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Chapter 15

Norway spruce mortality and critical air pollutant loads

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Abstract

We analyzed proportions of dead trees to exceedance of critical loads for acidification at regional scales in 3914 Norway spruce (*Picea abies*) plots (1994–1997) in southeastern Norway. The percentage of dead spruce was significantly higher within exceeded areas than in non-exceeded areas for all stands ($p < 0.001$). Within exceeded areas, both mortality and exceedance levels increased with elevation up to about 400 m a.s.l., and then declined correspondingly. No such covariation was observed in non-exceeded areas among elevation, mortality and exceedance levels. Mortality was also significantly higher in exceeded areas than in comparable stands in background areas having similar stand age, site productivity, and altitude. In areas that were exceeded, mortality was about two times higher than in background areas (21.3 and 11.4%, respectively). There were no significant differences in mortality between exceeded areas and background areas in the 1920s and early 1970s; however, mortality increased three-fold in exceeded areas, compared with a much smaller increase in background areas between 1970–1990s, corresponding closely to exceedance of critical loads. We conclude that, although mortality varies with age, site productivity, and other natural stressors, there is a general geographic relationship between mortality and exceedance of critical loads at regional scales. These results strengthen previous findings, which have shown the same pattern for tree increment, crown condition, and lake acidification. Although natural variation may obscure effects of long-range-transported air pollution at individual sites, there are consistent regional patterns suggesting a greater sensitivity to natural stressors in areas where critical loads are exceeded. More intensive studies should be conducted to clarify potential cause-effect relationships that cannot be established at these regional scales.

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1. Introduction

Extensive reductions in sulfur (S) emissions over Europe have occurred over the last decades (Posch et al., 1995). In 1985, the first S protocol under the UN convention on Long-range Transboundary Air Pollution was signed. Since the Convention was signed in 1979, there has been a significant increase in the knowledge and methodologies relating to these problems. Advanced mathematical models have been developed (Cosby et al., 1985; Posch et al., 1995). These models have made it possible to conduct qualified risk assessments by calculating critical load and have become a very important political tool for protocol work on emission reductions in Europe (Cronan and Grigal, 1995; Posch et al., 1995). Critical load is the maximum allowable deposition that does not increase the probability of damage to forest soils and surface waters (Hettelingh et al., 1995).

In 1994, the second sulfur protocol, based on modelled critical loads, was signed; proposed reductions should protect 90% of the ecosystems' area in Europe by 2010 (Posch et al., 1995; Hettelingh et al., 1995). Nitrogen emissions increased from 1960 to 1980; the first NO_x protocol was signed in 1988, but emissions have remained at a high level (Pacyna et al., 1991; Robertsson, 1991; Barrett and Berge, 1996). The second NO_x protocol was signed in 1999, again based on the critical loads concept. Currently, northern Europe has areas with the lowest critical loads (Hettelingh et al., 1995).

The response variable used in critical loads calculations is the calcium : aluminium (Ca : Al) ratio (Sverdrup and Warfvinge, 1993; Raitio and Kilponen, 1994). A ratio of 1 : 0 in the soil solution is estimated to give a 50 : 50 risk of adverse impacts on tree growth (Cronan and Grigal, 1995), with risk increasing with a lower ratio. Potential impacts of acidification damage and deposition of excess nitrogen on the trees include nutritional imbalances, foliar discoloration, needle loss, susceptibility to secondary stress, growth decline, and increased tree mortality (Freer-Smith, 1998).

Tree mortality as a result of air pollution has been related to heavy pollution from point sources (Kandler and Innes, 1995). In countrywide studies, mortality or tree growth is often given as a mean for countries or large geographic areas and the general conclusion is that mortality lies within the normal range of 0.5–3% (Hall, 1995; Nellemann and Esser, 1998), and increment often shows large variations (Spiecker, 1999). However, Sverdrup et al. (1994) concluded that, under continued deposition in the Nordic countries at 1990 levels, tree dieback and stemwood growth loss would increase significantly. Mortality can be caused by numerous factors, including frost, drought, insects, pathogenic fungi, etc., but also as a result of increased sensitivity to such factors indirectly induced by ozone stress, soil acidification, or nutrient imbalances (Schulze et al., 1989). Few studies have considered mortality in relation to exceedance of critical loads at regional scales, even though patterns, if they exist, emerge on a regional scale. In the present study, we hypothesize that tree mortality is greater in areas where critical loads are exceeded.

