PHYTON

ANNALES REI BOTANICAE

VOL. 32, FASC. 2 PAG. 177–320 29. 12. 1992

Phyton (Horn, Austria)	**Vol. 32**	Fasc. 2	177–200	29. 12. 1992

Ecosystem Studies at Different Elevations in an Alpine Valley *)

By

S. SMIDT and F. HERMAN **)

With 5 Figures

Received October 15, 1991

Key words: Altitude profile, air pollution measurements, plant analysis, early diagnosis of plant stress.

Summary

SMIDT S. & HERMAN F. 1992. Ecosystem studies at different elevations in an Alpine valley. – Phyton (Horn, Austria) 32 (2) 177–200, with 5 figures. – English with German summary.

The project "Altitude Profile Zillertal" is a contribution to the Austrian forest ecosystem research program. The main goal was an interdisciplinary investigation of interactions of air pollutants and various ecological parameters. Among other studies within this project several (potentially) phytotoxic air pollutants were measured as well as various ecological parameters. Among other studies within this project several (potentially) phytotoxic air pollutants were measured as well as various compounds in plant material; plant physiological paramters were used to describe the natural and anthropogenic induced stress patterns caused by different environmental conditions (at different altitudes, daytimes and seasons).

---

*) The Project „Altitude Profile Zillertal" (Tyrol, Austria) – Ecosystem Research of the Federal Forest Research Institute.

**) Dipl.-Ing. Dr. St. Smidt, Forstliche Bundesversuchsanstalt, Institut für Immissionsforschung und Forstchemie, Seckendorff-Gudent-Weg 8, A-1131 Wien.

The mean concentrations of SO_2, NOx, NH_3, hydrocarbons and of particular pollutants (NO_3^-, NH_4^+ etc.) decreased from the valley bottom up to the timberline, whereas ozone concentrations increased. Ozone concentrations exceeded effect-related limiting values especially above the valley bottom, and the "very sensitive" European larch *(Larix europea)* seems to be mostly endangered. On the other hand the Norway spruce *(Picea abies)* appeared to be less ozone sensitive during fumigation experiments in the field. Comparisons between different meteorological situations and ozone concentrations showed e. g., that high ozone cencentrations were observed during foehn periods and high pressure situations.

The mean ion concentrations in wet depositions (rain and snow) decreased with increasing elevation except the hydronium ion.

The contents of N, Mg, S, Pb and Cd in the needles of Norway spruce decreased with elevation, and organic compounds (e. g. ascorbic acid, thioles, peroxidases, pigments) showed different kinds of altitudinal dependence. The Pb-content in the needles disclosed occasionally an indication of anthropogenic input. No connection between heavy metal content in the needles and soil samples was noted.

Within the stress physiological concept the measurement of chlorophyll fluorescence (as a parameter for quantifying plant stress) was a practical method for detecting disturbed photosythetic capacity also in the field, when other parameters were analysed simultaneously for the interpretation of the stress causes.

The results provide further knowledge about:

- vertical gradients of various parameters (air pollutants; meteorological parameters; contents of nutrients, pollutants and biochemical compounds in needles) and the possible interactions with plant stress;
- season dependent variation of pollutants in the air and in needles;
- connections between pollutant concentrations in the ambient air and meteorological parameters;
- the possibility of interpretation of the air quality data with regard to effect related limiting values;
- methods which shall be applied for early diagnosis of plant stress.

Zusammenfassung

SMIDT S. & HERMAN F. 1992. Ökosystemare Studien in einem alpinen Tal. – Phyton (Horn Austria) 32 (2); 177–200, 5 Abbildungen. – Englisch mit deutscher Zusammenfassung.

Das von der Forstlichen Bundesversuchsanstalt bearbeitete Gemeinschaftsprojekt „Höhenprofil Zillertal" stellt einen Beitrag zur österreichischen Waldökosystemforschung dar. Das Hauptziel war eine interdisziplinäre Untersuchung von immissionsökologischen Fragen im Zusammenhang mit „neuartigen Waldschäden". Im Rahmen des umfangreichen Projektes wurden auch zahlreiche (potentiell) phytotoxische Luftschadstoffe und Pflanzeninhaltsstoffe sowie pflanzenphysiologische Parameter zur Charakterisierung von natürlichen und anthropogenen Stressoren unter verschiedenen Bedingungen (Seehöhe, Tages- und Jahreszeit) gemessen.

Die mittleren Konzentrationen von SO_2, NOx, NH_3, Kohlenwasserstoffen und partikulären Luftschadstoffen (NO_3^- NH_4^+ u. a.) waren am Talboden am höchsten und nahmen mit zunehmender Seehöhe ab. Demgegenüber nahmen die Ozonkonzentrationen deutlich bis zur Waldgrenze zu, wobei wirkungsbezogene Grenzwerte überschritten wurden; sie stellen eine zunehmende potentielle Gefährdung der

empfindlichen Vegetation (insbesondere der Lärche) dar. Demgegenüber erwies sich die Fichte aufgrund von Langzeit-Freilandbegasungsversuchen mit Ozon als wenig empfindlich. Bei der Untersuchung des Zusammenhanges zwischen Wetterlagen und Ozonkonzentrationen ergaben sich relativ hohe Konzentrationen während Föhnsituationen oder Hochdruckwetterlagen. Die mittleren Ionenkonzentrationen in nassen Depositionen nahmen mit Ausnahme der H-Ionen mit zunehmender Seehöhe ab.

Einen Höhengradienten in Form einer deutlichen Abnahme zeigten auch die Gehalte an N und Mg in Fichtennadeln sowie die S, Pb und Cd-Gehalte; organische Verbindungen (z. B. Ascorbinsäure, Thiole, Peroxidasen, Pigmente) zeigten unterschiedliche bzw. inhaltsstoffspezifisch bedingte Höhengradienten. Zusammenhänge zwischen Pb- und Cd-Gehalten in Nadeln und im Boden konnten nicht gefunden werden.

Die im Rahmen der streßphysiologischen Erhebungen gemssene Induktionskurve der Chlorophyllfluoreszenz erwies sich für eine Streßdetektion im photosynthetischen Apparat und für eine praxisorientierte Anwendung als geeignet, wenn für die Interpretation der Streßursache weitere Parameter erhoben werden.

Die forstliche Relevanz der Ergebnisse ergibt sich u. a. aus Erkenntnissen über

- Vertikalprofile verschiedener Parameter (Luftschadstoffe; meteorologische Parameter; Pflanzeninhaltsstoffe) und den daraus ableitbaren Pflanzenstreß,
- jahreszeitliche Variationen von Schadstoffkonzentrationen in der Luft und von Inhaltsstoffen in Pflanzenmaterial,
- Zusammenhänge von Luftschadstoffkonzentrationen und meteorologischen Meßgrößen,
- die Beurteilung von Luftschadstoffdaten anhand von wirkungsbezogenen Grenzwerten,
- Methoden, die für eine Frühdiagnose von Pflanzenstreß geeignet sind.

1. Introduction

Some centuries ago the upper tree line was about one to several hundred meters higher than today and the main causes for the present situation are conversion of forest land into grazing land, over-use for mining purposes and forest fires. Because of increasing problems with avalanches originating in the former forest belt, an afforestation program in many subalpine sites was startet in the fifties. Various setbacks occurred caused by fungal diseases and in the course of discussions around the "new-type-of-forest-decline" the question was raised which role air pollution plays in such subalpine sites. This was the background for initiating an interdisciplinary study called the Zillertal Project.

