Pre-harvest Soil Acidification, Liming or N Fertilization Did Not Significantly Affect the Survival and Growth of Young Norway Spruce

Ulf Sikström

Sikström, U. 2005. Pre-harvest soil acidification, liming or N fertilization did not significantly affect the survival and growth of young Norway spruce. Silva Fennica 39(3): 341–349.

Acidification, liming, and N fertilization affect a number of soil properties. Such changes may have an impact on forest regeneration and yield. The aim of this study was to investigate the survival and growth of *Picea abies* (L.) Karst. planted on plots that had been acidified (in 12 annual treatments totalling 600 or 1200 kg S ha^{-1} in the form of elemental sulphur), limed (12 × 500 = 6000 kg lime ha^{-1} in the form of $CaCO_3$) or N-fertilized (3 × 200 = 600 kg N ha^{-1} in the form of urea) prior to harvest. Trees growing on plots treated with a combination of the N plus the lower S application were also tested. None of the treatments, applied in three replicate stands, significantly influenced either survival or growth of *Picea abies* trees during the first 11 growing seasons after planting.

Keywords limestone, regeneration, sulphur powder, *Picea abies*, urea
Author's address SkogForsk, Uppsala Science Park, SE-751 83 Uppsala, Sweden
E-mail ulf.sikstrom@skogforsk.se
Received 22 February 2005 **Revised** 25 May 2005 **Accepted** 26 August 2005
Available at http://www.metla.fi/silvafennica/full/sf39/sf393341.pdf

1 Introduction

Several soil properties are affected by acidification (Tamm 1989, Abrahamsen et al. 1994), liming (Hallbäcken and Popovic 1985, Derome et al. 1986, Abrahamsen et al. 1994, Smallidge et al. 1993, Staaf et al. 1996), and by N fertilization (Bååth et al. 1981, Popovic 1985, Martikainen et al. 1989, Nohrstedt et al. 1989, Nohrstedt 1990, Nohrstedt 1992, Jacobsson and Nohrstedt 1993). Such changes to the soil may affect forest regeneration and forest yield either directly, for instance by influencing nutrient supply to the seedlings, or indirectly, by altering the development of field vegetation (Gerhardt and Kellner 1986, Kellner 1993), causing changes in competition for light, water and nutrients. In addition, fine-root production (Persson et al. 1995) and the ectomycorrhizal communities (Finlay 1995, Arnebrant et al. 1996) associated with conifer trees may be affected by acidification, and by the addition of lime or N. However, published data based on field experiments have not confirmed any distinct short-term effects on the regeneration, i.e. survival and early growth of coniferous seedlings, as a result of pre-harvest soil acidification, liming or N fertilization (Högbom et al. 2001, Sikström 2001a, 2004). However, the long-term effects of these treatments are unclear.

Sikström's (2001a) conclusion on the lack of short-term effects was based on a field experiment conducted at the Farabol-experimental site in SE Sweden. The original experiment at that site was designed to study the effects of experimental acidification, liming and nitrogen fertilization on subsequent tree-stem growth and soil properties in mature stands of *Picea abies* (L.) Karst. (Andersson et al. 1995). The study by Sikström (2001a) assessed the experimental plots after clearcutting. In the present paper, data from an additional assessment, conducted 11 years after planting, is reported. Thus, the aim of the study was to investigate the survival and growth of *P. abies* trees planted in plots that had been acidified, limed or N-fertilized prior to the final felling. To my knowledge, this is the only field experiment describing survival and growth of conifer seedlings on pre-harvest acidified and limed forest soils, and one of few on pre-harvest N fertilized soils.

2 Materials and Methods

2.1 Site Description

The experimental site is situated in SE Sweden (56°26´N, 14°35´E), 140–150 m a.s.l. The annual mean temperature (1961–1990) is +6.4° and the precipitation 669 mm at the nearest climate station, Ryd, 10 km away (Alexandersson et al. 1991). The soils are mesic, sandy-silty tills, characterized as Haplic podzols according to the FAO soil classification system (1988). Site indices were estimated to be G30–G32 according to the Swedish classification system (H_{100}, m; Hägglund 1973), corresponding to site quality classes of 10.1–11.3 $m^3\,ha^{-1}\,yr^{-1}$ (Hägglund and Lundmark 1982). The stand and site characteristics, as well as deposition (bulk and throughfall) are described in detail by Andersson et al. (1995) and reviewed by Sikström (2001a).

