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Rapid recovery of stem increment in Norway spruce at reduced SO_2 levels in the Harz Mountains, Germany

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ABSTRACT

Tree-ring width of *Picea abies* was studied along an altitudinal gradient in the Harz Mountains, Germany, in an area heavily affected by SO_2-related forest decline in the second half of the 20th century. Spruce trees of exposed high-elevation forests had earlier been shown to have reduced radial growth at high atmospheric SO_2 levels. After the recent reduction of the SO_2 load due to clean air acts, we tested the hypothesis that stem growth recovered rapidly from the SO_2 impact. Our results from two formerly damaged high-elevation spruce stands support this hypothesis suggesting that the former SO_2-related spruce decline was primarily due to foliar damage and not to soil acidification, as the deacidification of the (still acidic) soil would cause a slow growth response. Increasing temperatures and deposited N accumulated in the topsoil are likely additional growth-promoting factors of spruce at high elevations after the shortfall of SO_2 pollution.

1. Introduction

During the second half of the 20th century, Norway spruce (*Picea abies* (L.) H. Karst.) was affected by pollutant-caused forest dieback especially on exposed mountain ridges of Central and Eastern Europe (Schulze et al., 1989; Elling et al., 2007). Even more severe damage occurred in silver fir (*Abies alba* Mill.), which is supposed to be the most pollution-sensitive European forest tree (Elling et al., 2009). Similar declines as in Norway spruce were observed in red spruce (*Picea rubens* Sarg.) in eastern North America (Johnson et al., 1992).

High concentrations of SO_2 and its derivatives formed in aqueous solution in the atmosphere combined with the acidification of precipitation are the widely accepted causes of the dieback of conifers in mountain forests (Schulze et al., 1989; Eagar and Adams, 1992). The high sensitivity of spruce and fir to acidic air pollutants is mostly explained by their large canopy surface area, which intercepts more substances from the atmosphere than do broad-leaved tree canopies (Nihlgård, 1970; Rothe et al., 2002). However, different hypotheses have been developed for explaining the mechanisms behind the conifer dieback. While some researchers attributed the dieback primarily to foliar damage due to the direct contact with SO_2 and protons (Lange et al., 1989; Johnson and Fernandez, 1992), others emphasized the contribution of soil acidification for the dieback of forests (Ulrich, 1989). Soil acidification was thought to cause root damage due to the release of Al^{3+} (Godbold et al., 1988) and needle yellowing due to the leaching of Mg^{2+} from the upper soil (Stock, 1994; Armbruster et al., 2002). There are links between foliar SO_2 uptake and soil chemistry, since the assimilated SO_2 is partly detoxified to the anion SO_4^{2-} which requires cations such as K^+ or Mg^{2+} (Slovik, 1996; Slovik et al., 1996) implying a demand for soil-borne cations to react with foliar SO_2. However, this causal link does not necessarily exclude that other stressors such as Al^{3+} and related root damage are key factors predisposing montane spruce or fir forests to dieback.

Symptoms of SO_2-related damage in spruce and fir include the reduction of annual stem increment. Reduced tree-ring widths in association with elevated atmospheric SO_2 concentrations was observed in Europe in silver fir (Elling et al., 2009) and Norway spruce (Worbes, 1989) as well as in North America in red spruce (Cook and Zedaker, 1992; Reams and van Deusen, 1993). These growth reductions often became apparent between the 1950s and the 1970s with strongly increased coal combustion at that time. Both in Western and Central Europe and North America, clean air acts caused the decline of atmospheric SO_2 levels from the 1980s on to presently nearly pre-industrial levels. SO_2 emissions rose in

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Europe within one century from 1880 to 1980 from less than 5000 to more than 40,000 Gg yr^{-1} (Mylona, 1996). After 1980, they declined rapidly to only 7000 Gg yr^{-1} in 2008 (European Environment Agency, unpublished). For the highly SO_2-sensitive species silver fir, Elling et al. (2009) showed that stem growth rapidly recovered within a few years after the reduction of atmospheric SO_2 concentrations. This was taken as a proof that the earlier fir decline was primarily caused by foliar damage and not soil acidification, as the deacidification of the soil would take much longer than a few years.

In the present study, we analyzed the putative impact of recent alterations in the atmospheric SO_2 load on tree-ring width of Norway spruce along an altitudinal gradient, which is one of Europe's economically most important tree species (Ellenberg and Leuschner, 2010). This species is assumed to be less susceptible to SO_2 than silver fir; in fact, the stem growth response to this pollutant has been found to be generally less pronounced in spruce than in fir and it differed between regions. In the Bavarian Forest, southern Germany, for instance, Wilson and Elling (2004) found marked growth depressions in silver fir, but not in co-occurring Norway spruce. However, in the northern German Harz Mountains with an even higher SO_2 pollution, tree-ring width in Norway spruce was strongly reduced from the 1950s onwards (Worbes, 1989). Therefore, we selected the Harz Mountains as a study area to investigate the recovery of tree-ring width in Norway spruce after the recent reduction of atmospheric SO_2 concentration. In the upper elevations of the Harz Mountains, the mean SO_2 concentration was as high as c. 50 μg m^{-3} still in 1985 (German Federal Environment Agency, unpublished). Holland et al. (1995) showed in a fumigation experiment that even much lower SO_2 concentrations between 10 and 35 μg m^{-3} are capable of reducing radial stem growth in Norway spruce.

