Ultic Haploxeralf of the Wilkeson series. At Camp Grisdale, where the parent material is old alluvium and glacial drift, fine-loamy Umbric Dystrochrepts of the Hoquiam series have been formed. In 1997, all sites except Cedar River were fully stocked with second-growth, pure Douglas-fir (*P. menziesii* [Mirb.] Franco) stands. At Cedar River, 10% western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) is admixed to the Douglas-fir. Productivity, referred to as site index (SI) 50, which represents the mean height of dominating Douglas-fir trees at age 50 years, varies considerably from site to site (Table 1).

## 2.2. Experimental treatments

In the late 1960s and the early 1970s, N and P fertilization trials were set up at all sites to study the effects of repeated N and P fertilization on stand growth. Each experimental set up comprised several plots, either 0.06 ha rectangular plots (Cedar River,

Camp Grisdale) or 0.04 ha square plots (all other sites). All sites include one unfertilized control plot and one adjacent plot that had been fertilized repeatedly with urea between 1969 and 1991 (Table 2). These two variants of each experiment will be discussed in this paper. Fertilization included an initial treatment with 448 kg N ha<sup>-1</sup>, followed by repeated applications of 224 kg N ha<sup>-1</sup>, as specified in detail in Table 2. In total, 1120 kg N ha<sup>-1</sup> were applied (Pack Forest: 896 kg N ha<sup>-1</sup>). At Pack Forest, the mature stand was harvested by clear-cut in 1997, with the slash being homogeneously distributed on the site, and the subsequent generation of Douglas-fir trees was established by planting. The stands at Coyle, Hank's Lake, and Simpson Log Yard were harvested between 2 and 12 weeks before the initiation of the study. Also at these sites, the slash has been distributed homogeneously after logging. The stands at Cedar River and Camp Grisdale remained fully stocked during the study period.

## 2.3. Forest floor sampling, incubation techniques, and analytical methods

In March 1999 forest floor material was sampled at the control plots and the fertilized plots of each site. The samples were collected at four subplots (size 0.5 m × 0.5 m) located 4 m from the plot center on

Table 2  
Experimental treatment regimes at the different sites

	Pack Forest	Coyle	Simpson Log Yard	Hank's Lake	Camp Grisdale	Cedar River
Installation establishment (year)	1972	1972	1975	1975	1969	1969
Fertilization (kg N ha <sup>-1</sup> )	0/896	0/1120	0/1120	0/1120	0/1120	0/1120
Fertilization dates	1972–1980– 1984	1972–1980– 1984–1988	1975–1983– 1987–1991	1975–1983– 1987–1991	1969–1977– 1981–1985	1969–1977– 1981–1985
Fertilization regime (kg N ha <sup>-1</sup> )	448–224–224	448–224– 224–224	448–224– 224–224	448–224– 224–224	448–224– 224–224	448–224– 224–224
Date of logging (month/year)	3/1997	12/1998	1/1999	3/1999	Not harvested	Not harvested
Time elapsed between harvest and study	24 months	12 weeks	6 weeks	2 weeks		
Date of planting (month/year)	3/1997	1/1999	6/1999	6/1999	–	–
Stand age at harvest (years)	67	61	76	79	–	–
Time elapsed between last fertilization and study (years)	15	11	8	8	14	14

bearings of 0°, 90°, 180°, and 270°, respectively. After removal of the ground vegetation, slash, and coarse woody debris, the forest floor was collected and its field-moist weight determined. A composite sample from the four samples taken at each plot was formed (total sampled area = 1 m<sup>2</sup>). This composite sample was sieved through a 1 cm mesh sieve to remove remaining coarse woody debris and homogenized carefully. According to Jenkinson and Powlson (1980) and Ross et al. (1985), this procedure neither affects soil microbial biomass pools nor microbial activity. On a subsample of each plot, the mass was determined after drying at a temperature of 105 °C to constant weight, and the ratio field-moist mass/dry mass was calculated for each forest floor sample.

To provide information regarding net N mineralization and nitrification under site conditions, 24 subsamples of 50 g field-moist O layer material of each plot were placed into polyethylene bags (Eno, 1960; Binkley and Hart, 1989), and reburied underneath the O layer at a representative site of each plot. Additionally, one bag containing a miniaturized temperature data logger (Hobo H8, Onset Computer Corp., Pocasset, MA) was buried at the same place in order to monitor ambient soil temperatures in 30-min intervals. The water contents of the field-moist O layer materials ranged between 53 and 86% field capacity. To obtain information about potential net N mineralization and nitrification under optimal conditions for microbial activity (Binkley and Hart, 1989), we incubated 24 subsamples of each sample in the laboratory at a

temperature of 22.7 ± 1.7 °C, a relative air humidity of 50%, and a soil water content of at least 60% field capacity.

At the beginning of the experiment, important chemical and physical properties of the studied samples were determined. Water contents of field-moist soil, field capacity, as well as concentrations of KCl-extractable inorganic N (NH<sub>4</sub><sup>+</sup>-N + NO<sub>3</sub><sup>-</sup>-N), and NH<sub>4</sub>Cl-extractable cations were analyzed on field-moist, 1 cm sieved subsamples. The pH in deionized water and 0.01 M CaCl<sub>2</sub> was measured on air-dried (40 °C), 2 mm sieved subsamples at a soil:solution ratio of 1:10 (w/w). Total concentrations of C, N, P, and S were analyzed on subsamples that had been fine-ground in a Wiley mill. Total C and total N was determined with a LECO analyzer CHN 1000; total P and S with a Thermo Jarrell Ash ICP-OES after sample digestion with hot concentrated HNO<sub>3</sub>. For all sites, forest floor C and N pools were calculated on a per-hectare-basis by multiplying the C and N concentrations of the samples with the total mass of the respective sample collected on the 1 m<sup>2</sup> plots and a conversion factor of 10,000.