2.2 Experimental Design and Treatments

A randomised block design was used, including three blocks and six treatments. Each experimental plot was 30 m × 30 m in size, except for the plots in block 3, which were 34 m × 34 m. The six treatments were: control (0), low sulphur (S), high sulphur (2S), lime (CA), nitrogen (N) and a combination of N and S (NS). The S treatment consisted of annual applications of 50 $kg\,ha^{-1}$ and 2S of 100 $kg\,ha^{-1}$ elemental sulphur powder (100% S) over the 12-year period 1976–1987. The CA treatment also involved annual applications, of 500 $kg\,ha^{-1}$ limestone powder. The limestone consisted of 90% calcium carbonate ($CaCO_3$), with 0.3% Mg (the 12 annual treatments totalling 18 $kg\,ha^{-1}\,yr^{-1}$), 0.2% K (12 $kg\,ha^{-1}\,yr^{-1}$), 0.04% P (2.4 $kg\,ha^{-1}\,yr^{-1}$) and 0.02% S (1.2 $kg\,ha^{-1}\,yr^{-1}$). N was given in doses of 200 $kg\,ha^{-1}$ as urea [$(NH_2)_2$ CO] on three occasions, in 1976, 1980 and 1985.

Data collected in 1991, a year before the final felling and the start of the regeneration study, showed that many soil chemical properties had been affected by the treatments (Andersson et al. 1995; shown, in part, in Sikström 2001a). In treatment CA, for example, pH, BS and exchangeable Ca and Mg had increased significantly compared with the control. In contrast, pH had decreased significantly after the addition of sulphur powder, as had exchangeable K and Mg in the humus. The addition of N resulted in minor residual effects on soil chemical properties.

2.3 Regeneration, Seedling Survival and Growth

The regeneration study was based on 20 m × 20 m plots located in the centre of the original plots. The former mature stands were whole-tree har-

Table 1. Mean number and proportion of living *Picea abies* seedlings per plot (n = 3) planted on three different occasions in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). Values are given for the different treatments and refer to the inventory in autumn 2002. The planting occasions were spring 1992 (S92), autumn 1992 (A92) and spring 1994 (S94).

Variable	Planting occasion	Treatment 0	S	2S	CA	N	NS
All seedlings							
Numbers	S92	48	60	54	58	33	55
	A92	10	5	7	7	18	7
	S94	12	14	18	11	17	12
%	S92	68	76	68	74	49	75
	A92	15	6	9	10	26	9
	S94	17	18	23	16	25	16
All undamaged seedlings							
Numbers	S92	28	32	29	37	14	26
	A92	4	2	4	3	5	3
	S94	8	9	13	8	6	8
%	S92	71	73	62	73	58	71
	A92	9	5	9	7	15	8
	S94	20	22	29	20	27	21

vested at final felling in February 1992. Three months later the plots were planted with *P. abies* seedlings (provenance Minsk Krupki) in unscarified soil. The planting procedure, including the seedling protection methods, is described in detail by Sikström (2001a). One batch of replacement seedlings was planted in October 1992, and a second in April 1994 (see Sikström 2001a).

In autumn 2002, the survival of the trees, along with their total height and diameter at breast height, were recorded. The stem volume was estimated using equations published by Andersson (1954).

In the survival analysis, the original seedlings, i.e. those planted in May 1992, and replacement seedlings were analysed both separately and together. Calculations for all the growth variables (mean tree per treatment) were based on the data for the original seedlings that had not been seriously damaged during the experimental period. However, a severe episode of browsing by roe deer in April 1993, resulting in damage to most of the seedlings, forced a major exception to this general rule. The differences between treatment means (proportion of browsed seedlings) were not statistically significant (for further details, see Sikström 2001a). The growth variables presented on an area basis (mean per plot) were based on all living trees in the plots in the autumn of the year 2002. The total numbers of seedlings and "undamaged" seedlings per plot used in the growth calculations for 2002 were 79–114 and 22–68, respectively (see also Table 1).

