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Effect of Air Pollution on the Health Status of Spruce Stands

A Case Study in the Krkonoše Mountains, Czech Republic

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*This paper presents the results of research on local air pollution (nitrogen and sulfur concentrations) and on the changes in the health status of trees observed in spruce stands in the period 1980–2011 in the Krkonoše Mountains National Park. Data on precipitation and sulfur and nitrogen deposition were collected in regular 2-week intervals from 1994 to 2010. Precipitation was measured at 5 monitoring stations; the health status of forest stands was evaluated on 6 research plots located in stands dominated by Norway spruce (*Picea abies *[L.] Karst) in zones where there has been a significant threat from air pollution since 1980. The health status of spruce stands was assessed on the basis of the degree of defoliation, classified into 6 levels. In all localities since 1994, the total deposition of sulfates decreased significantly, from 50–80 kg ha^{-1} $year^{-1}$ to 8–13 kg ha^{-1} $year^{-1}$; however, no clear trend in the development of nitrogen deposition could be stated. The mean defoliation of living and all trees was 32% (± 0.5 SE) and 63% (± 0.8 SE), respectively, on plots with autochthonous stands, and 91.5% (±5.8 SE) and 97.6% (±1.7 SE), respectively, on a plot with an allochthonous stand. The defoliation of living and all trees differed across research plots. Despite a negative relationship between defoliation of all trees on plots and atmospheric deposition of sulfur ($P = 0.012$; $r = -0.25$), air pollution in the Sudeten still represents a serious hazard for the forest ecosystem. This relationship differed across research plots ($F[5, 96] = 110$, $P < 0.001$). Close-to-nature management techniques aimed at the enhancement of forest complexity and preferential use of autochthonous populations of trees in timely regenerated forest stands may be of crucial importance for the restoration and preservation of these mountain forest ecosystems.*

Keywords: *Air pollution; defoliation; Norway spruce; Krkonoše Mountains; forest management; Czech Republic.*

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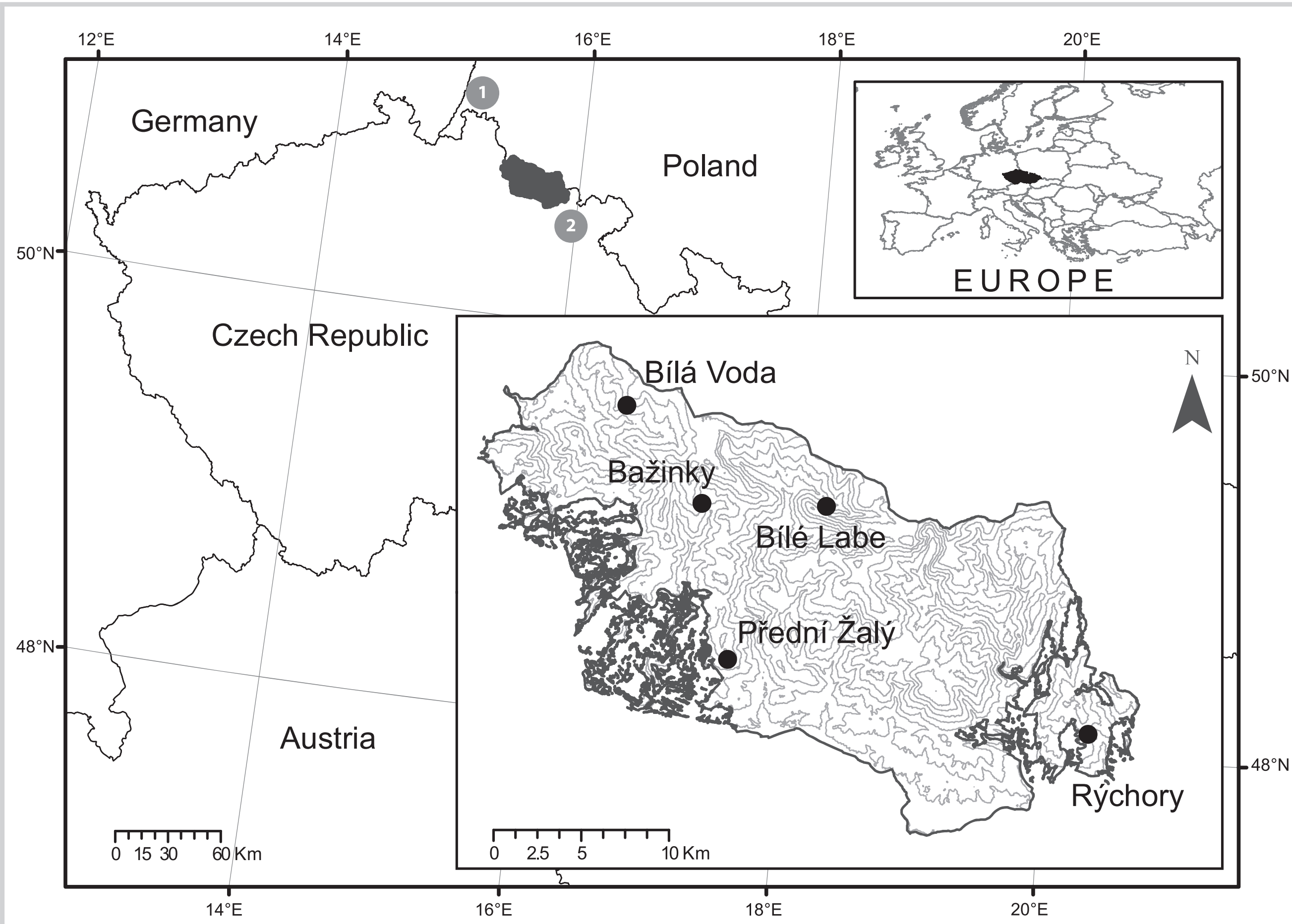
Introduction

