

## Chapter 14

### Forest growth and critical air pollutant loads in Scandinavia

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#### Abstract

We investigated radial increment in relation to natural growing conditions and critical loads exceedance for 8577 Norway spruce forest inventory plots in Norway, Sweden, and Denmark. Tree age, growing season, stand density and site productivity accounted for about 50% of the variation in increment, underlining the importance of natural variation for forest growth. We developed a model for assessing increment in comparable forest stands in relation to exceedance of critical loads for nitrogen. Increment was 8–17% lower in exceeded areas. Increment declined with increasing exceedance of critical loads for nitrogen. These results demonstrate that natural growing conditions may conceal important patterns in forest vitality correlated to pollution loadings. Although forest condition thus varies primarily with natural stressors, air pollution may have weakened forest health in exceeded areas in parts of Scandinavia. As air pollution is likely to enhance natural stressors for tree growth, geographic patterns of forest damage are likely to continue to be highly variable and complex.

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## 1. Introduction

Strategies to reduce levels of atmospheric sulfur (S) and nitrogen (N) in Europe are currently focused on exceedance of critical loads and acceptance levels for forests. Exceedance of critical loads and levels for forests currently form the basis for abatement strategies on sulfur and nitrogen in Europe (DeVries, 1993; Sverdrup and Warfvinge, 1993; Raitio and Kilponen, 1994; Cronan and Grigal, 1995; Hansson, 1995; Jönsson et al., 1995; Posch et al., 1995; UN, 1996). Effective abatement strategies were implemented under the United Nations I and II. Sulfur protocols have resulted in a steady reduction in the deposition of S in Nordic countries and elsewhere in Europe since 1985 (UN, 1994; Posch et al., 1995; Hansen et al., 1998). However, N emissions in Europe reached relatively high levels in the late 1980s and only a small decrease has been observed since then (Pacyna et al., 1991; Robertson, 1991; Grennfelt et al., 1994; Barrett and Berge et al., 1996).

Cumulative effects of long-range-transported air pollutants have primarily been of concern in relation to increased leaching of calcium (Ca) and magnesium (Mg) (van Breemen et al., 1983; Abrahamsen et al., 1994), reduced availability of phosphorus (P) and a shifting of fine roots to higher, more drought-sensitive horizons (Schulze, 1989; Schulze et al., 1989; Schulze and Freer-Smith, 1991) due to aluminium toxicity in forest soils (Driscoll et al., 1985; Mulder et al., 1990, 1995). High deposition of N to nutrient-limited areas may result in eutrophication, nutrient imbalance, increased growth, and, hence, increased acidification (Nihlgård, 1985; Wright et al., 1995; Gundersen, 1989; Gundersen and Rasmussen, 1995). Furthermore, the combined action of soil acidification, reduced availability of essential mineral elements, increased drought sensitivity, and N-eutrophication is most likely to cause nutrient imbalances and forest damage in the long term (Driscoll et al., 1985; van Breemen et al., 1983; Mulder et al., 1989; Abrahamsen et al., 1994; Nellemann and Frogner, 1994; Bytnerowicz and Fenn, 1996; Wright et al., 1995; Nellemann and Esser, 1998), with subsequent impacts on forest growth (Nellemann and Thomsen, 2001).

Defoliation has increased in most of Europe (Müller-Edzards et al., 1997). The high levels of defoliation in the Nordic countries are, to a large extent, related to factors such as a short growing season, advanced age, and climatic stress (Thomsen and Nellemann, 1994). However, when data on growth are analyzed excluding the confounding effect of natural factors, the degree of defoliation appears to be relatively higher, while growth is lower, in areas where the critical loads for forest soils are exceeded (Nellemann and Frogner, 1994; Thomsen et al., 1995; Nellemann and Thomsen, 2001). Effects of acidification on forest soils have been noted in parts of Scandinavia, including reduced availability of cations and lower concentrations of phosphorous in the south-

ern areas where the highest input of S and N is received (Dahl, 1988; Tamm and Hallbäcken, 1988; Billett et al., 1990; Løbersli et al., 1990; Mulder et al., 1990; Løbersli, 1991; Frogner, 1991; Eriksson et al., 1992; Gustafson and Jacks, 1993; Steinnes et al., 1993; Nellemann and Esser, 1998). However, correlation with forest growth at regional scales is still lacking.

