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Nitrogen deposition along differently exposed slopes in the Bavarian Alps

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HIGHLIGHTS

- NO_2 and NH_3 air concentrations low
- Open field nitrogen deposition relatively independent of location
- Nitrogen throughfall deposition high at wind-exposed sites
- Extreme inversion frequency in Bavarian Alps in November 2011
- Different vertical distribution of air temperature along south- and north-facing slopes

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ABSTRACT

The Alps are affected by high nitrogen deposition, particularly in the fringe of the Northern and Southern Alps. In the framework of a two-year monitoring study performed in 2010 and 2011, we investigated the ammonia and nitrogen dioxide air concentration and ammonium and nitrate deposition at different altitudes between 700 and 1600 m a.s.l. in the Garmisch-Partenkirchen district in the Upper Bavaria region (Germany). Four-weekly measurements of deposition collected with bulk open field samplers and under-crown were performed in a profile perpendicular to the axis of the Loisach valley; measurements were conducted at eight sites. Whereas open field deposition ranged from 5 to 11 kg ha^{-1} a^{-1}, nitrogen throughfall has reached up to 21 kg ha^{-1} a^{-1}. Data from the valley and the slopes were compared with measurements performed on the platform of the Environmental Research Station Schneefernerhaus (Zugspitze) at an altitude of 2650 m a.s.l. For the rough estimation of the total yearly deposition rate of nitrogen, the canopy uptake model was applied. By regarding nitrogen uptake by the trees, total deposition can exceed the throughfall in all sites by up to 50%. Additionally, we estimated the total deposition from the sum of wet and dry deposition. On the one side, the wet deposition could be extrapolated from the open field deposition. On the other side, we used the inferential method to calculate the dry deposition on the basis of NH_3 and NO_2 air concentrations and their literature based deposition velocities. Since fixed deposition velocities are inappropriate particularly in complex orography, we tried to find correction factors based upon terrain characteristics and meteorological considerations. Temperature monitoring at the eight sites and wind measurements at two sites provided some evidence for the semi-empirical parameterization. Due to numerous imponderabilities, the results of the two methods were not consistent for all sites.

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1. Introduction

Nitrogen can be both a limiting nutrient and a pollutant in ecosystems (Fenn et al., 2009). The Alps, situated in the center of Europe, are dissected by high-traffic roads and surrounded by urban agglomerations and agricultural areas causing high emissions of air pollutants like nitrogen compounds. The highest impacts of such air pollutants on ecosystems are recorded in the northern and southern mountain fringes and in the Alpine foothills, particularly in Bavaria, Northern Switzerland and Lombardy (Lorenz et al., 2008; Kaiser, 2009). Despite a slightly negative trend (Rogora et al., 2006; Lorenz et al., 2008; Eickenscheidt and Brumme, 2012; ICP Forests, 2012), the input of both reduced and oxidized nitrogen into forest ecosystems in the alpine and subalpine areas is still well above the estimated critical loads (10–20 kg ha^{-1}) of nutrient nitrogen in many spruce forest sites (Jandl et al., 2012). The observed acceleration in tree growth rates is likely to be the result of fertilization by nitrogen, enhanced atmospheric CO_2 concentrations, and temperature increase (Eriksson and Johansson, 1993; Hunter and Schuck, 2002). However, as long as forest ecosystems in the Southern and Northern Limestone Alps are still deficient in nitrogen, high deposition rates increase the demand (Jandl et al., 2012). A further nitrogen deposition may consequently influence nutrient balance, soil acidification, and groundwater composition of forests (Aneja et al., 2001; MacDonald et al., 2002; Wuyts et al., 2011) and has an impact on the forest floor composition (Bernhardt-Römermann et al., 2006).

Nitrogenous gases such as nitrogen oxides and ammonia as well as ammonium and nitrate containing particles can be deposited as dry and wet deposition. Particularly on mountain ridges, where wind speed is higher than along the slopes, the wet deposition by rain and snow can be enhanced by occult deposition when fog droplets are trapped by foliage and branches of trees. Particularly spruce forests represent a much larger receptor than other vegetation types due to their higher aerodynamic roughness and their ability to capture fine particles. Forests at high elevations are likely to be wet for longer periods of time than vegetation in the valleys because of the greater cloud immersion (Lovett and Kinsman, 1990). Frequent fog, cloud events (Kalina et al., 2002), and rime (Burns, 2003) enhance the rates of atmospheric N deposition. The dry deposition of pollutants like ammonia increases with decreasing atmospheric stability (Phillips et al., 2004). Generally, the deposition rate in forests is largely influenced by orographic and meteorological characteristics such as altitude, orientation of the valley and exposure to the main wind directions, slope aspect, and slope steepness (Segal et al., 1988).