The investigations startet 1984 with special attention to air pollutants and their effects on ecological systems. The main goals were to describe the various time and altitude-dependent stress factors and the effects on the content of several needle compounds, the physiological reactions in needles as well as further description of marginal parameters (soil, biogenic factors etc.). These investigations were carried out by the Federal Forest Research Institute in cooperation with several institutes of universities.

Based on an extensive documentation of the actual "environmental situation", the investigations were intensified in 1988 by the stress physiological research concept which included plant physiological tests to measure the photosynthetic activity in spruce needles under seasonal and altitude influenced differing stress paterns due to varying meteorological and pollutant conditions.

The main goals of the investigations were:

- developing an inventory of the forest condition (condition of the crowns), characterization of the soils and the soil vegetation, description of the stress situation (concentrations of [potentially] phytotoxic pollutants in the air, in the wet depositions, in the soil und in plant material as well as the nutritional level in plant material depending on the altitude);
- evaluating air quality data with regard to (potential) effects on plants (considering effect-related limiting values);
- finding interrelations between meteorological conditions and the concentration of pollutants;
- finding a connection between stress patterns and photosynthetic activity (stress-physiological research concept) by the application of biochemical and physiological methods;
- documentating the development of pollutant inputs and of the nutritional status during the investigation period.

2. Materials and Methods

Investigation area and sample plots

The investigation area is situated on a southeast to east exposed slope on the Schwendberg in the Zillertal and runs from an altitude of 600 m up to 2140 m a.s.l. (Fig. 1 and Table 1). Belonging mainly to the sub-alpine spruce-fir forest, the sample

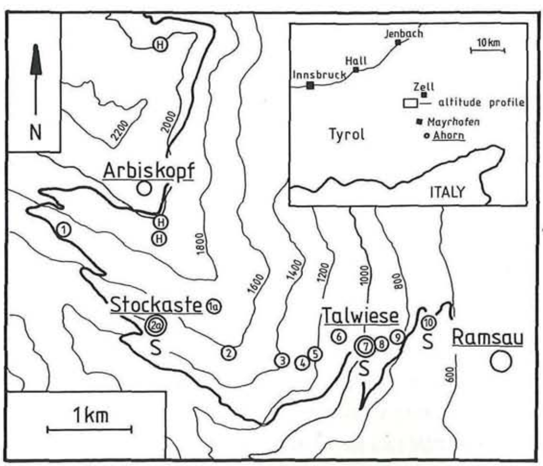

Fig. 1. Research and sample plots
Stockaste, Talwiese & Ramsau: container stations
S: sites of the stressphysiological research concept

Table 1

Measuring sites and investigations at the altitude profile

REG: SO_2-, NOx- and O_3-monitoring *(container stations)*

INT: K: O_3- and NOx-candles
- F: stack filters: gaseous HNO_3, SO_2, NH_3; NO_3-, SO_4- & NH_4-particles
- D: denuders: gaseous HNO_3, SO_2, NH_3, HCl, HCOOH, CH_3COOH; NO_3-, SO_4-, Cl- and NH_4-particles
- P: passive samplers: gaseous SO_2, NO_2, NH_3, HCl and HNO_3
- X: hydrocarbons

DEP: wet depositions (pH, conductivity, SO_4, NO_3, Cl, NH_4, Ca, Mg, Na, K):
- T: bulk-totalisators (*: an additional WADOS-sampler)
- S: snow-, hoar-frost and rime-sampling (additional fog analyses at the container stations)

MET: meterological measurements:
- T: temperature, relative humidity, pressure
- W: wind direction & wind speed

NEE: N: chemical needle analyses (N, P, K, Ca, Mg, S, Pb, Cd)
- B: biochemical needle analyses (thiols, ascorbic acid, peroxidases, chlorophyll, xanthophyll and carotines, lipides)

WZI: forest condition inventory

ENT: entomological investigations

MYC: mycorrhiza and fine root investigations

SOI: chemical soil analyses

VEG: V: determination of the ground flora
- A: chemical analysis of the ground flora

Phys: plant physiological investigations:
- C: measurement of the chlorophyll fluorescence (* additional measurement of CO_2-fixation)
- L: long-term measurements on a 65 year old Norway spruce tree

			Air quality			Needles/soil						Phys.
Station	a.s.l.	REG	INT	DEP	MET	NEE	WZI	ENT	MYC	SOI	VEG	
Arbiskopf	2140 m	–	KPD	S	TW	–	–	–	–	–	–	–
H1-H3	~2000 m	–	–	–	–	N	–	–	–	+	V	–
1	1720 m	–	K P	T S	T	NB	+	–	+	–	–	–
1a	1730 m	–	K	S	–	N	+	–	+	+	VA	C
2	1560 m	–	K	–	–	N	+	–	+	+	V	C
2a	1560 m	+	KFDPX	S	TW	NB	–	+	+	–	–	C*
3	1400 m	–	K	S	–	NB	+	–	+	+	V	–
4	1300 m	–	K	S	–	NB	–	–	+	+	V	–
5	1200 m	–	K	–	–	NB	+	–	+	+	VA	C
6	1140 m	–	–	S	–	NB	–	–	–	–	–	–
7	1000 m	+	KFDPX	T*S	TW	NB	+	+	+	+	V	C* L
8	930 m	–	–	–	–	NB	+	–	+	–	–	–
9	850 m	–	K P	S	T	NB	–	–	+	+	VA	–
10	700 m	–	–	S	–	NB	–	+	+	+	V	C*
Ramsau	600 m	+	KFDPX	T S	TW	–	–	–	–	–	–	–

plots 1–10 are represented by Norway spruce *(Picea abies)* and afforestations of the alpine highlands with Swisse stone pine *(Pinus cembra)*. The area, which is remote from industrial emittors, is polluted by local traffic and domestic sources.

Experimental arrangements

Air quality measurements

Continuous monitoring of gaseous pollutants (SO_2, NOx, O_3) has been carried out at three container stations since 1984 and 10 km south of the altitude profile ozone concentrations were also measured (Ahorn, 1950 m a.s.l.). Continuous summation measurements were performed with NOx- and O_3-candles from 1986 to 1989. Further summation measurements were done from April 1989 to July 1990 with Palmes tubes (SO_2, NO_2). In addition to measuring of the "classical" phytotoxic air pollutants, measurements of potentially phytotoxic compounds were performed selectively with stack filters and denuders during the same period (stack filters: 8 periods of 2 days each; denuders: 2 periods of 2 days each); hydrocarbons were measured with special tubes (2 series, July/August 1990) by gas chromatography after adsorption.

Wet falling depositions were collected with bulk samplers at three sites since 1984 in the field. Additional samplings regarding snow, rime and hoar-frost were taken during the winters 1986 and 1987, and fog was collected in 1989/90.

Meteorological measurements

Meteorological parameters were measured at the container stations and at three additional sites since 1984. The free valley atmosphere was studied in summer 1988 with SODAR (sonic detection and ranging) and tethered balloon soundings at the valley bottom to investigate the thermal and dynamic structure of the free valley atmosphere.

Chemical analyses of plant material

Chemical analyses of nutrients and pollutants in Norway spruce needles were made from 1984 to 1990 at 11 sites and in the three afforestation areas of Swiss stone pine. The analyses of organic compounds were made in 1989 at seven locations. Chemical analyses of nutrients and heavy metals in the ground flora were performed in 1984 and a full description was compiled.

Chemical soil analyses

Chemical analyses for nutrients, heavy metals and chemical parameters of the soil were investigated in 1984 and 1989.

