

Evaluation of air pollution-related risks for Austrian mountain forests

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“Capsule”: *Despite strong reduction of emissions in Europe, pollutants are still a potential stress factor, especially for sensitive mountain forest ecosystems in Austria.*

Abstract

The present paper describes air pollution status and evaluation of risks related to effects of phytotoxic pollutants in the Austrian mountain forests. The results are based on Austrian networks (Forest Inventory, Forest Damage Monitoring System, Austrian Bioindicator Grid), the Austrian sample plots of the European networks of the UN-ECE (ICP Forests, Level I and Level II) and interdisciplinary research approaches. Based on the monitoring data and on modelling and mapping of Critical Thresholds, the evaluation of risk factors was possible. Cause–effect relationships between air pollution and tree responses were shown by tree-physiological measurements. Sulfur impact, proton and lead input, concentrations of nitrogen oxides, nitrogen input and ozone were evaluated. The risk was demonstrated at a regional and large-scale national level. Especially the increasing O₃ level and the accumulation of Pb with altitude present most serious risk for mountain forests.

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1. Introduction

Forty-seven percent of the Austrian territory is covered by forests. The total area of mountain forests makes up 2.95 million hectares, that is 75% of the total Austrian forest.

Mountain forests are defined as forests at the montane and sub-alpine zone of the Alps from approx. 1000 to 2000 m a.s.l. (Frank et al., 1998). The main part of the mountain forest area in Austria is stocked with coniferous mixed forests with Norway spruce (*Picea abies*) being the main tree species. At the timberline, forests with *Picea abies*, European larch (*Larix decidua*), Mountain pine (*Pinus mugo*) and Swiss stone pine (*Pinus cembra*) prevail.

The need to preserve the forest area through sustainable management has top priority due to the fact that according to the Forest Development Plan (Bundesministerium für Land- und Forstwirtschaft, 1988) 31% of the forest area has above all a protective function (Fig. 1).

Mountain forests protect soils against erosion. They also protect settlement areas and infrastructure against natural hazards like avalanches, mudflows, flood and rockfall. The protection of settlement area by mountain forests is of great importance to nearly half of the population of Austria.

The impact of stress plays a major role in forest ecosystems. Damage by game and cattle and forest management has led to a strong reduction of ecologically important mixed forest tree species such as *Abies alba* and *Fagus sylvatica*. For example, *A. alba* now forms stands only in 15% of the area where it should naturally occur. Eighty-five percent of the forest regeneration areas are affected by browsing; on 40% of these areas at least one tree species shows heavy damage. In the mountain forests one stem out of 10 is peeled; bark injuries are caused additionally by rockfall and harvesting operations (Schieler et al., 1996).

Another risk to mountain forests is atmospheric pollution (Smidt, 1998; Smidt and Englisch, 1999). The main source of air pollution in Austria is traffic, especially transit traffic, as the Alps form a geographic barrier for the continuously increasing mobility of Europeans. For instance, 8 million vehicles, 20 times as many as 20 years ago, transit over the Brenner Pass

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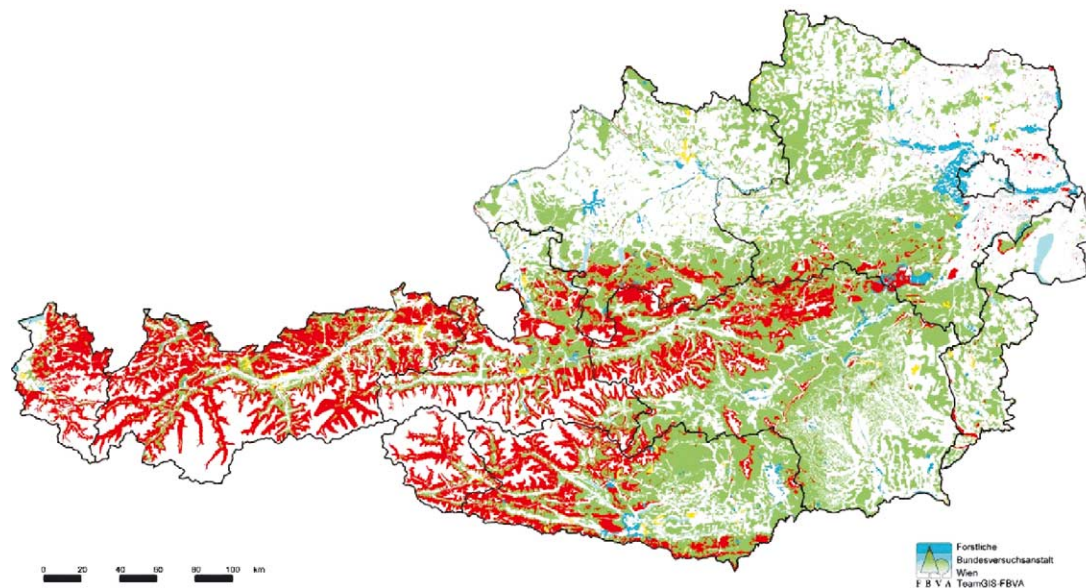


Fig. 1. Key functions of forests according to the Forest Development Plan (Bundesministerium für Land- und Forstwirtschaft, 1988): green: commercial; red: protective; yellow: recreation; blue: environmental.

(Tyrol/Austria) every year. Further sources for air pollution are tourism and local emitters and, especially in the case of O_3 , long-range transport.

Networks were established since the early eighties in Austria (Bundesministerium für Land- und Forstwirtschaft, 1996) to survey the spatial variability and to monitor the long-term condition of forests. Additionally, interdisciplinary forest decline research projects have been initiated to improve the knowledge about cause–effect relationships and to diagnose stress for forest ecosystems even before the occurrence of visible damage (Bolhar-Nordenkamp, 1989; Smidt et al., 1994, 1996; Herman et al., 1998a,b). By combining meteorological data, forest monitoring results and data from small-scale interdisciplinary programs, it is possible to identify relationships between the impact and the effects of pollutants on various parts of the forest ecosystems. These investigations require information on biochemical and physiological parameters in tree foliage, soil–chemical and physical characteristics and root systems and allow the characterization of stress patterns (Bolhar-Nordenkamp and Lechner, 1989; Blank and Lütz, 1990; Krupa and Arndt, 1990; Wieser and Havranek, 1993, 1996; Smidt, 1996; Lütz et al., 1998; Tausz et al., 1998; Wieser et al., 1998).