2.4 Statistical Analyses

Data on the proportion of survivors, mean tree size and mean height growth (for the period 1996–2002) of the original seedlings, and the mean stem basal area and stem volume per plot in the autumn of 2002, were analysed using a two-way analysis of variance. Two-way analyses of variance were also used to assess the frequency of replacement seedling survival. The GLM procedure of the SAS® program (SAS Institute Inc. 1999) was used to calculate models of the form:

$$y_{ij} = \mu + \alpha_i + b_j + e_{ij} \quad (1)$$

where μ = the overall mean; α_i = the fixed effect of pre-harvest treatment, $i = 1,..., 6$; b_j = the random effect of block, IND$(0,\sigma_b^2)$, $j = 1, 2, 3$; e_{ij} = the random error, IND$(0,\sigma_e^2)$. In addition, several covariates were tested in the model. The covariates, proportion of seedlings from the different planting occasions in the individual plots [(i) original seedlings, (ii) replacement seedlings planted in autumn 1992, and (iii) replacement seedlings planted in spring 1994] were tested individually to determine their influence on mean stem basal area and stem volume per plot.

Statistical analyses were also performed assuming a split-plot experimental design. In this case, pre-harvest treatment was regarded as the main plot and planting occasion as the subplot treatment. The following variables were tested: survival and tree size in autumn 2002, and height growth for the period 1996–2002. The MIXED procedure of the SAS® program (SAS Institute

Inc. 1999) was used to calculate models of the form:

$$y_{ijk} = \mu + \alpha_i + b_j + p_{ij} + \gamma_k + (\alpha\gamma)_{ik} + d_{ijk} \quad (2)$$

where p_{ij} = the random error of the main plot, IND $(0,\sigma_p^2)$; γ_k = the fixed effect of planting occasion, k = 1, 2, 3 (S92, A92 and A94; see Table 1); $(\alpha\gamma)_{ik}$ = the interaction between treatment and planting occasion; and d_{ijk} = the random error, IND$(0,\sigma_d^2)$. For the other terms, see Eq. 1.

Differences between the class means for treatment, block and planting occasion were evaluated using Tukey's significant differences (HSD) mean separation test. In addition, differences due to adding N [(N-0) + (NS-S)] and S [(S-0) + (NS-N)] were tested.

3 Results

There were no statistically significant treatment effects ($p = 0.21–0.95$) on the survival in 2002. This was the case for both the seedlings planted originally and for both of the two batches of replacement seedlings (Table 2, Fig. 1). For the original seedlings, the mean survival rate associated with most of the treatments was between 53% and 66%, except for the N treatment where it was 36%. When trees from all plantings were analysed together (the mixed model) there was no treatment effect, although the survival rate of seedlings planted in spring 1994 tended to be *c.*10% higher than those planted in spring or autumn 1992 (Table 3).

Variables describing the mean tree size and growth (mean height, mean stem basal area, mean stem volume and mean height growth 1996–2002) showed no significant ($p < 0.05$) differences between the treatments (Table 4, Fig. 2). This was also the case for the mixed-model analyses (Table 3). However, the means in the plots were larger for trees planted in spring or autumn 1992 than in autumn 1994 (Table 3).

The growth variables on an area basis (mean basal area and mean volume per plot) also did not show any differences between treatments (Table 4). The proportion of replacement seedlings in the plots planted in spring 1994 influenced the mean stem basal area per plot ($p_{covariate} = 0.098$) and the mean stem volume per plot ($p_{covariate} = 0.090$). However, the p-value of the treatment was only marginally affected ($p_{treatment} = 0.22–0.24$) compared with the analyses of variance where a covariate was not included in the model (Table 4). When a covariate was included, the relative least-square means per treatment (in relation to the control) were altered by less than 2 percent units (p.u.) for all treatments, except 2S (+7–8 p.u.) and N (+10–11 p.u.).