The Krkonoše Mountains, belonging geologically to the Hercynian (Variscan) system, with their unique biogeographical location in the middle of the Central European landscape, have become an important evolutional crossing, where elements of the Alpine and Arcto-alpine ecosystems come into repeated contact. Accordingly, the region is rich in glacial relicts, endemic species, and mountain ecosystems (Jeník 1998). Alpine grasslands, subarctic mires, dwarf pine stands, mountain spruce, beech, and mixed stands represent the area's biodiversity, which for Czech mountains is exceptional (Jeník and Price 1994; Jeník and Štursa 2003). Since 1992, the Krkonoše Mountains, with national parks on both the Czech and Polish sides of the border, have been part of the world network of UNESCO Biosphere Reserves (Jeník and Price 1994).

Ecosystems in higher mountain zones are likely to be more vulnerable to air pollution than ecosystems at lower altitudes. The synergistic effects of high and long-lasting air pollution and climatic stress can lead to extensive decline and dieback of the forest in these regions (Vávrová et al 2009). Due to their fragility and vulnerability to environmental change and to increasing demand for their ecological and nonproductive functions, mountain landscapes and mountain forests have become a major focus of discussions on sustainable development. Moreover, strong alterations in these ecosystems may be predictors of acidification and global change in ecosystems at lower altitudes (Rusek 1993).

Local forest damage as a result of air pollution has been identified in the area of the current Czech Republic since the middle of the 19th century (Nožička 1957); more pronounced damage of this kind occurred initially during the period between World Wars I and II (Materna 1989). Industrial air pollution became, from the 1970s to the 1990s, one of the most dangerous threats to forests not just in the Czech Republic but for the entire Central European region. Industrial emissions eventually resulted

FIGURE 1 Location of the Krkonoše Mountains in the Czech Republic with the major sources of industrial pollution: (1) Turów power plant, (2) Trutnov Poříčí power plant. Monitoring stations are indicated in the map of the study area. (Map by Petr Vopěnka)



in the large-scale decline of coniferous forest stands (mainly spruce) across vast mountain and submountainous areas. Severe damage to these stands and subsequent salvage felling have devastated spruce stands in the Krušné Mountains and Jizerské Mountains; ongoing damage and the decline of spruce stands have subsequently also started in the Krkonoše, Orlické, Beskydy, and Jeseníky mountain ranges, and to a lesser extent in other regions of the Czech Republic (see Figure 1 for the location of the study area).

The first more pronounced damage to forest trees in the Krkonoše Mountains, a major segment of the Sudeten in northeastern Bohemia and part of the western Czech-Polish frontier, was observed after an extreme climate event in March 1977, in which spruce suffered from ground frost–induced drought stress during winter (Tranquillini 1979), as well as at the beginning of 1979 in coincidence with a larch bud moth (*Zeiraphera griseana* Gn.) outbreak. Later this large-scale forest damage was accelerated by other factors such as climate extremes, pathogenic organisms, and worsening soil conditions (Ulrich 1986; Karnosky et al 2003; Lomský et al 2012).

The total area of forest with significantly deteriorating health conditions in the Krkonoše Mountains amounted to 1355 ha (out of the Krkonoše Mountains National Park's total area of 32,189 ha) in 1980. After that, it dramatically increased, reaching a maximum of 6774 ha in 1987. As a consequence of air pollution and related stress factors, approximately 7000 ha of forest in the Krkonoše Mountains was harvested (Vacek et al 2007). Some stands were recovered to a certain extent by experimental layering (Vacek et al 2012).

Health status monitoring in 1979 in the Krkonoše Mountains (Tesař et al 1982) has confirmed the principal role of air pollutants in forest dieback (Figure 2). The most threatened zones were the northwestern and northeastern parts of the mountain range.

The climatically exposed ridges of the Krkonoše Mountains (at an elevation of approximately 900 masl) suffered the greatest damage (Schwarz 1997). However, influential anemo-orographic systems (Jeník 1961) also allowed the penetration of air pollutants to leeward parts of glacial cirques and mountain valleys. After 10 years (in 1989), the monitoring was repeated (Vacek and Vašina

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FIGURE 2 Ongoing forest decline in protected spruce forests in the Krkonoše Mountains, 1988. (Photo by J. Smejkal)

1991). The results confirmed that forest damage is greater at higher altitudes. Spruce altitudinal vegetation zones suffered the greatest damage, followed by beech–spruce and spruce–beech vegetation zones; the least damage was observed in beech–fir vegetation zones.

There are numerous exceptions to this general pattern of forest damage. A crucial role was played by the genetic characteristics of the stands and their position within larger forested areas (Vacek 1987, 1989); allochthonous spruce stands (formed by spruce populations originating from other areas) under comparable conditions experienced a worse health status than autochthonous spruce stands (formed by native spruce populations adapted to local site and climate conditions); distance from 2 to 5 m has led to optimal ecological sheltering without strong intraspecific competition (Vacek and Lepš 1987, 1996); and the suppressed trees are those suffering most from air pollution. Defoliation rate and tree mortality in spruce stands was not always proportional to changes in the structure of herbal and moss vegetation and soil dynamics (Vacek et al 1999; Matějka et al 2010). Figure 3 shows the relation between forest type and the dynamics of forest damage during the last 3 decades.