Determination of lichens, mycorrhiza, fine roots and the vegetation.

The determination of vegetation was done 1984 at six sites. The mapping of lichens of the trees in the area between Zell/Ziller and Mayrhofen was done 1990 to indicate the zones influenced by airborne (acidulous) components. Investigations of the formations of mycorrhiza and fine roots were performed in 1989 at five sites.

Forest Health Survey

The number of green needle sets of eight selected Norway spruce sites (230 sample trees) was estimated yearly from 1986 to 1990 according to the methods of the Austrian Forest Condition Inventory (POLLANSCHÜTZ & NEUMANN 1987).

Physiological and biochemical investigations

The stressphysiological research concept: The aim of these studies was to test the variety of physiological reactions affecting the photosynthetic capacity (characterized by the $F_v/F_{max.}$-values; F_v = variable fluorescence, $F_{max.}$ = maximal fluorescence), which is very sensitive to any stress. The photosynthetic capacity was determined by measuring the chlorophyll fluorescence (with a portable Fluorimeter – Plant Stress Meter) and the light-dependent CO_2-fixation (measured with a portable CO_2-porometer). Additional investigations at six sites of the altitude profile (three trees on each site) were done in 1989 with the portable Plant Stress Meter.

Within the investigation framework three Norway spruce tress in 700 m, 1000 m and 1560 m a.s.l. were selected and their biotopes characterized. Therefore an extented investigation became necessary to describe the seasonal and altitude dependent stress patterns as well as the physiological and biochemical variations during the investigation period (January to August 1988). The following tasks had to be performed: air quality measurements, meteorological analyses and determination of invisible inversions, measurements of wet depositions, contents of nutrients, pollutants and organic compounds in needles; morphological, anatomical, histological and ultrastructural features of needles, forest entomological studies on mycorrhizae and fine roots as well as the characterization of the water potential were done.

Net photosynthesis and stomatal conductivity: Measurements with Waltz-chambers of the net photosynthesis and conductivity were undertaken during the vegetation months of a 65-year old Norway spruce in 1000 m a.s.l. from 1988 to 1990; five O_3 levels were applied to the twigs: 0 µg/m³ (= activated coal filtered air) ambient air (A), A + 60 µg/m³, A + 120 µg/m³ and A + 180 µg/m³ O_3.

Biochemical investigations: The applicability of biochemical parameters (contents of thiols, ascorbic acid, pigments, epicuticular waxes and lipides in Norway spruce needles) was tested to describe natural and anthropogenic stress situations.

Detailed information on the investigations, results and authors is given in Tab. 2.

3. Results

3.1 Airborne pollutants

The concentrations of air pollutants (measured with different methods and within different periods) were characterized by varying levels, daily variations and vertical gradients which lead, beside meteorological influences, to varying stress patterns of plants.

3.1.1. Contents of gaseous pollutants and aerosols

Sulfur compounds

Continuous monitoring of sulfur dioxide (SO_2) showed the highest concentrations at the valley bottom where the mean concentrations per month reached 48 µg/m³. The mean concentrations decreased with increasing elevation and at the mountain stations values up to 23 µg/m³ were measured (Fig. 2, above). The highest values were observed during the winter months. The effect-related SO_2-limiting values were exceeded only in February 1986, when a SO_2 episode was registered throughout Central Europe. Measurements of gaseous SO_2 with passive samplers (Palmes tubes) also showed decreasing mean concentrations up to 1560 m, but an unexplained increase at 2200 m a.s.l. during the measuring campaign 1989/1990 (mean concentrations 5.8 to 1.6 µg/m³).

The concentrations of SO_4-particles (dry deposition) measured with denuders were nearly constant (2.8–3.4 µg/m³) during the day and also at different elevations.

Nitrogen compounds

Like SO_2, the highest values of nitrogen dioxide (registring measurements) were obtained at the valley bottom during the winter; the monthly overall mean values reached 75 µg/m³ at the valley bottom and 10 µg/m³ at the mountain stations (Fig. 2, above). The NO_2-measurements exceeded the effect-related NO_2 limiting values of the ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN (1989) only at the valley bottom. Passive sampling (1989/90) with Palmes tubes also showed a pronounced decrease of the mean NO_2-concentrations above the valley bottom (2.4 to 0.1 µg NO_2/m³).

Continuous passive samplings of NOx (NO + NO_2) during 4 years with candles showed at an average a strong decrease above the valley bottom up to 1560 m a.s.l. and a light increase from 1560 m up to 2040 m a.s.l.

Sampling of nitrate particles showed a decrease with increasing elevation (grand averages of 2 denuder series: 0.45 to 0.08 µg/m³; grand averages of 8 stack filter series: 1.91 to 0.55 µg/m³; Fig. 2, above).

Concentrations of nitric acid aerosol measured with denuders showed a maximum at noon and a minimum during the night. An unpronounced height dependence was noted (minimal values at 1000 m a.s.l.; grand averages 0.35 to 0.94 µg/m³). The NO_3-behaviour was similar to that of SO_4 (Fig. 2, center).

Maximal denuder values of ammonium were found at the bottom of the valley: 2.3 µg/m³ (mountain: $\leq$0.94 µg/m³), whereas stack filter measurements resulted in concentrations between 1.19 and 0.66 µg/m³.

Ozone

The grand average ozone concentrations increased from the valley bottom up to the timber line (Fig. 2, center; analogous results were given by the summation method with O_3-candles at the 12 test plots). The ranges of the monthly mean values were from 11 to 152 µg/m³, the lowest monthly mean values were measured at the valley bottom, the highest at the 1000 m-station.

The ozone data were evaluated on the basis of the effect-related limiting values of the ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN (1989): The 0.5-h limiting value (300 µg/m³) was never exceeded. 20 % of the

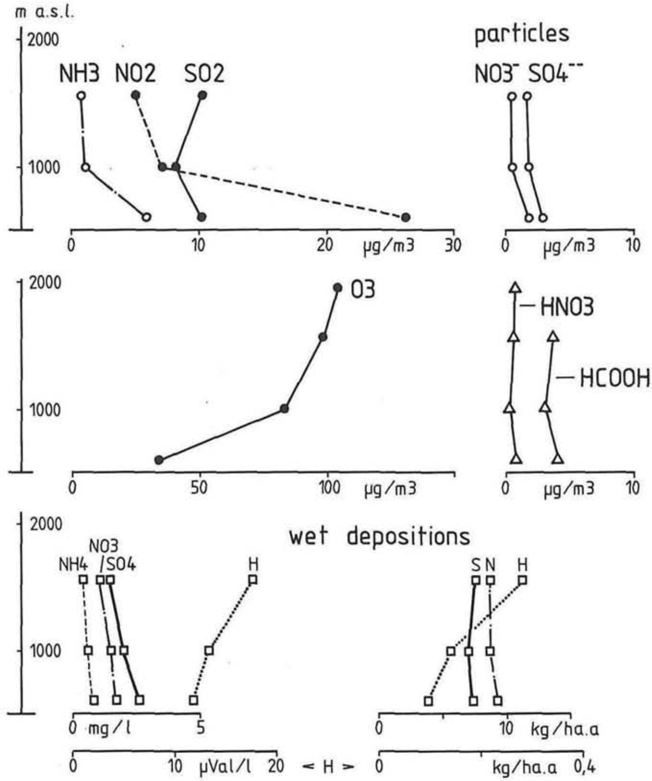

Fig. 2. Height dependence of the mean concentrations of airborne pollutants
● registring measurements (1986–1990)
○ stack filter measurements (8 series, 1989/90)
△ denuder measurements (2 series, 1989)
□ bulk collectors (1984–1990)
above: left: SO_2, NO_2 (registring measurements)
right: NH_3 and NO_3- and SO_4-particles (stack filters)
center: left: O_3 (registring measurements)
right: HNO_3 and HCOOH (stack filters),
below: left: SO_4, NO_3, NH_4- and H-concentrations (wet despositions)
right: H-, S- and N-deposition rates in wet depositions

1h-mean values were above the limiting value (150 μg/m³), and the 8h-limiting value (60 μg/m³) was almost always exceeded (Fig. 3). The limiting value for the vegetation period (60 μg/m³) was exceeded on all stations except at the valley bottom in 1990; Fig. 3).

