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## Seasonal Ozone Uptake of Mature Evergreen Conifers at Different Altitudes

By

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**Key words:** *Picea abies*, *Pinus cembra*, ozone, stomatal conductance, tree age, altitudinal gradient.

### Summary

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Seasonal patterns of ozone (O<sub>3</sub>) uptake in mature Norway spruce and cembra pine trees were estimated at six rural sites between 580 m and 1950 m a.s.l. Seasonal variations in O<sub>3</sub> uptake reflect variation in both ambient O<sub>3</sub> concentration and stomatal conductance. At all the study sites the annual course in the O<sub>3</sub> regime exhibited seasonal cycles with maxima between April and July and minima in winter. Seasonal variations in stomatal conductance and O<sub>3</sub> uptake were mainly attributed to the course of the prevailing temperature. Average O<sub>3</sub> uptake rates decreased with increasing tree age. However, in trees similar in age O<sub>3</sub> uptake increased with increasing altitude.

### Introduction

During the past two decades, there has been increasing attention to the impact of ozone (O<sub>3</sub>) on coniferous forests, which are a major sink for O<sub>3</sub> in the lower troposphere (MATYSSEK & al. 1995, SANDERMANN & al. 1997). Within the

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canopy the needles are the primary sites of  $O_3$  deposition, with the stomata representing the interface for the  $O_3$  uptake from the atmosphere into the tree.  $O_3$  uptake however, depends both on ambient air  $O_3$  concentration and on stomatal conductance. In alpine regions mean  $O_3$  concentrations (STOCKWELL & al. 1977) as well as soil water reserves, relative humidity of the air and irradiance tend to increase with increasing altitude (FLIRI 1975). Consequently, trees at high altitudes are rarely forced to restrict their water loss (TRANQUILLINI 1979) so that  $O_3$  uptake may be high under the high-altitudinal  $O_3$  regimes. Furthermore, stomatal conductance and hence also  $O_3$  uptake has been reported to be affected by tree age (for a review see: KOLB & al. 1997). Thus our objectives were to characterise  $O_3$  uptake of forest trees of different age at various sites, in order to determine the impact of altitude and tree age on  $O_3$  uptake.

### Material and Methods

The study was carried out at six rural forest sites between 580 and 1950 m a.s.l. (Table 1).

Table 1. Study sites, altitude, tree species, tree age and period of investigation.

Station (country)	Altitude [m]	Species	Age [yrs]	Period	Reference
Klimahaus (A)	1950	<i>P. cembra</i>	65	1996	HAVRANEK & WIESER unpubl.
Davos (CH)	1660	<i>P. abies</i>	216	1987-1988	HÄSLER & al. 1991
Zillertal (A)	1000	<i>P. abies</i>	60-65	1989-1990	WIESER & HAVRANEK 1993
Lägeren (CH)	685	<i>P. abies</i>	127	1987-1988	HÄSLER & al. 1991
Aschenbrenner- marter (GER)	600	<i>P. abies</i>	65	1987-1989	KOCH & LAUTENSCHLAGER 1988, KOCH 1993
Grafrath (GER)	580	<i>P. abies</i>	17	1992-1993	GÖTZ 1996

During the period 1987 through 1996 seasonal courses of gas exchange were measured, tracking ambient conditions with fully climatized chambers (Walz, Effeltrich, Germany) in the upper sun crown of Norway spruce (*Picea abies* (L.) Karst.) and cembran pine (*Pinus cembra* L.) trees. Cembran pine has been chosen because data from spruce were not available at the highest altitude for this comparison. Furthermore, between these two conifer species there were no significant differences in maximum stomatal conductance as well as in the stomatal behaviour to changes in environmental conditions (WIESER 1999). Additionally, ambient  $O_3$  concentration and climatic parameters were measured in order to calculate  $O_3$  uptake according to:

$$FO_3 = [O_3] * gO_3$$

where  $FO_3$  is the uptake rate of  $O_3$  into the needles,  $[O_3]$  is the  $O_3$  concentration in the ambient air, and  $gO_3$  is the stomatal conductance for  $O_3$ . The latter was calculated by multiplying the conductance for water vapour by 0.613, the ratio of diffusivities of water vapour and  $O_3$ .  $O_3$  concentration inside the needles was assumed to be zero, because  $O_3$  concentrations in the leaf mesophyll are undetectable low (cf. TINGEY & TAILOR 1982, LAISK & al. 1989). Data were condensed to daily means. Cumulative  $O_3$  uptake (CU) was calculated as the uptake rate ( $FO_3$ ) integrated over time.