During the last two decades, Austria participated in the European ICP-Forests networks Level I and Level II (de Vries et al., 2002) and contributed to the Critical Levels and Critical Loads concept, respectively (UN-ECE 1994; WHO, 1995; Nagel and Gregor, 1999; Fuhrer, 2000). Based on monitoring data and findings of the interdisciplinary forest decline approaches, Austrian and European maps of Critical Thresholds (Posch et al., 1995) as well as Austrian risk maps were devel-

oped (Loibl and Smidt, 1996; Knoflacher and Loibl, 1998).

The goal of this review is to present and evaluate pollution-related risks to Austrian forests with special consideration of mountain forests. The results are based on monitoring activities of the Federal Office and Research Centre of Forests (BFW), by other scientific institutions as well as on the projects coordinated by the BFW under participation of numerous university institutes and research centers. The findings should be the basis for legal measures to improve the air quality.

2. Material and method

This review addresses the spatial distribution as well as the physiological response of forest trees to five essential air pollutants. The risk is assessed using data from monitoring grids (Table 1) of the Office and Research Center for Forests (BFW), from the Austrian Federal Environment Agency, the Austrian Federal Provinces, parts of forest soil surveys in the area of working associations “ALP countries and ALPS ADRIA”, the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests, Level II Program) as well as from pollution-related forest ecosystem research projects of the BFW. The legal standard for sulfur impact and the evaluation ranges for proton (H^+) and Pb have been established by the BFW in cooperation with other related institutions; further thresholds listed in Table 2 were established by the European Community.

Table 1
Austrian and European forest and air pollution monitoring networks (BFW: Federal Office and Research Center)

Monitoring grid	Parameters used in this paper	Number of plots	Responsibility Database	References
Forest Inventory	Species, age, stock	5,500	BFW, Austria ^a since 1971	Schieler et al. (1995)
Forest Soil Monitoring System	Soil chemistry (pH, base saturation, cation exchange capacity, heavy metals)	514	BFW, Austria ^a 1989	Forstliche Bundesversuchsanstalt (1992a,b)
Tyrolean Forest Soil Monitoring	Soil chemistry	263	Amt der Tiroler Landesregierung, 1988 ^b	Amt der Tiroler Landesregierung (1989)
“Alp countries” and “Alps-Adria” ^c	Pb in the soil	1255	Member countries; 1980–1995	Huber and Englisch (1998)
Bioindicator Grid	Sulfur content in needles	760	BFW, Austria ^a since 1983	Stefan and Fürst (1998)
Gaseous air pollutants	SO ₂ , NO _x , ozone	25/25/120	Federal Provinces of Austria, Umweltbundesamt; since 1984	Umweltbundesamt (2001)
Level II	Wet deposition	20	ICP Forests ^b since 1994	Smidt (2002)
WADOS-network	Wet only deposition	31	Technical University Vienna since 1983	Limbeck et al. (1998)
Bioindication by mosses	Pb	220	Austrian Federal Environment Agency 1991, 1995	Zechmeister (1997)

^a Systematical grid.

^b Part of a systematical grid.

^c Parts of Austria (Burgenland, Carinthia, Salzburg, Styria, Tyrol, Upper Austria, Vorarlberg and the alpine parts of Lower Austria), Germany (Bawaria), Italy (Bozen—South Tyrol) and Switzerland (St. Gallen, Grisons, Ticino).

2.1. Monitoring networks

The Austrian Forest Inventory is one of the most intensive national forest monitoring systems in Europe covering 40 years from 1961 up to now. The sampling design is characterized by a grid pattern where quadratic tracts are systematically distributed over Austria in a regular manner (2.87×2.87 km). Over four decades it has changed from a survey of stock and increment aiming at sustainability to a more complex monitoring system covering many aspects of the ecosystem (Schieler et al., 1996). Various parameters of this grid are incorporated in the modelling of O₃ impact for Austria and in the modelling of Critical Loads for the North Tyrolean Limestone Alps.

The Forest Soil Monitoring System is a part of the Forest Damage System (Neumann, 1996) as well as of the International Cooperative Programme (ICP) Forests. In 1989, the first sampling was laid out for the entire forested area of Austria (8.7×8.7 km). The investigated parameters included biological and chemical soil properties. The major goals were the description of the soil condition and the influence of pollutant input (Forstliche Bundesversuchsanstalt, 1992a,b; Mutsch, 1992). Soil chemistry parameters of the Soil Monitoring System were used to calculate Critical Loads for H⁺ and N input for the North Tyrolean Limestone Alps and to describe the Pb input especially for the Northern slopes of the Alps. The data of the Tyrolean Soil Monitoring System, arranged in a 4×4 km grid, are additionally included in the modelling of Critical Loads for the area of the North Tyrolean Limestone Alps (Amt der Tiroler Landesregierung, 1989).

Data from the “ALP countries” and “ALPS ADRIA” forest grids were chosen to assess the Pb input into the soil (Huber and Englisch, 1998): “ALP countries and ALPS ADRIA” 1980–1995 and the grid of the Forest Soil Monitoring System (first sampling: 1988). From the European network of bioindication with mosses (Rühling, 2002) the Austrian results were used to assess Pb input (Zechmeister, 1997).

Since 1983 the country-wide systematic Bioindicator Grid (16×16 km) provides data to assess the S impact on Austrian forest areas (Stefan, 1992; Stefan and Fürst, 1998). Where required by specific topographic conditions, e.g. for the Alps or in areas affected by large emitters, the grid has been condensed. Due to the fact that annual samplings have been carried out since 1983, and the high density of the grid, it is possible to study time-related development and statements of regional stress and transboundary pollution.

