Sveriges lantbruksuniversitet
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Ökad tillväxt hos gran (*Picea abies* (L.) Karst.) genom små årliga tillsatser av kvävegödsel

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Abstract

Many studies show that elevated nitrogen (N) levels through atmospheric deposition will increase forest growth in boreal ecosystems. However, these studies have mainly been indirect, correlating forest growth to present and historical N deposition. The atmospheric N deposition over Sweden varies from > 20 kg N ha^{-1} yr^{-1} in the south to c. 1 kg N ha^{-1} yr^{-1} in the north. During the later part of the 20th century forest growth in Sweden increased about 30 %, an increase mostly believed to originate from improved forest management. The topic of this thesis was to elucidate how significant N deposition may be, and may have been, to forest growth in Sweden and the growth of *Picea abies* (L.) Karst. in particular. I measured tree year ring widths and current year needle N levels in a long-term experimental site subjected to 14 years of consecutive low dose N fertilization (12,5 and 50 kg N ha^{-1} yr^{-1}). The site was situated in north Sweden with a low background N deposition (c. 2 kg N ha^{-1} yr^{-1}). The experimental forest is relatively dense, about 25 m^2 ha^{-1}, and dominated by *P. abies* with an age of c. 130 years (in breast height). The low dose N application (12.5 kg N ha^{-1} yr^{-1}) is similar to past and ongoing N deposition over large parts of southern Sweden.

I found that radial tree stem growth increased and that needle N levels were elevated in current year needles as a result from the annual N fertilizations. A c. 12 % radial growth increase from the N addition of 12.5 kg N ha^{-1} yr^{-1} were measured and a c. 80 % increase from 50 kg N ha^{-1} yr^{-1}, both compared to the control as 14 years accumulated radial tree growth. Needle N contents were elevated by c. 8 % in the low dose application and by c. 30 % in the high dose, compared to the control. After 14 years of repeated fertilization there was still an ongoing fertilization effect since annual tree year rings were still wider than they were before fertilization started. Annual tree year rings in fertilized trees have been wider compared to control trees during the whole fertilization period. My calculations show that a low dose annual application of N fertilizer for 14 years (∑175 kg N) will increase growth slightly more than a theoretical single large application of equal magnitude. From the 30 % forest growth increase witnessed during the later part of the 20th century I suggest, based on the results from this study, that about ⅓ should be conferred to the increased N deposition rate during that same period. In forests where growth is restricted by the N supply a growth increase, such as the one seen in this study, should be expected from N deposition rates of comparable size. At least in forests alike the one in this study.

Key words: Nitrogen (N) deposition, N fertilizer, P. abies, Norway spruce, Forest growth, Stem growth, Northern Sweden, Drill cores, year needles, C:N-ratio.

Sammanfattning (Swedish)

Idag finns en rad studier som visar att förhöjda nivåer av kvävenedfall (N) ökar skogstillväxten i boreala ekosystem. Dessa studier har dock varit indirekta, tillväxten i skogen har korrelerats till historiska och nutida nivåer av kvävenedfall. Den atmosfäriska bakgrundsdepositionen av kväve varierar idag från ca 1 kg N ha^{-1} yr^{-1} i norra Sverige till över 20 kg N ha^{-1} yr^{-1} i de mest utsatta sydvästra delarna av landet. Sedan 1950-talet och framåt har skogstillväxten i Sverige ökat med ca 30 %, detta tror man till stor del beror av förbättrad skötsel. Med den här rapporten vill jag undersöka hur stor betydelse kvävenedfallet kan ha, och kan ha haft, för tillväxten hos *Picea abies* (L.) Karst. i Sverige. Jag har mätt årsringsbredd och kväveinnehåll i årsbarr från träd som ingår i ett långtidsexperiment där ytor årligen har gödslats med låga doser av kväve: 12,5 och 50 kg N ha^{-1} yr^{-1} har spridits för hand i början av varje tillväxtssäsong sedan 1996. Försöksskogen ligger i norra Sverige där bakgrundsdepositionen är ca 2 kg ha^{-1} yr^{-1}. Försöksområdet består av en relativt tät granskog, ca 25 m^{2} ha^{-1}, med en brösthöjdsålder på ca 130 år. Den låga kvävedosen 12,5 kg N ha^{-1} yr^{-1} är i samma storleksordning som det nedfall som pågått och pågår idag i stora delar av södra Sverige. Effekten av 50 kg N ha^{-1} yr^{-1} utvärderades eftersom det finns en chans att den globala kvävedepositionen kan komma att öka i framtiden.

Mina mätningar visade att gödslade träd hade en större årsringsbredd samt ett förhöjt kväveinnehåll i årsbarren jämfört med ogödslade träd. En nästintill tolvprocentig ökning av diametertillväxten sågs hos träd som gödslats med 12,5 kg N ha^{-1} yr^{-1} och för träd som gödslats med 50 kg N ha^{-1} yr^{-1} ökade diametertillväxten med ca 80 %, båda jämfört med kontrollen och som ackumulerad diametertillväxt under 14 år. Den lägre kvävegivan ökade barrens kväveinnehåll med ca 8 % och i den högre ökade innehållet med ca 30 %, jämfört med kontrollen. Efter 14 år av kontinuerlig kvävegödsling fanns en fortsatt gödslingseffekt eftersom årsringsbredden på gödslade träd är större än vad de var före experimentet startade. Mina beräkningar visar att en årlig kvävegödsling i 14 år med 12,5 kg N ha^{-1} år^{-1} (totalt 175 kg N) troligtvis är något effektivare i avseende på diametertillväxt än vad en engångsgiva av samma storlek skulle varit. Baserat på mina resultat föreslår jag att: av den dokumenterade 30 % -iga tillväxtökningen i skogen, under slutet av tjugohundratalet, så bör ca ⅓ tillskrivas det kvävenedfall som pågick under samma tid. I skogar vars tillväxt begränsas av kvävetillgången bör en tillväxtsökning, likt den som dokumenterats i denna studie, förväntas från kvävenedfall av likartad storlek.

Sökord: Kvävedeposition (N), kvävegödsel, P. abies, gran, skogstillväxt, stamtillväxt, norra Sverige, borrkärnor, årsbarr, C:N-kvot.

Table of contents

Introduction

In Sweden the atmospheric nitrogen (N) deposition over terrestrial ecosystems ranges from > 20 kg N ha^{-1} yr^{-1} in the south-west to c. 1 kg N ha^{-1} yr^{-1} in the far north (Lövblad 2000). The atmospheric N deposition originates from two main sources; the combustion of fossil fuels and agricultural management. The higher regional deposition in south-west Sweden is due to large areas of agricultural land and large emission sources in Western Europe, and prevailing winds bringing in precipitation and thereby wet deposition from there (Lövblad 2000). Hence, 60 % of the N deposition in southern Sweden originates from other European countries. That portion decreases to 35 % in the north. Forest growth in boreal ecosystems is mostly limited by the N supply (Tamm 1991) and atmospheric N deposition is thus likely to cause increased forest growth and consequently increased carbon (C) sequestration in forest ecosystems (Solberg *et al.* 2004; Högberg 2007; Pregitzer *et al.* 2008; Sutton *et al.* 2008; Bedison and McNeil 2009; de Vries *et al.* 2008; Solberg *et al.* 2009). Nitrogen is the only nutrient that when given alone will increase radial stem width in the majority of Swedish coniferous forest stands on mineral soils (Sikström and Nohrstedt 1995). Different studies have estimated the effect of atmospheric N deposition on forest growth and found different responses. For example Bedison and McNeil (2009) found that low N deposition rates (varying from c. 3 to 7 kg N ha^{-1} yr^{-1}) did have a positive or neutral effect on temperate forest tree growth in north-eastern United States. Higher rates of N deposition rendered in larger basal area increments (Bedison and McNeil 2009). A study in Norway concluded that N deposition had increased forest growth by c. 25 % in the southern parts where deposition was c. 20 kg N ha^{-1} yr^{-1} (Solberg *et al.* 2004). A forest rotation experiment with *P. abies* in south-western Sweden perceived a 40 % volume increase in the second rotation period compared to the first rotation period. Nitrogen deposition was c. 20 kg N ha^{-1} yr^{-1} in the second rotation period which was established in the middle of the 20th century (Eriksson and Johansson 1993). Nitrogen deposition was believed to be one of the most important factors contributing to better growth in the second rotation. In a study by Pregitzer *et al.* (2008) a hardwood forests in Michigan was exposed to simulated N deposition in magnitude of 30 kg N ha^{-1} yr^{-1}. After ten years an increase of 5000 kg C ha^{-1} could be noted. An extensive study by Solberg *et al.* (2009) concluded that each kg of deposited N had a fertilization effect on forest growth by 1 to 1.9 %, naturally the effect being higher in sites with more severe N deficiency. They calculated that 19 kg C would be fixed for every kg N added.

The studies referred to above that have examined N deposition effects on forest growth have mainly been indirect, i.e. they have correlated forest growth to present and historical N deposition. Very few, if any, experiments have been done to verify and quantify the correlation between N deposition and forest growth. In contrast to the idea that N deposition increases forest growth, Elfving and Tegnhammar (1996) suggested that the 30 % increase in forest growth between 1953 and 1992 in Sweden was mainly due to improved forest management. The objective of the current study was to verify and quantify that increased forest growth can be obtained from low annual N additions. To achieve this objective I measured forest growth in a long-term N addition experiment in a region with low background N deposition (< 3 kg N ha^{-1} yr^{-1}) (Forsum *et al.* 2006; Forsum 2008). Basal area tree growth was measured through analyzing drill cores. The N doses applied were 12.5 and 50 kg N ha^{-1} yr^{-1}. The low N dose is thus similar to current N deposition over large parts of south Sweden (Lövblad 2000). The high N dose was examined since global N deposition is believed to increase during this century (Lamarque *et al.* 2005). The experiment was originally set up to study initial as well as long-term N deposition effects on forest understory vegetation.