No effects of either N [(N-0) + (NS-S)] or S [(S-0) + (NS-N)] were detected, for either the growth variables or survival.

Table 2. Survival (%) of *Picea abies* seedlings 11 growing seasons after planting in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). Data refer to the seedlings originally planted in spring 1992 (S92), replacement seedlings planted in autumn 1992 (A92) and spring 1994 (S94), as well as the total number of seedlings planted on the three occasions (TOT = S92 + H92 + S92) and all living seedlings (ALL) at the time of the latest inventory in autumn 2002. Means of three blocks per treatment. Treatment effects from the analyses of variance (GLM) and least significant differences (HSD) between treatments are given.

Variable	Treatment						p-value, treatment/ HSD
	0	S	2S	CA	N	NS	
S92	53	66	59	64	36	61	0.21/41
A92	64	56	55	61	56	50	0.95/53
S94	60	65	71	76	58	66	0.53/35
TOT	56	64	61	66	46	61	0.43/34
ALL	78	86	87	84	75	82	0.55/26

4 Discussion

The results, 11 years after planting, are in agreement with those reported for the site five years after planting (Sikström 2001a).

In the previous report (Sikström 2001a), a tendency towards reduced survival amongst the original seedlings following pre-harvest N addition was

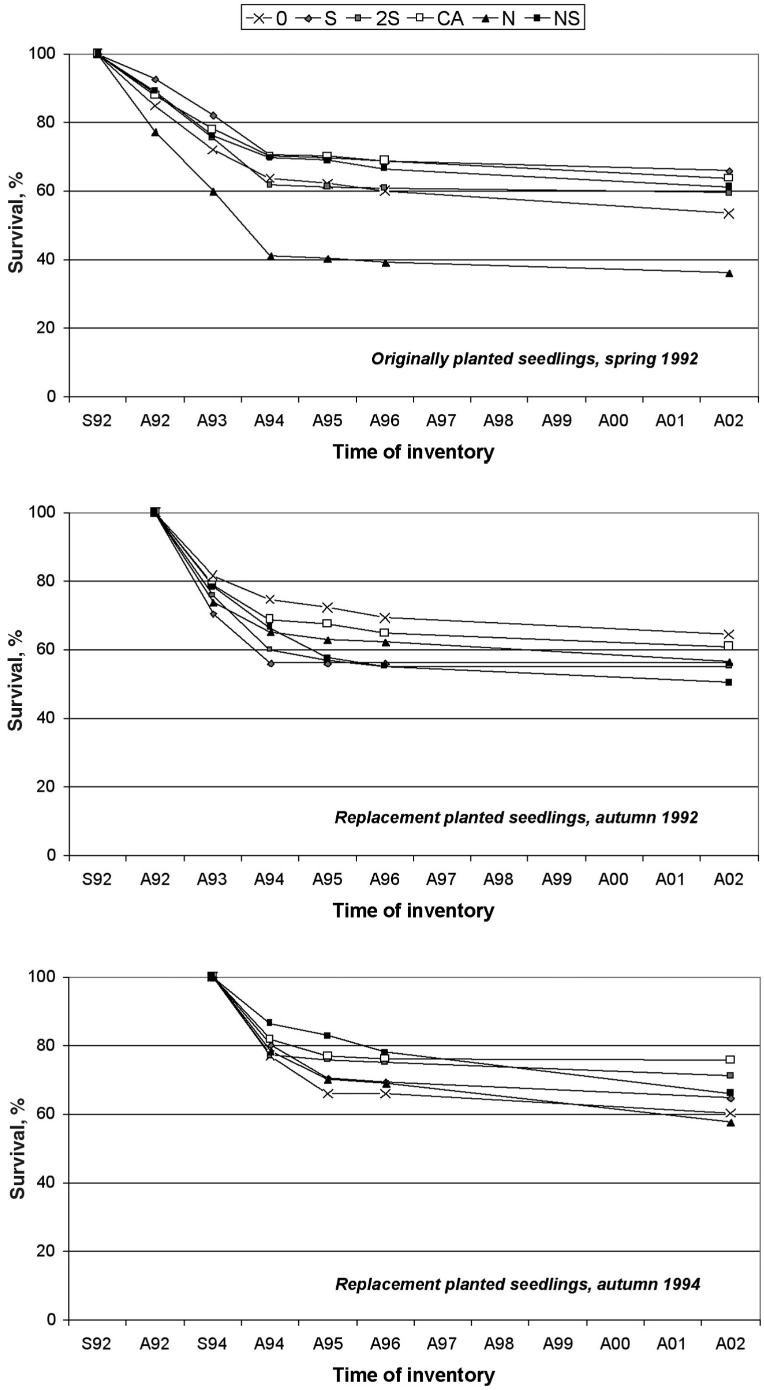

Fig. 1. Survival (%) of *Picea abies* trees after planting in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). Data refer to seedlings originally planted in spring 1992 (S92), replacement seedlings planted in autumn 1992 (A92) and in spring 1994 (S94) at each time of monitoring. Means of three blocks per treatment. For details of statistical analyses, see Table 2.

Table 3. Fixed effects from the analyses of variance (mixed model) for survival and growth variables of *Picea abies* (means per tree) 11 growing seasons after planting in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). N = nominator, D = denominator and df = degrees of freedom. Means and contrasts are mainly given for the classes of statistically significant ($p < 0.05$) effects. The planting occasions were spring 1992 (S92), autumn 1992 (A92) and spring 1994 (S94).