SO₂, NO_x and O₃ are measured at numerous forested and non-forested areas in Austria under the responsibility of the Federal Provinces (Umweltbundesamt, 2001). The Austrian Umweltbundesamt (Austrian Federal Environment Agency) is the administrative body

Table 2
Legal standard for S impact, evaluation ranges and European thresholds

Pollutant	Criteria	References
Sulfur; needles of <i>Picea abies</i>	Legal standard: S content: 0.11% S (needle year 1) 0.14% S (needle year 2)	Austrian Federal Law Gazette (1984)
Proton input	<0.25 kg H ⁺ ha ⁻¹ yr ⁻¹ for acidic parent material	WHO (1995)
Proton; soil	pH base saturation cation exchange capacity Zn ≤200 ppm, Cu and Zn ≤14 ppm	≤4.2 ≤18% ≤100 μmol g ⁻¹ Mutsch and Smidt (1994)
Pb; soil	“Lead Accumulation Index”: Quotient of Pb contents topsoil (0–10 cm)/mineral soil (30–50 cm): <1.40 1.41–2.00 2.01–4.00 >4.00	No accumulation Low accumulation Medium accumulation High accumulation Herman et al. (2001)
Pb; impact, needles of <i>Picea abies</i>	No indication Remote areas Urban areas	<4 mg Pb kg ⁻¹ <0.80 mg Pb kg ⁻¹ >1.70 mg Pb kg ⁻¹ Knabe (1984); Herman (1998)
Ozone	Critical Level: AOT40=10 ppm.h; accumulated exposure above a threshold of 40 ppb, 24 h per day, over a 6-month growing season (e.g. April–September), reduction of biomass production ≤10%	WHO (1995); UN-ECE (1994)
NO ₂	NO ₂ : 30 μg m ⁻³ (annual mean value)	Österreichische Akademie der Wissenschaften (1989)
NO _x	NO _x =(NO+NO ₂): sum of the ppb NO+NO ₂ , expressed as μg m ⁻³ : 30 μg m ⁻³ (annual mean value)	EU (1999/30/EG); WHO (1995)
Nitrogen deposition	Coniferous ecosystems: 10–12 (>20) kg N ha ⁻¹ yr ⁻¹ (depending on effect) Deciduous forests: <15 kg ha ⁻¹ yr ⁻¹	WHO (1995)

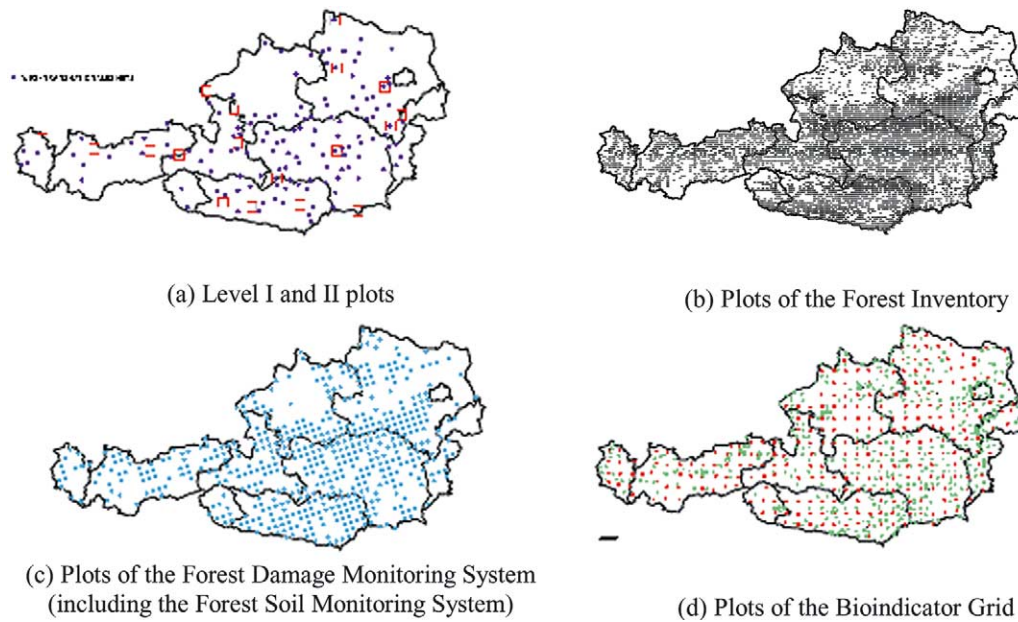


Fig. 2. (a)–(d): Systematical networks of the BFW for monitoring forest health and pollutant input in Austria: (a) Forest Inventory; (b): Forest Damage Monitoring System including the Forest Soil Monitoring System; (c) Bioindicator Grid (d): Level I and Level II.

for the data bank. The data were used for the calculation of the trends and for the modelling and mapping of O_3 risk.

The International Co-operative Programme (ICP Forests) under the Geneva Convention on Long Range Transboundary Air Pollution (UN/ECE) was implemented in 1985. One year later, the Council of the European Union agreed to a Community Scheme on the Protection of Forests against Atmospheric Pollution (Council Regulation EEC No. 3528/86) including a common survey on forest damage in the member states (deVries et al., 2002). Presently, 38 countries all over Europe participate in this programme. Monitoring is performed at different levels. The large scale (Level I, systematic network of 5700 plots) provides a general overview on forest condition and its temporal development. Level II for intensive monitoring (860 plots) includes intensive monitoring to improve the knowledge about cause-effect relationships. In this review, the deposition data from the 20 Austrian Level II plots were used to assess the risk due to H^+ and N input.

Fig. 2a–d and Table 1 outline the Austrian systematic networks.