At 0, 2, 4, 8, and 12 weeks after start of the incubations, 3 of the 24 bagged subsamples of each sample were taken from the field or the incubation room. For all subsamples, the mass change during incubation was determined. Within 24 h of storage in a dark room at a temperature of 2 °C, we placed 25 g of each incubated subsample in a 250 ml Erlenmeyer flask, and extracted it with 100 ml 2 M KCl by 1 h

shaking in a horizontal shaker. The suspensions were filtered through Whatman #42 filter paper and their concentrations of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  determined according to Keeney and Nelson (1982). For the spectrophotometrical measurements a Perkin Elmer apparatus 55E was used. Net N mineralization rates were calculated by subtracting initial soil inorganic N ( $\text{NH}_4^+$ -N plus  $\text{NO}_3^-$ -N) from the inorganic N concentrations of the incubated soil samples. Net nitrification rates were calculated by subtracting the initial soil  $\text{NO}_3^-$  concentrations from the  $\text{NO}_3^-$  concentrations of the incubated samples.

### 3. Results

#### 3.1. Soil chemical status at the beginning of the experiments

The O layers of all sites and experimental treatments generally had high base saturations (BS) and only moderately acid pH values (Table 3). For all samples except the fertilized plot of Camp Grisdale (BS: 75%), base saturation exceeded 92%. This is a typical feature of forest soils in the Pacific Northwest, which are less than 10,000 years old, and where soil acidification via nutrient export by harvesting and atmospheric acid deposition has been low.

The forest floor C/N ratios on the unfertilized plots ranged between 27 and 39 (Table 3). In this range, limitations in the N supply of the forest stands must be expected due to competition of soil microbes for mineralized soil N. A significant positive correlation

( $r = 0.54$ ) was observed between the Site Index 50 (mean height of dominating and co-dominating trees at age 50 years) and the concentrations of extractable inorganic N in the forest floor of the control plots. The correlation was particularly high ( $r = 0.90$ ), when the Pack Forest site, which in contrast to all other sites had been clear-cut 2 years before the experiment started, was excluded from the analysis (Fig. 2a). In contrast, the SI 50 was only poorly correlated with the C/N ratio of the unfertilized O layers (Fig. 2b). The strongest correlation ( $r = 0.98$ ) was observed between the SI 50 and the forest floor N pools of the unfertilized plots (Fig. 2c). Forest floor C and N pools on the control plots (Table 3) were generally higher than those reported by Edmonds and Chappell (1994) for Douglas-fir stands in the Pacific Northwest.

A comparison of the unfertilized and the fertilized plots shows that repeated urea fertilization did not result in any systematic long-term change of the C/P ratio, the pH, or the base saturation in the forest floor (Table 3). In contrast, at all sites the C/N ratios of the fertilized O layers were consistently lower than those of the respective control plots. The decreases were particularly large on the most N-deficient sites with the highest C/N ratios on the control plots (Fig. 3). The most pronounced long-term retention of fertilized N in the forest floor was observed for the very poor site Hank's Lake (SI 50 = 20 m). At that site the forest floor N pool on the fertilized plot increased by more than 100% compared to the control plot (Table 3). This was caused by both 70% increase in the mass of O layer humus (referred to as  $\text{Mg C}_{\text{org}} \text{ha}^{-1}$  in Table 3), and a concomitant 25% enrichment of the forest floor

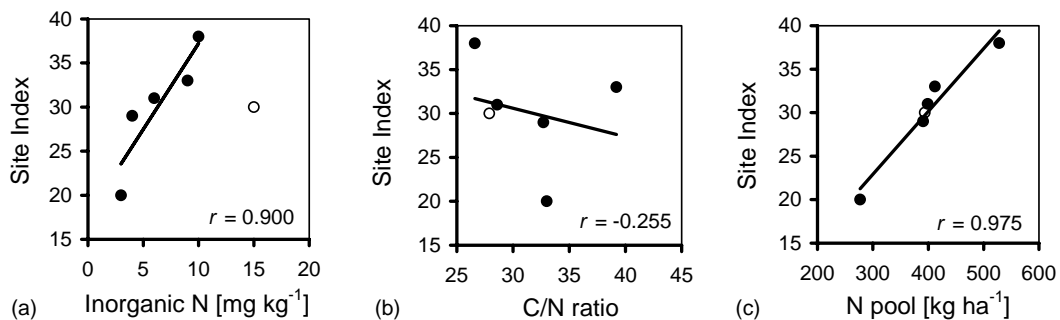


Fig. 2. Relationship (March 1999) between the Site Index 50 of the studied stands (unfertilized plots) and (a) inorganic N contents in the O layer, (b) forest floor C/N ratios, and (c) forest floor N pools. The empty circle represents the Pack Forest site, which in contrast to all other sites had been clear-cut 2 years before the experiment started.

Table 3  
Important properties of the forest floor at the beginning of the incubation experiments (CON, control plot; FER, fertilized plot)

	Pack Forest		Coyle		Simpson Log Yard		Hank's Lake		Camp Grisdale		Cedar River	
	CON	FER	CON	FER	CON	FER	CON	FER	CON	FER	CON	FER
pH (H <sub>2</sub> O)	5.0	5.1	4.2	4.1	4.9	4.9	4.6	4.7	4.6	4.6	4.2	3.9
CEC <sub>eff</sub> (mmol <sub>c</sub> kg <sup>-1</sup> )	327	234	205	199	235	176	173	263	192	136	175	190
BS (%)	99	99	95	95	97	97	95	98	94	75	93	94
C <sub>org</sub> (g kg <sup>-1</sup> )	391	274	302	269	295	235	406	439	316	299	323	341
N <sub>tot</sub> (g kg <sup>-1</sup> )	14.0	11.8	7.7	8.4	9.0	9.4	12.3	16.8	11.9	11.6	11.3	13.4
P <sub>tot</sub> (mg kg <sup>-1</sup> )	917	610	760	752	1482	1358	999	864	1771	1569	1541	1238
S <sub>tot</sub> (mg kg <sup>-1</sup> )	1303	958	843	724	938	1032	999	1190	1067	1001	945	952
C/N ratio (w/w)	27.9	23.2	39.2	32.0	32.7	25.0	33.0	26.1	26.6	25.8	28.6	25.4
C/P ratio (w/w)	426	449	397	358	199	173	406	508	178	191	210	275
C/S ratio (w/w)	300	286	358	372	314	228	406	369	296	299	342	358
NH <sub>4</sub> <sup>+</sup> -N (mg kg <sup>-1</sup> )	12	16	9	5	4	4	3	7	10	8	6	7
NO <sub>3</sub> <sup>-</sup> -N (mg kg <sup>-1</sup> )	0	2	0	0	0	0	0	0	0	0	0	0
C-Pool, Mg ha <sup>-1</sup>	11.0	13.9	16.2	11.1 (2.7)	12.8	11.7	9.1	16.0	14.0	3.1 <sup>a</sup>	11.4	10.6
(standard error)	(2.0)	(0.6)	(4.0)	12.8 (1.3)	(1.3)	(1.2)	(1.6)	(1.8)	(5.4)	(0.3)	(1.3)	(2.7)
N-Pool, kg ha <sup>-1</sup>	394 (72)	598 (30)	412 (102)	345 (84)	391 (39)	470 (50)	277 (48)	611 (70)	528 (202)	120 <sup>a</sup> (11)	399 (44)	417
(standard error)												(104)