However, not only the atmospheric SO_2 concentration has changed in the last three decades, but other important growth-controlling factors as well. Summer air temperature increased in Central Europe by 0.7 °C per decade since the 1980s (Luterbacher et al., 2004). N deposition declined moderately in the past 30 years, but is still at a high level (Böhlmann et al., 2005). Therefore, the influence of reduced SO_2 levels cannot be analyzed without considering potential effects of global warming and eutrophication. In this study, we aim at separating the possible influence of temperature, precipitation, SO_2 concentration and N deposition on spruce ring width chronologies along elevation and precipitation gradients in the Harz Mountains. We tested the hypotheses that annual stem increment (1) increases with decreasing acidic sulphurous deposition, (2) is positively correlated with the atmospheric deposition of N, (3) increases with the long-term rise in temperature at higher elevations, but (4) decreases with the temperature increase at lower elevations due to more frequent growth limitation by drought events. The potential effect of these factors cannot be studied in isolation in the field, but the potential contribution of individual factors can be identified by correlation analysis. The altitudinal gradient was included to enlarge the variation of climatic parameters covered by the study. How spruce stands respond to the altered climate and pollution conditions in Central Europe is of high economic and ecological importance, because parts of Central Europe's forest area consists of spruce plantations, which were established for achieving high timber yields. Confirmation of the first hypothesis would imply that foliar damage, rather than soil acidification, was the main cause of spruce decline in the Harz Mountains during the 20th century. Such a result would be important for future forest management in the Central European uplands on acidic soil.

2. Material and methods

2.1. Study area and sample plot selection

The study was carried out in five submontane and montane stands of Norway spruce (*P. abies* (L.) H. Karst.) in the Harz Mountains, northern Germany. The Harz Mountains are the highest mountain range in northern Germany with elevations up to 1142 m a.s.l. (Mt. Brocken) and primarily consist of acidic Paleozoic rocks. The Harz Mountains stretch out over more than 100 km in west-east direction and up to 40 km in north-south direction. Since the highest summits are located in the western part of the mountain system and the prevailing winds come from the southwest and west, the eastern Harz Mountains receive much less precipitation (c. 500 mm a^{-1}) than the western rim (950 mm) or the highest peaks (>1500 mm) of the mountain ridge. The annual mean temperature varies from 8 °C in the submontane belt (300–500 m a.s.l.) to 2.5 °C on the summits of the upper montane belt (>800 m a.s.l.). Norway spruce is native to the Harz Mountains at elevations above 700–800 m a.s.l. (Schubart, 1978).

Five spruce forest stands that were characteristic for the upper montane and lower montane belts and for high- and low-precipitation regimes in the Harz Mountains were selected for dendroecological study (Fig. 1). Sites A (Mt. Brocken, 51°47′ N, 10°38′ E, 900–1000 m) and B (Bruchberg, 51°48′ N, 10°34′ E, 800–850 m) were located in the upper montane belt in areas which had been affected by severe needle loss and needle yellowing during the second half of the 20th century

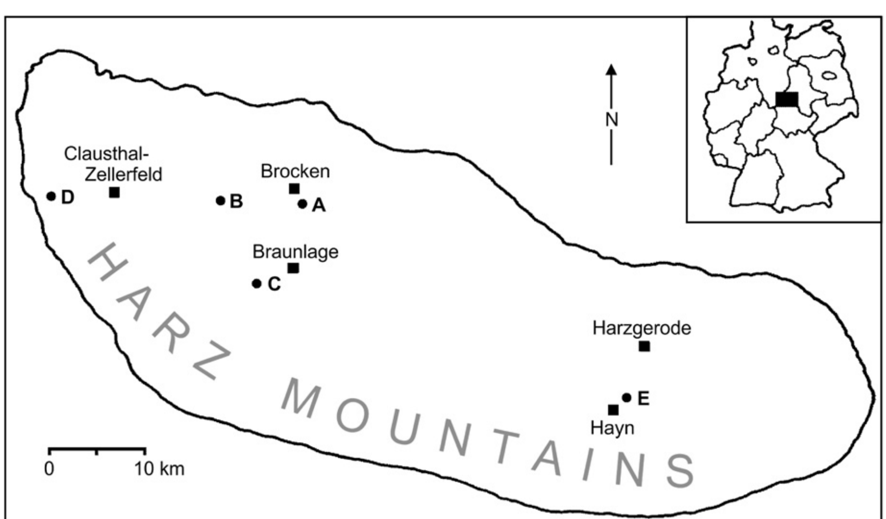

Fig. 1. Study area with the location of sample plots (dots: site A, Mt. Brocken; B, Bruchberg; C, Oderhaus; D, Bad Grund; E, Dankerode) and weather stations (squares with station names) in the Harz Mountains.