

Dissolved Al reduces Mg uptake in Norway spruce forest: Results from a long-term field manipulation experiment in Norway

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ABSTRACT

Dissolved aluminium (Al) in soils, mobilized by acid deposition, is considered a threat to forest health through hampering root growth and nutrient uptake. Since the end of the 1980s dissolved Al in forest soil water plays a key role in the assessment of critical loads of acid deposition. So far, most evidence for toxicity of dissolved Al in forest soil water is based on nutrient solution studies and pot experiments. Here, we present results from one of the few *in situ* ecosystem-scale forest manipulation experiments to study the effect of Al on mature forest trees. A plotwise addition of dilute AlCl_3 was conducted during seven years in an even-aged spruce forest (*Picea abies*) in an area in Norway with low acid deposition. Soil solution concentrations of Al were increased to potentially toxic levels (up to $500 \mu\text{mol L}^{-1}$) and base cation (Ca + Mg + K) to inorganic Al ratios in the soil solution in the root zone were mostly below 1 in the Al-addition treatments. In the control treatment (only water addition) Al concentrations did not exceed $15 \mu\text{mol L}^{-1}$ and base cation to inorganic Al ratios were above 1. The toxic effects of Al on fine root growth and plant growth found in hydroponic studies and pot trials are not confirmed by this field manipulation. However, magnesium (Mg) contents in needles decreased significantly and persistently in plots with elevated Al concentrations, whereas the needle Ca content did not respond. The depletion of the Mg content in needles is suggested to be due to antagonistic effects of high Al concentrations at the root surface, consistent with observed reductions in Mg to Al ratio of inner bark. This study clearly supports a role for Al in critical load functions for forests as dissolved Al causes a decrease in uptake of Mg. However, other signs of reduced forest vitality were not observed. Soil base cation status may need to be included in risk evaluations of forest health under acid deposition.

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1. Introduction

Forest condition in Europe has been monitored since the early 1980s because of concerns relating acid deposition to forest vitality (Fischer et al., 2007). Acid deposition on base-poor soils leads to mobilization of potentially toxic aluminium (Al) (Mulder et al., 1989). Significant correlations between sulphur (S) deposition and enhanced concentrations of aluminium (Al) in soil solutions have been shown for acidic forest soils in Europe (de Vries et al., 2003).

Enhanced dissolution of aluminium (Al) by acid deposition has long been considered a probable threat to forest vitality (Ulrich, 1984; Ulrich et al., 1980). Hypothesized mechanisms of Al toxicity are hampered root growth and inhibition of uptake of vital nutri-

ents (Matzner and Murach, 1995; Schulze, 1989). Indeed, nutrient deficiency symptoms in trees have been found at sites where high soil solution Al concentrations were measured (e.g. Alewell et al., 2000). At other sites, however, healthy trees under similar levels of soil solution Al have been found (Huber et al., 2004). Effects of high concentrations of Al on trees were tested in a variety of studies from laboratory experiments (for overviews see Rengel, 1992; Kinraide, 2003) to large scale ecosystem manipulations (see Abrahamsen et al., 1993a; Beier et al., 1998; Huber et al., 2004; Kreutzer and Weiss, 1998). Primarily based on pot trials and hydroponic studies, the Ca to Al ratio emerged as a predictor for forest vitality (Cronan and Grigal, 1995; Sverdrup et al., 1992). The Ca to Al ratio was changed to also include other base cations (Ca + Mg + K)/Al, which is now the most common chemical criteria for the calculation of critical loads of forests (i.e. de Vries et al., 2003). If the ratio is lower than 1 then reduced forest vitality is expected. However, the relation between these soil chemical criteria and forest vitality characteristics has been questioned.

Analyses of large data sets, obtained from forest ecosystems monitoring programs, have failed to confirm the hypothesized rela-

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tions between forest vitality and Al toxicity unambiguously. In general, European monitoring programmes of forest vitality do not report strong relations between forest health (crown condition) and acid deposition (Fischer et al., 2007; Klap et al., 2000). Rather, they point at confounding factors such as site conditions, stand age, insect and fungi attacks and weather conditions, which make it difficult to attribute observed patterns in crown condition to Al per sé. Neither do critical load models predict adequate relations between forest vitality and exceedances of critical loads (Løkke et al., 1996; Watmough and Dillon, 2003). Still, the ratio plays a crucial role in predicting recovery of forest ecosystems from acid deposition (see e.g. Martinson et al., 2005).

Also, the relevance of laboratory experiments with regard to evaluating Al toxicity in field conditions has been disputed (Binkley and Hogberg, 1997; De Wit et al., 2001c; Kreuzer, 1995; Løkke et al., 1996). In addition, whole-ecosystem experiments, designed to test effects of acid deposition on forests, have been inconclusive with respect to Al toxicity effects on root growth and nutrient uptake. Reasons for this include potentially toxic levels of dissolved Al in the control treatment (Höglwald, Germany: Hahn and Marschner, 1998), lack of data collection describing belowground processes (Nordmoen, Norway: Abrahamsen et al., 1993b) and addition of nitrogen which in itself may affect root and tree growth (Skogaby, Sweden: Majdi and Bergholm, 1995); NITREX, northern Europe: Persson and Ahlstrom (2002); EXMAN, northern Europe: Tietema et al. (1998). Thus, while Al toxicity and associated base cation to Al ratios are at the basis of risk evaluation of forest damage due to acid deposition, empirical support for this contention remains inconclusive.