<sup>a</sup> Fertilization resulted in intensified bioturbation activity and thus in a considerable decrease of the O layer organic matter pool.

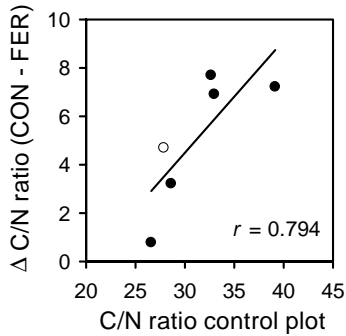


Fig. 3. Relationship between the forest floor C/N ratios at the studied control plots (CON) and their respective decreases as induced by repeated urea fertilization (CON-FER). Empty circle: Pack Forest.

organic matter in nitrogen. A similar, but less pronounced reaction was observed for Pack Forest (SI 50 = 30 m). For Simpson Log Yard and Cedar River, which are also characterized by low site indices (SI 50 ≈ 30 m), the C/N ratios of the fertilized O layers were also considerably decreased compared to the respective control plots. However, in contrast to Pack Forest and Hank’s Lake, forest floor humus pools were fairly similar for the control and the fertilized variants.

Yet, the enrichment of the O layer humus in organic N resulted in a 5–10% increase in forest floor N pools (Table 3). At the most productive sites Coyle and Camp Grisdale, fertilized plots had considerably decreased forest floor C and N pools compared to the respective control plots. Particularly at the fertilized plot of Camp Grisdale, numerous earthworm casts and molehills indicated intensive bioturbation by soil meso- and macrofauna, resulting in increased mixing of humus (and probably fertilizer N) into the mineral topsoil. In summary, less productive sites (SI 50 < 31 m; n = 3) showed sustained accumulation of fertilizer N in the O layers, whereas the forest floors of more productive sites (SI 50 ≥ 30 m; n = 3) have not accumulated or even lost organic C and N after repeated N fertilization (Fig. 4).

3.2. N mineralization and nitrification in the field incubation experiment

During field incubation of the unfertilized forest floor samples, net N mineralization was negligible at all sites with forest floor C/N ratios between 33 and 39 (Hank’s Lake, Simpson Log Yard, Coyle), and small for most sites with C/N ratios below 29

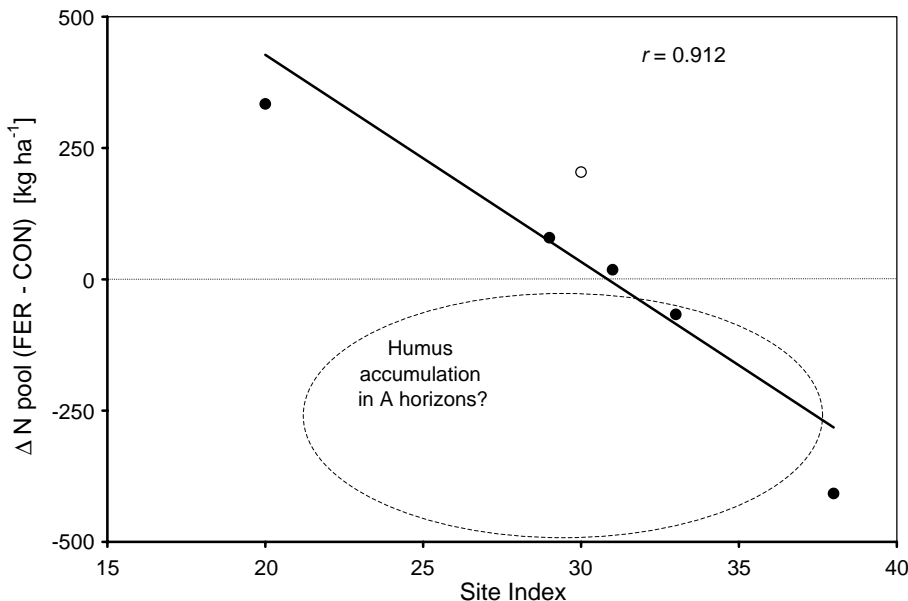


Fig. 4. Relationship between the productivity (SI 50) of the studied Douglas-fir sites and the changes of their forest floor N pools induced by repeated urea fertilization.