2. Materials and methods

Data on mortality were derived for a total of 3914 plots from a 3 × 3 km grid system covering southeastern Norway from the National Forest Inventory for the period 1994–1997 (Nellemann and Frogner, 1994). For the most part, only plots dominated by Norway spruce (*Picea abies*) were included. However, data on Scots pine (*Pinus sylvestris*) were used in the analysis of the historical development of mortality. Within each site, cutting (age) class, site productivity, and elevation were recorded. Mortality for Norway spruce was defined as the proportion of dead standing trees compared with live trees within each plot. All trees with $a > 5$ cm diameter were included.

Critical loads were calculated on the basis of soil and surface water chemistry data from 712 grid squares, each 12 × 12 km (Posch et al., 1995), covering the forested areas of Norway. The molar ratio Ca : Al in soil solution was used as the modelling criterion, where critical load is exceeded when $\mathrm{Ca} : \mathrm{Al} < 1$. This is the threshold at which root damage is expected (DeVries, 1993; Cronan and Grigal, 1995; Posch et al., 1995). The dynamic soil acidification catchment model MAGIC was used to calculate critical loads and exceedances (Cosby et al., 1985; Wright et al., 1988). The exceedance data from this model have also been found to correlate to forest damage, soil chemistry, and tree increment in this region (Nellemann and Frogner, 1994; Nellemann and Thomsen, 2001).

We compared forest condition in exceeded areas in southeastern Norway with background areas, using the zones specified in Nellemann and Thomsen (2001). The exceeded area primarily includes the southern part of eastern Norway, whereas background areas extend east and north of the exceeded area (Fig. 1). The western coastal and northern regions of Norway were not included as they experience substantially different weather and climatic conditions and, therefore, require more specialized methods for comparison.

Defoliation generally increases with altitude (Thomsen and Nellemann, 1994). To avoid potential confounding effects of altitude, site productivity, and tree age on mortality, we analyzed the proportion of dead trees for plots with comparable elevation (0–99 m; 100–199 m; 200–299 m; 300–399 m, etc.), site productivity indices (6–8 lowest, 11–14 and 17–23 highest productivity), and cutting (age) classes (class III represent young stands typically 15–30 years old, class IV 30–60 years old, and class V mature forest typically 60–120 years old), using data stratification (Nellemann and Frogner, 1994; Nellemann and Thomsen, 2001). As deposition and, thus, pollution loadings and exceedance,