The more specific aims of the study were to determine: (1) If small annual N additions, 12.5 kg N ha^{-1} yr^{-1} during 14 consecutive years have resulted in increased growth in *P. abies*? (2) If the tree growth responses to N addition differ between N1 and N2? (3) If the needle C:N ratio has changed following N addition? (4) If the low rate (12.5 kg N ha^{-1} yr^{-1}) fertilization effect on tree growth would be similar to the effect obtained from a ‘normal’ commercial fertilizer application?

Materials and methods

Site description

The experimental forest in Svartberget is located in Vindeln at 64^{o} 14’ latitude and 19^{o} 46’ longitude in northern Sweden; hence it is located in the middle boreal zone (SNA 1996; 2000). The soil is a podzol moraine consisting of a mix of fine sand and sand, geotechnical nomenclature: coarse-grained till (SLU 2007). The area has a light slope facing S-SW. Site index (SI) in Svartberget is about G19 (c. 3.4 m^{3}sk ha^{-1} yr^{-1}) (Hägglund 1972) and the sites used in this study are located at about 200 to 250 m a.s.l. The forest is dominated by coniferous species, mainly *P. abies*. *Vaccinium myrtillus* (L.) and *V. vitis-idaea* (L.) dominate the field layer. For more specific forest data see *results*. Average annual precipitation (mean values of 1981 to 2008, see Fig. 1) is about 600 mm; c. one third comes as snow during winter (SLU 2006) and c. half as rain during the growing season (Table 1). The remainder falls as rain during late autumn and early spring. Mean year temperature is 0 ^{o}C (SLU 2006). Temperature sum, the sum of mean temperatures for all days with mean temperature above 5 ^{o}C, is c. 950 (Table 1). Growing season stretches from the end of May to the end of September, c. 148 days (Table 1). According to Forsum *et al.* (2006) the atmospheric N deposiotion through rainfall during the growth period at this study site is c. 2.0 kg ha^{-1} yr^{-1} and the deposition consists of 78 % NH_4^+, 17 % amino acid N and 5 % NO_3^-. Snowmelt contributes with an additional c. 0.3 kg N ha^{-1} yr^{-1} (Forsum 2008).

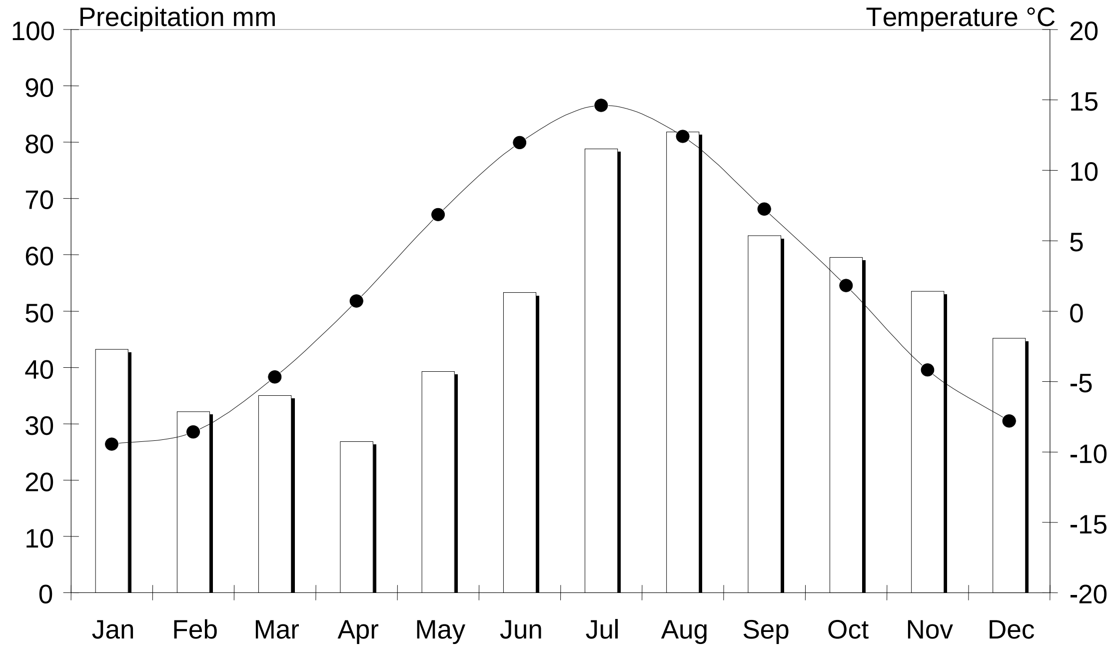

Figure 1*. Precipitation and temperature, in mean monthly values from 1981 to 2008, in Svartberget Experimental Forest (data from Ottosson-Löfvenius (2009b), pers. comm.). Temperature (dotted line) on the right Y-axis and precipitation (bars) on the left.*

Table 1. *Climate conditions of the experimental site. Length of growing period (days), temperature sum and precipitation (mm) during growing periods for years 1994 to 2008. Means for the 15-year period are also shown (Ottosson-Löfvenius 1995, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2007, 2008, 2009a).*

Year	*94*	*95*	*96*	*97*	*98*	*99*	*00*	*01*	*02*	*03*	*04*	*05*	*06*	*07*	*08*	**Mean**
Length of growing period (days)	145	130	145	129	152	141	173	169	150	139	160	148	168	101	170	**148**
Temperature sum of growing period	865	868	834	1049	840	954	950	995	1228	1062	914	992	1206	641	844	**949**
Precipitation during growing period (mm)	159	221	284	231	409	185	483	561	216	392	394	323	307	250	341	**317**

Experimental design

The experiment was set up in spring 1996. Six replicates (n = 6) of three treatments (the control, N1 and N2) were made resulting in 18 plots, in a randomized block design (Fig. 2). Each treatment plot was 0.1 ha (1000 m^2). The controls were 0.25 ha (2500 m^2) but for this study an inner plot of 0.1 ha was established to enable easier comparisons between plots. All N1 plots have been given 12.5 kg N ha^{-1} yr^{-1} and all N2 plots 50 kg N ha^{-1} yr^{-1} as granulated $NH_4NO_3^-$ by hand, close to the commencing of the growing period each year since 1996. No fertilization was added to the controls.

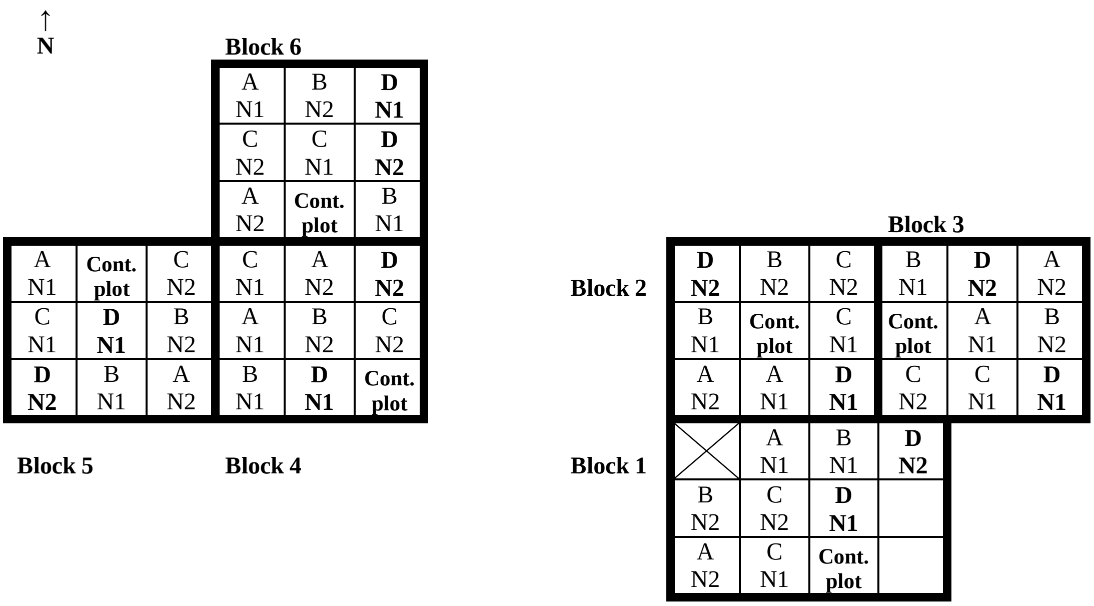

Figure 2. *The block design of the N addition experiment at Svartberget. All plots have a total area of 2500 m^2 (50 · 50 meters), whereas the fertilized area differs between plots; 1 m^2 (A plots), 10 m^2 (B plots), 100 m^2 (C plots) and 1000 m^2 (D plots). In the current study only D plots and control plots (Cont. plot) were used. For further information about this experimental design see Strengbom et al. (2006).*

Basal area and sample trees

Every tree larger than 50 mm at breast-height (1.3 m), at all examined plots, were cross-callipered in August 2009. In total 1497 trees had a breast height diameter larger than 50 mm. These trees were used to determine basal area per ha (m^2 ha^{-1}) of each plot. First, basal area was calculated for each tree (using equation 1); thereafter for every plot by summarizing all tree specific basal areas, multiplied by ten (since plots were 0.1 ha).

$$(1) \qquad Basal\ area = \left(\frac{Diameter}{2}\right)^2 \cdot \pi$$

After basal area of each plot was determined, four sample trees were chosen from each plot for more time-consuming measurements of tree-growth variables. These sample trees for each plot were chosen to have basal areas as close to the plot average as possible. For the selection procedure the plot total basal area was divided with the number of trees resulting in the mean tree basal area. With the mean tree basal area I counted backwards and thus achieved the corresponding diameter (according to equation 2).

$$(2) \qquad Sought\ mean\ plot\ diameter = 2 \cdot \sqrt{\frac{Mean\ tree\ basal\ area}{\pi}}$$

These diameters were referred to as ‘basal area-weighted mean tree diameters’ and are presented in Table 2.