2.2. Pollution-related forest ecosystem research of the BFW

The pollution-related forest research activities started 1984 in an Alpine valley in the Central Alps of North Tyrol (Stöhr, 1988; Gregori, 1992; Smidt and Herman, 1992; Puxbaum et al., 1990). Emphasis was placed on

the evaluation of natural and anthropogenic risk factors for forest ecosystems on a small scale basis with investigation in the open field with mature trees. The environmental status was assessed and the reactions of the trees to the prevailing circumstances were measured based on early-stress diagnosis parameters on the biochemical and physiological level (Bolhar-Nordenkamp, 1989). Since 1990, the research activities have been pursued in the Limestone Alps and the investigation program has been extended markedly: Potentially phytotoxic air pollutants such as organic compounds have been measured during intensive studies and also continuously monitored in the air (Haunold, 1997; Rosenberg et al., 1998), in the humus layer and in needles (Schröder and Plümacher, 1998; Weiss et al., 1998). Furthermore, new bioindication methods evaluating status of fine roots and mycorrhiza have been developed and standardized (Smidt et al., 1996). Simultaneous evaluation of the monitoring and research results enabled the preparation of models and allowed large-scale risk assessments. In recent years, O_3 risk maps for the forest areas of the Austrian Federal territory and risk maps for N for the area of the North Tyrolean Limestone Alps have been prepared (Herman et al., 2001).

2.3. Criteria

The evaluation of the pollutant data was performed according to the Austrian legal standard for S impact, to established European evaluation ranges and thresholds (Table 2).

Table 3
Plant-physiological parameters (needles and fine roots of *Picea abies*)

Parameters	Ranges		References
Photosynthetic capacity F_v/F_m (ratio of variable to maximal fluorescence)	0.85 0.72 <0.60 <0.30	Normal Lower limit of natural variation Strong, reversible disturbances Strong, also structural disturbances	Bolhar-Nordenkampf and Lechner (1989); Bolhar-Nordenkampf and Götzl (1992)
Thioles	0.25–0.70	$\mu\text{mol/g d.w. (needle year 1)}$	Bermadinger-Stabentheiner (1994)
Ascorbic acid	–3.9	$\text{mg/g d.w. (needle year 1)}$	
Peroxidase activity	5–50	$\text{Units/g d.w. (needle year 1)}$	
Glutathion reductase	0.6–1.5	$\text{Units/g d.w. (needle year 1)}$	
Total chlorophyll	60–1500	$\mu\text{g/g d.w. (needle year 1)}$	
Glutathion-S-transferase	0.1–1.0	nkcat/mg protein	Plümacher and Schröder (1994)
Total fatty acids	<0.6–>0.8	% d.w. (total)	Puchinger and Stachelberger (1994)
Unsaturated fatty acids	<50–>60	Rel.% of total fatty acids	
Linoleic acid	<25–>30	Rel.% of total fatty acids	
Oleic acid	<8/>8	Rel.% of total fatty acids	
Steroles	<0.25–>0.35	% d.w. (total)	
Triglycerides	<0.15–>0.25	% d.w. (total)	
Fine roots; cytogenetic bioindication of chromosomal aberrations	Cytogenetic site index (CSI) > 1.4		Müller and Bermadinger-Stabentheiner (1996)

For the assessment of S impacts on *P. abies*, the Austrian legal standards were used which are based on the S content of needles of needle set 1 and 2. Together with wood increment analysis, these standards determine SO_2 -related increment losses. Because of the close-meshed monitoring grid, the regional and transboundary impact of S can be outlined. For the evaluation of the H^+ input, the Critical Load was the criterion (WHO, 1995). For the assessment of the potential risk through H^+ input, parameters of the Forest Soil Monitoring System were used which are related to the sensitivity against H^+ input.

To assess the accumulation of airborne Pb into the soil, the “Lead Accumulation Index” for forest soils was defined as the ratio of total Pb in the soil layer 0–10 cm (topsoil) vs. that of 30–50 cm (mineral soil). The Pb content of the organic layer was not used, because the specific gravity of organic layers varies to a higher extent than that of mineral layers and therefore the comparability of different sites would be more difficult.

On the basis of a 30 year investigation period, a classification scheme for areas differently polluted with Pb could be derived. The data sets of the Pb concentrations in needles of *P. abies* from six sample areas form the evaluation ranges (Table 3; Herman, 1998).

A statistical model was used to describe the risk due to O_3 for the forest areas of the Austrian Federal territory. In the first approach, the risk map of the AOT40 was based on the Austrian O_3 measuring stations, the Austrian Forest Inventory and other Austrian-wide measuring grids (meteorology, GIS; Smidt and Loibl,

1996). For the second approach, the AOT40 concept was modified including plant-physiological measurements and the factors which influence O_3 uptake.

To add knowledge on O_3 effects, the extension of visible injuries to forest trees and shrubs in relation to O_3 levels are assessed within the Level II Programme (de Vries et al., 2002) and the Working Group of Ambient Air Quality and its Effects on Forest Ecosystems, respectively (Nash et al., 1992; Sanz and Millan, 1999; Innes et al., 2001).

The criteria for the evaluation of the N pollutant data were the NO_2 concentrations (Österreichische Akademie der Wissenschaften, 1989) and the NO_x concentrations (WHO, 1995), respectively. The limit value for both is $30 \mu\text{g m}^{-3}$ for the annual mean. The assessment of the annual N deposition is based on the Critical Load concept of the WHO (1995).

Various parameters of the physiological response of *P. abies* needles were used to detect early stress, e.g. oxidative stress. Long-term measurements provided criteria and ranges of various parameters (Table 3): The photosynthetic capacity (F_v/F_m -ratio; Bolhar-Nordenkampf and Lechner, 1989), compounds of the anti-oxidative system (Bermadinger-Stabentheiner, 1994), Glutathion-S-Transferase (Plümacher and Schröder, 1994), lipoids (Puchinger and Stachelberger, 1994) and the chromosomal aberrations (Müller and Bermadinger-Stabentheiner, 1996). The principal component analysis and the classification of the response patterns by cluster analysis enabled a distinction between differently polluted forest areas (Tausz et al., 1998, 2002).