The ozone concentrations between 1000 m and 2000 m a.s.l. were about 5–20 ppb higher than those recorded at the "mid-tropospheric" station Zugspitze (Bavaria/Germany), especially in spring and summer; this

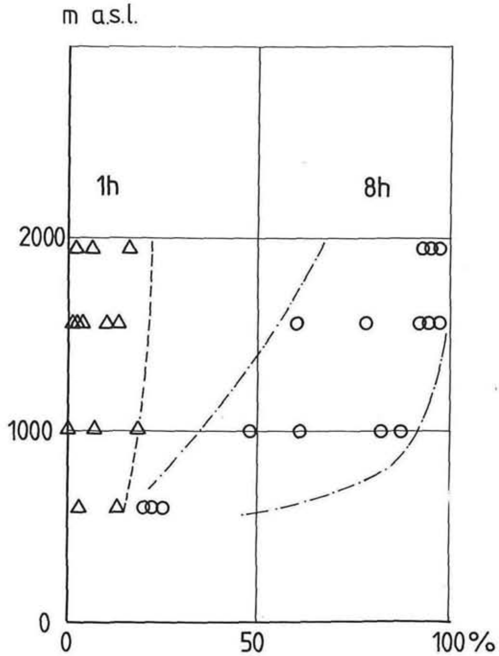

Fig. 3. Exceeding of ozone-limiting values (percentages of exceedings)
Limiting values according to the ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN (1989):
1h-limiting value: 150 µg/m³ (% exceedings: △)
8h-limiting value: 60 µg/m³ (% exceedings: ○)
(values projected to 100 % availability of the half-hour values [≥ 60 % availability])

phenomenon is called "ozone belly". The excessive ozone concentration demonstrates the additional effect of local and regional ozone production in addition to the general influx of ozone from the mid-troposphere.

Different meteorological conditions lead to contrasting ozone levels: relatively high ozone concentrations do not only occur on fair-weather days, but also during foehn situations (the latter are connected with high wind speed, relatively low humidity and rather high temperatures); this could be shown on the basis of the O_3 daily means of three alpine altitude profiles (Loisachtal and Nonntal/Bavaria, Zillertal). Of great influence on the O_3-concentrations at the valley bottom are the relative humidity, the NO-concentration and wind velocity.

Hydrocarbons

During the two measuring campaigns 45 (also biogenic) hydrocarbons could be identified (detecting limit 0.1 µg/m³). The mean concentrations were 262 ppbC (Ramsau), 152 ppbC (Talwiese) and 80 ppbC (Stockaste) respectively. The biogenic content in the samples was up to 40 %.

Organic acids

The mean concentrations of formic, (Fig. 2, center), acetic and lactic acid measured with denuders showed a slight height dependence from 600 to 1560 m a.s.l.

3.1.2 Ion contents in wet depositions

The mean ion concentrations, except the hydronium ion in wet depositions (rain and snow), decreased with increasing altitude.

On the other hand, the mean sulfur and nitrogen inputs were approximatively equal at all three levels, whereas the hydronium input increased markedly with increasing altitude (Fig. 2, below). Analogous decreasing ion concentrations were found in winter depositions, however remarkably high NO_3- and SO_4-concentrations were observed in rime at the 2340 m site.

3.2 Meteorological studies

The structure of the vertical temperature profiles in the valley atmosphere was studied comparing monthly averaged mean values of the slope stations and also describing the daily and seasonal variation of the temperature. Below a height of 1500 m a.s.l. the vertical temperature structure showed a strong variation by season and by daytime: during spring and during the early afternoon at all seasons the lapse rate was least stable, during autumn and during the early morning at all seasons the lapse rate was most stable. Further studies of the temperature structure of the free valley atmosphere were conducted with tethered balloons and SODAR soundings during a summer measuring campaign to verify the slope results.

The comparison of the ozone concentrations (daily mean and the average of the maximum half-hourly means) with eight dominant weather situations in the Alps (4–9/1987) showed that high ozone concentrations were connected with high pressure weather situations.

3.3 Contents in plant material

3.3.1 Needles of Norway spruce

Nutrients: The chemical analyses of nutrients revealed malnutrition of nitrogen and magnesium, which worsened from the 700 m-sampling site up to the timberline. The adequacy regarding the other main nutrients (P, K, Ca) was mostly sufficient (Fig. 4, above).

Sulfur and heavy metals: The mean sulfur contents indicated a decreasing trend with increasing elevation. Up to 1000 m a.s.l. the limiting value of the 2nd regulation against forest damaging air pollutants (0.11 %

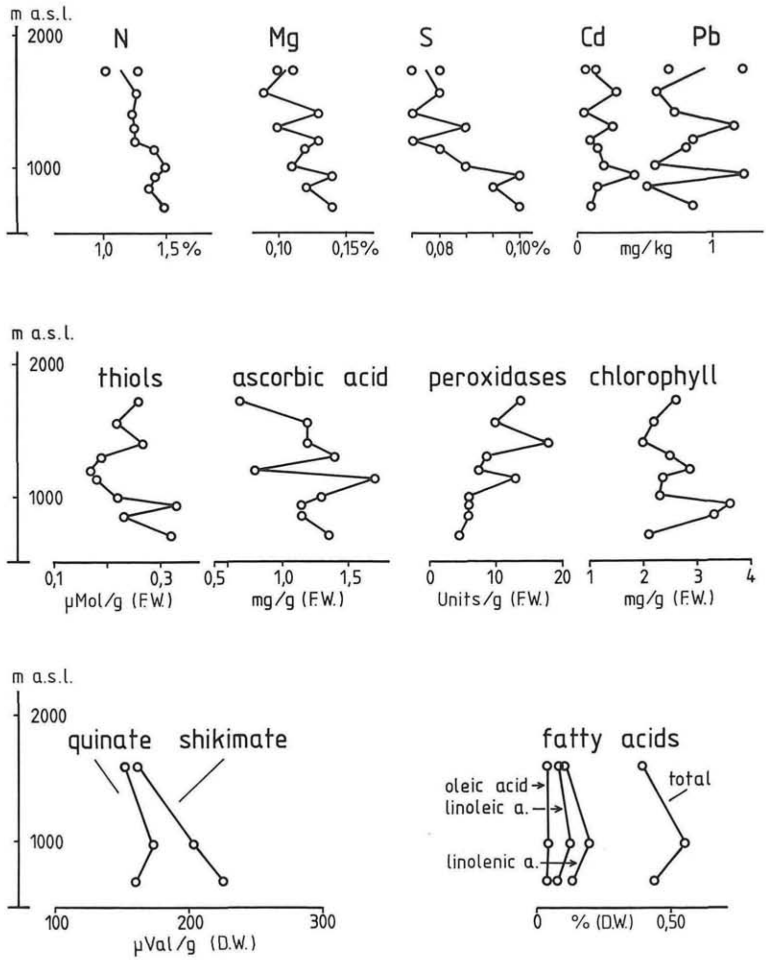

Fig. 4. Height dependence of the contents of nutrients, pollutants and organic substances in Norway spruce needles
(D. W.: dry weight; F. W.: fresh weight)

above: N-, Mg-, S- and Pb- and Cd-contents (D.W.); mean values (1984–1989)
center: thiols, ascorbic acid, peroxidases and chlorophyll contents (1988, needle year 1988)
below: left: shikimate and quinate
right: fatty acid contents (1988, needle year 1987)

sulfur) was exceeded in several years (Fig. 4, above). The Pb contents (up to 2.5 mg/kg) did not indicate excessive anthropogenic input and the Cd contents were minimal (up to 0.45 mg/kg).