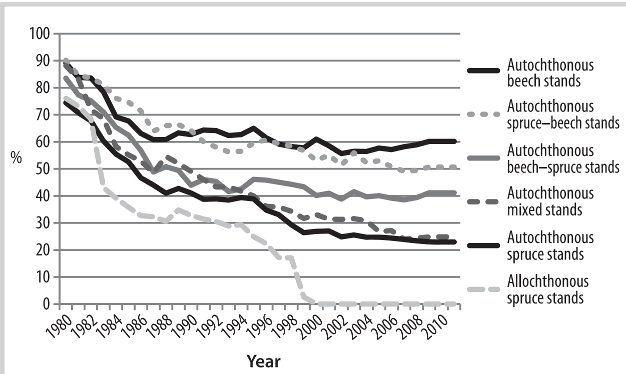
The forest ecosystems of the Czech mountains, dominated by Norway spruce, are the most threatened. This paper presents research results on local air pollution, that is, concentration of sulfur in the form of SO_4^{2-} and of nitrogen in the form of NO_3^- and NH_4^+ in throughfall (stock flows for particular ions under the forest canopy) and precipitation deposition, and on the changes in the health status of trees observed in spruce stands in the period 1980–2011, that is, during the worst of the region's air pollution and related ecological stress and as environmental conditions improved (Figure 4).

Material and methods

Study site

The health status of forest stands was evaluated on 6 research plots (RPs) located in stands dominated by

FIGURE 3 Average foliation (calculated for all trees) of particular forest types expressing the altitudinal gradient of forest damage in the Krkonoše Mountains.

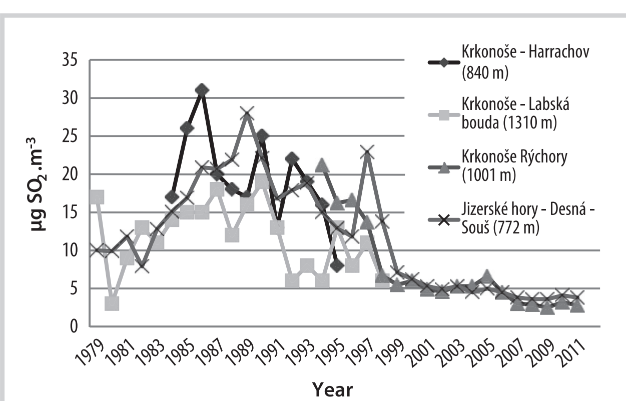


Norway spruce (*Picea abies* [L.] Karst) in zones with a high level of threat from air pollution (Table 1). Five RPs were classified as autochthonous spruce stands and one, RP 16, as an allochthonous spruce stand, according to Vacek (1983). Individual plot size was 50 × 50 m (0.25 ha), mostly in regular shapes. For a more detailed description of research plots, see Matějka et al (2010). Data on precipitation and sulfur and nitrogen deposition were collected at monitoring stations in various parts of the Krkonoše Mountains (Figure 1). For the purposes of our study we selected pairs of research plots and monitoring stations with special attention to similarities in anemo-orographic system. For closer approximation, the deposition on particular research plots with specific site and stand conditions was calculated according to Umweltbundesamt (1996).

Evaluation of health status of forest stands

The health status of forest stands on research plots was evaluated every year from 1980 to 2011. Determination of Norway spruce tree conditions was based on assessment of crown defoliation carried out for living trees and for all trees (living and dead) within each permanent plot. The degree of defoliation was evaluated in terms of the proportion of living foliage out of total potential foliage (Tesař and Temmlová 1971); based on this, the health status of spruce stands was then classified into 6 categories, as shown in Table 2 (Vacek and Matějka 2010).

FIGURE 4 SO_2 concentrations on selected climate stations in the region of the Krkonoše and Jizerské Mountains between 1979 and 2011. Conditions in the western part of the Krkonoše Mountains are well characterized by conditions in the locality Desná-Souš.



Measurement of precipitation and sulfur and nitrogen deposition

Data on precipitation and sulfur and nitrogen deposition were collected in regular 2-week intervals from 1994 to 2010. The amount of precipitation was measured on plots with different precipitation gauges for summer and winter. The rain gauge consisted of a polyethylene funnel with a diameter of 120.6 mm (cross-sectional area 114.2 cm^2), which drained into a scaled 2-liter bottle. The funnel was fastened at a height of 1.3 m above the terrain in a special shelter that protected the equipment from direct radiation. The gauge that measured snowfall was a cylindrical polyethylene canister with a diameter of 150 mm (cross-sectional area 176.7 cm^2) and 50 cm depth. The top edge of the cylinder was fastened at a height of 1.7 m above the terrain.

Plots in forest stands were always equipped with 9 precipitation gauges, placed on 2 perpendicular transects with north–south and east–west orientation. The distance between the collectors on the transect was 10 m, and the center of the monitoring plot was selected at random. Two supplementary precipitation collectors in an open area were assigned to each plot in a forest stand. The sample bottles were collected every 2 weeks. Ion chromatography was used to determine SO_4^{2-}, NO_3^-, and NH_4^+ concentrations (Schwarz et al 2009). From the total precipitation and obtained concentrations, stock flows for particular ions under the forest canopy (throughfall deposition) and on a free area (precipitation or gravitational deposition) were obtained.