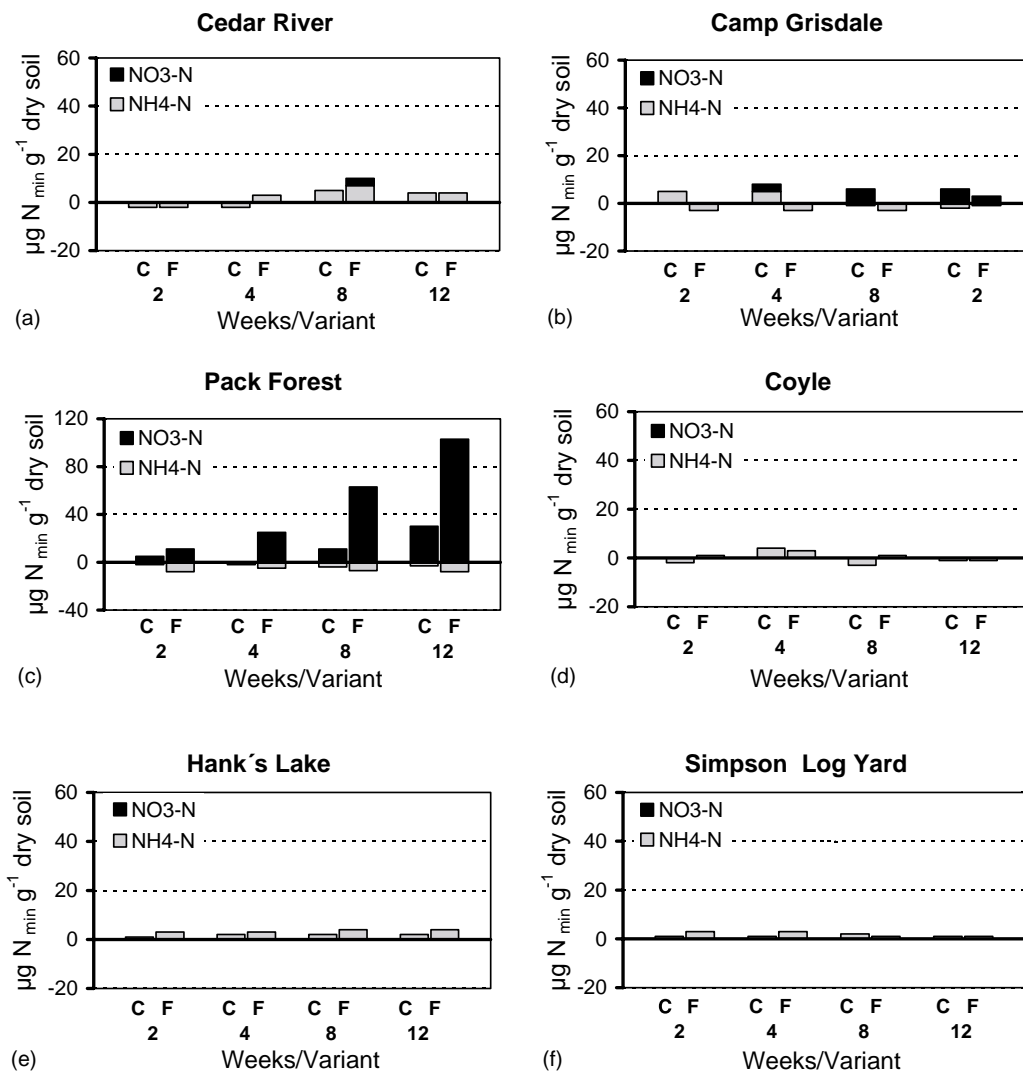


Fig. 5. Net  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  formation (field incubation) of forest floor samples from control (C) and N-fertilized (F) plots of (a) Cedar River, (b) Camp Grisdale, (c) Pack Forest, (d) Coyle, (e) Hank's Lake and (f) Simpson Log Yard.

(Camp Grisdale, Cedar River) (Fig. 5). In contrast to all other study sites, at Pack Forest considerable net N mineralization was observed (Fig. 5c); all mineralized N was present as  $\text{NO}_3^-$ .

For all sites except Pack Forest, no or only small (Hank's Lake) increases in net N mineralization or nitrification could be observed for the fertilized O layers compared to the respective controls in the field incubation experiment (Fig. 5). A different feature was observed for Pack Forest, where net N mineralization and nitrification during field incubation was three

times as high on the plot that had been fertilized repeatedly with urea 15–27 years ago compared to the control plot, and more than 10 times higher than on the fertilized plots of all other sites.

### 3.3. N mineralization and nitrification in the laboratory incubation experiment

Net N mineralization and nitrification in the laboratory incubation experiment (Fig. 6) was generally significantly larger than in the field incubation experiment.