## Results and Discussion

### Seasonal trends

Variations in  $O_3$  uptake reflect variation in both ambient  $O_3$  concentration and stomatal conductance. Typical seasonal variations of ambient  $O_3$  concentration, stomatal conductance and  $O_3$  uptake are shown for 685, 1660 and 1950 m a.s.l. (Fig. 1).  $O_3$  concentration generally exhibited a seasonal cycling with maxima between April and July and minima during the winter (Fig. 1). The high summer values can be attributed to an accumulation of  $O_3$  precursors during sunny, hot and dry periods, such conditions favouring the photochemical production of  $O_3$  (STOCKWELL & al. 1997)  $O_3$  uptake was highest during the growing season and

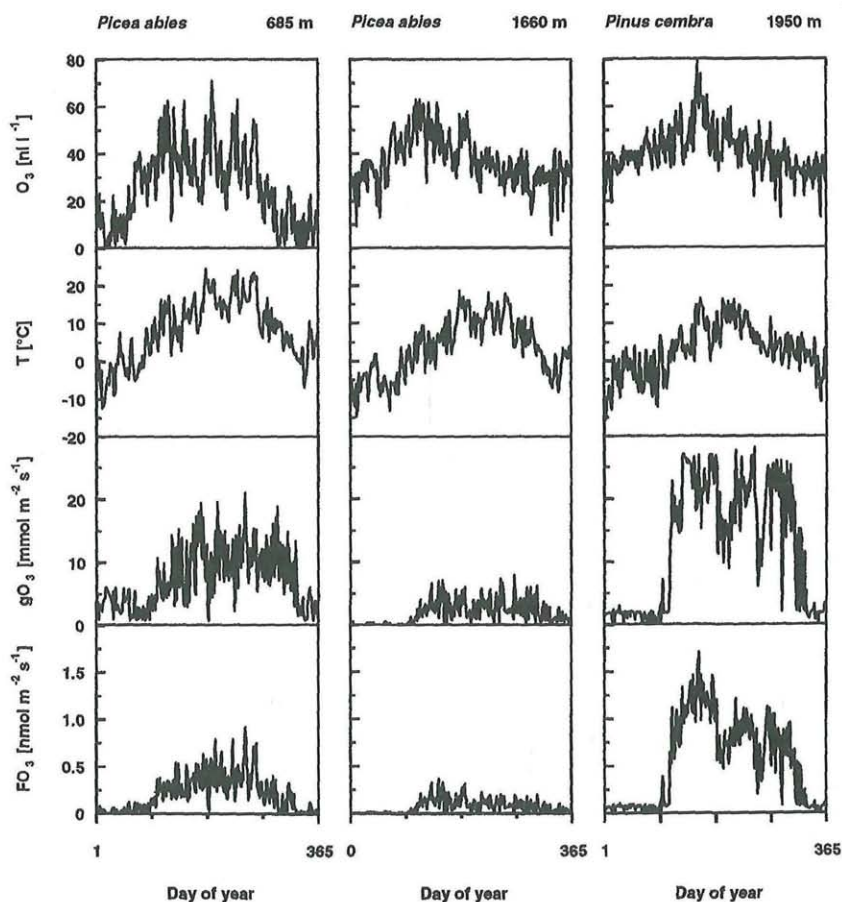


Fig. 1. Annual courses of daily mean ambient  $O_3$  concentration ( $O_3$ ), air temperature ( $T$ ), stomatal conductance for  $O_3$  ( $gO_3$ ) and  $O_3$  uptake ( $FO_3$ ) in the sun crown of Norway spruce (*Picea abies*, Switzerland) and cembran pine (*Pinus cembra*, Austria).

reached minimum values in winter, when the stomata were closed. The fall decline and spring increase in stomatal conductance and O<sub>3</sub> uptake was coincident with seasonal temperature trends (Fig. 1).