Table 4

Trends (first line) of annual mean values of SO₂, H⁺-input and Pb-input, total mean values over the measuring period (second line) and measuring period (in parentheses)

Measuring site	SO ₂ (μg m ⁻³)	H (kg ha ⁻¹ yr ⁻¹)	Pb (g ha ⁻¹ yr ⁻¹)	NO ₂ (μg m ⁻³)	O ₃ (μg m ⁻³)
Nebelstein (Lower Austria), 1012 m a.s.l. (Smidt et al., 1999)	–1.6 ^b 16.8 (1986–1996)	–	–	–0.1 n.s. 9.2 (1986–1995)	
Lenzing (Upper Austria), 510 m a.s.l.	–1.7 ^c 17.8 (1982–1999)	–	–	–1.3 ^c 20.8 (1984–2000)	+ 0.4 ^a 49.0 (1983–2000)
Schöneben (Upper Austria), 920 m a.s.l.	–0.7 ^c 6.5 (1984–2000)	–0.01 ^c 0.14 (1984–2000)	(–0.78) 2.05 (1994–2000)	–0.3 n.s. 8.8 (1984–1993)	+ 0.1 n.s. 70.7 (1984–2000)
Steyregg (Upper Austria), 335 m a.s.l.	–1.8 ^c 16.4 (1982–2000)	–0.00 n.s. 0.01 (1984–2000)	(–0.84) 4.21 (1994–2000)	–2.9 ^c 35.2 (1984–2000)	+ 1.0 ^c 42.8 (1982–2000)
Salzburg, Tyrol	–	–0.02 ^c 0.19 (1984–1996; <i>n</i> = 5/Tyrol, Salzburg)	–2.2/–3.8 ^c 0.026 (1984–1995; <i>n</i> = 2, Salzburg)	–	–

n.s.: *P* > 0.05;

^a *P* = 0.01–0.05;

^b *P* = 0.01–0.001;

^c *P* < 0.001.

3. Results and discussion

The impact of five of the most important air pollutants (S compounds, H⁺, Pb, N compounds, O₃) for Austrian forest ecosystems was evaluated using legal standards, evaluation ranges, thresholds and physiological criteria.

3.1. Trends of pollutants

Since the early eighties, the air pollution situation has considerably changed in Austria. SO₂-concentrations, S and Pb-deposition in forest areas decreased markedly (EMEP, 2002). On the other hand, the NO₂-concentrations and the wet N-deposition showed no significant trend since the eighties. The wet N depositions, however, remained at a high level. Ozone concentrations increased at the three Austrian long-term measuring stations (Smidt et al., 1999).

Long-term trends may only be assessed from data of a few measuring stations in forest areas and are therefore not representative for Austrian forest ecosystems. Table 4 gives examples for trends including recent data sets for the available long-term stations. SO₂-concentrations have shown remarkable decreases since the early eighties. The highest mean decrease of SO₂ was found nearby emitters corresponding to the local and regional reductions of SO₂-emissions.

Proton input decreased significantly in clean-air areas, but not at the measuring station Steyregg which is heavily influenced by various large emitters of the industrial area of Linz (Upper Austria; Amt der Oberösterreichischen Landesregierung, 2002).

Pb input decreased significantly at 2 stations in Salzburg (for two stations in Upper Austria, the time series were too short for a statistical evaluation).

3.2. Evaluation of pollution-related stress factors

3.2.1. Sulfur impact

The number of plots of the Austrian Bioindicator Grid with exceedances of the legal standard decreased markedly from 1995 (26% of the plots) to 2000 (8%), but imports from neighboring countries still is significant. This could be illustrated by the SO₂-emissions of the power plant Sostanj running in Slovenia which is located 30 km south of the border of Austria. In 1991, the SO₂-emissions amounted to 90,000 tons which represents 90% of the total Austrian output (Fig. 3; Stefan and Fürst, 1998). Results from the Austrian Bioindicator Grid (Fürst et al., in preparation) additionally supported by the continuously ongoing SO₂-measurements in Austria, the transboundary impact could be proved and is demonstrated for the year 2000 in Fig. 3.

3.2.2. Proton input

On sensitive stands in Austria with acidic parent material such as granite and quartzine, the Critical Load of $<0.25 \text{ kg H}^+ \text{ ha}^{-1} \text{ yr}^{-1}$ is exceeded. At the sampling plots located in these sensitive areas within the Austrian Level II grid, exceedance of the Critical Load was observed. The H^+ input 1996–2001 scored $0.32 \text{ kg H}^+ \text{ ha}^{-1} \text{ yr}^{-1}$ (Smidt, 2002).

Proton-sensitive forested regions could be distinguished by analysing the data of the Austrian Forest Soil Inventory (Forstliche Bundesversuchsanstalt, 1992b). Thereby four parameters (pH, base saturation, cation exchange capacity and content of Mn, Cu and Zn) were applied (Mutsch and Smidt, 1994). Carbonate-influenced soils (35% of the sample plots) are less sensitive against proton input. The remaining 65%, not carbonate-influenced soils, were differentiated on the basis of the number of lower deviations of these parameters (Table 5).

For the North Tyrolean Alps (380,000 hectares, 150,000 of these with crystalline bedrock), Critical Loads were mapped by Knoflacher and Loibl (1993, 1998) using a Steady State Mass Balance Model. The lowest Critical Loads ($<1.5 \text{ kg H ha}^{-1} \text{ yr}^{-1}$) were calculated for the silicate bedrock areas.

3.2.3. Lead input

In Austria, up to approx. $10 \text{ g Pb ha}^{-1} \text{ yr}^{-1}$ by wet Pb deposition could be measured (Amt der Oberösterreichischen Landesregierung, 2002). In the framework of a one-year measuring campaign of wet, dry and occult deposition (fog, dew) in the North Tyrolean Limestone Alps the share of occult Pb deposition at 1758 m a.s.l. resulted in a 2-fold Pb-input compared to the valley station (920 m): During the measuring period the Pb input amounted to $17.4 \text{ g ha}^{-1} \text{ yr}^{-1}$ at 1758 m and to $9.9 \text{ g ha}^{-1} \text{ yr}^{-1}$ at 920 m a.s.l. Although these inputs are low, accumulation over years may result in