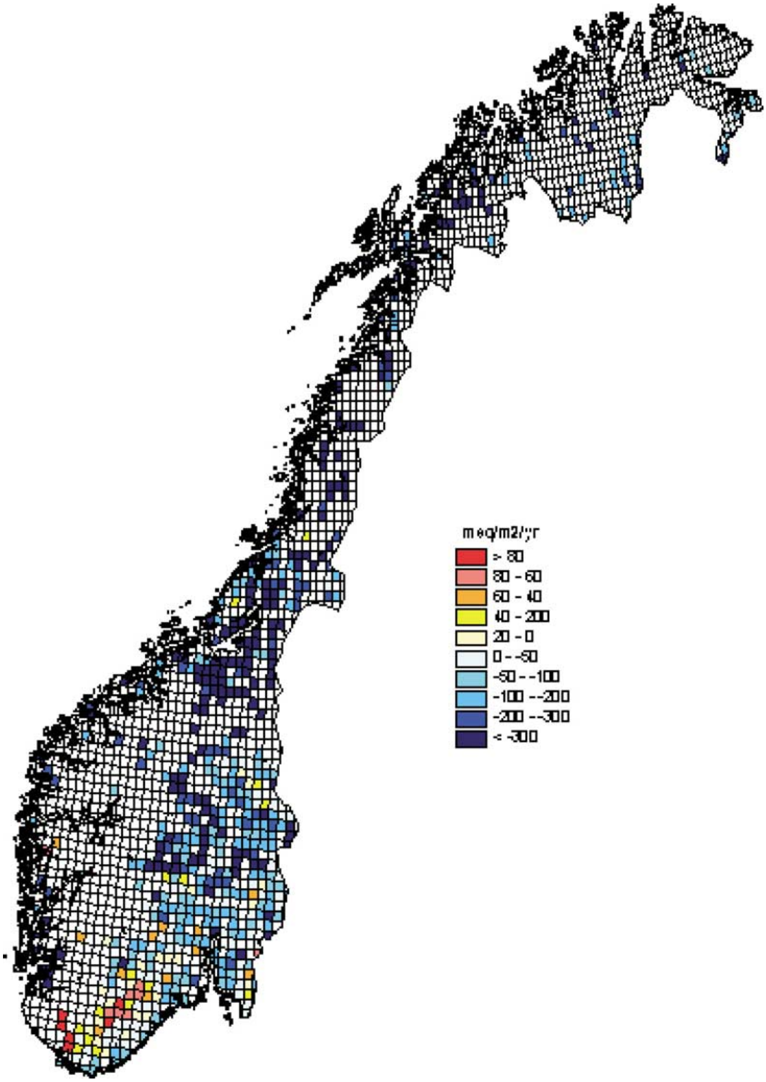

Figure 1. Exceedance of critical loads for acidification calculated by MAGIC in southern Norway. Note the exceeded area in the southeast, a contiguous, elongated exceeded (red) area.

vary substantially with altitude, we compared the variation in exceedance with altitude and the corresponding changes in mortality with elevation for the exceeded and background areas, respectively. This was done using polynomial regression.

We compared volume percentage of dead trees with total live volume on more than 10 000 plots from 1920–1925 (for 1920–1925, only combined conifers, i.e., Norway spruce and Scots pine); 1970–1976; 1986–1992; and 1992–1996. These were the only periods available. Data were accessible from historic county records from the Norwegian Institute of Land Inventory for the years 1920–1996. We compared potential differences in mortality over time between exceeded and background areas from 1920–1996.

Statistical analysis was performed in Sigmastat (Kuo et al., 1992). Data were subjected to a Kolmogorov–Smirnov test of normality. Correlation analyses were performed using Spearman Coefficient of Rank Correlation. Pairwise comparisons were done using Student t-tests or Mann–Whitney tests. In all cases, p-values < 0.05 were considered statistically significant.

3. Results

Critical loads are primarily exceeded in southeastern Norway, 10–50 km from the coast at 200 to 600 m a.s.l. Previous studies have shown that for spruce forests, there are no significant differences in soil depth between the exceeded and background areas (Nellemann, 1997; Nellemann and Thomsen, 2001). Therefore, the higher exceedance of critical loads for acidification in southeastern Norway is primarily due to higher levels of deposition in this region.

Exceedance of critical loads increased with altitude up to approximately 400 m in exceeded areas ($r_S = 0.55$; $p < 0.01$; $n = 113$), and then declined (Fig. 2(a)), whereas there was no pattern evident in background areas ($r_S = -0.03$; $p = 0.71$; $n = 155$) (Fig. 2(b)). To avoid bias of altitude on forest vitality, only forests below 400 m a.s.l. were considered in the following analysis (Thomsen and Nellemann, 1994; Nellemann and Frogner, 1994).

Tree mortality for forest located below 400 m a.s.l., was on average two- to threefold higher in exceeded areas ($23.1 \pm 1.1\%$ and $9.6 \pm 0.3\%$, respectively). These differences were not attributable to potential differences between the areas in site productivity or cutting (age) class distribution ($p < 0.05$).