Table 2. *Basal area weighted mean tree diameters (mm) for each block and treatment (control, N1 and N2) along with the treatment mean values.*

	Block 1	*Block 2*	*Block 3*	*Block 4*	*Block 5*	*Block 6*	*Mean*
Control	245	220	224	225	173	213	**217**
N1	202	198	255	181	152	227	**202**
N2	259	253	236	211	204	226	**231**

A lot of emphasize was put on choosing the sample trees, and in most cases the measured mean sample tree diameter (Table 6) concurred (mean deviation ± 4 mm) with the diameters sought after (Table 2). *P. abies* was focused upon, since it was the study purpose to determine this species growth response. This resulted in 72 sample trees (4 x 18 = 72). The following parameters were recorded for them; tree height (m), lower crown height (m), diameter (mm), bark thickness (mm) and basal area close to the sample tree (m^2 ha^{-1},with a relaskop). Furthermore, current year-needles, and 5 mm increment cores from 1.3 m tree height were collected from the trees. Increment cores were taken on the side of the trunk facing south whenever possible, otherwise from the side facing north.

Plot tree volume

To achieve a fairly correct estimation of the total stem volume in each plot, without having to measure the height of every tree, the trees were divided into five groups of diameter classes, with roughly the same amount of trees in them, and two trees were sampled in each group. The ten trees represented different parts of the diameter spectrum and hereafter these 10 sample trees from each plot are referred to as spectrum trees. The two group spectrum trees were roughly the two trees around the median in each spectrum group to simplify field work (Table 3). The spectrum goes from smallest to biggest diameter; group one containing the smallest diameters and group five the largest. Height (m), lower crown height (m), bark thickness (mm) and diameter (mm) were measured on spectrum trees. In this study only height and diameter were used when calculating tree volume. The other parameters were collected out of precaution, in case other volume functions would have been used, such as Näslund's (Näslund & Hagberg 1950). Tree species were selected by looking at the tree distribution in the specific spectrum. An example of how trees were chosen, and measured values from these trees can be seen in Tables 3 and 4, respectively.

Table 3. *The original datasheet from block one with the control treatment used to determine which trees are to be sampled as spectrum trees. Each spectrum contains approximately 20 % of the total number of trees in that plot. Since there was 47 trees in this plot (n = 47) every spectrum should contain 9.4 trees, which is impossible, however spectrum classes were made as close to it as possible.*

Tree id	*Diameter, mm*	*Spectrum*	*Tree id*	*Diameter, mm*	*Spectrum*
47	460	5	**23**	219	3
46	384	5	**22**	208.5	3
45	375.5	5	**21**	207.5	3
44	345	5	**20**	205	3
43	343	5, Sample tree	**19**	203.5	2
42	330	5, Sample tree	**18**	192.5	2
41	319	5	**17**	191	2
40	310.5	5	**16**	190	2
39	308	5	**15**	189.5	2, Sample tree
38	307.5	4	**14**	188	2, Sample tree
37	283	4	**13**	183	2
36	275	4	**12**	166.5	2
35	272.5	4	**11**	162	2
34	271	4, Sample tree	**10**	159.5	1
32	270	4, Sample tree	**9**	154.5	1
33	270	4	**8**	140	1
31	266	4	**7**	136	1
30	264	4	**6**	119	1, Sample tree
28	262.5	3	**5**	102	1, Sample tree
29	262.5	3	**4**	75	1
27	252.5	3	**3**	71	1
26	245	3	**2**	66.5	1
25	243.5	3, Sample tree	**1**	62.5	1
24	235.5	3, Sample tree			

Table 4. *The spectrum-data collected from block one with the control treatment. Rows go from spectrum one to five and then the total values, were such is noteworthy. There are two sampled spectrum trees in every row and in the last columns are their mean volumes (m^3) and total spectrum volume (m^3). Diameter is in cm, volume in m^3 and height in m.*

Spectrum	*Number of trees in spectrum*	*Species*	*Diameter 1, cm*	*Height 1, m*	*Diameter 2, cm*	*Height 2, m*	*Mean spectrum volume, m^3*	*Total spectrum volume, m^3*
1	10	*P. abies*	10.2	10.0	11.9	12.5	0.0594	0.594
2	9	*P. abies*	19.0	19.0	18.8	15.5	0.2443	2.198
3	10	*P. abies*	23.9	19.0	24.6	18.5	0.4094	4.094
4	9	*P. abies*	27.0	20.5	27.1	20.0	0.5388	4.849
5	9	*P. abies*	34.3	23.5	32.9	23.5	0.9215	8.294
Total	**47**							**20.03**

Tree volumes were calculated using Brandle's functions (see equation 3 and 4) (Brandel 1990). Height is in m and diameter in cm therefore resulting in volume being in dm^3; though in all Tables and Figures volume is converted to m^3. For a few trees, i.e. *Betula pubescens* (Ehrh.), Brandle's function could not be used since some spectrum trees were less than 6 m high. Therefore Laasasenaho's function was used, as the prerequisite is only 4 m in high (see equation 5) (Laasasenaho 1982).

(3) *P. sylvestris* volume (dm^3) = $10^{-1.20914} \times \text{Diameter}^{1.94740} \times (\text{Diameter}+20.0)\text{-}^{0.05947} \times \text{Height}^{1.40958} \times (\text{Height}-1.3)^{-0.45810}$

The prerequisites are that height has to be at least 4 m in height, diameter at least 4.5 cm and the forest needs to be north of the 60° latitude.

(4) *P. abies* volume (dm^3) = $10^{-0.79783} \times \text{Diameter}^{2.07157} \times (\text{Diameter}+20.0)^{-0.73882} \times \text{Height}^{3.16332} \times (\text{Height}-1.3)^{-1.82622}$

The prerequisites are the same as for *P. sylvestris*.

(5) ln(*B. pubescens* volume (dm^3)) = $-4.49213 + 2.10253\ln(\text{Diameter}) + 3.98519\ln(\text{Height}) - 2.65900\ln(\text{Height}-1.3) - 0.0140970*\text{Diameter}$

$e^{(B.\ pubescens\ \text{volume in dm3})}$ = volume in dm^3

The prerequisite is that height has to be at least 4 m.

Drill cores

Core samples were taken from the four sample trees, of each plot, at breast height (1.3 m). These core samples were stored in paper cylinders in a fridge until preparation. Preparation involved soaking cores in water for at least twelve hours, or until saturated, and then slicing. The purpose of soaking them was to ensure that cores had not dried up or twisted and thus, making upcoming slicing easier. After saturation about one third of the cores were carefully sliced off, using a special plane, so that they could be properly scanned. A specific scanner (Epsilon expression 1680 WINDENDRO STD 1600+, at 800 dpi) and the software programme WinDendro 2008a (Regent Instruments, Quebec, Canada) were used to analyze the core samples. A resolution of 800 dpi were used so that the *.TIFF images would not be too big, quality was ideal and there was no problem analyzing the cores (an example image can be seen in appendix 1). The program produces a text file with annual tree ring width, in mm, and total tree age along with some other parameters (which were not important in this study). An example of the result is shown in Table 5.

Table 5. *Tree ring widths (mm) of the four samples trees in the N2 plot within block six from 1989 to 2009, mean values at the bottom.*

Year	***1989***	***1990***	***1991***	***1992***	***1993***	***1994***	***1995***	***1996***	***1997***	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	***2009***
Tree # 1	0.53	0.65	0.57	0.97	0.60	0.71	0.78	1.13	1.91	1.91	2.34	3.08	2.38	2.40	2.42	1.69	1.07	1.27	1.30	0.95	0.88
2	0.57	0.31	0.37	0.33	0.47	0.38	0.42	0.80	0.76	0.77	0.87	1.00	0.98	0.86	1.71	1.46	1.27	1.27	1.05	0.98	0.82
3	1.36	1.68	1.52	1.39	0.92	1.14	1.23	1.17	1.27	1.52	1.40	1.59	2.16	2.92	2.75	2.46	2.46	1.92	1.79	1.99	1.81
4	0.17	0.22	0.28	0.14	0.25	0.20	0.06	0.25	0.35	0.28	0.35	0.22	0.24	0.20	0.41	1.94	1.08	1.05	0.67	0.64	0.51
Mean across samples trees	*0.66*	*0.71*	*0.69*	*0.71*	*0.56*	*0.61*	*0.62*	*0.84*	*1.07*	*1.12*	*1.24*	*1.47*	*1.44*	*1.59*	*1.82*	*1.88*	*1.47*	*1.38*	*1.20*	*1.14*	*1.01*

Tree ring data were used to determine annual basal area increase. Basal area was calculated through first measuring the tree radius (from pith to inner bark) in WinDendro and then subtracting the last 21 tree year rings for each sample tree. From there, basal area was computed for each year current radius from 1989 to 2009. For some of the following analyses the 21 years was divided into 7 periods, each period consisting of three years mean values (see *results*).