Organic compounds: A different height dependence was observed for organic compounds. The contents of chlorophyll and other pigments decreased with increasing altitude, the thiols and ascorbic acid had a maximum at 1200 m a.s.l. and peroxidases showed a rather homogenous increase with increasing altitude (Fig. 4, center).

Mineral ion contents and the pattern of water soluble ionic constituents of Norway spruce needles showed normal contents, but light deviations from the results regarding total contents: relatively low N-, K-, Ca- and Mg-contents, normal microelement contents (order of magnitude: 5 ppm Cu, 80 ppm Fe and 50 ppm Zn; Fig. 4, below).

3.3.2 Needles of Swiss stone pine

The nutrient contents disclosed deficiencies of N, P and K. In the needles of the upland pines higher contents of Pb and Cd were found than in the spruce needles (up to 4.1 mg/kg Pb and 1.5 mg Cd/kg).

3.4 Lichens, mycorrhiza and soil vegetation

The framework of mapping of lichens was distinguished among four (from five possible) zones (1 = no pollution, 2 = slightly pollution, 3 = medium pollution, 4 = strong pollution). Zone 4 was only found on the valley bottom near the villages Hippach/Ramsau and Mayrhofen. Zone 3 was predominant and was also at the bottom of the valley. Zone 2 was situated just above the valley bottom up to 900/1000 m a.s.l. and zone 1 was at the levels above up to 2000 m a.s.l. The mycorrhiza types at the sample plots were different and it is concluded that the population of fungi in the soil consists of a multitude of species; the content of mycorrhizae was found to be normal. The soil vegetation and its chemical analyses have been described in detail by GLATTES & al. 1985.

3.5 Soil analyses

The soils of the six sample sites were all acidulous and extremely deficient of P, K and Ca, but the supply with nitrogen and organic matter was sufficient. The noticably elevated Pb and Cd contents in the upper layer as well as in the upper layers of the mineral soil in comparison with the lower layers permit the conclusion that pollution is present. Based on the analytical data no typical height gradient could be determined.

3.6 Crown conditions

The crown conditions of the eight sample areas over the five years of investigation indicated no more defoliation than normal and no significant height dependence was noted.

3.7 Physiological and biochemical investigations

3.7.1 The stress-physiological research concept

This sub-project demonstrated the applicability of methods for a causal analytical interpretation of the detectable damage for an early diagnosis of plant stress. The measurement of the photosynthetic capacity by chlorophyll fluorescence and light-dependent CO_2 fixation showed, that alterations of the photosynthetic capacity could be established whenever a comprehensive description of the tested tree and the surrounding area was done simultaneously.

3.7.2 Net photosynthesis and stomatal conductivity

Net photosynthesis and stomatal conductivity measured on the needles of the shade crown of the 65-year old Norway spruce at the 1000 m a.s.l. site indicated a significant reduction of net photosynthesis only when the needles were treated with ambient air ozone concentration + 180 µg O_3/m^3.

During a three month treatment of the needles of the sun crown with ambient air, the ozone flux was tested against filtered air. The needles showed no gas exchange alteration, but an increase of conductivity and a loss of the regulatory capacity after treatment with ambient air ozone concentration + 120 µg O_3/m^3.

3.7.3 Biochemical analyses

The chemical analysis of the lipid pattern of Norway spruce needles showed that saturated and unsaturated fatty acids were specifically altered due to varying environmental influence and showed different height dependent characteristics (Fig. 4, below). Therefore, this method is suited to recognize plant stress. The contents of organic acids (shikimate, quinate) showed low contents, but a differing height dependence could be proved (Fig. 4, below). Also the contents of thiols, ascorbate and pigments indicated different stress patterns due to airborne pollutants, which indicate photooxidative influence at the mountain sites (higher levels of thiols without elevated S-content of the needles and ascorbic acid; minor chlorophyll content in second and third needles class as well as a relatively higher Xanthophyll/Carotene quotient) and SO_2-influence near the valley bottom (high content of thiols in correlation with S-content of needles, lower ascorbic acid amounts and a chlorophyll maximum in the third needles age class).

3.7.4 Seasonal variations

The seasonal variations of several meteorological parameters and airborne pollutants potentially influence biochemical and/or biophysical reactions, e. g. during the sensitive needle flushing period in spring.

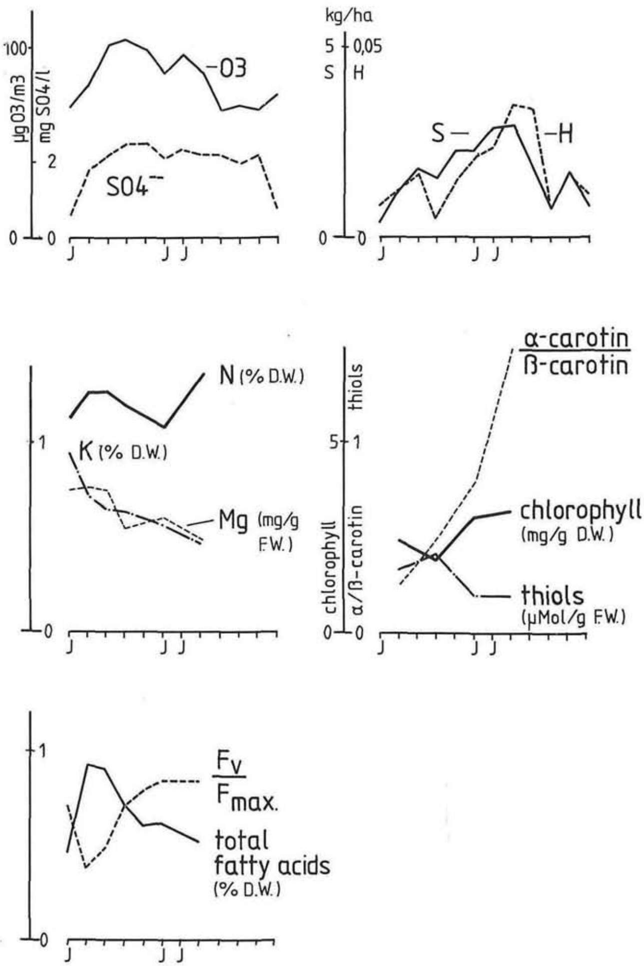

Fig. 5. Seasonal variations (Talwiese, 1000 m)

above: left: mean concentrations of ozone (ambient air, 1986–1990) und SO_4 (wet depositions, 1984–1990)

right: sulfur- and nitrogen depositions (wet depositions, 1984–1990)

center: left: nitrogen-, potassium- and magnesium contents (1988, needle year 1987)

right: α/β-Carotin, chlorophyll and thiols (1988, needle year 1987)

below: Fv/Fmax.-values and contents of total fatty acids (1988, needle year 1987)