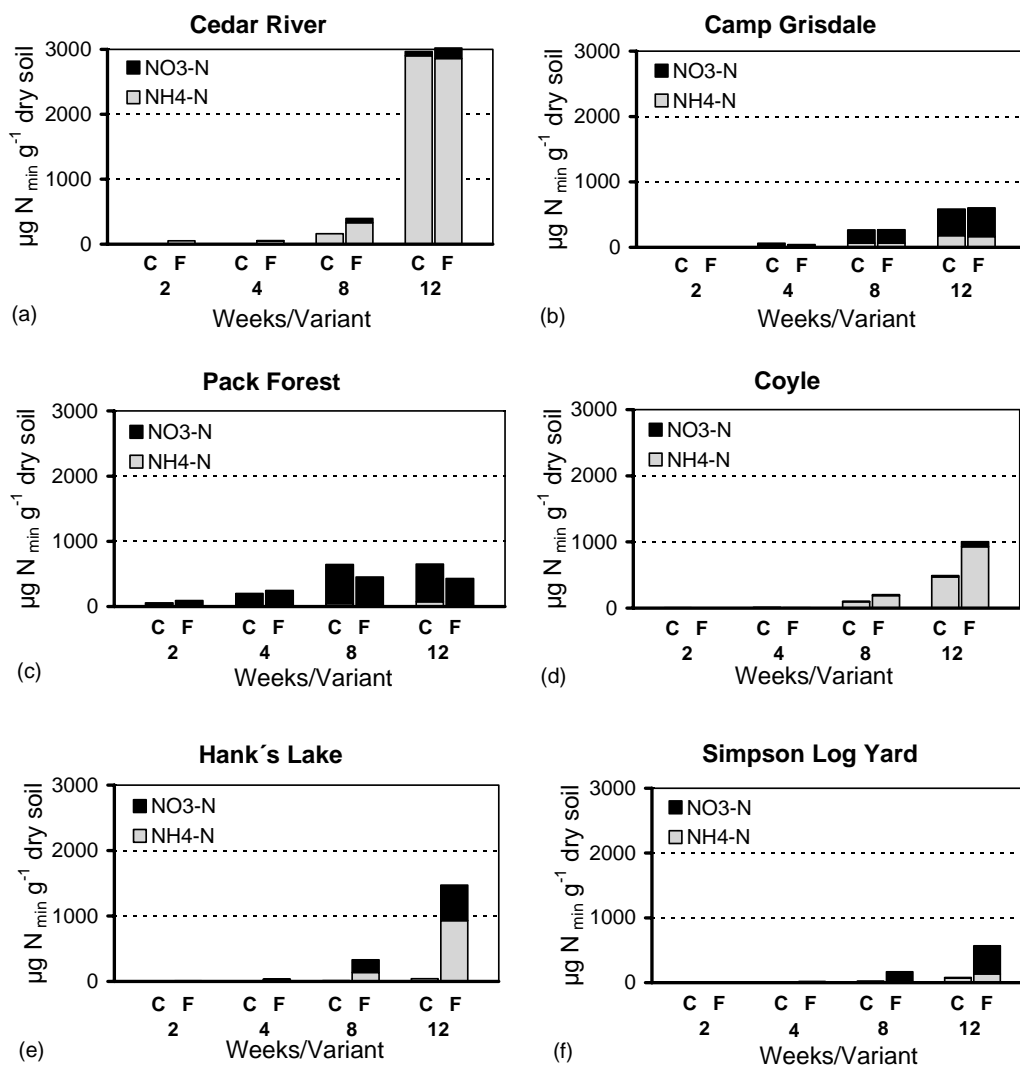


Fig. 6. Net  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  formation (laboratory incubation) of forest floor samples from control (C) and N-fertilized (F) plots of (a) Cedar River, (b) Camp Grisdale, (c) Pack Forest, (d) Coyle, (e) Hank's Lake and (f) Simpson Log Yard.

Based on their temporal pattern of net N mineralization and nitrification during the period of laboratory incubation, the unfertilized plots of the different study sites can be classified into three types: (i) sites where during the entire incubation period only insignificant amounts of inorganic N were produced (Hank's Lake, Simpson Log Yard), (ii) sites where some (Coyle) or a large amount (Cedar River) of N was mineralized after a lag phase of at least 4 weeks, predominantly existing as  $\text{NH}_4^+$ , and (iii) sites where a considerable amount of inorganic N, predominantly  $\text{NO}_3^-$ , was

produced after a lag phase of less than 4 weeks (Camp Grisdale, Pack Forest). The latter group of sites has the lowest forest floor C/N ratio (27–28) and C/S ratio (300).

After 12 weeks laboratory incubation, the forest floor of control plots with C/N ratios lower than 30 (Cedar River, Camp Grisdale, Pack Forest) generally showed markedly higher amounts of mineralized N than those with C/N ratios above 30 (Coyle, Hank's Lake, Simpson Log Yard) (Fig. 7; empty symbols). However, for none of the different incubation periods

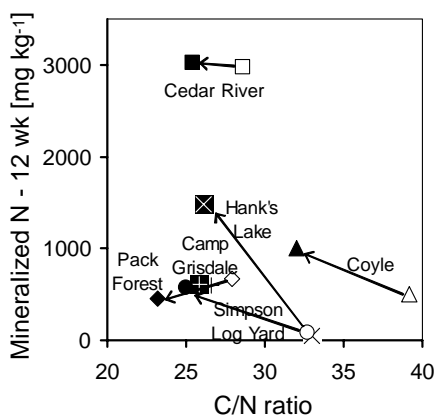


Fig. 7. Relation between the forest floor C/N ratios of the investigated plots and the amounts of N mineralized during 12 weeks of laboratory incubation. Empty symbols represent control plots, filled symbols the respective fertilized plots. Direction and length of arrows describe the changes in C/N ratios and N mineralization induced by N fertilization.

that could be evaluated in our study (2–12 weeks), a tight relationship between the forest floor C/N ratio and net N mineralization was observed. On the other hand, the portion of mineralized N present as  $\text{NO}_3^-$  showed a strong correlation with the pH value of the forest floor (Fig. 8); significant nitrification was observed only in forest floors with a pH above 4.5. Nitrification was particularly high at the Pack Forest site, which had been clear-cut already 2 years prior to our experiment.

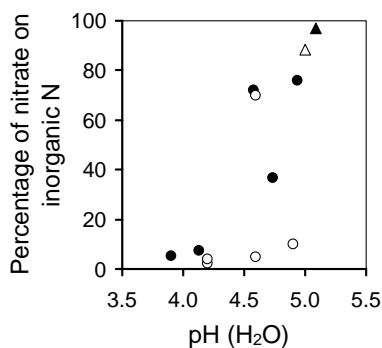


Fig. 8. Relationship between the pH of the studied O layers (empty symbols: control plots; filled symbols: fertilized plots) at the beginning of the experiment and the respective percentages of nitrate on total inorganic N formed during 12 weeks of laboratory incubation. Triangles represent the Pack Forest site.

The effects of repeated N fertilization on net N mineralization in the laboratory incubation experiment were different for the examined sites (Fig. 7). At Coyle, Hank's Lake, and Simpson Log Yard, where the unfertilized plots had forest floor C/N ratios above 30 and showed only little net N mineralization, the latter was increased on the fertilized plots by a factor ranging from 2 (Coyle, Simpson Log Yard) up to 35 (Hank's Lake). In contrast, at Cedar River, Camp Grisdale, and Pack Forest, where the control plots had forest floor C/N ratios below 30 and reasonably high N mineralization rates during 12 weeks of laboratory incubation, no further increase of net N mineralization was observed for the fertilized plots.

#### 4. Discussion

A comparison of the forest floor C and N pools on the fertilized and the unfertilized plots of the study sites indicates a long-term (>8–15 years) positive effect of repeated N fertilization on these pools particularly for sites with low productivity. This is due to a general enrichment of the forest floor in N as proven by decreased C/N ratios at all sites; at sites with low productivity, additionally the forest floor organic matter pool has increased after repeated urea fertilization (Table 3). Consequently, forest floor N pools of the less productive sites were increased markedly on the fertilized plots compared to the respective control plots (Fig. 4). At the poorest site (Hank's Lake; SI 50 = 20 m), 7 years after the last fertilization the N content of the forest floor at the fertilized plot exceeded that of the control plot by  $330 \text{ kg ha}^{-1}$ , which is more than 30% of the totally applied N amount. At Pack Forest, 22% of the applied N was still present in the forest floor even 15 years after the last fertilizer application, and 2 years after the stand had been harvested. As shown by the decreased C/N ratios, also at the more productive sites Cedar River, Coyle, and Camp Grisdale the forest floor became enriched in N after fertilization. A sustained decrease of forest floor C/N ratios after urea amendments to N-limited forest has been reported by several researchers (Nohrstedt, 1990; Chappell et al., 1999; Nohrstedt et al., 2000). Most studies in boreal forest ecosystems (Mälkönen, 1990; Nohrstedt, 1990; Tamm et al., 1995; Nohrstedt et al., 2000) also report increases in soil N

pools after repeated N fertilization. In our study, information can be provided only for N pool changes in the forest floor. Our results show an inverse relationship between the initial N pool of the forest floor and the extent of additional N accumulation after repeated N fertilization.