Mortality varied with both age and site productivity. Old stands or stands experiencing more marginal growth conditions (lower site indices) had, on average, higher mortality. A comparison of mortality between exceeded and non-exceeded areas revealed a significantly higher proportion of dead trees in exceeded areas among all age categories compared with background areas (Fig. 3). This was also true for site productivity (Fig. 4). Forest mortality increased with elevation, corresponding to exceedance patterns (see Fig. 2(a), (b)) in exceeded areas, whereas no such pattern existed in background areas

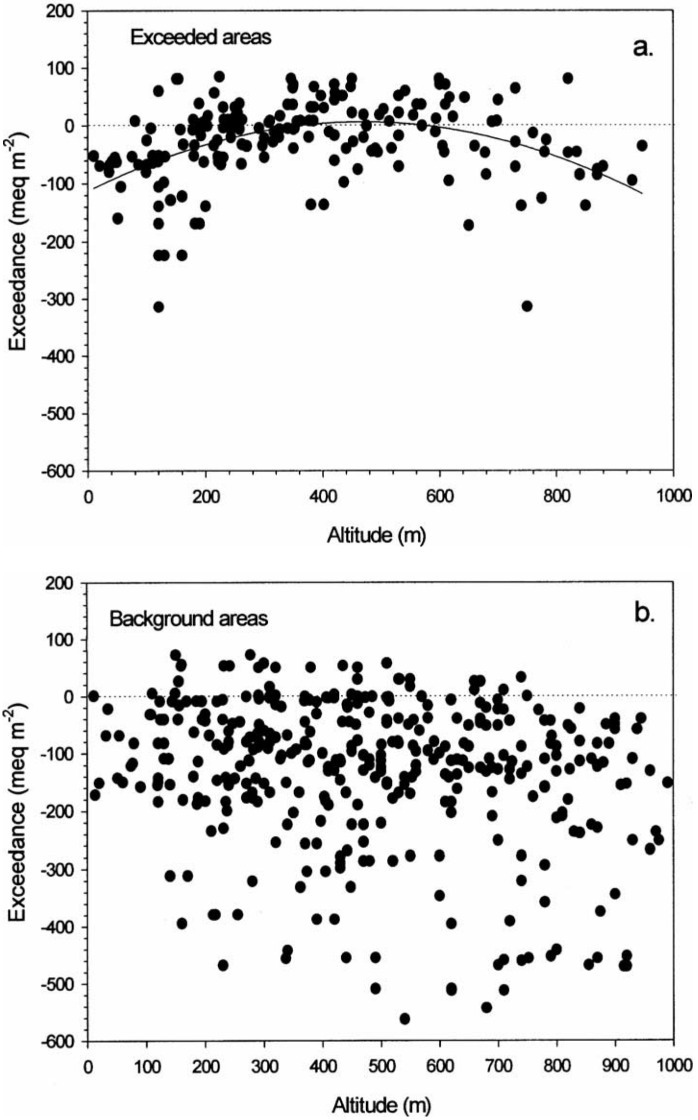

Figure 2. Exceedance of critical loads in relation to altitude for (a) exceeded and (b) background areas.

(Fig. 5). Around 1920 and in the early 1970s, there were no significant differences in mortality between exceeded and background areas. After 1975, mortality increased in both areas (Fig. 6). However, mortality increased much

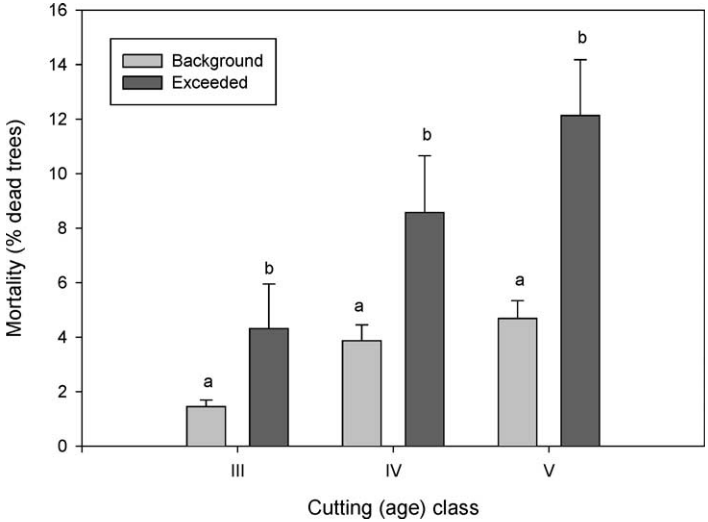

Figure 3. Mortality of Norway spruce in exceeded and background areas for different age classes (class III represent young stands of typically 15–30 years old, class IV 30–60 years old, and class V mature forest, typically 60–120 years old). Different letters for pairs indicate significant difference using Mann–Whitney tests ($p < 0.05$).