The total atmospheric deposition was calculated as the sum of interception and gravitational deposition (Bredemier 1988). Gravitational deposition is the result of processes that are independent of the quality of the receptor surface (snow, rain, and dust sedimentation), whereas interception deposition depends on the quality of the receptor surface and consists of gas absorption, aerosol adsorption, and the particulate interception of atmospheric water. Due to their complex architecture, the crowns of forest tree species considerably influence the amount of interception deposition, and canopy leaching can enrich the stock flow (canopy leaching) or absorb some of the transported ions (negative canopy leaching). Forest canopy stock flow (throughfall) is thus the sum of gravitational deposition,

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TABLE 1 Basic characteristics of research plots and location of the associated monitoring station.

Plot number (RP)	GPS coordinates	Location of monitoring station	Altitude (masl)	Stand origin	Exposition	Soil type
4	50°46′39.42″N 15°30′32.72″E	Bílá Voda	1180	Autochthonous	Southwest	Histosols, Gleysols
10	50°46′56.25″N 15°33′43.64″E	Bílé Labe	1240	Autochthonous	South	Podzol, Gleysols
11	50°45′01.03″N 15°33′46.52″E	Bažinky	1220	Autochthonous	Northeast	Haplic Podzols
16	50°45′58.64″N 15°34′54.16″E	Bílé Labe	1170	Allochthonous	Southeast	Haplic Podzols
20	50°41′11.98″N 15°41′25.11″E	Přední Žalý	1260	Autochthonous	Southwest	Haplic Podzols
23	50°39′33.92″N 15°44′36.28″E	Rýchory	1190	Autochthonous	Northeast	Histosols

gas interception, particulate interception, and canopy leaching.

Data analysis

Since the data have a normal distribution, parametric tests were used. Atmospheric deposition was considered as an independent variable, defoliation as a dependent variable. The relationships between defoliation of living trees and all trees, respectively, and atmospheric depositions of sulfur and nitrogen were tested separately by simple linear regression. The differences among research plots were tested by analysis of covariance with atmospheric depositions of sulfur as covariate. The significant differences among plots were tested by the Tukey HSD test.

TABLE 2 Degrees of defoliation based on percentage of remaining foliage (Vacek and Matějka 2010).

Degree of defoliation	Remaining foliage	Tree health
0	91–100%	Sound
1	71–90%	Slightly damaged
2	51–70%	Severely damaged
3	31–50%	Very severely damaged
4	1–30%	Extremely damaged
5	0%	Dead

Results

Atmospheric deposition

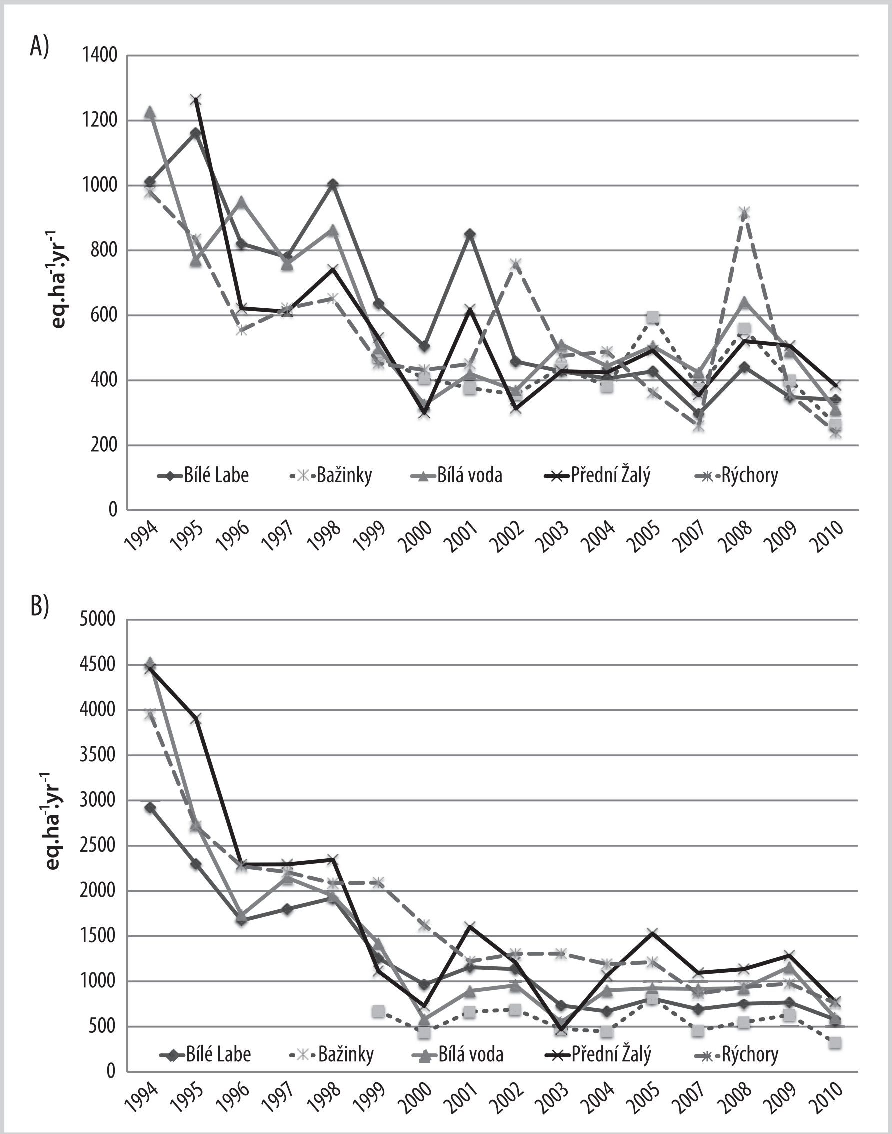
The total deposition of sulphates has significantly decreased in all localities since 1994. The first important reduction of sulfur deposition, from 50–80 kg ha^{-1} $year^{-1}$ to 26–36 kg ha^{-1} $year^{-1}$, occurred between 1994 and 1996. A second and less pronounced reduction, from 30–35 kg ha^{-1} $year^{-1}$ to 6–10 kg ha^{-1} $year^{-1}$, occurred between 1998 and 2000. In 2010 the input of sulfur in all localities ranged from 8 to 13 kg ha^{-1} $year^{-1}$, which is a slight increase of sulfur deposition in spruce stands compared to the year 2000. The values of precipitation deposition and throughfall are shown in Figure 5.