Effect	N, df	D, df	*F*	p-value
Survival				
Block	2	10	0.66	0.539
Treatment	5	10	0.59	0.708
Planting occasion [a)]	2	24	3.80	0.037
Treatment × Planting occasion	10	24	1.10	0.399
Height				
Block	2	10	4.83	0.034
Treatment	5	10	1.20	0.375
Planting occasion [b)]	2	24	25.8	<0.001
Treatment × Planting occasion	10	24	0.57	0.823
Height growth 1996–2002				
Block	2	10	5.00	0.031
Treatment	5	10	0.96	0.486
Planting occasion [c)]	2	24	23.2	<0.001
Treatment × Planting occasion	10	24	0.52	0.857
Basal area				
Block	2	10	4.30	0.045
Treatment	5	10	1.55	0.259
Planting occasion [d)]	2	24	27.4	<0.001
Treatment × Planting occasion	10	24	0.69	0.728
Volume				
Block	2	10	4.27	0.046
Treatment	5	10	1.46	0.286
Planting occasion [e)]	2	24	25.9	<0.001
Treatment × Planting occasion	10	24	0.68	0.731

Means and p-values for the contrasts:
[a)] S92 (57%) and A92 (57%) < S94 (66%); $p < 0.076$
[b)] S92 (4.16 m) and A92 (4.07 m) > S94 (3.40 m); $p < 0.001$
[c)] S92 (3.31 m) and A92 (3.29 m) > S94 (2.75 m); $p < 0.001$
[d)] S92 (0.194×10^{-3} m^2) and A92 (0.175×10^{-3} m^2) > S94 (0.104×10^{-3} m^2); $p < 0.001$
[e)] S92 (0.0058 m^3) and A92 (0.0052 m^3) > S94 (0.0030 m^3); $p < 0.001$

identified. In spite of this, it was concluded that pre-harvest N fertilization is unlikely to substantially affect survival of *P. abies* (Sikström 2001a) seedlings. This conclusion has been strengthened as a result of the latest monitoring, since the tendency reported earlier was reduced (Table 2), as found in similar studies (Högbom et al. 2001, Sikström 2004). The current survey also identified a somewhat higher survival rate for plants from the last planting occasion (spring 1994) than plants from the two other planting occasions (spring 1992 and autumn 1992). However, for the three seedling categories there were different lengths of the calculation periods, i.e. the time from planting to the last survival assessment.