Current year needles

Current year needles were collected from the four sample trees at each plot. The needles were collected at about 4 to 5 m tree height from branches facing southward. A handful of needles were taken from every tree. The collected needles were first kept in paper bags and put in a freezer (-17 ˚C) for storage. They were later oven-dried, in 70 ˚C for 24 hours. To be able to measure the C:N ratio, needles were grinded using a Bead grinder and small amounts, 2 to 3 mg, were put in tiny tin cups. The cups were sent to the laboratory at Plant Science Centre in Umeå for C:N analysis using a Soil NC Analyzer machine.

Statistical Analysis

Statistical analyses were made testing both the effect of block and of treatment on tree growth parameters. Since there never was a significant effect of blocks this parameter was excluded from further analyses. All statistics were made with the software MYSTAT (the student version of SYSTAT), using a repeated measure ANOVA design. Effects of N treatment over time were tested on tree ring width, basal area, annual basal area increase and basal area increase of fertilized trees relative control trees for all years from 1989 until 2009 in different compilations (e.g. 21 years, seven periods or the five or four last periods). Repeated measure ANOVAs were used since the same variable was measured on the same plots each year. When analysing the C:N ratio a one-way ANOVA was used since there were only values from one year.

Results

The measured sample tree diameters (Table 6) did not vary much from the diameters sought to sample (Table 2) e.g. the basal area-weighted mean diameters representative for each plot. Fertilization with 12.5 (N1) and 50 (N2) kg N ha^{-1} yr^{-1} for 14 consecutive years had changed tree growth, although differences in growth between control plots and N2 plots were more clear than differences between control plots and N1 plots. Trees on N1 plots had lower age, lower volume and lower mean diameter than trees on control and N2 plots (Table 7). Sample trees on N1 plots had a lower mean sample tree volume than those on the control and N2 plots had a higher volume compared to the control plots (Table 8). N1 plots also had the largest number of trees accompanied with the largest variance for all measured and calculated growth variables (Tables 6, 7 and 8).

Table 6. *Mean sample tree diameter (mm), of the four trees chosen as sample trees, in each treatment, control (no fertilization), N1 (12.5 kg N ha^{-1} yr^{-1}) and N2 (50 kg N ha^{-1} yr^{-1}) and block, along with the treatment mean values. Means (n = 6) ± SE.*

Treatment	***Block 1***	***Block 2***	***Block 3***	***Block 4***	***Block 5***	***Block 6***	***Mean***
Control	247 ± 0.4	218 ± 0.5	224 ± 0.2	225 ± 0.1	173 ± 0.2	220 ± 0.4	**217.8**
N1	200 ± 0.1	212 ± 1.3	258 ± 0.0	181 ± 0.1	153 ± 0.1	231 ± 0.2	**205.8**
N2	254 ± 0.4	254 ± 0.2	236 ± 0.0	211 ± 0.1	204 ± 0.1	225 ± 0.1	**230.8**

Table 7. *Mean tree diameters (2009 and 1989), mean tree heights, mean basal areas, mean volumes, mean age in breast height, mean number of trees per plot and added N for each treatment (control, N1 and N2) along with their respective standard errors (SE), data collected in the end of 2009's growing period. Means (n = 6) ± SE.*

Treatment	***Mean plot diameter, mm***	***Mean plot diameter in 1989, mm***	***Mean height, m***	***Mean m^2 ha^{-1}***	***Mean m^3 ha^{-1}***	***Mean age years***	***Mean trees plot $^{-1}$***	***Added N (kg ha^{-1})***
Control	201 ±10.4	188 ± 2.8	16.4 ± 0.6	23.0 ± 1.9	228 ± 23.6	131 ± 3.6	75 ± 8	0
N1	186 ± 15.7	169 ± 3.7	15.3 ± 0.7	23.4 ± 2.0	244 ± 26.9	121 ± 6.5	95 ±18	175
N2	216 ± 7.5	188 ± 2.4	17.2 ± 0.7	28.1 ± 1.4	287 ± 25.6	136 ± 4.9	79 ± 5	700

Table 8. *Mean sample tree volume (m^3) for each treatment (control, N1 and N2) and plot with the treatment mean value in the last column, as it were in the end of 2009's growing period. Means (n = 6) ± SE.*

Treatment	***Block 1***	***Block 2***	***Block 3***	***Block 4***	***Block 5***	***Block 6***	***Mean***
Control	0.449 ± 0.24	0.357 ± 0.27	0.357 ± 0.13	0.354 ± 0.14	0.165 ± 0.90	0.349 ± 0.24	**0.338 ± 0.38**
N1	0.246 ± 0.40	0.270 ± 0.20	0.513 ± 0.13	0.218 ± 0.30	0.141 ± 0.40	0.407 ± 0.21	**0.299 ± 0.56**
N2	0.435 ± 0.20	0.517 ± 0.40	0.405 ± 0.16	0.304 ± 0.30	0.276 ± 0.10	0.337 ± 0.14	**0.379 ± 0.37**

Tree ring width

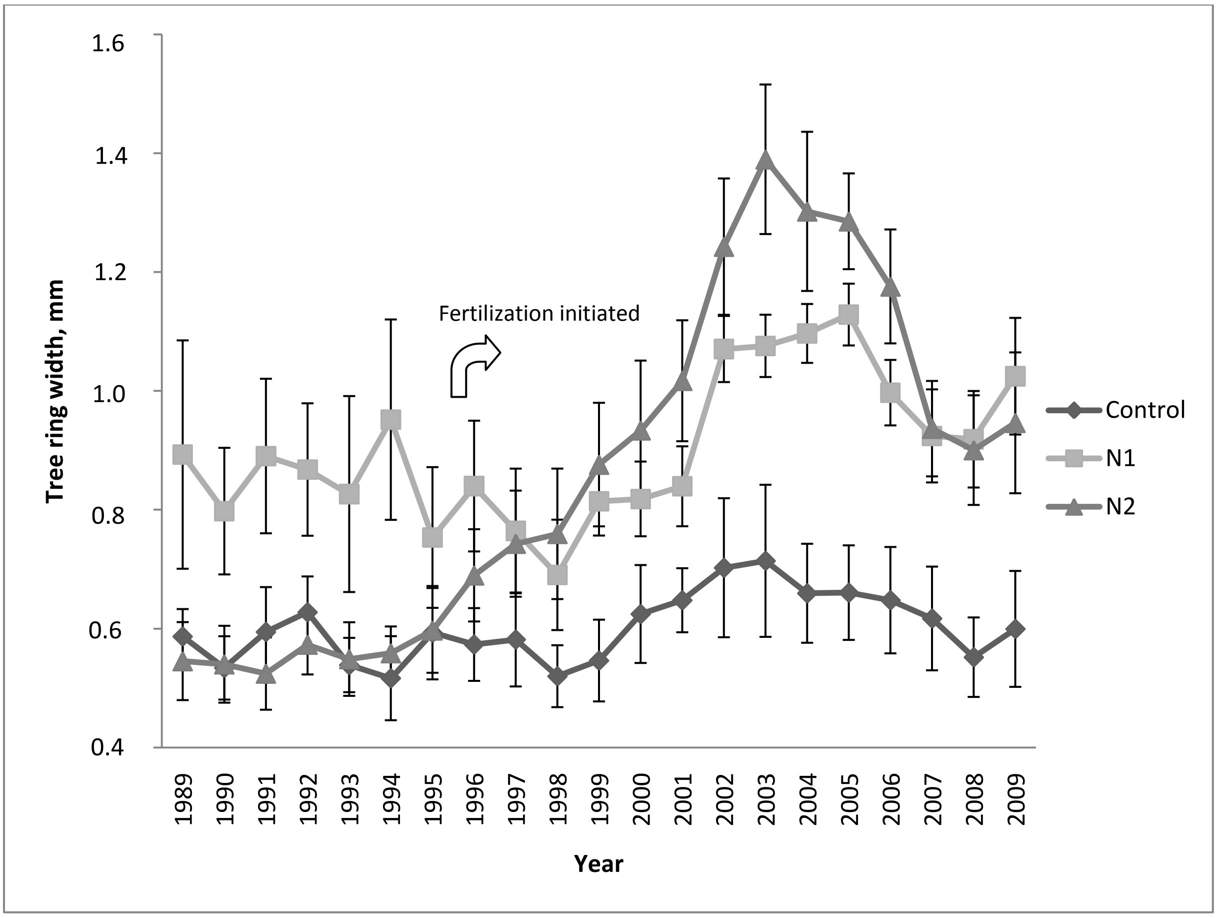

Figure 3. *Mean annual tree ring width (mm) for each treatment (control, N1 and N2) from 1989 to 2009. The curved arrow indicates when fertilization started (in 1996). Means (n = 6) ± SE.*

Before 1996 trees on N2 plots and control plots had about the same annual tree ring width, while trees on N1 plots had c. 50 % higher annual tree ring width (Fig. 3). Upon the start of fertilization in 1996, trees on N2 plots showed a clear and enduring annual tree ring width increase, separating them from trees on control plots (Fig. 3). This trend was not equally obvious for trees on N1 plots. When fertilized the tree year rings in N1 plots reaches almost the same width (low SE) regardless of prior widths before fertilization (Fig. 3). This suggests that the fertilization had a diverse effect on trees. In 2003 tree ring width on N2 plots peaked, followed by a gradual decline until 2009 when all treatments showed a slight increase again (Fig. 3). In 2003 the tree rings on N2 plots were almost twice as wide as the tree rings on the control plots. In 2005 fertilization effect peaked in the N1 plots when tree rings was c. 1.7 times as wide as the controls. A repeated measure ANOVA displayed a significant year · fertilization interaction, indicating that fertilization had a significant effect on tree ring width over time (Table 9).