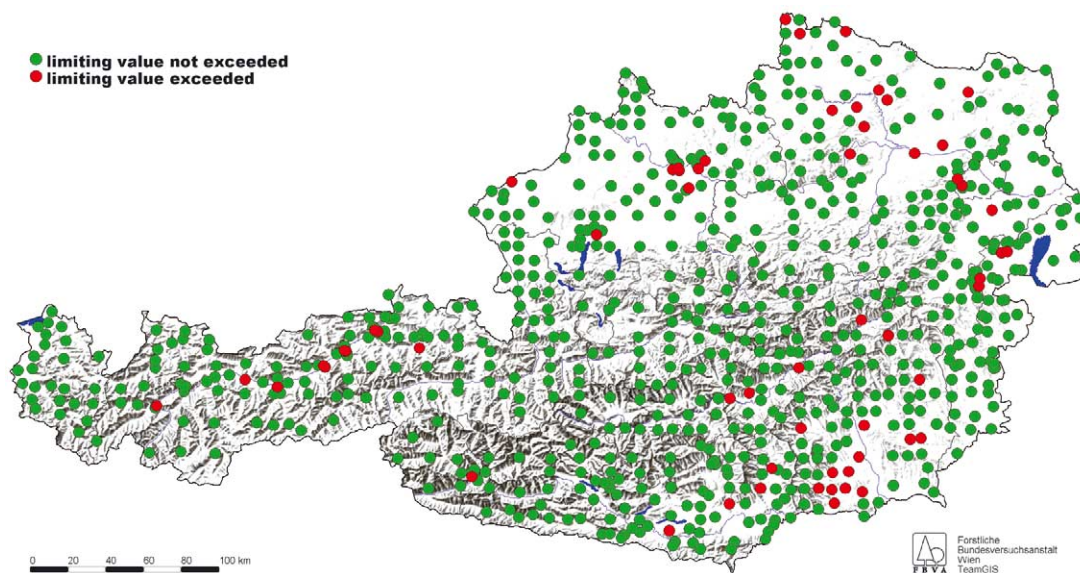


Fig. 3. Austrian Bioindicator Grid (2000): sulfur impact. Red: exceedance of the legal limit values (1100 ppm for *Picea abies* needles of year 1; 1400 ppm for needles of year 2; green: no exceedance of these limit values.

Table 5

Number and percentages of carbonate-influenced and carbonate-free sample plots of the Austrian Forest Soil Monitoring System and their possible endangerment by proton input (Mutsch and Smidt, 1994)^a

	Number of plots	Percentage of the plots
Carbonate-influenced	181	35
Not carbonate-influenced	333	65
No endangerment (1 lower deviation)	104	20
Endangerment possible (2 lower deviations)	123	24
Endangerment (3 lower deviations)	25	5
Endangerment (4 lower deviations)	5	1

^a Limit values pH = <4.2 , base saturation = $<18\%$, cation exchange capacity = $<100 \mu\text{mol g}^{-1}$, Mn = $<200 \text{ ppm}$ or Cu = $<14 \text{ ppm}$ or Zn = $<14 \text{ ppm}$. Classification: Class 1–4: 1–4 lower deviations from the limit values.

Lead accumulation index for forest soils

Ratio of total lead content
in soil layer 0–10 cm versus 30–50 cm

- < 1,40 no accumulation
- 1,41–2,00 low accumulation
- 2,01–4,00 medium accumulation
- > 4,00 high accumulation

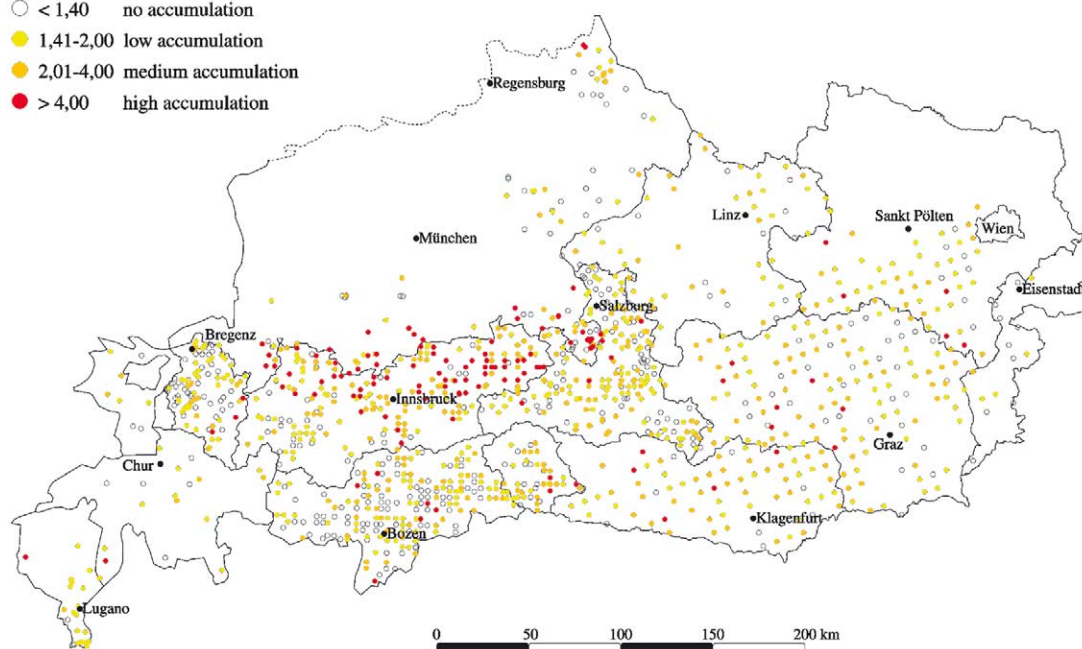


Fig. 4. Lead accumulation index for forest soils (Herman et al., 2001).

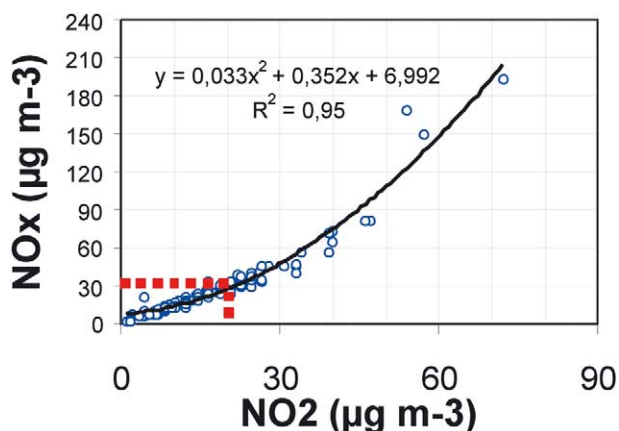


Fig. 5. Annual mean values of NO_2 vs. NO_x at Austrian forested stations.

an enhanced risk to forest ecosystems and groundwater quality (de Vries and Bakker, 1996; Mutsch, 1998; Stopper, 2001).