In 2010 the total deposition of nitrogen ranged from 14 to 19 kg ha^{-1} $year^{-1}$. The highest values of nitrogen deposition, on some monitoring stations exceeding 25 kg ha^{-1} $year^{-1}$, were measured in 1999, 2002, and 2008, with somewhat higher nitrogen loads in the eastern part of the Krkonoše Mountains. However, no clear trend in the development of nitrogen deposition could be identified. In general, variability between particular years is more apparent for nitrogen than for sulfur deposition.

Foliage development

The evaluation of development on each research plot was based, first, on the proportions of trees with different degrees of defoliation and, second, on the trend of average foliation (calculated both for all trees on the research plot and separately for living trees) (Figure 6). The proportion of sound trees (degree 0 of defoliation) was very small in all investigated stands and continuously

FIGURE 5 Stock flow of sulfur in the form of SO_4^{2-} on an open area (precipitation deposition) and under the forest canopy (throughfall).



decreased during the observation period. On most plots after 1984 there was a total lack of sound trees. The average proportion of trees with slightly damaged crowns (degree 1) dropped, especially during the first decade of the study (from 54.7% in 1980 to 14.7% in 1991) and remained rather constant during the last 2 decades (18.0% in 2011). The proportion of severely damaged trees (degree 2) dramatically increased from 1980 (26.1%) to 1985 (50.4%) and after that continuously decreased to 13.5% in 2011. Similarly, the proportion of very severely damaged trees (degree 3) grew from an initial 7.6% in 1980 to 22.7% in 1986 and then dropped to 2.2% in 2011. Extremely damaged trees (degree 4) reached the maximal proportion in 1987 (8.2%), which since then has continuously declined to the current 0.5%. The proportion of dead trees increased rapidly from 0.0% in 1980 to 65.8% in 2011 (ranging from 40.7% to 100% on individual research plots).

The mean defoliation of living and all trees was 32% (±0.5 SE) and 63% (±0.8 SE), respectively, on plots with autochthonous stands, and 91.5% (±5.8 SE) and 97.6% (±1.7 SE), respectively, on the plot with an allochthonous stand. The defoliation of living and all trees differed across research plots (Table 3). There was no relationship between defoliation of living trees and atmospheric deposition of sulfur ($P = 0.14$; $r^2 = 0.022$), between defoliation of living trees and atmospheric deposition of nitrogen ($P = 0.69$; $r^2 = 0.001$), or between defoliation of

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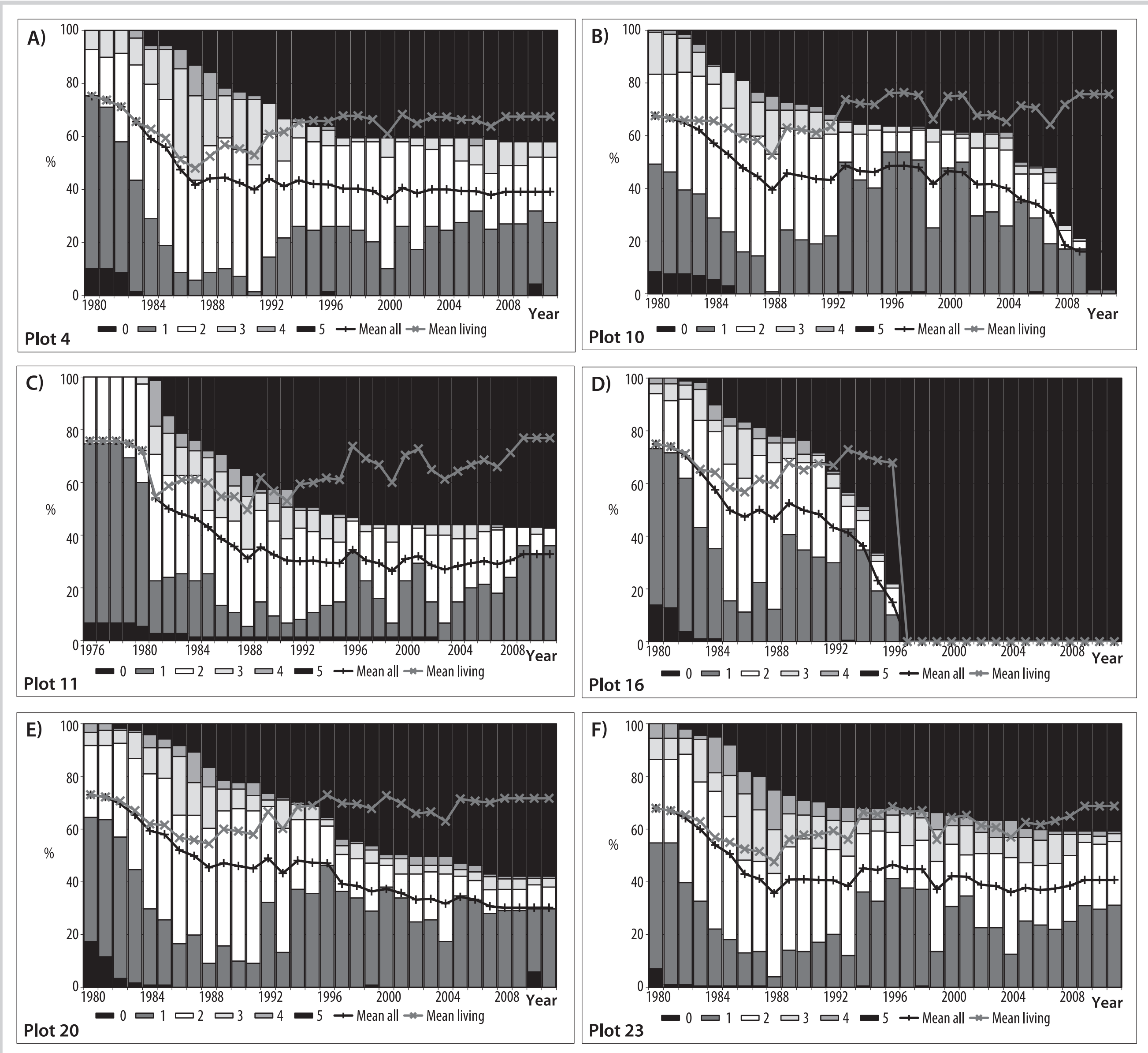
FIGURE 6 Proportion of defoliation degrees and trend of average foliation (calculated both for all trees and for living trees) in spruce stands on particular research plots in the Krkonoše Mountains from 1980 to 2011.