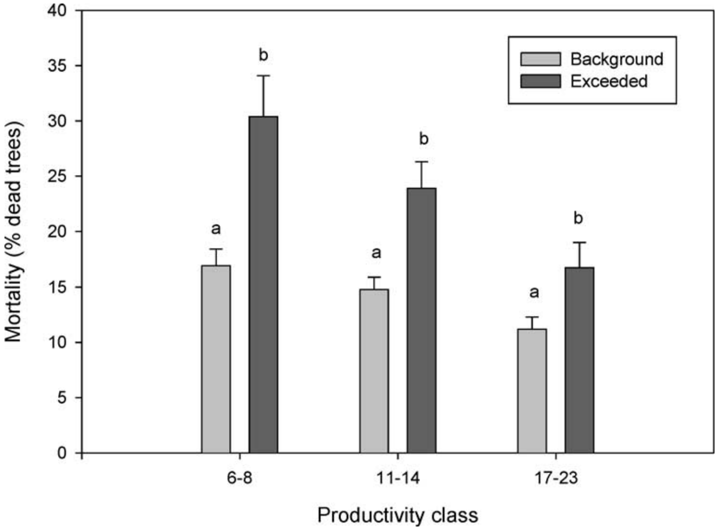

Figure 4. Mortality of Norway spruce in exceeded and background areas in relation to site productivity. Different letters for pairs indicate significant difference using Mann–Whitney tests ($p < 0.05$).

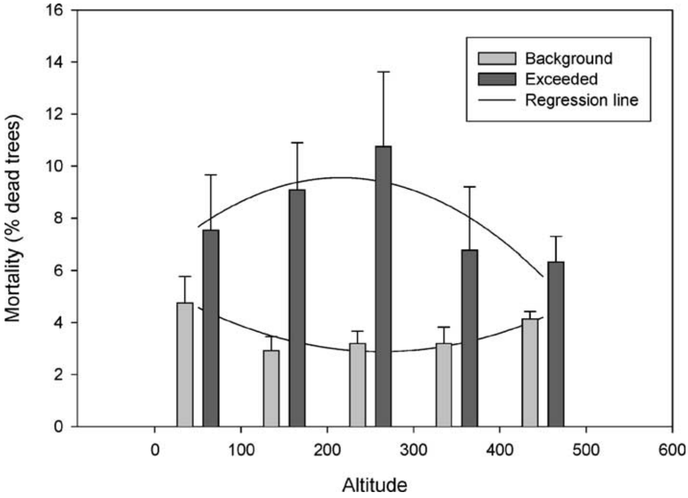

Figure 5. Pairwise comparisons of mortality in Norway spruce in exceeded and non-exceeded areas at different altitudes.

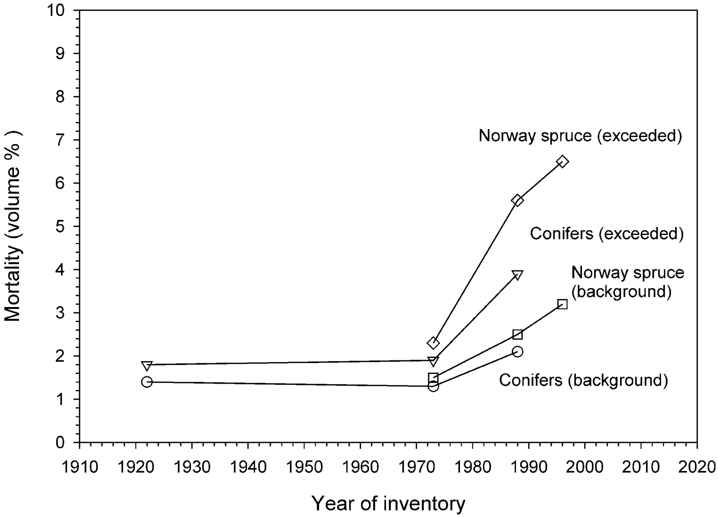

Figure 6. Changes in mortality between background areas and exceeded areas between 1920 and 1996 for conifers and for Norway spruce.