For the estimation of total nitrogen deposition, wet and dry deposition input data are needed. Compared with wet deposition, which is easily measurable by wet-only or bulk funnels, it is much more difficult to determine the dry deposition of gases and aerosols. Micrometeorological methods for measuring dry deposition can be performed only in homogenous terrain and require sophisticated and expensive instrumentation (Schmitt et al., 2005). Therefore, surface analysis methods such as throughfall measurement are much more prevalent in measuring campaigns. The estimation of dry deposition by under-crown measurements shows some uncertainties related to canopy interaction processes such as leaching and uptake as the throughfall flux of nitrogen can differ from the sum of wet and dry deposition (Draaijers and Erisman, 1995). Methods separating the contribution of dry deposition from canopy exchange processes, so-called canopy budget models, are based upon a work of Ulrich (1983) and have been developed and refined by several authors (Andersen and Hovmand, 1999; Devlaeminck et al., 2005; Thimonier et al., 2004; Schmitt et al., 2005; Adriaenssens et al., 2012).

With the inferential method, dry deposition can be estimated by multiplying the atmospheric gas concentration and the appropriate deposition velocity. Deposition velocities have been determined in many measuring campaigns by different methods, for a wide range of forest stands. In many studies, data were taken from the literature and adapted for the particular conditions (Schmitt et al., 2005).

The aim of this study, which was part of the project KLIMAGRAD, was to quantify the annual nitrogen deposition into forests along a measuring transect including different altitudes and aspects in the vicinity of Garmisch-Partenkirchen/Bavaria. We performed bulk and throughfall deposition measurements to depict the general situation and estimated the total deposition. Firstly, we used the canopy budget method, refined by Devlaeminck et al. (2005), in order to include the possible nitrogen uptake. Secondly, we calculated the total nitrogen input by the inferential method based on air concentration measurements and literature-based deposition velocities. As fixed deposition velocities are rather appropriate for flat terrain and homogenous forest stands and unlikely to represent the reality of a complex orography, we modified the deposition velocities on the basis of a semi-empirical parameterization. The installation of a basic meteorological instrumentation aimed to characterize the study sites.

2. Material and methods

2.1. Location and experimental sites

The study area was situated in the calcareous Alps near Garmisch-Partenkirchen in the Upper Bavaria region in Southern Bavaria (Germany). It consisted of eight sites along a transect perpendicular to the axis of the Loisach valley (Fig. 1). This region is characterized by an average annual precipitation amount of 1350 mm in the valley (719 m a.s.l.) and 2000 mm on top of the Zugspitze (2964 m a.s.l.); the mean annual air temperature (1961–1990) in Garmisch-Partenkirchen is 6.5 °C and on the Zugspitze −4.8 °C with a strongly variable monthly lapse rate between −0.35 °C/100 m in January and −0.61 °C/100 m in July (Kirchner et al., 2013). The prevailing wind directions on top of the mountains are SW and W. At lower altitudes, winds are influenced by topography; frequently mountain and valley breezes dominate the wind pattern.

The eight sites investigated exhibited different altitudes and expositions (Table 1). The sites were located in 80–150 year old Norway spruce forests [*Picea abies* Karst. (L.)] at 700, 1000, 1300, and 1600 m a.s.l on the northern and southern slopes of Mount Kreuzeck. On the opposite slope of the W–E oriented Loisach valley, two additional plots at 700 and 1000 m a.s.l on Mount Kramer were chosen. In the vicinity of each forested site, we selected an open field plot within a clearing. All plots are uninfluenced or scarcely influenced by traffic and agricultural emissions. Because of remoteness, lack of electric power, severe weather conditions, and widely fluctuating snow depths in winter, the logistic difficulties were enormous; some of the forest sites could only be reached by four-wheel drive vehicles or by foot in summer and ski mountaineering equipment in winter. Aside from the gradient study, simultaneous measurements were performed at the platform of the Environmental Research Station Schneefernerhaus/Zugspitze (UFS) in 2650 m a.s.l.

2.2. Measurement technique and analytical procedures

Deposition is calculated by multiplying the precipitation amount measured by the bulk samplers by the ion concentration in the sampled precipitation. Precipitation was sampled in open field and under crown by using bulk samplers (Ø = 200 mm) with a sampling interval of four weeks. During winter months, bulk samplers with greater funnel apertures (Ø = 40 mm) were used. In the framework of two years, we collected 26 open field bulk and 156 throughfall water samples at each site of the transect. Due to the rough terrain with steep slopes and limited accessibility, we exposed only six bulk samplers at each forest site and one in the open field, slightly in discordance with the recommendations for deposition measurements in forested areas (Starr et al., 2007). With heavy snow fall events, sampling intervals of