all trees and atmospheric deposition of nitrogen ($P = 0.55$; $r^2 = 0.004$). There was, however, a negative relationship between defoliation of all trees on a plot and atmospheric deposition of sulfur ($P = 0.012$; $r = -0.25$) (Figure 7). This relationship differed across research plots ($F[5, 96] = 110$, $P < 0.001$) (Table 3).

Discussion

The health conditions of maturing and mature spruce stands in the Krkonoše Mountains are to a great extent differentiated. Exposure to the emission load, the characteristics of the forest site, tree species composition, the origin of the forest stand, the degree of "naturalness" (level of hemeroby), and past forest management may be the most important explanatory variables. The set of 5 monitoring stations included in the study is relatively dense compared to the usual situation in the Czech Republic, but not frequent enough to explain the influence of mountain topography, stand conditions, and other environmental factors on the processes of atmospheric deposition. Nevertheless, study results are consistent with research results from other European mountain regions, where critical levels of sulfur and nitrogen deposition are

TABLE 3 Defoliation of trees and atmospheric deposition of sulfur and nitrogen on permanent plots.[a)]

Plot number (RP)	Defoliation of living trees (%)		Defoliation of all trees (%)		Sulfur deposition (kg ha^{-1} $year^{-1}$)		Nitrogen deposition (kg ha^{-1} $year^{-1}$)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
4	33.7 a	0.47	60.4 a	0.35	17.8	3.09	15.9	1.39
10	28.4 a	1.06	62.5 a	2.87	17.2	2.85	16.6	1.46
11	31.9 a	1.32	69.9 b	0.54	17.9	2.92	16.9	1.44
16	91.5 a	5.83	97.6 c	1.66	16.9	2.77	16.9	1.46
20	30.4 a	0.68	64.4 a,b	1.35	20.1	2.95	21.7	1.06
23	36.1 b	0.97	59.5 a	0.83	21.3	3.05	22.2	1.03

[a)]Defoliation of living and all trees with the same letter within one category do not differ significantly among plots.

continuously exceeded (Akselsson et al 2004; Augustin et al 2005; Lorenz et al 2006).

The emission of SO_2 during the observation period decreased in the Czech Republic as a whole (by about 20% from the values recorded at the end of 1980s), and atmospheric deposition decreased as well; nevertheless, the damage to spruce stands in the Krkonoše Mountains continues. RPs 4, 11, 20, and 23 showed the usual process of defoliation in autochthonous spruce stands during the period of greatest ecological stress and air pollution, without bark beetle impact and with different magnitudes of forest damage. RP 10 illustrates the accelerated dynamics of disruption in an autochthonous spruce stand with bark beetle attacks after 2007, whereas RP 16 represents disruption of an allochthonous spruce stand with an early bark beetle attack after 1982, which was a typical decline scenario for this type of forest stand in this area. The average foliage of autochthonous spruce stands in 1976 reached values around 79.0% of total potential foliage, and in 2011 the average foliage amounted to only 23.0%, which represents an average annual defoliation of 1.6%, whereas average annual defoliation of allochthonous spruce stands amounted to 3.8% (Vacek and Matějka 2010). Beside factors like heavy historical pollution in this part of the country and the generally higher sensitivity to environmental stress of mountain ecosystems, the high age of the investigated stands (on average 184 years for the upper story in 2011) may be a crucial factor in their deteriorating health.