faster in exceeded areas, becoming significantly ($p < 0.001$) higher in exceeded areas, corresponding closely with reduced increment, higher defoliation, and extensive lake acidification in that period (Nellemann and Thomsen, 2001)

4. Discussion

Mortality expressed as the proportion of dead to live trees was significantly higher in exceeded areas. The ratio of dead to live trees varied with stand age and site productivity, but was also, in general, two- to threefold higher in exceeded areas compared with background areas.

The regional covariation between exceedance of critical loads and mortality only provides a geographic indication of a possible correlation. The resolution of our data was not sufficient for more detailed comparisons. There are several indications that the observed pattern corresponding with air pollution loadings may be at least partially causal, although certainly interactive with natural stressors also (Chappelka and Freer-Smith, 1995).

The areas that are classified as exceeding critical loads have a series of characteristics suggesting possible long-term impacts of acidification and N deposition. In humus, base saturation is about 60% lower, and the contents of major base cations and phosphorus are 30–60% lower for comparable soil types and soil depths compared with background areas (Nellemann and Frogner, 1994; Nellemann, 1997; Nellemann and Esser, 1998). Combined with increased soil acidification, these factors may result in reduced forest vitality through increased sensitivity to frost or drought or impeded growth or nutrient imbalances (Nihlgård, 1985; Driscoll et al., 1985; Schulze et al., 1989; Wright et al., 1995; Bytnerowicz and Fenn, 1996).

Forest vitality is consistently poorer in exceeded areas compared with background areas, when forest sites of similar age, site productivity, and altitude are compared. Defoliation is 10–30% greater (Nellemann and Frogner, 1994), on average, and increment correspondingly lower (Thomsen et al., 1995; Solberg and Tveite, 2000; Solberg and Strand, 2000; Nellemann and Thomsen, 2001).

Around 1920, forest surveys indicated little difference in mortality between these regions in southern Norway. The differences in mortality increased throughout 1960–1980 in response to increasing pollution loadings (Nellemann and Thomsen, 2001). Increment followed a remarkably similar pattern. A study of more than 31 000 forest plots from 1954–1996 revealed only minor differences in growth for comparable stands in exceeded and background areas before 1960 (Nellemann and Thomsen, 2001). Increment increased in exceeded areas in the period 1960–1970, closely corresponding to the elevated N deposition. Increases were greatest in exceeded areas, slightly lower in the lowlands, and nearly absent in background areas. During the late 1970s, increment declined following the same pattern, most dramatically in exceeded areas at 200–400 m a.s.l., again without any great changes in background areas. These patterns coincide roughly with exceedance of critical loads and higher mortality at these elevations, as well as with increases in mortality at this time.

Hindcast modelling has shown a distinct covariation in these patterns with exceedance of critical loads (Nellemann and Thomsen, 2001). Similar covariation in comparable stands for exceedance of critical loads and increment has also been observed in the other Scandinavian countries (Tomppo and Henttonen, personal commun.; Nellemann et al., 2002).

We consider it unlikely, that air pollution and nutrient imbalance alone caused these patterns in the forests studied. There is, however, a significant body of studies documenting potential long-term cumulative impacts of air pollution, stressing that most of the damage likely results from elevated sensitivity to abiotic stress as a result of nutrient imbalance, soil acidification or ozone-related impacts (Sverdrup et al., 1994; Chappelka and Freer-Smith, 1995; Cronan and Grigal, 1995; Freer-Smith, 1998). It is likely, therefore, that the observed damage patterns are the result of the combined action of air pollution and natural stressors (climatic changes). We conclude that there is a relatively consistent pattern between forest mortality and exceedance of critical loads at regional levels, and support the use of these criteria for regional risk assessments and, thus, as a basis for emission protocols.

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