Basal Area

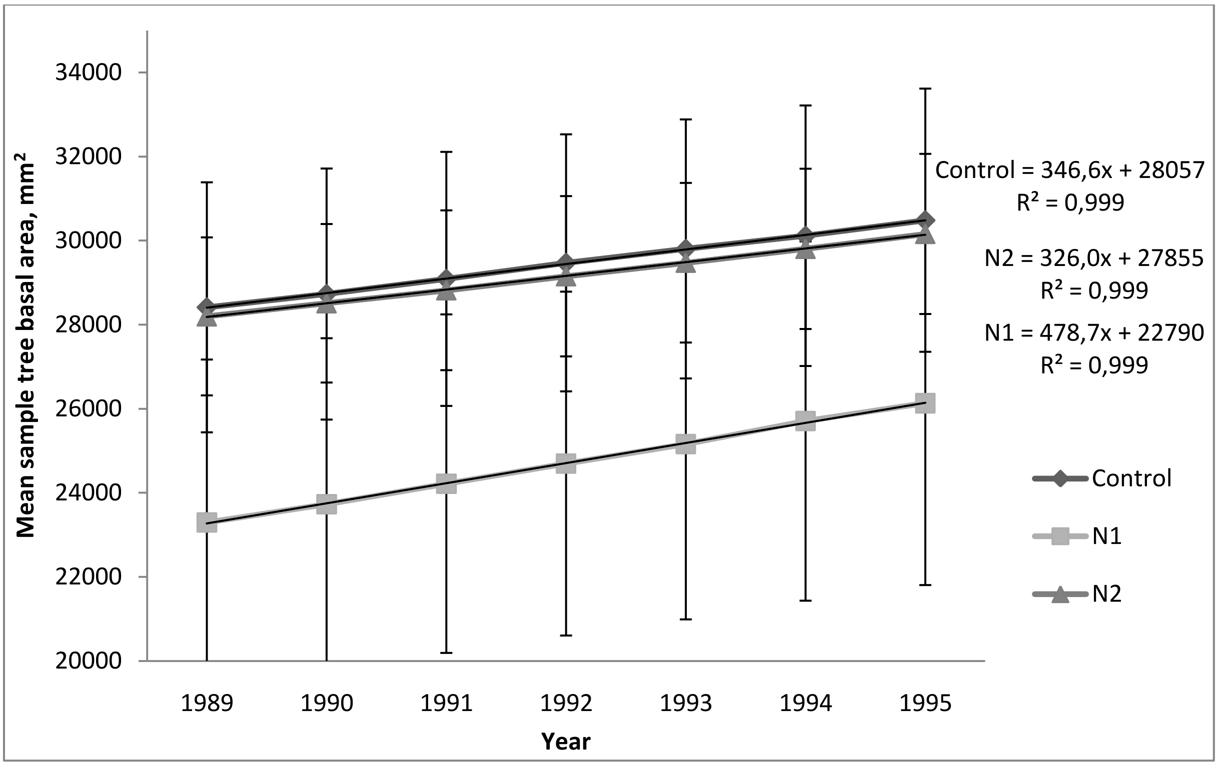

Figure 4. *Mean basal area per sample tree (mm^2) in 1989 to 1995 (before fertilization) for each treatment (control, N1 and N2). The regression line equations are shown on the right side. Means (n = 6) ± SE.*

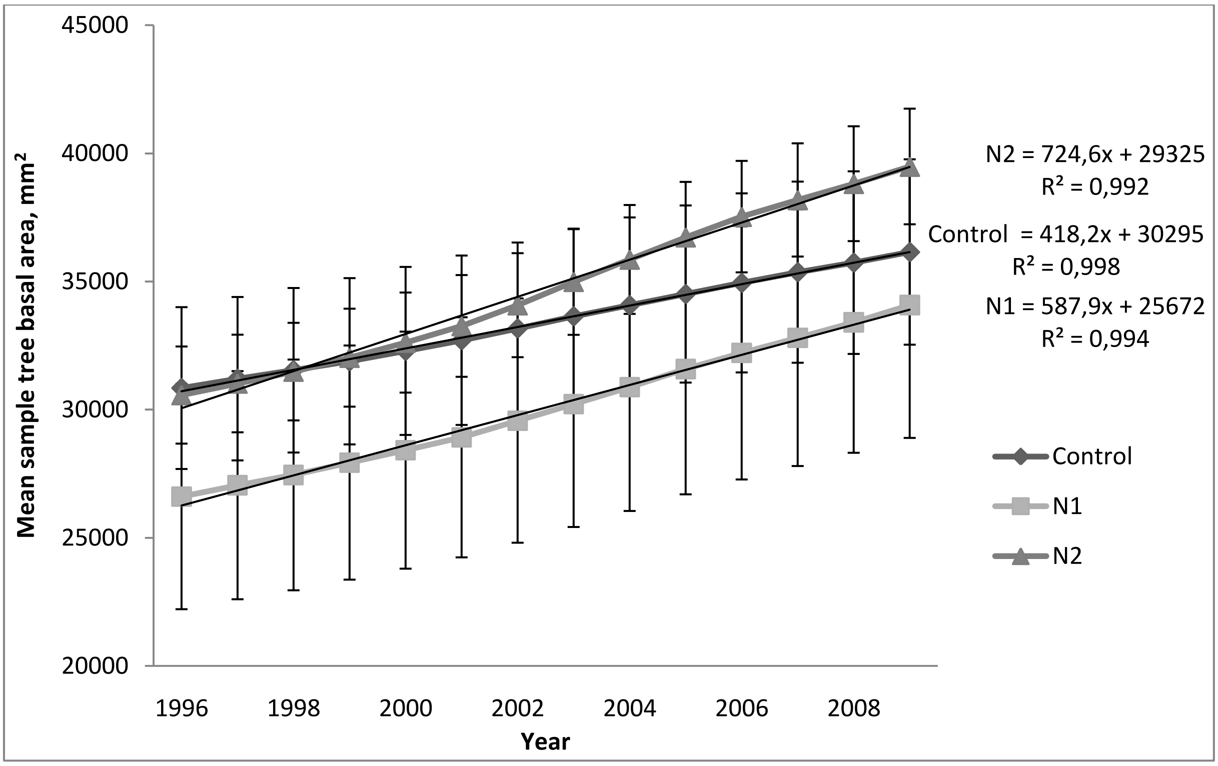

Figure 5. *Mean basal area per sample tree (mm^2) in 1996 to 2009 (the fertilization period) for each treatment (control, N1 and N2). The regression line equations are shown on the right side. Means (n = 6) ± SE.*

The normal forest growth before fertilization can be seen in Figure 4 and how trees reacted to the fertilization can be seen in Figure 5. Trees on N1 plots started on a lower basal area than trees on control plots, only about 83 % of that on control plots, and still at the end of the period the tree basal area is lower on N1 plots than on control plots (Fig. 4). However, the slope of the linear regression, which shows the accumulated basal area growth over time, is steeper for N1 plots than for control plots (and steepest for N2 plots during fertilization) (Fig. 4 and 5). In 2001 a fertilization effect on basal area can be seen on N2 plots where sample trees separated from those on control plots gaining a higher basal area per sample tree (Fig. 5). During fertilization N2 plots gained c. 10 % more basal area compared to the control, and N1 plots gained c. 11 % more than the control, making the gap between N1 and the control 6 % instead of 17 % as it were in 1989. Trees on control plots elevated their basal area increase over time with c. 70 mm^2 per year $(71.6 = 418.2 - 346.6)$ (Fig. 4 and 5) during the fertilization period compared to before fertilization. This is the normal forest growth increase. On N1 plots trees increased c. 110 mm^2 more in basal area per year during the fertilization lapse compared to the years before fertilization, a larger increase than the control had (Fig. 4 and 5). N2 trees had the largest increase; c. 400 mm^2 more per year, an increase larger than their basal area growth was before fertilization (326 mm^2 per year, Fig. 4). A repeated measure ANOVA displayed a significant year · fertilization interaction (Table 9), indicating that fertilization had a significant effect on basal area over time.