Table 2.
Investigations and authors

Description of the area	Majer 1989
altitude profile	Glattes & al. 1989
highland afforestations	Donaubauer 1968, 1980
Air quality and meteorological measurements	
registring measurements	Smidt & al. 1988 a, b; 1990 a, b Smidt 1989, Smidt & Herman 1991 Glattes & Smidt 1987, Smidt & Leitner 1992
– ozone profiles	Puxbaum & al. 1991
– ozone profiles	Smidt & al. 1991 a, b
– ozone profiles	Gabler 1990, Gabler & al. 1991
– ozone limiting values	Smidt & al. 1991, Smidt 1991 b
O_3- and NOx-candles	Smidt & Leitner 1992
denuders/stack filters/Palmes tubes	Gregori & Puxbaum 1991, 1992
hydrocarbons	König & Puxbaum 1991
wet depositions	
– rain & snow	Smidt 1991 a, 1992
– snow, rime, hoarfrost	Stöhr 1987, 1988
setting up of containers	Plattner & Pausch 1992
temperature profiles	Kaiser 1989
tethered balloon, SODAR	Kaiser 1992
ozone and different weather situations	Werner 1990
ozone and foehn	Gabler 1990
Chemical analyses of plant material	
nutrients & pollutants in *Picea abies* (and *Pinus cembra*)	Glattes 1989, Albert 1989, Herman 1992, Glattes & Smidt 1987
nutrients and organic compounds in *Picea abies*	Albert 1989
thiols, ascorbic acid, pigments etc. in *Picea abies*	Bermadinger & al. 1989 Bermadinger & Grill 1992
nutrients/heavy metals in ground flora	Glattes & al. 1985 Karrer & Mutsch 1992
Chemical soil analysis	Glattes & al. 1985
Determination of lichens, mycorrhiza and soil vegetation etc.	
lichens	Hofman 1992
mycorrhiza	Göbl 1992
soil vegetation	Glattes & al. 1985
Forest condition inventory	Kristöfel 1992
Physiological investigations (stress-physiological research concept and further investigations)	
stress-physiological research concept	Bolhar-Nordenkampf 1989 Bolhar-Nordenkampf & al. 1988
chlorophyll fluorescence	Lechner & Bolhar-Nordenkampf 1989 a, b Bolhar-Nordenkampf & al. 1989

Table 2 – Continuation

CO_2-fixation	BOLHAR-N. & LECHNER 1989 a, b
gas exchange	WIESER & HAVRANEK 1990, 1992
	WIESER & al. 1991
plant stress meter	BOLHAR-N. & GÖTZL 1992
forest-entomological analysis	SCHMUTZENHOFER 1989
mycorrhizae	GÖBL 1989
nutrients	GLATTES 1989, ALBERT 1989
anatomical studies	DRAXLER & RUPPERT 1989
chloroplast ultrastructure	ZELLNIG & GAILHOFER 1989
thiols, ascorbic acid, pigments	BERMADINGER & al. 1989
lipids	PUCHINGER & STACHELBERGER 1989
water potential	HAVRANEK & WIESER 1989

As an example, the averaged monthly values of different parameters at the 1000 m-site are reproduced in Fig. 5. The seasonal variation of ozone and sulfate concentrations have a more or less pronounced "spring maximum", the sulfur and protone inputs have a maximum in autumn. N, K and Mg had a differing course during January–August (decrease of K and Mg, varying contents of N; Fig. 5, left). Chlorophyll, xanthophyll an carotines had a minimum in April and an increase up to August, thiols an increase to April and then a decrease till August (Fig. 5). The $F_v/F_{max.}$-quotient increased till February and decreased until August, the total fatty acids showed an inverse characteristic (Fig. 5, below).

4. Discussion

The main goal of the project "Altitude Profile Zillertal" was to investigate in the course of a year the following subjects along the profile in connection with the "new-type-of-forest-decline": characterization of the forest condition, measurement of the concentrations of pollutants in the ambient air, in plant material and in the soil, application of biochemical and biophysical methods in order to find connections between stress patterns and physiological reactions. The air quality data were evaluated with regard to effect-related limiting values for an endangerment prognosis of the local woodlands. The aim of the project is in some respect similar to that of the "Wank-project" (GESELLSCHAFT FÜR STRAHLENFORSCHUNG 1991) which was started 1987 in Bavaria, and therefore the results can be discussed together.

The results of the project "Zillertal" provided further knowledge about methodical attempts for the investigation of stress patterns in Norway spruce and about the occurrence of airborne pollutants up to the timberline. Related literature ist given in Table 2.

The installation of Alpine measuring stations, compared with stations in the fields, was connected with many difficulties as special precautions had to be taken against extreme weather situations (protection against storm and lightning resp. excess voltage).

The total stress acting on plants is determined by the combined action of biotic and abiotic impacts. The most important abiotic impacts are climate, nutrient deficiency and air pollutants, whereby climatic stress is increasing up to the timberline (e. g. extreme weather situations and shortened vegetation periods).

The vertical profiles of the measured air pollutants in the Zillertal in most cases indicate a decreasing input of "primary" compounds (gaseous SO_2, NOx and particles) and ion input (wet depositions) except the increasing protone input; also the mean ozone concentrations are increasing with altitude. As PUXBAUM & al. (1991) described, remarkable vertical ozone profiles were found, which were characterized by belly-shaped mean concentrations especially in spring and in summer (elevated concentrations compared with mid-trospospheric concentrations). The concentration profiles of SO_2 and NOx are caused by increased domestic smoke and traffic on the valley bottom. Differing mixtures of air pollutants result in varied stress patterns in different altitudes. The total input-related stress along an altitude profile therefore depends on the pollutant sources in the valley, the sensitivity of the vegetation, the orographical preconditions as well as the background pollution.

Near the timberline relatively high ion concentrations (SO_4, NO_3) in winter depositions (rime, hoar-frost) could be found in the Zillertal as well as a relatively high Pb-content in the needles of Swiss stone pine; also relatively high Pb-content in the upper layers of the soil were observed all over Austria by MUTSCH (1991). Furthermore, near the timberline relatively high levels of ozone concentrations are characteristic. These facts indicate an input over extended areas, but little is known of the effects on plants near the timberline.

Meteorological parameters are characterized by seasonal variations which are also altitude-dependent. They are characterized as follows (FLIRI 1975):

parameter	maximum	minimum
temperature	July/August	January
relative humidity –		
mountain stations	June/July	December
lowland/valley bottom	December/January	April
solar radiation	June/July	April
precipitation	July/August	var.

Due to these variations and the varying emissions and transmission preconditions, pollutant concentrations and inputs in the Zillertal (and at other stations in Austria) showed the following seasonal variations:

parameter	maximum	minimum
SO_2/NOx-concentrations	winter months	summer
ozone	spring (summer)	winter
SO_4-, NO_3-concentrations in wet deposition	spring	winter
S-, N-, H-input	July/September	December/January

The seasonal variation of these parameters result in a relatively high degree of stress particularly during the very sensitive leaf flushing period. Knowledge of the seasonal course of biochemical (thiols, ascorbic acid, pigmets as chlorophyll, xanthophyll, α/β-carotin) and biophysical parameters, which are connected with detoxification mechanisms, and the seasonal course of the photosynthetic activity are necessary for the interpretation of the differing stress patterns.