Even so, total forest growth increased in the last half of the 20th century in Europe (Spiecker et al., 1996), possibly in response to N eutrophication (Kauppi et al., 1992). In the Nordic countries, cutting rates have been below the overall increment and, thus, have resulted in increased standing stock, and, therefore, increased total volume growth (Tomter, 1996). However, based on the combined action of soil acidification and potential nutrient imbalances, forest increment has been hypothesized to decline (Nihlgård, 1985). Because of the complexity of the effects of N deposition, such analyses are, however, very complicated.

Cumulative effects of acid rain and N deposition on increment are likely to be confounded with those of other growing conditions, such as age, site productivity, stand density, soil condition, and climate (Thomsen and Nellemann, 1994). To avoid confounding of these effects, investigations of forest increment and air pollution must necessarily include a thorough assessment of forest stands in both polluted and background areas, with particular reference to sites of similar age, growing season, and soil conditions in order to isolate any potential impacts of air pollution (Thomsen and Nellemann, 1994; Klap et al., 1997; Müller-Edzards et al., 1997). This is particularly complicated in Scandinavia where the southern high-deposition areas also have the most favorable climate and longest growing seasons.

Few researchers, if any, have analyzed the radial increment on a regional scale in relation to deposition loadings in Europe. Although a substantial number of experimental studies have predicted effects of air pollution, regional correlations between exceedance of critical loads and forest growth are virtually non-existent. As critical loads form the basis of emission protocol negotiations, it is crucial to know if these models actually reflect forest condition on a more regional scale. In the following, we present an analysis of increment in Scandinavian forests seen in relation to natural growing conditions and exceedance of critical loads for N.

## **2. Methods**

Data for this study were derived from the National Forest Inventories of Norway 1992–1994 (2339 plots) and Sweden 1988–1994 (6206 plots), and from monitoring plots in Denmark 1987–1995 (32 plots), representing the most recent data sets available for each country. Data included 5-year radial increment,

stand age, basal area, basal area increment, site productivity ( $H_{40}$ -system for Norway, SIS for Sweden, and the Møller-system for Denmark), and growing-season variables. The three countries use different parameters as indicators for growing season, i.e., altitude in Norway (Thomsen and Nellemann, 1994), temperature sum in Sweden (sum of temperature for days  $> 5^{\circ}\text{C}$ ) (Odin et al., 1983), and standard growth regime classes in Denmark. All plots are located below  $62^{\circ}$  latitude. Despite differences in terminology of forest for classification systems, all three countries rely on standard techniques for measurements of radial increment, using increment cores (1/10 mm) taken at 1.3 m above ground level. All site productivity indices are based on age-height curves.

Critical loads for N in boreal forests are currently suggested to be  $7\text{ kg N ha}^{-1}\text{ yr}^{-1}$  (UN ECE, 1996; Esser and Tomter, 1996). We used a modelled deposition map from Lövblad (in: Strand, 1997) to calculate estimated exceedance of N-critical loads for forests in three deposition zones receiving  $< 7\text{ kg N ha}^{-1}\text{ yr}^{-1}$ ;  $7\text{--}14\text{ kg N ha}^{-1}\text{ yr}^{-1}$ , and  $> 14\text{ kg N ha}^{-1}\text{ yr}^{-1}$ , in Norway, Sweden, and Denmark, respectively (Fig. 1). Mean exceedance for each deposition zone was calculated by averaging mean deposition for an EMEP-grid (Posch et al., 1995; Strand, 1997) in relation to a critical load for N for northern boreal forests of  $7\text{ kg N ha}^{-1}\text{ yr}^{-1}$  (Werner and Spranger, 1996).

In order to avoid potential bias resulting from differences in forest management, forest types, or methodology among the countries, a separate analysis was conducted for each country. Firstly, the importance of stand age, site productivity (using the three different classification systems available in each country), climate, and stand density for variation in radial increment was investigated for each country using multiple linear regression analysis.