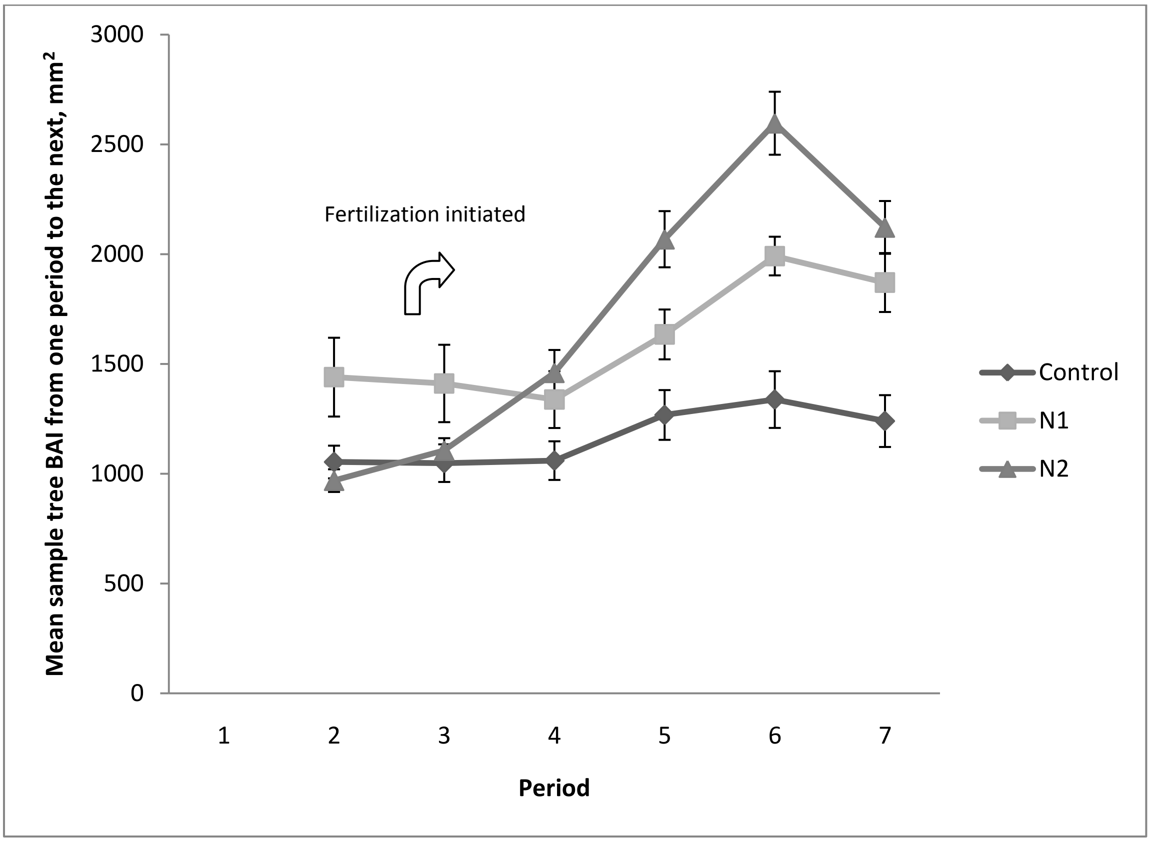

Figure 6. *Mean sample tree basal area increase from one period to the next, in mm^2, for all treatments (control, N1 and N2). Each period consists of the combined mean value from three years starting with 1989 ending in 2009. The curved arrow indicates when fertilization started. Means (n = 6) ± SE.*

To enable accurate comparisons between treatments the basal area increase (BAI) has been used to determine actual growth differences. BAI was used since tree ring width alone equals different amount of tree volume depending on the already established diameter of the tree measured, hence comparisons between basal areas are more accurate. Here BAI expresses the growth between periods (in mm^2), by presenting the basal area gained since the period before. Each period consists of the mean value from three years, thus period three consist two fertilized years and one unfertilized year. All treatments, control, N1 and N2, peaked in period six, their respective BAI values were 1300 mm^2, 2000 mm^2 and 2600 mm^2 (Fig. 6). All plots descend from period six towards period seven (Fig. 6). After fertilization trees on N2 plots steadily increase their BAI over time until peaking in period six, and then declining, when BAI in N2 plots is c. 90 % higher than on control plots (Fig. 6). BAI for N1 plots increases during the later part of the fertilization period, c. 14 % higher in period six and seven compared to period two and three, indicating that there is a fertilization effect (Fig. 6). The annual basal area increase after fertilization compared to before fertilization revealed that plots treated with N1 had a relative increase of c. 30 % comparing years before and after fertilization, the control had an increase of c. 17 % and N2 c. 110 % (see appendix 2). The c. 17 % increase in the control plots is an effect of BAI being dependent of the already established diameter, i.e. the normal forest growth. This means that after 14 years of consecutive fertilizing with 12.5 kg N ha^{-1} yr^{-1} (N1) the mean annual basal area increases c. 12 % $\left(1.117 = \frac{1.302}{1.166}\right)$ (see appendix 2) more compared to the control, and for 50 kg N ha^{-1} yr^{-1} (N2) the increase is c. 80 % more than the control. A repeated measure ANOVA revealed a significant interaction between fertilization and period, stating that there is a significant effect of fertilization on BAI over time (Table 9).

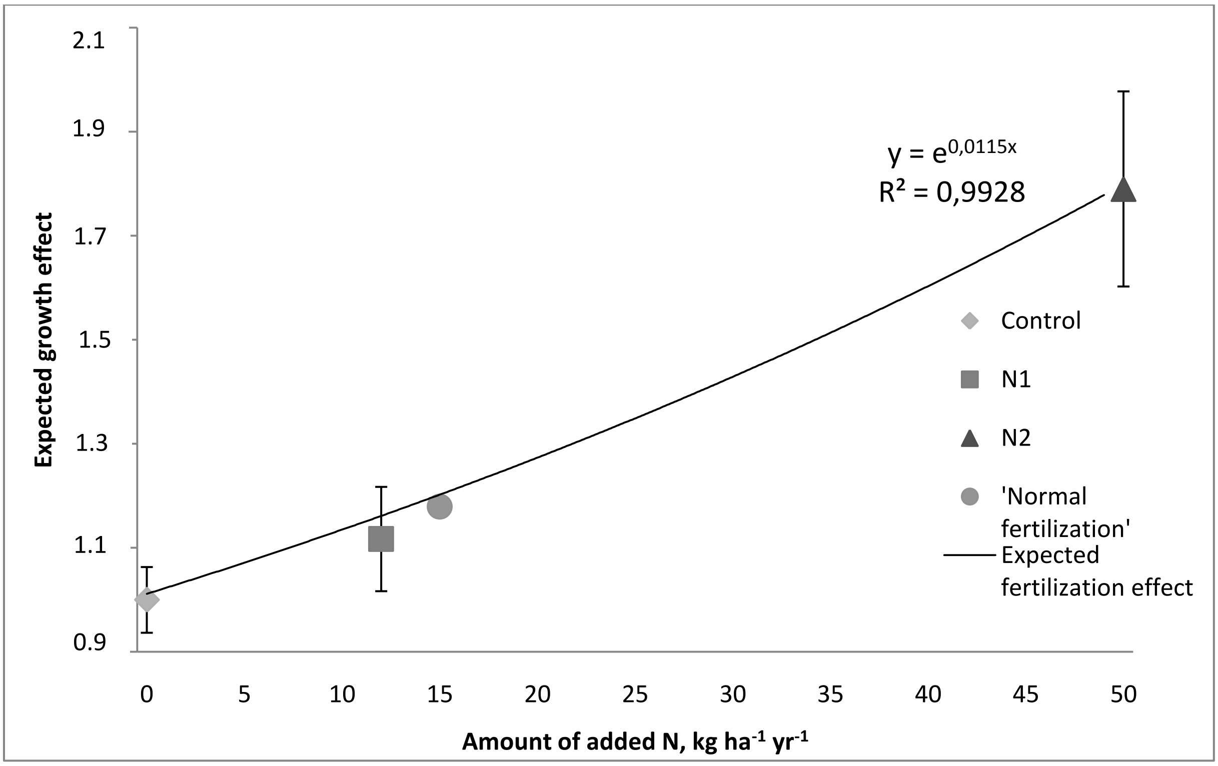

Figure 7. *The expected extra mean tree growth effect from fertilization compared to the control. All treatments are shown as after fertilization compared to before fertilization divided by the control values. The regression line shows a possible outcome of how much different amounts of N fertilization could affect growth. Regression line equation is shown in the upper right corner. Means (n = 6) ± SE.*

A model of how different amounts of annual applied fertilizer affect tree growth according to our measurements, during this experiment, is shown in Figure 7. Growth in this forest is c. 3.4 m^{3}sk ha^{-1} yr^{-1} (c. G19) (Hägglund 1972) and a ‘normal fertilization’ of 150 kg N ha^{-1} would yield c. 20 m^{3}sk in the N1 plots in ten years, according to a plain fertilization calculation tool (Skogforsk 2009). That is equivalent to c. 10 % volume increase. My measurements suggest that the increase would be c. 19 % (Fig. 7) $\left(c. 1.188 = e^{(0.0115*15)}\right)$ if the fertilization was divided upon ten years (i.e. 15 kg N ha^{-1} yr^{-1}). The measured effect from 12.5 kg N ha^{-1} yr^{-1} yields a growth increase of c. 12 % and from 50 kg N ha^{-1} yr^{-1} growth increased c. 80 % (Fig. 7). On N1 plots BAI increased with c. 1 % for every added kg of N, compared to the control, and on N2 plots BAI increased c. 1.6 % (Fig. 7).