The average and maximum daily mean O<sub>3</sub> uptake rates and ambient O<sub>3</sub> concentrations estimated from May throughout October for all the years are summarised in Table 2. The magnitude of O<sub>3</sub> flux into the needles varied considerably and no clear trend with respect to altitude and ambient O<sub>3</sub> concentration could be observed (Table 2). However, the trees under study differed significantly with respect to tree age (Table 2). Tree age is known to affect stomatal conductance (for a review see KOLB & al. 1997), and hence also the potential for O<sub>3</sub> uptake. Therefore, we analysed the impact of tree age and altitude as single factors on its capacity influencing O<sub>3</sub> uptake.

Table 2. Average and maximum daily means of O<sub>3</sub> uptake rates (FO<sub>3</sub>, nmol m<sup>-2</sup>s<sup>-1</sup>) and O<sub>3</sub> concentrations (nl l<sup>-1</sup>) from May throughout October during the years of investigation.

Altitude [m]	Year	Species	Tree age [yrs]	Average FO <sub>3</sub>	Maximum FO <sub>3</sub>	Average O <sub>3</sub>	Maximum O <sub>3</sub>
1950	1996	<i>P. cembra</i>	65	0.90	1.71	45	80
1660	1987	<i>P. abies</i>	216	0.11	0.37	38	62
	1988			0.14	0.40	39	60
1000	1989	<i>P. abies</i>	60-65	0.84	1.91	37	43
	1990			0.35	0.68	29	27
685	1987	<i>P. abies</i>	127	0.33	0.92	34	71
	1988			0.30	0.83	38	72
600	1987	<i>P. abies</i>	65	0.62	1.41	30	66
	1988			0.48	0.99	40	77
	1989			0.46	1.10	41	77
	1990			0.58	1.35	42	80
580	1992	<i>P. abies</i>	17	0.71	1.66	40	75
	1993			0.50	1.08	25	51

#### Tree age related differences

Fig. 2 shows that O<sub>3</sub> uptake significantly decreased with increasing tree age.

As O<sub>3</sub> concentrations did not differ significantly between the environments for any tree size class, observed differences in O<sub>3</sub> uptake can for the most part be attributed to a decline in stomatal conductance with increasing tree age and tree size (data not shown) as also found by others (SCHOETTLE 1994, YODER & al. 1994, KOLB & al. 1997). FREDERICKSEN & al. 1996 also observed higher rates of O<sub>3</sub> uptake in mature canopy trees as compared to seedlings and saplings of *Prunus serotina*. The opposite however, has been reported for *Quercus rubra* by HANSON & al. 1994.

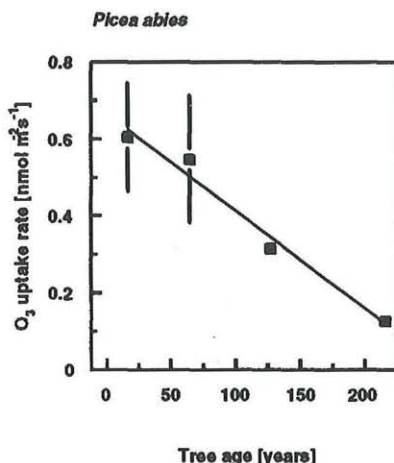


Fig. 2. Correlation of tree age and ozone uptake rate during the growing season (May throughout October) in the sun crown of Norway spruce trees (*Picea abies*) growing between 580 and 1660 m altitude). Measurements were made during the period 1987 through 1992 at a mean ambient O<sub>3</sub> concentration of  $36 \pm 5 \text{ nl l}^{-1}$ .  $n = 1$  to  $4 \pm \text{SD}$ . (see Table 2) The points were fitted by linear regression:  $y = -0.0025 \cdot x + 0.665$ ,  $r^2 = 0.98$ .