The investigations at the altitude profile Zillertal within the "early diagnosis of stress" program showed that the complex causes of wood diseases have to be investigated by intricate methods so that the influencing factors as well as the biochemical, biophysical and cell-anatomical reactions can be measured. Therefore, methods measuring the influence of the photosynthesis by an early diagnosis play a dominant role.

The analysis of organic compounds in the needles of Norway spruce (long term exposures in open-top chambers at low concentrations) suggest the following input-related alterations (BERMADINGER & al. 1990; ▽ decrease, △ increase, = no significant change):

parameter	SO_2	O_3	SO_2+O_3	climatic stress
thiols (glutathione)	△	▽	△△	△
ascorbic acid	(▽)	△	△△	
pigments	▽	=	▽	
glutathionreductase	▽	▽	▽	

In connection with the estimation of the endangerment of the woodlands the evaluation of air quality data according to effect-related limiting values of SO_2, NO_2 and O_3 gives an indication which compounds are affecting (sensitive) forest plants. Little is known about the combined effects of these compounds on plants with each other and with other (potentially toxic) compounds. According to most of the results of laboratory experiments it can be assumed that synergistic effects are also most likely in the field.

Long-term measurements of the influence of different ozone levels on a 65-year old Norway spruce in the Zillertal (WIESER & HAVRANEK 1992) indicated that the ambient ozone-concentrations did not affect the net photosynthesis. Furthermore, it could be shown that the actual O_3 concentrations give less evidence about the endangerment than the stomatal uptake, which is influenced by meteorological and other parameters (e. g. soil humidity). Therefore, lower concentrations during opened stomata might be more endangering than higher concentrations during closed stomata. That means that during foehn-situations, which are connected with elevated ozone concentrations (as GABLER [1990] found for the Zillertal and further Alpine stations), the uptake might be reduced as a reaction to the lower relative humidity and the elevated wind speed.

The degree to which pollutants are endangering forested uplands is not known at this time. It is also unknown to which degree the trees near the timberline are genetically adapted to impacts of airborne pollutants – especially to the natural ("mid-tropospheric") ozone concentrations – which could be shown at the altitude profile.

When discussing the endangerment of the vegetation by gaseous SO_2-, NOx- and O_3-concentrations, one has to distinguish between long-term and short-term concentrations as well as between the impact during and out of the vegetation period: e. g. peak-concentrations of SO_2 are most dangerous to plants and relatively low long-term concentrations of ozone and NO_2 may affect sensitive vegetation; furthermore NO_2-impacts in winter can affect sensitive evergreen plants. The effect of the input by wet deposition depends on the quality of the respective site (also the additional input by the crown must be taken into account). Furthermore, it must be pointed out that the evaluation of the effect of air pollutants on the basis of the leaf sensitivity and the effect on the photosynthetic activity may lead to different results. Therefore the interpretation of data with respect to possible effects on plant species and woodland ecosystems is based on a combined evaluation, including the connection between environmental and physiological data.

The evaluation of Zillertal and other Austrian and Bavarian ozone data showed that the concentrations near the timberline are characterized by relatively high long-term values which affect "very sensitive" plants. Therefore, especially the European larch (VEREIN DEUTSCHER INGENIEURE 1989) whose growing stock is increasing with rising altitude, seems to be potentially endangered. In contrast, the Norway spruce (and other "less sensitive" tree species representing approx. 75 % of the Austrian woodland) seems to be endangered to a lesser degree so that the ecosystem of woodlands in Austria appears not to be endangered by ozone.

Literature

ALBERT R. 1989. Mineralstoff- und Ionenhaushalt von Fichten entlang eines Höhenprofils im Zillertal. – Phyton 29 (3): 111–132.

BERMADINGER E., GRILL D. & GUTTENBERGER H. 1989. Thiole, Ascorbinsäure, Pigmente und Epikutikularwachse in Fichtennadeln aus dem Höhenprofil „Zillertal". – Phyton 29 (3): 163–186.

— & — 1992. Pflanzenphysiologische Untersuchungen am Höhenprofil Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

— , GUTTENBERGER H. & GRILL D. 1990. Physiology of young Norway spruce. – Environ. Pollut. 68: 319–330.

BOLHAR-NORDENKAMPF H. R. 1989. Streßphysiologisches Konzept einer kausalanalytischen Waldschadensforschung. – Phyton 29 (3): 11–14.

— & GÖTZL M. 1992. Chlorophyllfluoreszenzmessungen mit dem Plant Stress Meter. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

— & LECHNER E. G. 1989a. Saisonale und streßbedingte Modifikation der photosynthetischen Kapazität von Fichten im Höhenprofil „Zillertal". B. Lichtabhängige CO_2-Fixierung. – Phyton 29 (3): 207–228.

— & — 1989b. Synopse streßbedingter Modifikationen der Anatomie und Physiologie von Nadeln als Frühdiagnose einer Disposition zur Schadensentwicklung bei Fichte. – Phyton 29 (3): 255–302.

— , — & POSTL W. 1988. Perspektiven der Photosyntheseforschung zur Kausalität der neuartigen Waldschäden. – Forschungsinitiative gegen das Waldsterben, Symposium 27./28. 10. 1988, Univ. f. Bodenkultur, Proceedings 151–165.

— , LONG S. P. & LECHNER E. G. 1989. Die Bestimmung der Photosynthesekapazität über die Chlorophyllfluoreszenz als Maß für die Streßbelastung von Bäumen. – Phyton 29 (3): 119–135.

DONAUBAUER E. 1968. Zum Vorkommen von *Brunchorstia pinea* (Karst.) von Hoehn. in Österreich. – Anz. Schädlingsk. Berlin, 41. Jg., 2: 24–26.

— 1980. Über Pilzkrankheiten in Hochlagenaufforstungen. – Mitt. Forstl. Bundesvers. Anst. 129: 51–62.

DRAXLER G. & RUPPERT W. 1989. Anatomische Studien an geschädigten Fichtennadeln aus dem Höhenprofil „Zillertal". – Phyton 29 (3): 133–146.

FLIRI F. 1975. Das Klima der Alpen im Raume von Tirol. – Monographien zur Landeskunde Tirols, Folge 1 (LEIDLMEIER A. & HUTER F., eds.). – Universitätsverlag Wagner, Innsbruck–München.

GABLER K. 1990. Verhalten von Ozon in Alpentälern. – Symposium „Bodennahes Ozon", Gesellschaft Österreichischer Chemiker, 13. 11. 1990 (Proceedings pp. 149–167).

— , SMIDT S. & PUXBAUM H. 1991. Ozone profiles in Alpine valleys. – Euroanalysis VII, 26. – 30. 8. 1990 (Poster).

GESELLSCHAFT FÜR STRAHLENFORSCHUNG 1991. 2. Statusseminar der PBWU zum Forschungsschwerpunkt „Waldschäden" 4.–6. 2. 1991, Proceedings.

GLATTES F. 1989. Nähr- und Schadstoffgehalte von Nadelproben aus dem Höhenprofil „Zillertal". – Phyton 29 (3): 103–110.

— , Bolhar-Nordenkampf H. R., Gabler K., Leitner J., Majer C., Plattner J. & Zwerger P. 1989. Die Biotope der Probebäume im Höhenprofil „Zillertal“. – Phyton 29 (3): 15–38.

— , Smidt S., Drescher A., Majer C. & Mutsch F. 1985. Untersuchung einiger Parameter zur Ursachenfindung von Waldschäden am Beispiel eines Höhenprofiles im Zillertal/Tirol, erste Ergebnisse. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 9.