Carbon:Nitrogen ratio

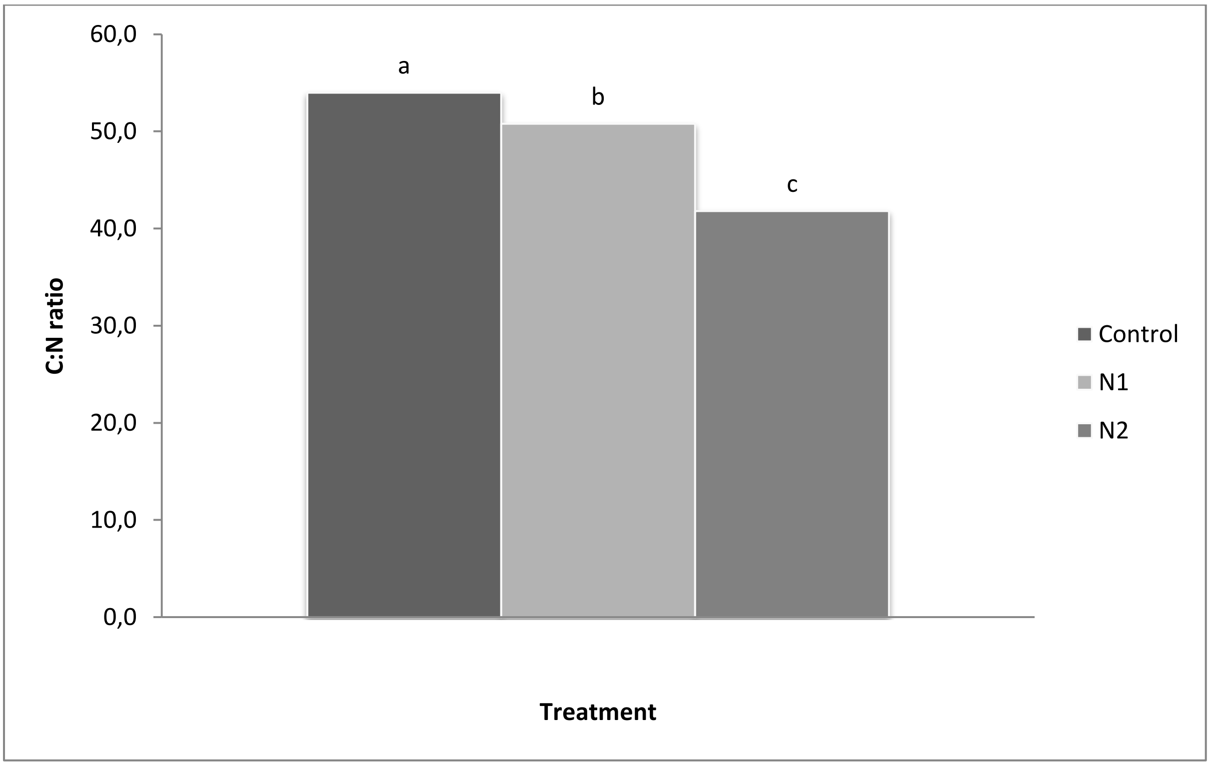

Figure 8. *C:N-ratio in current year needles for each treatment (control, N1 and N2). Different letters above bars denote that they are significantly different at $P < 0.05$ (Tukey's HSD, one-way ANOVA). Means ($n = 6$) ± SE.*

Fertilization decreased current year needle C to N ratios (Fig. 8). Needle C to N ratios were lowest on N2 plots followed by N1 and control plots. The average needle N % was 0.93 % for control plots, 1.0 % for N1 plots and 1.21 % for N2 plots; the equivalent numbers for C % were 49 %, 50 % and 50 %. On N2 plots trees thereby had c. 30 % more N in their current year needles compared to the control plots and N1 plots had c. 8 % more. There is an almost linear proportion between the measured needle N elevation and the amount of added N fertilizer. For every kilogram of added N the current year needle N levels were elevated by 0.64 % $\left(0.64 = \frac{8}{12.5}\right)$ in the N1 plots and by 0.60 % in the N2 plots, compared to the control's current year needles.

Statistical analysis

Table 9. *Output data from MYSTAT statistical software programme. The first column shows the variables tested. For some tests the years have been divided into 7 periods. Column two shows the results achieved from comparing the control, N1 and N2. Df (degrees of freedom), MS (mean square) and F-ratio (test statistic for multiple independent variables). Tests with significance are shown in bold text.*

Variable	**Control, N1, N2**			
Resultant	**Df**	**MS**	**F-ratio**	**P-value**
Annual tree ring width, 21 years				
Between subjects	**2**	**3.367**	**5.509**	**0.016**
error-term	15	0.611		
Within subjects	**40**	**0.116**	**5.109**	**< 0.001**
error-term	300	0.023		
Annual tree ring width after 1996				
Between subjects	**2**	**3.695**	**8.519**	**0.003**
error-term	15	0.434		
Within subjects	**24**	**0.05**	**3.226**	**< 0.001**
error-term	180	0.016		
Mean sample tree basal area				
Between subjects	2	2.55E+08	0.518	0.606
error-term	15	4.91E+08		
Within subjects	**12**	**3 001 009.397**	**2.973**	**0.002**
error-term	90	1 009 336.998		
Mean sample tree BAI, 7 periods				
Between subjects	2	3 093 258.028	2.493	0.116
error-term	15	1 240 741.535		
Within subjects	**10**	**468 762.850**	**8.921**	**< 0.001**
error-term	75	52 546.589		

Discussion

Numerous studies show that increased N supply will enhance forest growth (Solberg *et al.* 2004; Högberg 2007; Hyvönen *et al.* 2008; Pregitzer *et al.* 2008; Bedison and McNeil 2009; Solberg *et al.* 2009). Nitrogen deposition over Swedish forest has increased during the second half of the 20th century, but it is difficult to determine exactly how much the N deposition has affected forest growth. Most previous studies are based on correlative model estimates. In contrast, this study has used a long-term low dose N experiment set up in area with low background N deposition. It shows positive growth effects from annual N additions similar to the atmospheric N deposition loads in south Sweden.

Fertilization with both 12.5 kg N ha^{-1} yr^{-1} (N1) and 50 kg N ha^{-1} yr^{-1} (N2) during a 14 year experimental period increased basal area growth. On N1 plots basal area increased with c. 1 % for every added kg of N, and on N2 plots c. 1.6 %. Current year needle N content also increased from fertilization. The fertilization effect was more pronounced in the N2 treatment than in the N1 treatment. The N1 plots had a higher basal area increase (BAI) compared to both the control plots and N2 plots before fertilization started. Therefore the growth elevation during fertilization must be higher in the N1 plots compared to the control and N2 plots to achieve an equal relative increase. Besides fertilization, large inter-annual variations in precipitation and temperature sum have naturally effected forest growth. The increased growth trend seen in the control plots following year 2000 could partially be explained by a carry-over effect of the good weather conditions in prior years.

How the measuring method affected the result

The tree growth measuring method in this study is simplified. Since annual height measurements have not been done, only basal area increases, and comparisons between basal areas, were used to determine actual tree growth. Basal area increment has been used in previous studies to determine tree growth in presence of different N deposition rates (Bedison and McNeil 2009). Tree ring width equals different amount of BAI depending on the already established diameter of the tree measured. In 1989 the sample tree diameters were 188 mm for both N2 and the control and 169 mm for N1. A 1 mm increase thus means a basal area gain of 594 mm^2 for the control and N2, and 531 mm^2 for N1. So N2 and the control would gain c. 10 % more basal area from a ring width increase of 1 mm. Although in this study N1 sample trees had a much larger annual tree ring width increase than the others before fertilization started (c. 50 % larger), possibly because they were younger and more vivid. Therefore, N1 plots had a larger mean sample tree BAI (from year to year) compared to N2 plots and control plots before fertilization started.

The annual tree ring width for N1 plots decreases just before fertilization started and stays at that level for some years. It is possible that the canopies on N1 plots were more open compared to N2 plots and control plots, and that N1 plots did reach closure just before this experiment started. When considering the lower age, height, volume and diameter compared to the other treatments this explanation appears likely. Tree height was roughly the same for all treatments in 2009; on control plots trees had a mean height of c. 16 m, on N1 plots c. 15 m and N2 plots c. 17 m. It is possible that the height differences had an impact on the basal area growth computed in this study. This has not been accounted for but the differences should not affect basal area increase to the extent that the demonstrated differences in tree growth between the treatments are flawed. Stem form changes after fertilization; Valinger (1992) showed that more biomass is normally allocated to the upper parts of the stem in *P. sylvestris* after fertilization. More precise data would be obtained if trees were cut down and measured at several points along the stem although then future analysis would be impossible and therefore single measurements at breast height were used in this study. Another option would be to take drill cores from the sample trees at several heights. However, such method would take more time than I had available for this study. In this study all sample trees were considered to be cylindrical at the drill point to make basal area calculations easier. Not many trees are exactly cylindrical at their base, thus making this another source of error.

Variation in block design

The N1 plots had the largest variation in basal areas before fertilization started, a cause for this is that one N1 plot had about twice as many trees on it compared to all other plots. Hence, the mean diameter was also lower. Since this is a randomized block design it is just misfortune that this occurred. This could be one source of error in this study.

Fertilization

The forest growth curves in this study were similar to those in studies using high dose fertilizations (Pettersson and Högbom 2004). Single high dose applications have a growth peak after c. 5 years followed by a gradual decline. In my study the growth peaked after 9 to 12 years following initiation of fertilization but the growth curves have comparable slopes (except for the growth in 2009).

The N1 plots had a slower growth response than the N2 plots. BAI peaked in period six (2004 to 2006) on N2 and N1 plots, however their annual tree ring width peaked in 2003 (N2) and 2005 (N1). Whether the growth peak is due to fertilization or not can be discussed, since a similar trend can be seen in trees on the control plots. Also, it could be a temporary growth setback during the last couple of years and that future gains are to be expected. However, according to current data it will be referred to as a peak. Since fertilization continued something else must be limiting and/or have a counteracting effect on growth after the peak. It could be possible that supply of another nutrient is restraining, such as P or K (Jacobson and Nohrstedt 1993), but that seems unlikely since the same trend can be seen on control plots. Negative weather conditions and their carry-over effects between years is the most probable restraint for the experienced decline in forest growth, see *weather conditions* (p. 23).

With the slower fertilization reaction, the N1 plots do achieve a lower mean annual BAI for the 14 years of fertilization, since no extra growth could be recorded for the first six years of the experiment. The N1 plots’ first visible increases can be seen in year 2002 (between period five and six). The six year retard constitutes c. 43 % of the fertilization period this far. The slower fertilization reaction is probably due to that the trees on N1 plots allocated fertilizer N taken up to new needles (McNeil *et al.* 2007). After about 5 years all needles should have changed so there would only be new ones with higher levels of N. Then the BAI can benefit from the extra C sequestrated (Smith *et al.* 2002).