Secondly, an investigation of increment in relation to critical load exceedance was conducted for Norway and Sweden. In order to avoid bias resulting from potential natural differences, data were stratified so that we could obtain increment data for comparable forest types (Thomsen and Nellemann, 1994; Thomsen et al., 1995). Stratification was performed according to tree age, growing season, and site productivity indices (SIS 25–34 in Sweden,  $H_{40}$  11–20 in Norway). Tree age was split into three groups (40–59 years, 60–80 years, and  $> 80$  years) for each country, growing season in one group ( $< 400$  m altitude in Norway and  $> 1250$  day-degrees in Sweden), and site productivity into four groups for Norway (11, 14, 17, and 20) and ten groups for Sweden (25, 26, . . . , 34). This gave a total of 12 strata in Norway and 30 strata in Sweden. A pairwise comparison of increment between the deposition zones was made (Wilcoxon rank sum test) using mean weighted radial increment according to the equation shown below. We thus obtained an unbiased estimate of increment independent of tree age, site productivity, and growing season by comparing similar forest types in background and exceeded areas, respectively.

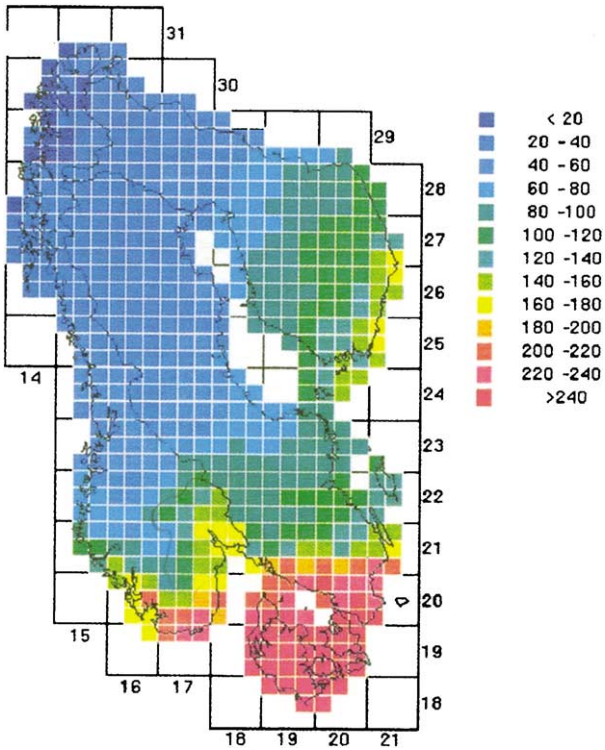


Figure 1. Total N deposition in Norway spruce stands ( $\text{cg N m}^{-2} \text{yr}^{-1}$ ) in the Scandinavian countries (courtesy of G. Lövblad, IVL, Sweden).

Mean difference in increment was tested by comparing paired samples according to a null-hypothesis of no difference in mean weighted increment ( $H_0: \theta_x - \theta_{nx} = 0$ ) against ( $H_1: \theta_x - \theta_{nx} \neq 0$ ), using the following equation (Nellemann and Thomsen, 2001):

$$D_T = \hat{\theta}_x - \hat{\theta}_{nx}$$

$$= \frac{1}{N} \left[ \sum \frac{n_{xi} + n_{nxi}}{2} \mu_{xi} - \sum \frac{n_{xi} + n_{nxi}}{2} \mu_{nxi} \right]$$

where  $D_T$  = mean weighted difference in radial increment between exceeded ( $> 7 \text{ kg N ha}^{-1} \text{yr}^{-1}$ ) and non-exceeded areas ( $< 7 \text{ kg N ha}^{-1} \text{yr}^{-1}$ ), respectively;  $\theta_x, \theta_{nx}$  = mean weighted radial increment in exceeded (x) and non-exceeded (nx) areas, respectively;  $n_{xi}, n_{nxi}$  = number of plots in strata  $i$  in exceeded (x) and non-exceeded (nx) areas, respectively;  $\mu_{xi}, \mu_{nxi}$  = mean radial

increment for strata  $i$  in exceeded (x) and non-exceeded (nx) areas, respectively; and  $N$  = number of strata (Nellemann and Thomsen, 2001).

Thirdly, an overall comparison of increment was conducted in relation to deposition loads for the two countries, Norway and Sweden. As these countries have slightly different classification systems for stand age and site indices, the mean radial increment in background areas ( $< 7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) was classified as being 100% for both countries, and then the mean radial increment was calculated as a percentage of that observed in background areas in each country for two additional deposition regions receiving  $7\text{--}14 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $> 14 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , respectively. A total of six observations (three in Norway and three in Sweden) of relative radial increment in relation to background areas was obtained. These percent measures of radial increment were tested against deposition using Pearson's coefficient of correlation. The analysis was conducted using 60- to 100-year-old forests, stratified by site indices, thus comparing sites of similar stand age and site productivity in different deposition zones. In order to control the confounding factors of tree age and site productivity, this analysis could not be performed on smaller geographic units than these deposition zones. Hence, the number of replicates in increment with deposition adjusted for differences in tree age and site index becomes six.