Here, we present the results of a forest ecosystem manipulation study, which was designed to test the Al toxicity hypothesis at a site little affected by acid precipitation, i.e. with low concentrations of Al and N in the control treatment. The objective of our study was to quantify the effect of chronically enhanced soil solution concentrations of inorganic Al on fine roots, on nutrient concentrations in needles, bark and fine roots, and on tree growth and crown condition in a middle-aged Norway spruce stand. Results from the first three years were reported in De Wit et al. (2001b,c) and Nygaard and de Wit (2004). Results on root biomass and chemistry after six years can be found in Eldhuset et al. (2006). In the present paper, we report effects on soil chemistry, soil solution, needle and bark chemistry during all the seven years of treatment (1997–2003). Additionally, we refer to previously published results on fine roots, tree growth and crown condition.

2. Materials and methods

2.1. Location

The Nordmoen area is located about 45 km north of Oslo (11°06'E, 60°16'N) in southeast Norway at 200 m above sea level. Mean annual precipitation and temperature are 862 mm and 3.8 °C, respectively. Annual acidic deposition was less than 5 kg S ha⁻¹ and 6 kg N ha⁻¹ from 1995 to 1999 (Aas et al., 2001). The study area is a flat glacio-fluvial sandy sediment of about 60 m depth, overlying Precambrian and Permian crystalline bedrock (Stuanes and Abrahamsen, 1993). The homogeneous, sandy soil is classified as a Typic Udipsamment and has a thin (2–4 cm) O horizon with a well developed Oe and Oi layer. Selected soil chemical characteristics are summarized in Table 1. The vegetation belongs to the *Eu-Piceetum myrtilletoseum* subassociation. The forest is a homogeneous Norway spruce stand (*Picea abies* (L.) Karst) planted in 1951. In 1996, basal area in the experimental area was 23.6 m² ha⁻¹, tree density was 2200 ha⁻¹ and tree volume was 160 m³ ha⁻¹. Fine root (<2 mm diameter) biomass was approximately 750 g m⁻² for the O

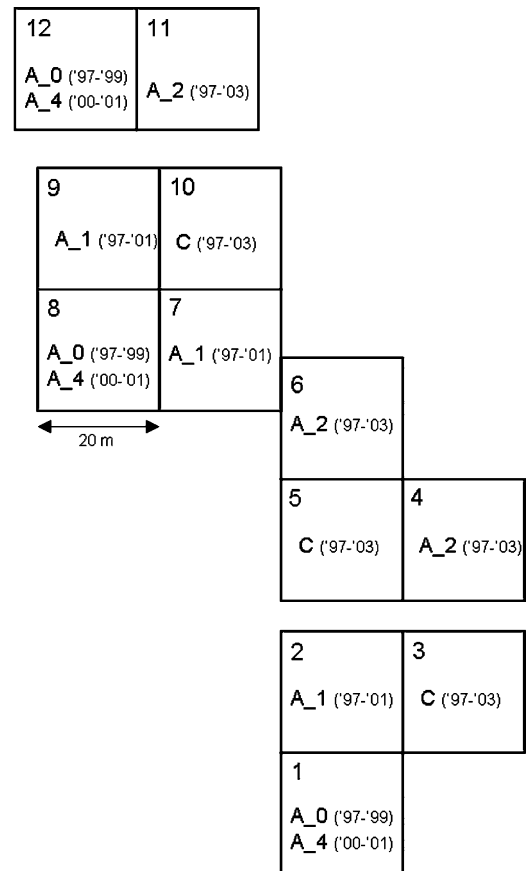


Fig. 1. Spatial design of manipulation treatment at Nordmoen. Numbers refer to plots, letters refer to treatments, and years refer to duration of the treatment.

horizon and the mineral soil down to 40 cm depth. Circa 80% of fine root biomass was in upper soil layer (O horizon and mineral soil to 20 cm depth) while 25% was in the O horizon only. For further details see De Wit et al. (2001b), Nygaard and de Wit (2004) and Eldhuset et al. (2006).

2.2. Experimental design

We aimed to establish various levels of potentially toxic Al concentrations in the soil solution of the root zone of the trees. Target levels of Al (0.1–0.4 mmol L⁻¹ Al) have been shown to have negative effects on growth and nutrient uptake of Norway spruce seedlings in hydroponic studies within hours after root exposure to the nutrient solution (Godbold et al., 1995; Göransson and Eldhuset, 1991; van Scholl et al., 2004) and to reduce root and shoot growth of one-year-old Norway spruce grown in quartz sand (Ilvesniemi, 1992).

Twelve adjoining plots of 20 m × 20 m were assigned to 4 treatments through a randomized block design (Fig. 1). The treatment involved addition of various levels of dilute AlCl₃ in deionised groundwater. Treatments were conducted during the snow- and frost-free season, i.e. from the end of May to mid-October. For more details about the irrigation system, reference is made to De Wit (2000) and De Wit et al. (2001c).

The treatments consisted of Control (C) receiving deionized groundwater and three Al addition treatments (A.0, A.1 and A.2). Irrigation water was evenly spread at all plots at a rate of 10 mm during 45 min using 30 evenly distributed sprinklers per plot. The Al addition treatments received an initial high dose (0.44 mol m⁻² Al) of dissolved AlCl₃ to raise the soil Al content and Al solubility, particularly in the forest floor. Previously, it has been shown that the solubility of Al in acid soils is controlled by the saturation of

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