At the time of the latest survey, in autumn 2002, the seedlings from the last planting occasion were significantly smaller than those planted earlier

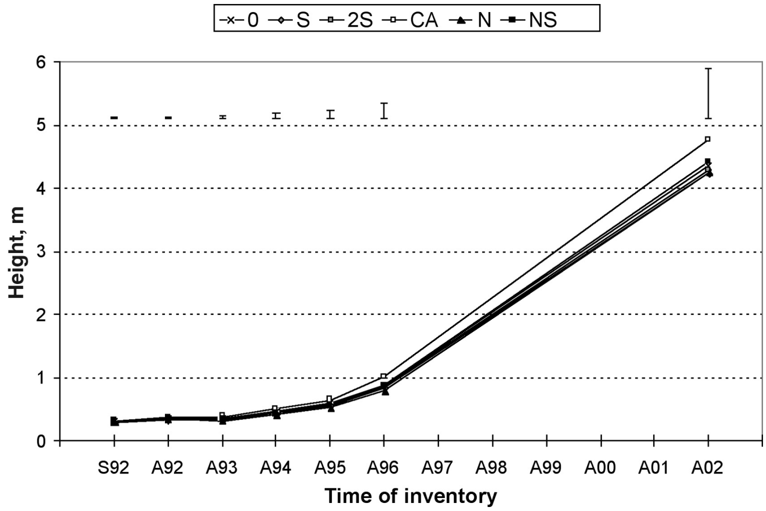

Fig. 2. Height development of *Picea abies* trees after planting in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). Means of three blocks per treatment. Intervals for least significant differences from the analyses of variance are given for each time of inventory. For statistical analyses, see Table 4.

Table 4. Growth of *P. abies* seedlings during the 11 growing seasons after planting in forest soils that were acidified (S, 2S), limed (CA) or nitrogen fertilized (N) prior to harvest (0 = control). Means of three blocks per treatment. Treatment effects from the analyses of variance (GLM) and least significant differences (HSD) between treatments are given.

Variable	Treatment						p-value,
	0	S	2S	CA	N	NS	treatment/HSD
Per tree [a)]							
Mean height (m)	4.35	4.24	4.29	4.78	4.26	4.42	0.26/0.80
Mean diameter(m × 10^{-3})	49	48	48	56	50	53	0.26/12
Mean stem basal area ($m^2 \times 10^{-3}$)	0.207	0.200	0.192	0.260	0.219	0.238	0.24/0.099
Mean stem volume ($m^3 \times 10^{-3}$)	6.24	5.98	5.74	7.98	6.47	7.13	0.23/3.18
Height growth, 1996–2002 (m)	3.49	3.39	3.43	3.74	3.45	3.49	0.49/0.64
Per plot [b)]							
Mean stem basal area ($m^2 \times 10^{-2}$)	0.160	0.171	0.163	0.221	0.134	0.171	0.16/9.7
Mean stem volume ($m^3 \times 10^{-3}$)	0.477	0.509	0.484	0.680	0.399	0.508	0.18/0.33

a) Data refer to seedlings planted in spring 1992 (S92) that remained undamaged throughout the experimental period, except for a severe browsing episode by roe-deer in April 1993.
b) Data refer to all seedlings in the plots in autumn 2002.

(Table 3). Thus, the proportion of seedlings in the plots originating from the last planting occasion influences the standing tree volume on an area basis. This was confirmed in the analysis of variance, when a covariate (proportion of replacement seedlings planted in spring 1994) was included in the statistical model. Consequently, the most relevant comparison of treatment effects on growth should be the mean tree size of individuals planted at the same time.

Simply considering the mean values, the trees in the limed plots were somewhat larger than those in the other treatments, although this difference was not statistically significant (Table 4, Fig. 2). This was also the case five years after planting (Sikström 2001a, Fig. 2). In this experiment, of all treatments, liming was associated with the most marked changes in many of the documented soil chemical properties, both in the humus and the mineral soil, before final felling and regeneration (Andersson et al. 1995). However, these effects were not reflected in the tree growth of the previous mature stand (Andersson et al. 1995). Liming is known to have variable effects on growth (see Sikström 2001a and references therein), and its effect seems to be associated with soil fertility (Sikström 2001b). In the former mature stand, N was the only element applied (in treatments N and NS) that significantly increased tree growth (Andersson et al. 1995), indicating that growth of the previous stand at this site was limited by N availability. The cover of field-layer vegetation tended to be denser in the CA-treated plots than elsewhere, four years after planting (Sikström 2001a). One possibility is that the pre-harvest liming might have promoted somewhat better growth conditions after final felling, for example by increasing plant-N availability, than the other treatments.