### 3. Results

Radial increment varies as a function of tree age (Fig. 2(a)), site productivity (Fig. 2(b)), and growing season (Fig. 2(c)). Tree age, site productivity and growing season explained 58% of the variation in increment in Denmark ( $R^2 = 0.58$ ,  $p < 0.01$ ,  $n = 32$ ), 47% in Norway ( $R^2 = 0.47$ ,  $p < 0.01$ ,  $n = 2339$ ), and 52% in Sweden ( $R^2 = 0.52$ ,  $p < 0.01$ ,  $n = 6206$ ).

On average, weighted and stratified increment was from about 9% (Sweden) ( $p < 0.01$ ) to about 20% (Norway) ( $p < 0.01$ ) lower in exceeded areas compared to background areas for comparable forest stands. A similar analysis was not possible for Denmark, as the entire country was located within one deposition zone, and sample size was too small for this type of analysis.

A combined assessment of increment for comparable forest types for the boreal spruce forest of Norway and Sweden revealed declining increment with increasing pollution loadings ( $r_p = -0.92$ ;  $n = 6$ ) (Fig. 3). This pattern was not attributable to potential differences in growing season, stand age, or site productivity, nor to stand density, which was not significantly different among areas.

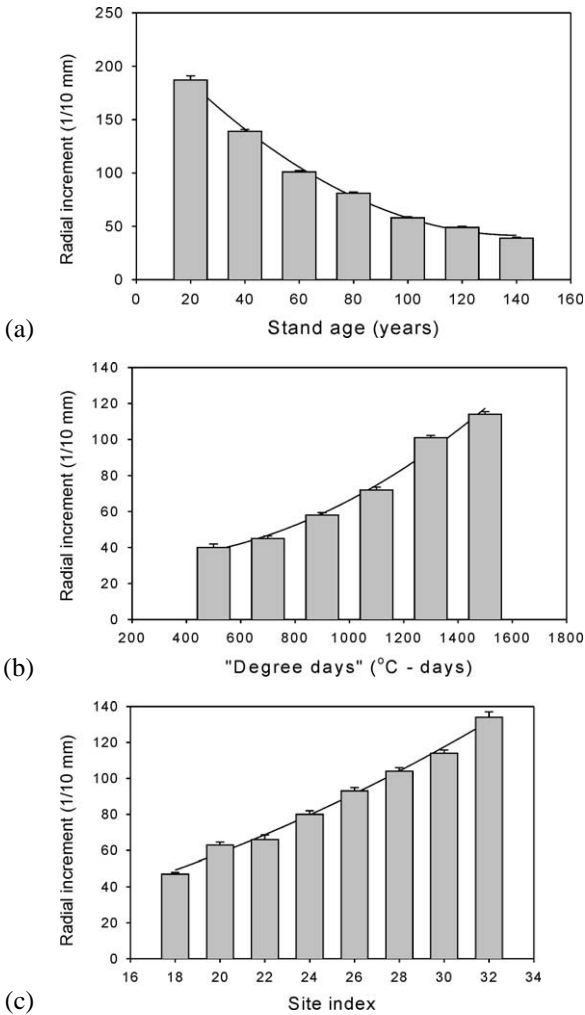


Figure 2. Mean 5-year radial increment ( $\pm$ SE) from 6206 Norway spruce plots in Sweden seen in relation to (a) stand age, (b) growing season, and (c) site index, 1988–1994.