For all sites, which either were still fully stocked at the time of the field incubation experiment (Cedar River, Camp Grisdale), or where the stands had been harvested between 2 and 12 weeks before the experiment started (Coyle, Hank’s Lake, Simpson Log Yard), net N mineralization and nitrification under ambient temperature conditions during spring (average topsoil temperature: 8–10 °C; Fig. 9) generally

were low and almost identical for the fertilized and unfertilized plot of each site (Fig. 5). In contrast to all other sites, the forest floor at Pack Forest, where the stand had been harvested already 2 years ago, showed elevated net N mineralization and nitrification at the unfertilized plot, and even more pronounced at the fertilized plot. The C/N ratio of the forest floor at the unfertilized Pack Forest plot was similar to those of the unfertilized plots of Cedar River and Camp Grisdale, and also the mean value and fluctuation of topsoil temperature was similar to those at Coyle and Simpson Log Yard (Fig. 9). Therefore, the main reason for the increased net N mineralization and nitrification at Pack Forest must be associated with the fact that the

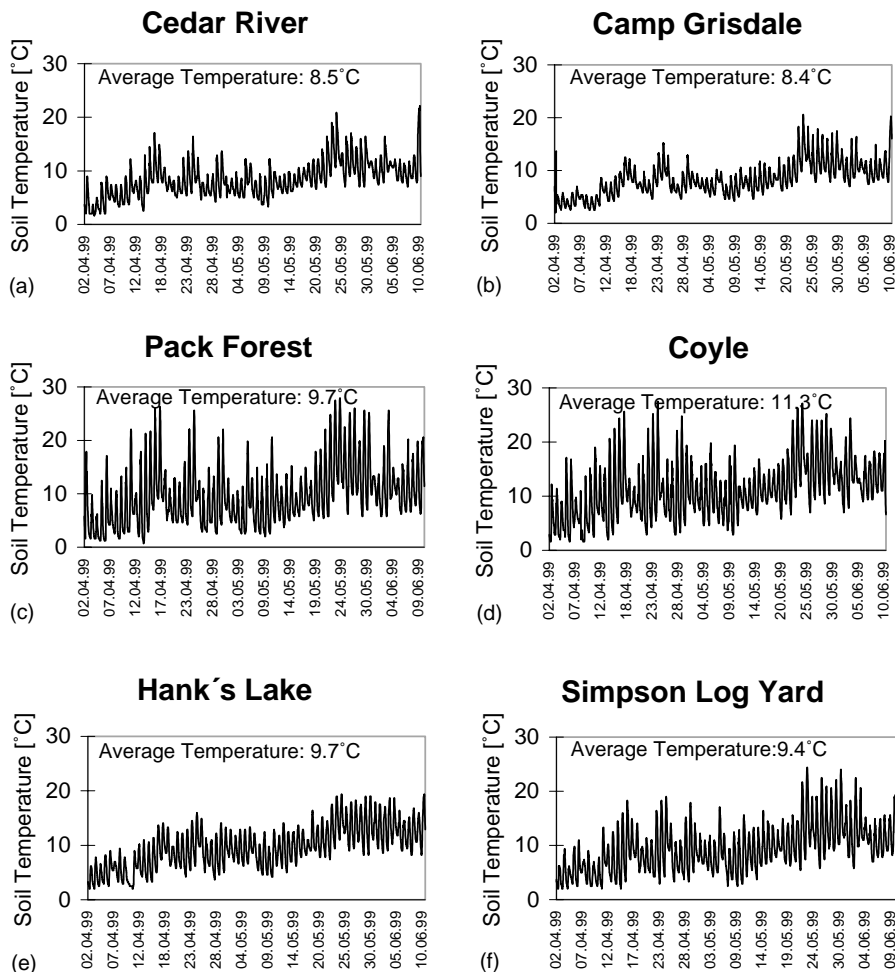


Fig. 9. Soil temperatures during field incubation (April 1999 to June 1999) in the forest floor of the sites (a) Cedar River, (b) Camp Grisdale, (c) Pack Forest, (d) Coyle, (e) Hank’s Lake and (f) Simpson Log Yard.

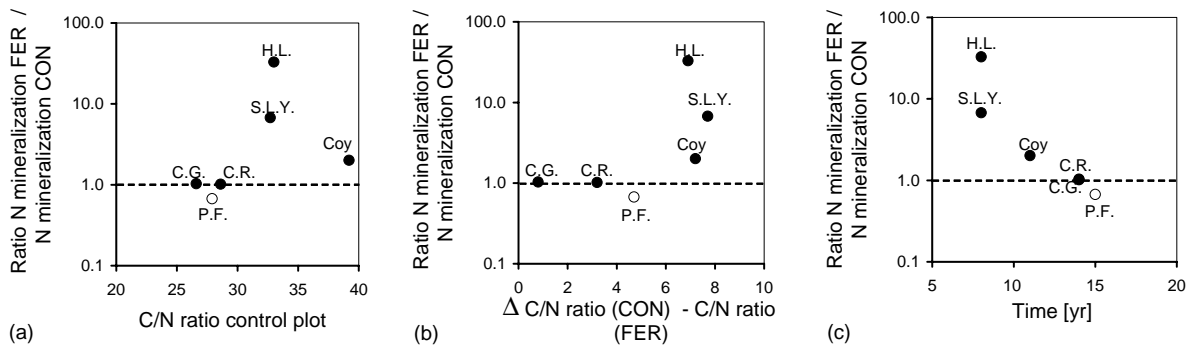


Fig. 10. Relationship between the relative increases of net N mineralization during 12 weeks of laboratory incubation as induced by N fertilization and (a) the forest floor C/N ratio of the unfertilized plot, (b) the change in forest floor C/N ratio as induced by fertilization (C/N CON–C/N FER) and (c) the time elapsed since the last fertilizer application. C.R., Cedar River; C.G., Camp Grisdale; COY, Coyle; H.L., Hank's Lake, P.F., Pack Forest, S.L.Y., Simpson Log Yard.

site had been clear-cut already 2 years before the experiment started. Increased N mineralization and nitrification on clear-cut sites and increased  $\text{NO}_3^-$  leaching after a certain delay has been reported in numerous studies (e.g. Smith et al., 1968; Vitousek et al., 1979; Prescott et al., 1992; Prescott, 1997; Ring et al., 2003).