Neither the survival nor growth (Table 2) of the *P. abies* seedlings was affected by the pre-harvest additions of sulphur powder alone, although the sulphur treatments (especially 2S) were associated with a significant reduction in the pH of the mineral soil, and in levels of exchangeable K and Mg in the humus, in the year before final felling and planting (Andersson et al. 1995). These results are consistent with growth data from other Nordic field experiments on soil acidification (Tamm and Popovic 1989, Tamm 1989, Abrahamsen et al. 1994), except when there was a very large input of acid, which resulted in decreased stem-wood growth (Abrahamsen et al. 1994).

In conclusion, allowing for both the advantages and the limitations of the Farabol experiment, as discussed by Sikström (2001a), the pre-harvest soil acidification, liming or N fertilization did not seem to significantly influence either seedling survival or growth of *P. abies* trees during the first decade after planting.

References

Abrahamsen, G., Stuanes, A.O. & Tveite, B. 1994. Long-term experiments with acid rain in Norwegian Forest Ecosystems. Ecological Studies 104. Springer Verlag, New York. 342 p.

Alexandersson, H., Karlström, C. & Larsson-McCann, S. 1991. Temperature and precipitation in Sweden 1961–90 – reference normals. Meteorologi 81. SMHI, Norrköping. 88 p. (In Swedish with English abstract).

Andersson, F., Bergholm, J., Hallbäcken, L., Möller, G., Pettersson, F. & Popovic, B. 1995. Farabolförsöket – försurning, kalkning och kvävegödsling av en sydöstsvensk granskog (The Farabol field experiment – acidification, liming and nitrogen fertilization of a Norway spruce forest in south-east Sweden). Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, Report 70. Uppsala. 136 p. ISBN 91-576-5163-9. (In Swedish with English summary).

Andersson, S.O. 1954. Funktioner och tabeller för kubering av småträd (Funktionen und Tabellen zur Kubierung kleiner Bäume). Meddelanden från Statens Skogsforskningsinstitut 44(12). 29 p. (In Swedish with German summary).

Arnebrant, K., Bååth, E., Söderström, B. & Nohrstedt, H-Ö. 1996. Soil microbial activity in eleven Swedish coniferous forests in relation to site fertility and nitrogen fertilization. Scandinavian Journal of Forest Research 11: 1–6.

Bååth, E., Lundgren, B. & Söderström, B. 1981. Effects of nitrogen fertilization on the activity and biomass of fungi and bacteria in podzolic soil. Zentralblatt für Bakteriologie und Hygiene, I. Abt. Orig. C2: 90–98.

Derome, J., Kukkola, K. & Mälkönen, E. 1986. Forest liming on mineral soils. National Swedish Environmental Protection Board, Report 3084. Solna. 107 p.

FAO. 1988. FAO/Unesco soil map of the world. Revised legend. World Resources Report 60, FAO, Rome. Reprinted as Technical Paper 20, ISRIC, Wageningen, 1989. 138 p.

Finlay, R.D. 1995. Interactions between soil acidification, plant growth and nutrient uptake in ectomycorrhizal associations of forest trees. In: Staaf, H. & Tyler, G. (eds.). Effects of acid deposition and tropospheric ozone on forest ecosystems in Sweden. Ecological Bulletins 44: 197–214.

Gerhardt, K. & Kellner, O. 1986. Effects of nitrogen fertilizers on the field- and bottomlayer species in some Swedish coniferous forests. Meddelanden 1986:1, Växtbiologiska institutionen, Uppsala University. Uppsala.

Hägglund, B. 1973. Site index curves for Norway spruce in southern Sweden. Royal College of Forestry, Department of Forest Yield Research, Research Notes 24. Stockholm. 49 p. (In Swedish with English summary).