4. Discussion

Radial tree increment varies primarily as a function of tree age, climate, stand density, and variation in site productivity across Scandinavia. However, the analysis of stands having comparable growth conditions clearly demonstrates reduced increment in exceeded areas for Norway and Sweden. The same pat-

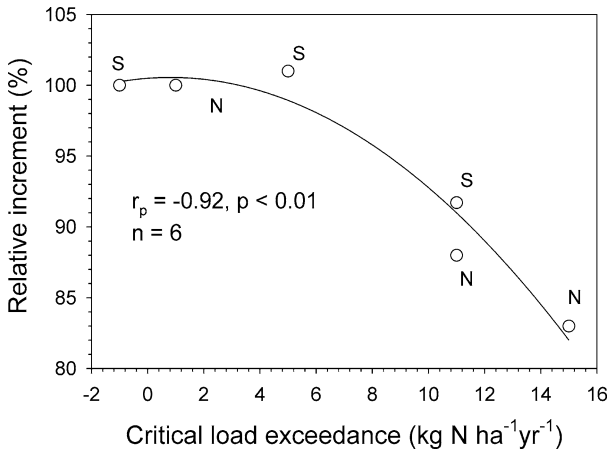


Figure 3. Mean relative radial increment for 8545 Norway spruce plots for three deposition zones ( $< 7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ;  $7\text{--}14 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $> 14 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , respectively) with varying exceedance of critical loads for nutrient N. Increment is expressed as percentage of background areas (= 100%), (S = Sweden and N = Norway).

tern was found in Finland (Tomppo and Henttonen, personal commun.). This agrees with previous studies in Norway (Nellemann and Frogner, 1994; Thomsen et al., 1995; Nellemann and Thomsen, 2001). In southern Norway, a study on more than 30 000 forest plots revealed that increment increased with increasing N-deposition throughout 1960–1970, without a similar response in comparable forests in background areas (Nellemann and Thomsen, 2001). This was followed by a substantial decline in exceeded areas, again with no similar decline in adjacent, comparable areas that did not receive N in exceedance of critical loads (Nellemann and Thomsen, 2001).

However, we could not perform such an analysis for Denmark. The country represents a relatively small geographic area with low variation in deposition, and most of the forest plots were found in exceeded areas.

Even though exceedance of critical loads is greatest in the southern part of the boreal region, forest growth is more abundant there than in the non-polluted but climatically marginal areas further north because the growing season is longer (Fig. 2(c)). Indeed, an absolute 75% reduction in mean increment for the areas with the longest growing season (and highest N deposition) would still leave these areas with an increment above that of the climatically growth-limited areas at higher latitudes and altitudes (Fig. 2(c)). Hence, difficulty in correlating increment to N deposition in areas with high defoliation and acid input is due in part to confounding factors.

This type of regional analysis does not allow for site-specific assessments of individual stress factors, but serves to document large-scale, regional pat-

terns associated with natural growth conditions, and, potentially, differences in pollution loadings. Empirical studies suggest that increased soil acidification may lead to antagonistic effects of  $\text{Al}^{3+}$  on nutrient and water uptake by fine roots. A shifting of fine roots combined with lower amounts of mycorrhizae in exceeded areas may reduce nutrient uptake and increase drought sensitivity (Shafer and Schoeneberger, 1991; Holopainen et al., 1996). As N fertilization may increase frost and drought sensitivity, the cumulative risk of abiotic damages will gradually increase over time (Nilsen, 1994; Chappelka and Freer-Smith, 1995). Indeed, substantially higher levels of needle discoloration have been observed in spruce forest having low humic pH (Nellemann and Esser, 1998). An indirect effect of long-range transported air pollution in these areas may, therefore, be greater annual forest growth in response to different weather conditions (Chappelka and Freer-Smith, 1995), along with a greater likelihood of insect damage. The result of this then is a highly variable damage pattern, depending on local climate and growth conditions. Even relatively moderate levels of N deposition ( $> 10 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) in these sensitive northern areas may affect forests over time (Wright et al., 1995). European data show that there is a good correlation between N deposition and N leaching (Gundersen, 1995). At N deposition levels of  $9\text{--}25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , N leaching has been observed; at levels beyond  $> 25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , substantial leaching has occurred well within the observed levels in the areas studied here (Wright et al., 1995). Although nitrogen saturation may occur over the long term, it is far more important to emphasize mechanisms related to nutrient imbalances at earlier stages, which, unfortunately, will also vary substantially according to growing conditions.

Forest growth varies primarily with stand age, growing season, and site index, and other obvious stand parameters. However, cumulative effects of long-range-transported air pollution may be a significant additive factor affecting forest growth in southern Scandinavia. Cause-effect relationships cannot be established from geographic analysis alone, but we conclude that when natural growth factors are controlled, there appears to be a spatial agreement between exceedance of critical loads of N in forest soils and lower radial increment in boreal forests of Scandinavia.

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