The altitudinal effect could also be shown with the soil data of the Austrian Forest Soil Monitoring System. Moreover, Pb showed remarkable enrichments in the organic top layer and upper layers of the mineral soil as compared to the subsoil and the concentrations in the soil increased clearly with the altitude (Mutsch, 1992, 1998).

The Pb input into the soil was evaluated by the “Lead Accumulation Index” (Table 2). With this criterium, differently polluted regions in Central Europe could be mapped. Significant Pb input was proved, especially in those parts of the Alps where north and west influenced weather situations mainly occur. In these “Nordstaulagen” high amounts of precipitation and a high flow of air masses are characteristic (Huber and Englisch, 1998; Herman et al., 2001) (Fig. 4).

The increase of heavy metal pollution over Austria with altitudes above sea level could be demonstrated by using mosses as accumulating bioindicators (Zechmeister 1995a, 1997). Heavy metal content in mosses is correlated with the heavy metal pollution status. At the altitudinal profile in the North Tyrolean Limestone Alps, the Pb concentration increased linearly from $17 \mu\text{g Pb g}^{-1}$ d.w. (920 m a.s.l.) to $40 \mu\text{g Pb g}^{-1}$ d.w. (1660 m a.s.l.; Zechmeister, 1995b).

3.2.4. Nitrogen

NO and NO_2 data from 39 stations in forested areas are available for 1990–2000 (Umweltbundesamt, 2002). The effect-related NO_2 -limit value for the annual mean value ($30 \mu\text{g NO}_2 \text{ m}^{-3}$) of the Österreichische Akademie der Wissenschaften (1989) was exceeded only five times, whereas on the basis of the more stringent European NO_x -limit ($30 \mu\text{g NO}_x \text{ m}^{-3}$) 45 exceedances were observed. Fig. 5 demonstrates, that an annual mean

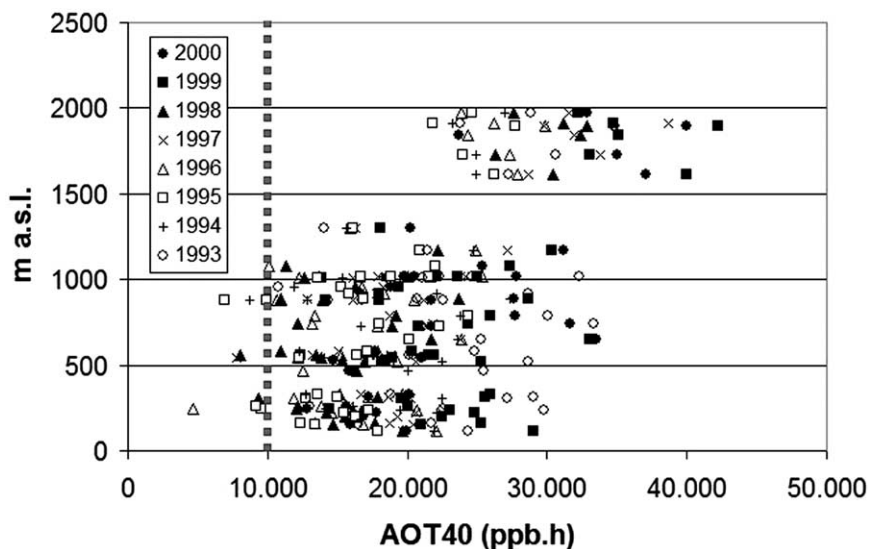


Fig. 6. AOT40 values (ppb.h) vs. altitude a.s.l. at 39 Austrian forest stations (1993–2000). Dotted line: AOT40 limit value.

value of approx. $20 \mu\text{g NO}_2 \text{ m}^{-3}$ corresponds to an annual mean value of $30 \mu\text{g NO}_x \text{ m}^{-3}$.

For the evaluation of N deposition, the Critical Loads regarding eutrophication and nutrient imbalances were applied. The Critical Loads range from 10 to $20 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ depending on the stand composition (WHO, 1995). On the 20 Austrian Level II plots the N input ranged from 4 to $25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the investigation period 1996–2001 (Smidt, 2002). Similar results were obtained within the Austrian WADOS-network: the wet-only depositions at the 31 plots ranged from 2 to $21 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the period 1993–1995 (Kalina and Puxbaum, 1996a,b; Limbeck et al., 1998).

For the area of the North Tyrolean Limestone Alps, the Critical Loads for N were modelled and mapped. The Critical Loads in limestone areas are within a range of 4 and $31 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and in silicate areas between 9 and $18 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. The special distribution of the Critical Loads is usually inversely related to the altitude of the site (Knoflacher and Loibl, 1998).

Risk assessment of eutrophication in the context of N atmospheric deposition has to be taken into account. Results from experiments with varying N supply (Wright and Tietema, 1995; Tietema et al., 1998) indicate, that enhanced N input can influence the turnover processes in the soil and lead to enhanced NO_3^- concentrations in the groundwater (Hagedorn, 1999). From 1997 onwards, the N pools and fluxes have been measured and calculated in the North Tyrolean Limestone Alps. The N status, the budget using internal fluxes in the above-ground and below-ground compartments, turnover processes in the soil, saturation and the impact of the N status on the groundwater quality were investigated (Smidt et al., 2002). The N input exceeded the Critical Loads (Kalina et al., 1998, 2002). However, the N discharge did not stem from deposition but from

processes within the system (Haberhauer et al., 2002; Härtel-Rigler et al., 2002).