— & Lundmark, J-E. 1982. Handledning i bonitering med Skogshögskolans boniteringssystem – Del 2, Diagram och tabeller. Skogsstyrelsen, Jönköping. 70 p. ISBN 91-85748-13-7. (In Swedish).

Hallbäcken, L. & Popovic, B. 1985. Effects of forest liming on soil chemistry – investigation of Swedish liming experiments. National Swedish Environmental Protection Board, PM 1880, Solna. 240 p. ISBN 91-7590-163-3. (In Swedish with English summary).

Högbom, L., Nohrstedt, H-Ö., Lundström, H. & Nordlund, S. 2001. Soil conditions and regeneration after clear felling of a Pinus sylvestris L. stand in a nitrogen experiment, Central Sweden. Plant and Soil 233: 241–250.

Jacobson, S. & Nohrstedt, H-Ö. 1993. Effects of repeated nitrogen supply on stemgrowth and nutrients in needles and soil. The Forestry Research Institute of Sweden, Report 1. Uppsala. 36 p.

Kellner, O. 1993. Effects on associated flora of silvicultural nitrogen fertilization repeated at long intervals. Journal of Applied Ecology 30: 563–574.

Martikainen, P.J., Aarnio, T., Taavitsainen, V.M., Päivinen, L. & Salonen, K. 1989. Mineralization of carbon and nitrogen in soil samples taken from three fertilized pine stands: long term effects. Plant and Soil 114: 99–106.

Nohrstedt, H-Ö. 1990. Effects of repeated nitrogen fertilization with different dozes on soil properties in a Pinus sylvestris stand. Scandinavian Journal of Forest Research 5: 3–15.

— 1992. Soil chemistry in a Pinus sylvestris stand after repeated treatment with two types of ammonium nitrate fertilizer. Scandinavian Journal of Forest Research 7: 457–462.

— Arnebrant, K., Bååth, E. & Söderström, B. 1989. Changes in carbon content, respiration rate, ATP content, and microbial biomass in nitrogen-fertilized pine forest soils in Sweden. Canadian Journal of Forest Research 19: 323–328.

Persson, H., Majdi, H. & Clemensson-Lindell, A. 1995. Effects of acid deposition on tree roots. In: Staaf, H. & Tyler, G. (eds.). Effects of acid deposition and tropospheric ozone on forest ecosystems in Sweden. Ecological Bulletins 44: 158–167.

Popovic, B. 1985. The effect of nitrogenous fertilizers on the nitrification of forest soils. Fertilizer Research 6: 139–147.

SAS Institute Inc. 1999. SAS/STAT , Guide for personal computers, version 8, edition. SAS Institute Inc., Cary, NC. 3884 p.

Sikström, U. 2001a. Effects of pre-harvest soil acidification, liming and N fertilization on the survival, growth and needle element concentrations of Picea abies L. Karst seedlings. Plant and Soil 231: 255–266.

— 2001b. Growth and nutrition of coniferous forests on acidic mineral soils – status and effects of liming and fertilization. Acta Universitatis Agriculturae Sueciae, Silvestria 182. Thesis. SLU Service/Repro, Uppsala. 54 p. plus five appendices. ISBN 91-576-6066-2.

— 2004. Survival, growth and needle element concentrations of Picea abies (L.) Karst. seedlings after brash removal in a previously N fertilized stand. Forest Ecology and Management 203: 123–134.

Smallidge, P.J., Brach, A.R. & Mackun, I.R. 1993. Effects of watershed liming on terrestrial ecosystem processes. Environmental Reviews 1: 157–171.

Staaf, H., Persson, T. & Bertills, U. 1996 (eds.). Skogsmarkskalkning – resultat och slutsatser från Naturvårdsverkets försöksverksamhet. Naturvårdsverket, Rapport 4559. Stockholm. 290 s. ISBN 91-620-4559-8. (In Swedish).

Tamm, C-O. 1989. Comparative and experimental approach – deposition effects on soils as substrate. Ambio 18(3): 184–191.

— & Popovic, B. 1989. Acidification experiments in pine forests. National Swedish Environmental Protection Board, Report 3589. 131 p. ISBN 91-620-3589-4.

Total of 30 references