On the plot of the Pack Forest site which had been repeatedly fertilized with urea prior to stand harvest, the forest floor had lower C/N ratios and higher concentrations of extractable mineral N (Table 3). In contrast to the results of Smolander et al. (1998), but in accordance with results of other studies (e.g. Berdén et al., 1997; Hope et al., 2003; Ring et al., 2003), net N mineralization and nitrification in the field incubation study were considerably increased for the forest floor material of the fertilized plot compared to that of the control plot.

The particular N mineralization pattern of Pack Forest compared to the other sites becomes even more evident in the laboratory incubation study. In contrast to all other sites, which exhibited lag phases of more than 4 weeks before vigorous N mineralization and in some cases also nitrification started, the lag phase at Pack Forest was less than 2 weeks. Similar results were published recently for a clear-cut site in the Canadian Rockies by Prescott et al. (1992).

Even though in our study repeated urea fertilization resulted in a decrease of the forest floor C/N ratio at all sites, only for sites with initial C/N ratios larger than 30, which showed little net N mineralization on the control plots (Coyle, Hank's Lake, Simpson

Log Yard), increases in net N mineralization during laboratory incubation were observed after fertilization (Fig. 10a). The heterogeneous reaction of the different studied forest floors to the fertilizer amendments reflects the heterogeneity of results reported in earlier studies (Prescott et al., 1993). Binkley and Reid (1985), Strader and Binkley (1989) and Prescott et al. (1992) report that forest fertilization with N resulted in increased N mineralization, whereas Chappell et al. (1999) did not observe such an increase.

In our study, the increases in N mineralization after fertilization were only poorly correlated with the initial C/N ratio of the forest floor or with the magnitude of the decrease of the forest floor C/N ratio after repeated N fertilization (Fig. 10b). A strong negative correlation was observed between the effect of urea fertilization on net N mineralization and the time that had elapsed between the last urea amendment and the start of the experiment (Fig. 10c). With factors of 33 and 7, the increases were highest at Hank's Lake and Simpson Log Yard (intermediate forest floor C/N ratio), where the last fertilizer application was carried out 8 years ago. They were moderate (factor 2) at Coyle (high C/N ratio), which had been fertilized last time 11 years ago. For Camp Grisdale, Cedar River, and Pack Forest, where the last fertilizer application occurred 14 or 15 years before the mineralization experiment started, no increases in net N mineralization were observed under laboratory conditions on the fertilized plots compared to the control plots. However, at Pack Forest, repeated urea amendments 15–27 years prior to our study resulted in strongly increased

N mineralization in the field incubation experiment compared to the unfertilized reference plot (Fig. 5c). Moreover, Douglas-fir seedlings, which had been planted at the clear-cut Pack Forest site in March 1997 to form the subsequent stand generation, grew much faster on the plot that had been fertilized for the last time more than 13 years ago than on the control plot. In May 1999, 2 years after the seedlings had been planted at the site, their average shoot height on the fertilized plot was  $79.7 \pm 6.6$  cm (mean value of 15 randomly selected trees  $\pm$  standard error), whereas that of the trees on the control plot was only  $55.2 \pm 2.5$  cm. The shoot height difference of  $24.5 \pm 7.1$  cm was statistically significant (*t*-test;  $P = 0.002$ ). This indicates that depending on the site conditions, beneficial effects of repeated N fertilization may sustain longer than 12 years, and may even be beneficial for the subsequent stand generation (“carry-over effect”).

## 5. Conclusions

- As indicated by decreased C/N ratios, repeated urea fertilization (total applied N amount:  $0.9\text{--}1.1$  Mg ha<sup>-1</sup>) of Western Washington Douglas-fir stands resulted in a sustained (>8 years) enrichment of the forest floor organic matter in N. The C/N ratio decreases were particularly large at sites with high initial C/N ratios.
- The less-productive sites (SI 50 < 33 m) show a considerable long-term retention of fertilized N in the forest floor. In addition to an enrichment of the organic matter in N, a marked accumulation of forest floor organic matter occurred on the fertilized plots of these sites.
- At all sites with initial forest floor C/N ratios larger than 30, repeated urea fertilization resulted in a long-term (at least 8–12 years) increase of net N mineralization in the laboratory incubation experiment.
- Significant net nitrification occurred only in O layers with a pH (H<sub>2</sub>O) higher than 4.5.

## Acknowledgements

We gratefully acknowledge the assistance in the analytical determination of chemical forest floor

properties by M. Engelschall, M.R. Lolley, and D. Xue. The study was funded by a grant of the Stand Management Cooperative to R.B. Harrison.