Previous studies show that there is no noteworthy effect from single dose fertilizations with less than 50 kg N ha^{-1} yr^{-1} since a large part of the N is accumulated in the soil (Jacobson and Nohrstedt 1993). In this study 75 kg N ha^{-1} yr^{-1} was needed (e.g. six years of fertilization) in the N1 plots before a significant fertilization effect could be visualized, supporting the theory that there is a minimum amount of N needed for fertilization effects upon forest growth to occur. This is probably the cause for the modest efficiency from the low rate fertilization this far; it is possible that the efficiency will increase in a couple of years when the proportion of the initial retard diminishes. In the N2 plots a growth response could be visualized the same year fertilization started (e.g. after 50 kg N ha^{-1} yr^{-1}).

Hyvönen *et al.* (2008) states that annual low fertilization rates are more effective in increasing tree C uptake per unit N added compared to high rates. In this study the higher rate had greater fertilization effect. However, if we disregard from the six years needed for the fertilization to take effect in the N1 plots, the fertilization effect was c. 47 % (as BAI). This would make the N1 treatment more effective to increase growth per unit N added than the N2 treatment. Furthermore, the lowest fertilization rate in the study by Hyvönen *et al*. (2008) was about 30 kg N ha^{-1} yr^{-1}. I believe that the effectiveness per unit N will increase in the N1 treatment if the experiment is carried on for a couple of more years.

Past forest growth: Management or N deposition?

The witnessed 30 % increase in tree growth in the middle and later part of the 20th century in Sweden (Elfving and Tegnhammar 1996) should partially be conferred to the N deposition occurring (Eriksson and Johnsson 1993). Elfving and Tegnhammar (1996) stress that the national homogenous trend in forest growth increase contradicts that N deposition would be a major cause; although they acknowledge that possible better management in northern parts of the country and higher deposition in southern parts could even each other out. The forest growth N deposition would have contributed with is impossible to exactly determine. Eriksson and Johansson (1993) hypothesize that N deposition plays a major part in their calculated forest growth increase in two consecutive stands in south-western Sweden. According to Solberg *et al.* (2009) the effect from N deposition upon forest growth depends on the original forest soil C:N ratio. Thus, northern forest would benefit more from N deposition than southern during the later part of the 20th century since southern parts have been exposed to N deposition for a longer time (e.g. through agriculture and emissions). The N deposition increase has been highest in southern Sweden, Högberg *et al*. (2000) roughly estimates that the total deposition in south Sweden in the 20th century was c. 500 – 1000 kg N ha^{-1}. In a report from ASTA (the Mistra funded programme Abatement Strategies for Transboundary Air Pollution) the mean deposition of N in Götaland (southern Sweden) was c. 10 kg ha^{-1} yr^{-1} between 1950 and 2000 (Westling 2001). An N deposition of that rate would, according to my study, increase tree growth as annual BAI by c. 12 %. Therefore it seems possible that c. ⅓ of the reported 30 % increase in south-Swedish forest growth in the middle and later parts of the 20th century was due to N deposition.

Comparison between single and repeated fertilizer applications

A direct increase in BAI after fertilization could be visualized for the N2 plots and a delayed increase for the N1 plots. For the fertilization period the N1 plots had c. 12 % and N2 plots c. 80 % higher annual basal area increase compared to the control plots. The mean sample tree diameter in the N1 plots was c. 180 mm in 1996, which is c. 90 % of the diameter in 2009, making a simplified estimation – saying that other forest values in 1996 would also be 90 % of their current values – the standing volume would be c. 220 m^3sk. Given the 180 mm diameter and 220 m^3sk in 1996 one can use a plain fertilization calculation tool (Skogforsk 2009) and calculate how different amounts of added N would affect forest growth. Thus I made a comparison between a single high dose application of N fertilization and the annual application used on N1 plots. If the forest was given all N fertilizer (175 kg

N ha^{-1}) at a single occasion in 1996 the volume gained would be c. 23 m^{3}sk (c. 10 % increase) (Skogforsk 2009), which is slightly lower than the measured BAI increase (compared to the control) in this study (c. 12 %). Therefore it appears that an annual low fertilization regime would yield a higher growth increase than a single large application with the same amount of N. That is, under the assumption that the relative relation between basal area increase and volume increase is, or is close to, 1:1.

Needle N content

Needle C:N ratios was the parameter documented besides tree growth, with a c. 8 % higher foliage N content in N1 plots and c. 30 % higher foliage N content in N2 plots, compared to control plots. An almost equal proportion of the N fertilizers added in both treatments were thus invested in needle N. N2 plots had an increased needle N level by 0.60 % per kg N added and N1 plots had an increase of 0.64 %. This elevation in needle N should improve tree production through higher photosynthesis (Sikström *et al.* 1998; Smith *et al.* 2002; McNeil *et al.* 2007).

Weather conditions

In 2009 trees on all treatment plots started to increase their ring width again after a few years of decline. This shows that also other parameters than N supply is affecting tree growth in this forest. Weather data from 2009 are not yet available and weather effects on growth cannot be excluded as a possible source for this sudden growth increase. The downward trend in tree growth towards the end of the study period could partially be explained by the very low temperature sum in 2007 and 2008, only 641 and 844 DD (degree days) (Ottosson-Löfvenius 2008; 2009a) compared to the average of 957 DD. Also, in 2006 the precipitation during the summer was very low; only 96 mm of rain fell during June, July and August (Ottosson-Löfvenius 2007). Such a dry year would most definitely affect forest growth and bring negative carry-over effects for future growth. One would think that weather conditions could be used as a covariate for more accurate statistics of the variables affecting the inter-annual variance in tree growth in this study. However, carry-over effects between years are difficult to account for in such analyses.

Future

Since global N deposition is believed to increase c. 2.5 times during this century (Lamarque *et al.* 2005) it is probable that forest growth and terrestrial C storage will increase (Pregitzer *et al.* 2008; Bedison and McNeil 2009; Reay *et al.* 2009). However, Westling (2001) estimates that the future mean N deposition in southern Sweden will be c. 11 kg N ha^{-1} yr^{-1} between years 2000 and 2050. If this is the case we can expect a forest growth increase of c. 11 %, at least in forests similar to the one in this study. A similar forest, to the one in this study, would be a rather dense (c. 25 m^2 ha^{-1}) and mature coniferous forest, dominated by *P. abies*, with a field layer vegetation consisting mainly of *Vaccinium* spp.

Conclusions

I found that tree growth increased and that the C:N ratio of current year needles decreased from low dose annual N fertilization. An N addition of 12.5 kg N ha^{-1} yr^{-1} increased annual growth by c. 12 % and N addition of 50 kg N ha^{-1} yr^{-1} by c. 80 %, compared to controls. Nitrogen content in needles increased by c. 8 % for the low level fertilization and by c. 30 % for high level, compared to the control. Since annual tree ring width in the end of this study period is above the average annual tree ring width before fertilization there is still an ongoing fertilization effect after 14 years. My estimates showed that the low level fertilization increased growth slightly more than an equivalent single application of identical size. I suggest that, based on the results in my study, c. ⅓ of the increased forest growth in south-Sweden in the middle of the 20th century could be conferred to the increasing N deposition during the period. Since atmospheric N deposition will increase foliage N content a similar growth increase, as seen in this study, is to be expected in Swedish forests with comparable deposition rates, if forests are not already N saturated or otherwise growth inhibited.

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Appendix 1.

Figure 9. *A scanned picture of the drill cores taken from block four with the control treatment (labeled as k, 0 kg N ha^{-1} yr^{-1}) and block three with treatment N2 (50 kg N ha^{-1} yr^{-1}). Notice how the third sample core from the right (b3n2:3) is affected by rot.*

Appendix 2

Table 10. *Mean annual BAI (mm^2) for all treatments (control, N1 and N2) and blocks for the years before (1989-1995) and after (1996-2009) fertilization accompanied by the treatments mean values, as well as the relative BAI increase (values after fertilization divided by before fertilization values). Means (n = 6) ± SE.*

	Block 1	***Block 2***	***Block 3***	***Block 4***	***Block 5***	***Block 6***	***Mean***
Mean annual BAI 1989-1995							
Control	365 ± 19	244 ± 17	305 ± 29	414 ± 26	231 ± 8	514 ± 29	**345 ± 44**
N1	271 ± 19	391 ± 12	598 ± 41	308 ± 18	338 ± 11	930 ± 57	**473 ± 103**
N2	299 ± 12	252 ± 19	329 ± 19	433 ± 20	247 ± 20	402 ± 13	**327 ± 31**
Mean annual BAI 1996-2009							
Control	369 ± 12	332 ± 18	328 ± 10	440 ± 7	260 ± 10	699 ± 34	**405 ± 63**
N1	436 ± 32	566 ± 37	694 ± 39	403 ± 28	467 ± 25	841 ± 32	**568 ± 70**
N2	582 ± 61	603 ± 52	736 ± 66	533 ± 24	603 ± 37	941 ± 61	**666 ± 61**
Relative BAI increase, %							
Control	1.012	1.361	1.075	1.061	1.127	1.359	**1.166 ± 0.06**
N1	1.612	1.446	1.161	1.308	1.382	0.905	**1.302 ± 0.10**
N2	1.949	2.393	2.236	1.232	2.443	2.338	**2.099 ± 0.19**