3.2.5. Ozone

The AOT40-values were calculated for 39 Austrian stations (Umweltbundesamt, 2002). Fig. 6 outlines that the AOT40 limit of 10 ppm.h is exceeded in most cases. The AOT40 increases with altitude.

For a country-wide illustration of the O_3 impact in forested areas, the exceedances of the AOT40 were estimated in a first approach based on an empirical model and hourly O_3 monitoring data of approx. 100 monitoring sites in Austria. The exceedances were accumulated for every hour using all daylight hours during the summer half year 1993. The Critical Level was exceeded up to 5-fold (Smidt and Loibl, 1996; Bolhar-Nordenkamp et al., 1999). In the Austrian Alps, the exceedances were highest along the high elevated northern slopes and in the Southern Alps.

As those patterns of high Critical Level exceedances do not reflect the forest health status in Austria (Federal Research Centre, 1998), a second approach was made. Thereby climate conditions responsible for stomata opening (temperature, solar radiation and relative humidity; Loibl et al., 1999; Fig. 7) were taken into account. This new approach led to a significant reduction of the calculated O_3 risk in low elevation regions. This reduction was less pronounced in higher elevation regions.

In the course of interdisciplinary research projects in the field, it was proved that under the present O_3 level, old trees show measurable reductions of CO_2 uptake. This result was particularly applicable at high altitudes if trees were influenced through additional climatic stress (Bolhar-Nordenkamp and Lechner, 1989; Lütz et al., 1998). Furthermore, higher levels of antioxidants pro-

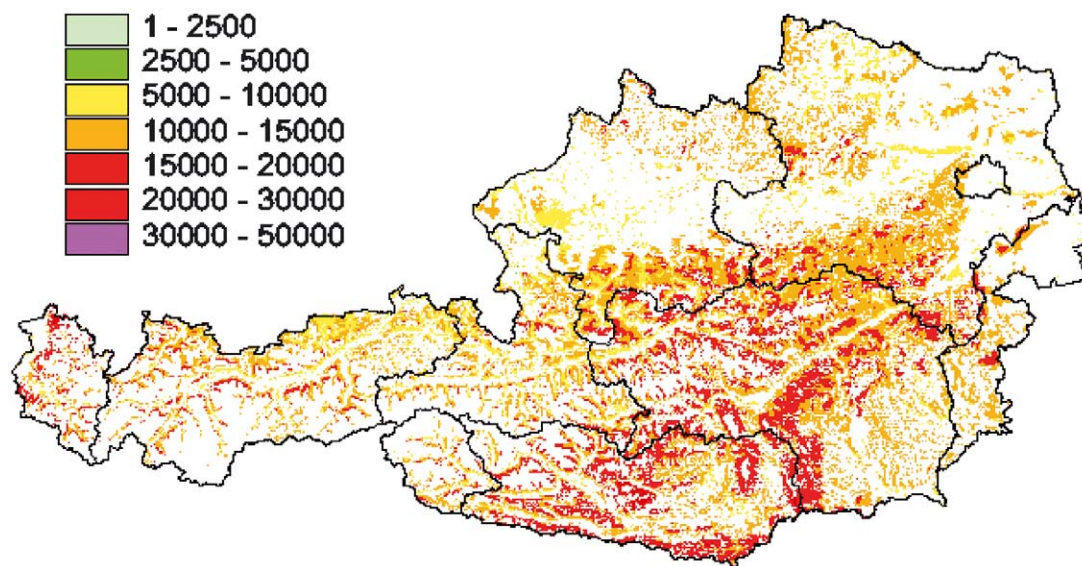


Fig. 7. AOT40 exceedances in Austrian forest areas during daylight hours considering effects of climatic factors on stomata opening and ozone uptake by plants (units: ppb h).

protecting plants from oxidative stress were found. Such phenomenon can be caused by pollutants (e.g. O_3), but also by natural stresses occurring at high elevations: Antioxidants in needles (e.g., ascorbate, thiols) increase with altitude, indicating increased protection from oxidative stress. Using principal component analysis and a cluster analysis of the biochemical results (pigments, pigment ratios, peroxidase activity), forest sites could be classified with regard to pollutant stress and oxidative stress (Tausz et al., 1998).

Within the framework of the intensive monitoring of forests in Europe (ICP Forests, Level II), injuries to vegetation induced by O_3 are investigated (Günthardt-Goerg et al., 2000; Innes et al., 2001). First assessments of visible symptoms in Austria were performed on one site of the Level II grid in the Vienna woods predominantly composed of deciduous trees. On *Fraxinus excelsior*, the brown stippling was assigned to O_3 impact and therefore this species is regarded as a suitable indicator species for O_3 impact. On *F. sylvatica* foliage a very fine brown stippling was observed, which could also be assigned to O_3 . However, because of the indistinct expression of this symptom *F. sylvatica* is regarded as a doubtful indicator for O_3 impact symptom assessments. For the Austrian main tree species *P. abies*, the symptoms could not be unmistakably attributed to O_3 phytotoxic effects.

4. Conclusions

The results of the monitoring network, interdisciplinary forest decline research projects and calculation and mapping of Critical Thresholds demonstrated that air pollutants are still a risk to Austrian forest ecosystems. Due to industrial emission reduction activities

in Austria and the neighbouring countries, the air quality shifted from an acidic to a more oxidant pollution mixture. Especially in the mountain forests, increasing levels of oxidant pollutants, e.g. O_3 , are the main problem. Due to the long-term accumulation, Pb input can also lead to a risk at high elevation ecosystems. The effect of the pollution input to the reaction of trees is detectable based on plant-physiological measurements and by the assessment of visible injury symptoms.

Future activities in Austrian Mountain forests should focus on the:

- evaluation of the effect of the reduction of S emissions based on the bioindication method to display the ongoing impact in various parts of Austria;
- evaluation of the effect of the reduction of Pb-emissions based on the repetition of the sampling within the Austrian Forest Soil Monitoring System and on existing long-term investigation plots,
- improved understanding of risks of O_3 and N deposition effects on mature trees based on physiological measurements and statistical evaluations including the present knowledge, and
- providing information needed for further developments of the Critical Level and Critical Load concepts.

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