## References

- Berdén, M., Nilsson, S.I., Nyman, P., 1997. Ion leaching before and after clear-cutting in a Norway spruce stand—effects of long-term application of ammonium nitrate and superphosphate. *Water Air Soil Pollut.* 93, 1–26.
- Binkley, D., 1986. *Forest Nutrition Management*. Wiley, New York.
- Binkley, D., Reid, P., 1985. Long-term increase of nitrogen from fertilization of Douglas-fir. *Can. J. For. Res.* 15, 723–724.
- Binkley, D., Hart, S.C., 1989. The components of nitrogen availability assessments in forest soils. *Adv. Soil Sci.* 10, 57–112.
- Chappell, H.N., Prescott, C.E., Vesterdal, L., 1999. Long-term effects of nitrogen fertilization on nitrogen availability in coastal Douglas-fir forest floors. *Soil Sci. Soc. Am. J.* 63, 1448–1454.
- Edmonds, R.L., Chappell, H.N., 1994. Relationships between soil organic matter and forest productivity in western Oregon and Washington. *Can. J. For. Res.* 24, 1101–1106.
- Edmonds, R.L., Hsiang, T., 1987. Forest floor and soil influence on response of Douglas-fir to urea. *Soil Sci. Soc. Am. J.* 51, 1332–1337.
- Eno, C.F., 1960. Nitrate production in the field by incubating the soil in polythene bags. *Soil Sci. Soc. Am. Proc.* 24, 277–279.
- Franklin, J.F., Durness, C.T., 1988. *Natural Vegetation of Oregon and Washington*. Oregon State University Press, USA.
- Gessel, S.P., Walker, R.B., 1956. Height growth response of Douglas-fir to nitrogen fertilization. *Soil Sci. Soc. Am. Proc.* 20, 97–100.
- Heilman, P.E., Gessel, S.P., 1963. The effect of nitrogen fertilization on the concentration and weight of nitrogen, phosphorus, and potassium in Douglas-fir trees. *Soil Sci. Soc. Am. Proc.* 27, 102–105.
- Hope, G.D., Prescott, C.E., Blevins, L.L., 2003. Responses of available soil nitrogen and litter decomposition to openings of different sizes in dry interior Douglas-fir forests in British Columbia. *For. Ecol. Manage.* 186, 33–46.
- Jenkinson, D.S., Powlson, D.S., 1980. Measurements of microbial biomass in intact cores and in sieved soil. *Soil Biol. Biochem.* 23, 579–581.
- Keeney, D.R., Nelson, D.W., 1982. Nitrogen—inorganic forms. In: Page, A.L., et al. (Eds.), *Methods of Soil Analysis*, Part 2, 2nd ed. *Agronomy* 9, 672–685.
- Mälkönen, E., 1990. Estimation of nitrogen saturation on the basis of long-term fertilization experiments. *Plant Soil* 128, 75–82.
- Miller, H.G., 1988. Long-term effects of application of nitrogen fertilizers on forest sites. In: Cole, D.W., Gessel, S.P. (Eds.), *Forest Site Evaluation and Long-term Productivity*. University of Washington Press, Seattle, pp. 97–106.
- Nohrstedt, H.-Ö., 1990. Effects of repeated nitrogen fertilization with different doses on soil properties in a *Pinus sylvestris* stand. *Scand. J. For. Res.* 5, 3–15.

- Nohrstedt, H.-Ö., Jacobsen, S., Sikström, U., 2000. Effects of repeated urea doses on soil chemistry and nutrient pools in a Norway spruce stand. *For. Ecol. Manage.* 130, 47–56.
- Pang, P.C., Barclay, H.J., McCullough, K.M., 1987. Aboveground nutrient distribution within trees and stands in thinned and fertilized Douglas-fir. *Can. J. For. Res.* 17, 1379–1384.
- Prescott, C.E., 1997. Effects of clear-cutting and alternative silvicultural systems on rates of decomposition and nitrogen mineralization. *For. Ecol. Manage.* 95, 253–260.
- Prescott, C.E., Corbin, J.P., Parkinson, D., 1992. Immobilization and availability of N and P in the forest floors of fertilized Rocky Mountain coniferous forests. *Plant Soil* 143, 1–10.
- Prescott, C.E., McDonald, M.A., Gessel, S.P., Kimmins, J.P., 1993. Long-term effects of sewage sludge and inorganic fertilizers on nutrient turnover in litter in a coastal Douglas fir forest. *For. Ecol. Manage.* 59, 149–164.
- Prescott, C.E., Kischchuk, B.E., Weetman, G.F., 1995. Long-term effects of repeated nitrogen fertilization and straw application in a jack pine forest. 3. Nitrogen availability in the forest floor. *Can. J. For. Res.* 25, 1991–1996.
- Priha, O., Smolander, A., 1995. Nitrification, denitrification and microbial biomass N in soil from two N-fertilized and limed Norway spruce forests. *Soil Biol. Biochem.* 27, 305–310.
- Ring, E., Bergholm, J., Olsson, B.A., Jansson, G., 2003. Urea fertilizations of a Norway spruce stand: effects on nitrogen in soil water and field-layer vegetation after final felling. *Can. J. For. Res.* 33, 375–384.
- Ross, D.J., Speir, T.W., Tate, K.R., Orchard, V.A., 1985. Effects of sieving on estimations of microbial biomass, carbon and nitrogen mineralization under pasture. *Aust. J. Soil Res.* 23, 319–324.
- Smith, W.H., Bormann, F.H., Likens, G.E., 1968. Response of chemoautotrophic nitrifiers to forest cutting. *Soil Sci.* 106, 471–473.
- Smolander, A., Priha, O., Paavolainen, L., Steer, J., Mälkönen, E., 1998. Nitrogen and carbon transformations before and after clear-cutting in repeatedly N-fertilized and limed forest soil. *Soil Biol. Biochem.* 16, 957–962.
- Stegemoeller, K.A., Chappell, H.N., 1990. Growth response of unthinned and thinned Douglas-fir stands to single and multiple applications of nitrogen. *Can. J. For. Res.* 20, 343–349.
- Strader, R.H., Binkley, D., 1989. Mineralization and immobilization of soil nitrogen in two Douglas-fir stands 15 and 22 years after nitrogen fertilization. *Can. J. For. Res.* 19, 798–801.
- Tamm, C.O., Aronsson, A., Popovic, B., 1995. Nitrogen saturation in a long-term forest experiment with annual additions of nitrogen. *Water Air Soil Pollut.* 85, 1683–1688.
- Turner, J., 1977. Effect of nitrogen availability on nitrogen cycling in a Douglas-fir stand. *For. Sci.* 23, 307–316.
- Vitousek, P.M., Gosz, J.R., Grier, C.C., Mellilo, J.M., Reiners, W.A., Todd, R.L., 1979. Nitrate losses from disturbed ecosystems. *Science* 204, 469–474.