— & Smidt S. 1987. Höhenprofil Zillertal, Ergebnisse 1985. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 20.

Göbl F. 1989. Mykorrhiza- und Feinwurzelausbildung von Probebäumen des Höhenprofils „Zillertal“. – Phyton 29 (3)&: 97–102.

— 1992. Mykorrhiza- und Feinwurzelausbildung an Waldstandorten des Höhenprofiles Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Gregori M. & Puxbaum H. 1991. Forschungsprojekt trockene Deposition Zillertal. Teil A: Meßergebnisse. – Bericht 1/91 Institut für Analytische Chemie, Technische Universität Wien.

— & — 1992: Konzentrationsverteilung von Schwefel- und Stickstoffverbindungen sowie organischen Säuren am Höhenprofil Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Havranek W. M. & Wieser G. 1989. Zum Wasserhaushalt dreier Probebäume (Picea abies) im Höhenprofil „Zillrtal“. – Phyton 29 (3): 229–232.

Herman F. 1992. Nähr- und Schadstoffgehalte der Nadelproben des Höhenprofils Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Hofmann P. 1992. Immissionsbezogene Flechtenkartierung im Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Kaiser A. 1989. Die vertikale Temperaturstruktur der Atmosphäre im Zillertal. – Phyton 29 (3): 49–62.

— 1992. Analyse der vertikalen Temperaturstruktur im Zillertal anhand von Fesselballon-, SODAR- und Hangmessungen. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Karrer E. & Mutsch F. 1992. Vergleich chemischer Analysendaten von Pflanzen und Böden an 3 Waldstandorten am Höhenprofil Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

König G. & Puxbaum H. 1991: Höhenprofil Zillertal – Ozonpräkursoren, Kohlenwasserstoffe. – Bericht 18/91, Institut für Analytische Chemie, Technische Universität Wien.

Kristöfel F. 1992. Terrestrische Kronenzustandsinventur am Höhenprofil Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

Lechner E. G. & Bolhar-Nordenkampf H. R. 1989 a. Fallstudie „Höhenprofil Zillertal“, Chlorophyllfluoreszenz- und CO_2-Gasstoffwechselmessungen zur Detektion von saisonalen Modifikationen der photosynthetischen Kapazität bei *Picea abies*. – Int. Kongr. Waldschadensforschung, Friedrichshafen, Posterkurzfassungen Vol. 1, 210.

— & — 1989b. Saisonale und streßbedingte Modifikationen der photosynthetischen Kapazität von Fichten im Höhenprofil „Zillertal". A. Induktionscharakteristika der Chlorophylfluoreszenz. – Phyton 29 (3): 187–206.

MAJER C. 1989. Bodenkundliche Untersuchungen an drei ausgewählten Meßpunkten des Höhenprofiles „Zillertal". – Phyton 29 (3): 39–48.

MUTSCH F. 1991. Überblick zur Schwermetallsituation österreichischer Waldböden. – FBVA-Berichte Nr. 49, Schriftenreihe der Forstlichen Bundesversuchsanstalt, 39–48.

ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN 1989. Luftqualitätskriterien Ozon. Bundesministerium für Umwelt, Jugend und Familie.

PLATTNER J. & PAUSCH J. 1992. Aufbau und Betreuung von alpinen Luftmeßstationen. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

POLLANSCHÜTZ J. & NEUMANN M. 1987. Waldzustandsinventur 1985 und 1986. Gegenüberstellung der Ergebnisse. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 23.

PUCHINGER L. & STACHELBERGER H. 1989. Standortabhängigkeit der Lipiddynamik von Fichtennadeln. – Phyton 29 (3): 233–254.

PUXBAUM H., GABLER K., SMIDT S. & GLATTES F. 1991: A one-year record of ozone profiles in an Alpine valley. – Atmos. Environ. 25A: 1759–1765.

SCHMUTZENHOFER H. 1989. Forstentomologische Untersuchungen der Fauna von Fichtenkronen im Höhenprofil „Zillertal". – Phyton 29 (3): 63–68.

SMIDT S. 1989. Luftschadstoffmessungen am Höhenprofil „Zillertal". – Phyton 29 3): 69–84.

— 1991a. Immissionsmessungen nasse Deposition der Forstlichen Bundesversuchsanstalt. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 50.

— 1991b. Beurteilung von Ozonmeßdaten aus Oberösterreich und Tirol nach verschiedenen Luftqualitätskriterien. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 47.

— , GABLER K. & HALBWACHS G. 1991. Auswertung von österreichischen Ozonmeßdaten nach VDI 2310. – Staub 51: 43–49.

— , GLATTES F. & LETTNER J. 1988a: Höhenprofil Zillertal – Meßbericht 1986 (Luftschadstoffmessungen, meteorologische Daten, Niederschlagsanalysen). FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 26.

— , — , & — 1988b. Höhenprofil Zillertal – Meßbericht 1987 (Luftschadstoffmessungen, meteorologische Daten, Niederschlagsanalysen). – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 32.

— , HERMAN F. & LEITNER J. 1990b. Höhenprofil Zillertal – Meßbericht 1988 (Luftschadstoffmessungen, meteorologische Daten, Niederschlagsanalysen). FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt, Nr. 44.

— & — 1991. Projekt „Höhenprofil Zillertal/Tirol". – GSF-Berichte, in press.

— & LEITNER J. 1992. Luftschadstoffmessungen am Höhenprofil Zillertal. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

— , PUXBAUM H. & GABLER K. 1990a. Zur zeitlichen und vertikalen Zunahme der Ozonkonzentrationen. – Österreichische Forstzeitung, Informationsdienst, 247. Folge: 58–60.

STÖHR D. 1987. Schadstoffbelastung durch Reifdeposition entlang eines Höhenprofils im Zillertal. – Bericht über den Workshop der Forschungsinitiative gegen das Waldsterben, 5. und 6. 3. 1987 an der Univ. für Bodenkultur.

— 1988. Winterliche Schadstoffdeposition in einem inneralpinen Tal – am Beispiel des Zillertales. – Thesis Universität für Bodenkultur Wien.

VEREIN DEUTSCHER INGENIEURE 1989. Maximale Immissionskonzentrationen für Ozon, Richtlinie 2310, Blatt 6.

WERNER R. 1990. Wetterlagen und Ozon eines alpinen Hangprofiles. – 21. Int. Tag. für Alpine Meteorologie, Engelberg/Schweiz, 17.–21. 9. 1990; Proceedings pp. 279–283.

WIESER G. & HAVRANEK W. M. 1990. The influence of different O_3 concentrations on the gas exchange of Norway spruce in the field. – Proceed. Int. Kongr. Waldschadensforschung, Friedrichshafen, Okt. 2–6, 1989 (Proceedings, in press).

— & — 1992. Die Ozonaufnahme in der Sonnen- und Schattenkrone von Fichten, ein Maß zur Quantifizierung der physiologischen Wirksamkeit der Ozonkonzentrationen in der Luft. – FBVA-Berichte, Schriftenreihe der Forstlichen Bundesversuchsanstalt (in preparation).

— , WEIH M. & HAVRANEK W. M. 1991. Ozone fumigation in the sun crown of Norway spruce. – GSF-Tagung Passau, November 1990 (Proceedings, 24/91, 567–573).

ZELLNIG H. & GAILHOFER M. 1989. Feinstruktur der Chloroplasten von *Picea abies* verschiedener Standorte im Höhenprofil „Zillertal“. – Phyton 29 (3): 147–162.