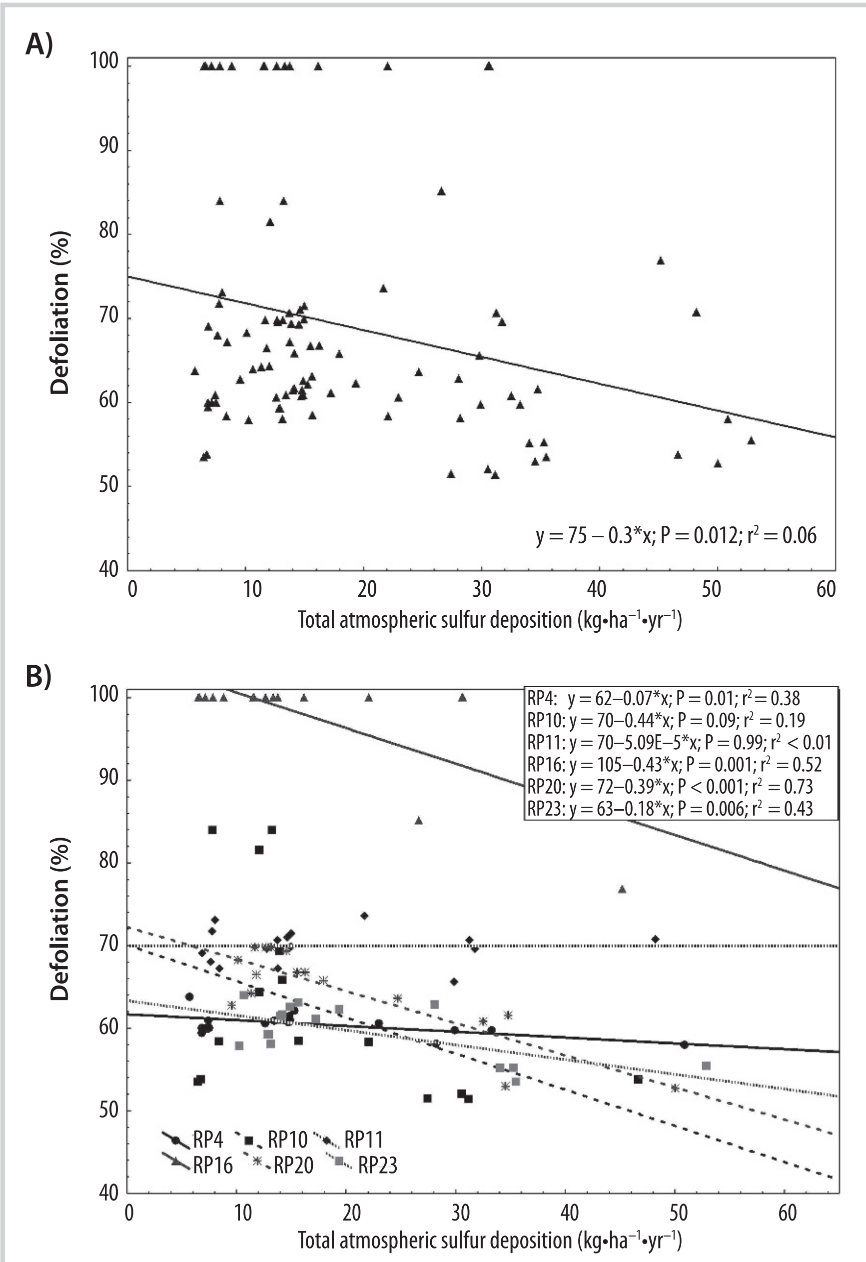
Lomský et al (2012) showed the relation between crown defoliation (health condition of the tree) and nutrients and stress elements. Unbalanced nutrition was affected by the ongoing nitrogen deposition, which was manifested as a disturbed nitrogen-to-phosphorous and nitrogen-to-magnesium ratios in the needles. Since important ecological processes in forest stands are associated with the dynamics of forest canopy, its decrease due to forest decline may have a crucial impact on several environmental factors, including incoming radiation, throughfall precipitation quantity, and soil moisture, structure, and chemistry. These changes may be followed by specific ground vegetation dynamics.

Vávrová et al (2009) showed that dominant ground cover during the period of massive dieback of climax Norway spruce stands in the Krkonoše Mountains, in the 1980s and at the beginning of the 1990s, shifted from mosses and sites without vegetation covered with spruce litter to *Avenella flexuosa* (L.) Drejer (hair-grass). A decrease in cover and species richness of mosses related to canopy damage was also reported by Vacek et al (1999). *Vaccinium myrtillus* L. (European blueberry) expanded, mainly under gradually defoliating tree crowns, whereas quickly deforested areas were colonized by grasses, especially *Calamagrostis villosa* (Chaix) J. F. Gmel. Changes in forest structure and associated alterations in ground vegetation cover may also result in variations of ecological processes like snow accumulation during winter, snow melting, evaporation, transpiration, soil moisture variability, and temperature variations.

Despite the overall improvement in air quality in the Krkonoše Mountains National Park, ongoing and cumulative sulfur and nitrogen deposition continue to exceed critical levels. Nitrogen deposition is still very high and corresponds to almost double or even triple the critical threshold; significant improvement cannot be expected, even in the long term (Schwarz et al 2009; Hošek and Schwarz 2010). As confirmed in this study, increased nitrogen deposition has no clear and direct effect on tree crown condition and vitality, but it impairs the ecosystem's water filtering function and enhances the risk of nitrogen output beyond an approximate threshold of carbon to nitrogen ratio C/NHumus 25 (Augustin et al 2005). On the other hand, a consistent correlation was found between the defoliation of all trees and total sulfur deposition, indicating that defoliation continues with decreasing sulfur deposition.

This phenomenon is the result of long-duration soil depletion caused by acidic deposition, which is responsible for base leaching (mainly calcium and magnesium) from the soil horizons. Calcium and magnesium were continuously washed out of the soil

FIGURE 7 Relationship between defoliation of all trees on plot and atmospheric deposition of sulfur: (A) on all plots together; (B) on each permanent research plot.



horizons, and increased soil acidity mobilized aluminum ions. Insoluble nontoxic forms of aluminum hydroxide and aluminum ions are dissolved into the water and become toxic to the root system of the spruce. The decrease of emission rates and sulfur deposition are still not sufficient to prevent this. Moreover, with the increasing rate of NO_x emission, the situation remains critical.

Beside contributing to soil acidification, higher nitrogen input can cause nutritional imbalance in trees and a related lower resistance to biotic and abiotic agents (Hruška and Cienciala 2002; Vacek et al 2007; Lomský et al 2012). Another reason for the dramatic decline of forests in the Sudeten may be that the accumulation of pollutants in forest ecosystems during past decades has exceeded the homeostatic capacity of most trees, as well as of whole ecosystems (Modrzyński 2003).

The decrease in sulfur deposition corresponds with the situation in the rest of the Czech Republic (e.g., Šrámek et al 2008). For example, in the Krušné Mountains (monitoring station Načetín), the emission load decreased during the same period from 40–50 kg ha^{-1} $year^{-1}$ to the current 10 kg ha^{-1} year^{-1}. During the observation period, the deposition of nitrogen ranged from 17 to 30 kg ha^{-1} year^{-1} with an average of 23 kg ha^{-1} year^{-1}. In less exposed areas of the Slavkovský les (a water catchment area Lysina), sulfur deposition in 1994 amounted to 30–35 kg ha^{-1} year^{-1}, in 2005 to less than 9–10 kg ha^{-1} year^{-1}. Deposition of nitrogen does not show any evident trend; there was a slight decrease, from 12 kg ha^{-1} year^{-1} in the beginning of the monitoring period to 9 kg ha^{-1} year^{-1}, one of the lowest values in the mountain areas of the Czech Republic, in 2010 (Hošek and Schwarz 2010).

The decline in sulfur deposition between 1995 and 2000 was due to the desulfurization of power plants and other large industrial sources of air pollutants. The average sulfur deposition in the Krkonoše Mountains National Park decreased from 210 meq m^{-2} year^{-1} in 1995 to the current 99 meq m^{-2} year^{-1}. Sulfur deposition was more evident in the western part of the mountain range, where it was in the past mainly influenced by the transfer of air pollutants from more distant industrial sources (such as the Turów power plant in Poland), an example of transboundary pollutant transport. In the eastern part, the decline of sulfur input was less evident; the major source of air pollutants there was the power plant in Poříčí near Trutnov in the Czech Republic.

For nitrogen compounds, on the other hand, total deposition in the Krkonoše Mountains increased slightly during the observation period, from an average of 93 meq m^{-2} year^{-1} in 1995 to 99 meq m^{-2} year^{-1} in 2000 (Vacek et al 2007). This development confirms data from the Krkonoše-Rýchory station, where annual average NO_x concentrations in 2010 amounted to 18.2 µg m^{-3} compared to 10.1 µg m^{-3} in 1995 (Czech Hydrometeorological Institute 2012). Staszewski et al (2012) noted that national parks are centers of intensive tourism and thus high motor traffic density. Within this area, the western part showed considerably improved conditions, while nitrogen deposition increased in the eastern part.

Conclusions

During the last 5 decades, air pollution has become a serious hazard for forests in the Czech Republic. Large-scale forest damage, mainly of spruce stands in mountain and lower mountain areas, has negatively influenced both the productive and nonproductive functions of these ecosystems. Air pollution continues to represent a serious hazard for the forest ecosystem in the Sudeten. For forest management, the main implications are as follows:

1. *Enhancement of forest complexity with respect to natural structure and tree species composition.* Close-to-nature management techniques aimed at the enhancement of forest complexity may be of crucial importance. This means mainly the transition from age-class forestry to differentiated small-scale management based on the Dauerwald and individual selection principles. Additionally, we need to develop silvicultural approaches based on principles of disturbance ecology and natural stand development that are more aligned with natural processes (Franklin et al 2002). Such approaches enhance ecosystem functions, including soil protection and nutrient and water retention. Maintaining biodiversity in multifunctional forests is also supported by forest legislation and new forest management plans.
2. *Preferential use of autochthonous populations of trees in timely regeneration and restoration of forest stands.* Abiotic and biotic disturbances occurred regularly in the Krkonoše Mountains, including in the remote past, but severe large-scale forest damage did not appear until the 1980s, where mainly even-aged (to a greater extent allochthonous) spruce monocultures were affected. In the Krkonoše Mountains National Park, the regeneration of these forest stands has followed the restoration of species diversity and reconstruction of more natural forest ecosystems. On most forest sites, a relatively high potential for natural regeneration has been confirmed.
3. *Active approach to the prevention of related biotic and abiotic forest damage.* Nature protection authorities often have to decide whether to protect the nonproductive functions of mountain forests or natural processes often negatively influenced by past forest management or unfavorable development of environmental conditions (eg degradation of forest soils). Selective fertilizer treatments can lead to improved health conditions (Vacek et al 2009) of trees with symptoms of yellowing; similarly, silvicultural measures are the most efficient for the control of bark beetles.

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