#### Altitude related differences

In trees similar in age however, average O<sub>3</sub> uptake rate during the growing season tended to increase with increasing altitude (Fig. 3). This could be attributed to an increase in both ambient O<sub>3</sub> concentration and stomatal conductance with increasing altitude (Fig. 3). The higher conductance values at elevations above 1000 m might be attributed to more favourable water relations at high than at low altitudes as also found for European larch growing at a high and a low elevation site (WIESER & HAVRANEK 1995).

These data also allow an assessment of potential cumulative O<sub>3</sub> uptake throughout one vegetation period. However, one has to bear in mind that the vegetation period (i.e. the snow-free period, HAVRANEK & TRANQUILLINI 1995) decreases from approximately 250 days in the valley floor to about 180 days at the alpine timberline (HAVRANEK & TRANQUILLINI 1995, TRANQUILLINI 1979). Cumulative O<sub>3</sub> uptake rates into needles of evergreen conifers obtained by this calculation were  $11.4 \pm 1.7$  in the valley floor (600 m above sea level), and  $14 \text{ mol m}^{-2}$  of total needle surface area at the alpine timberline (1950 m). Apparently the difference in cumulative O<sub>3</sub> uptake rate between the alpine timberline and the valley floor was about 20% for the whole vegetation period. On the other hand however, the detoxification capacity for O<sub>3</sub> also increases with increasing altitude (POLLE & al. 1995, RENNENBERG & al. 1997). This might explain, why typical altitude-dependent effects on biochemical and physiological parameters could not be attributed to O<sub>3</sub> itself (RENNENBERG & al. 1997).



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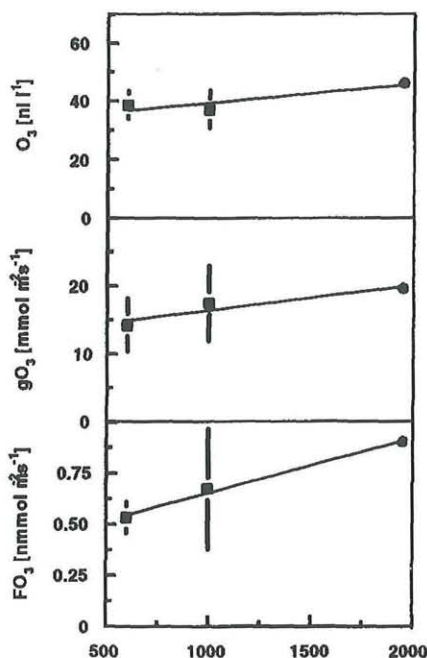


Fig. 3. Mean ambient ozone concentration ( $O_3$ , top), average stomatal conductance for ozone ( $gO_3$ , middle) and average ozone uptake rate ( $FO_3$ ) during the growing season (May throughout October) in 60- to 65-year-old *Picea abies* (■) and *Pinus cembra* (●) trees in relation to increasing altitude in the central European Alps. Measurements were made during the period 1987 through 1996.  $n = 1$  to  $4 \pm \text{SD}$ . The points were fitted by linear regression: stomatal conductance for ozone ( $gO_3$ ):  $y = 0.0037 \cdot x + 12.69$ ,  $r^2 = 0.89$ ; ozone uptake rate ( $FO_3$ ):  $y = 0.00027 \cdot x + 0.38$ ,  $r^2 = 0.99$ .

## Conclusions

In conclusion, in evergreen conifers  $O_3$  uptake during the growing season (May throughout October) is mainly influenced by tree age and altitude. Stomatal conductance and  $O_3$  flux into needles of evergreen conifers most strongly declined with increasing tree age. In comparison to tree age the altitudinal effect was small, but evident in trees similar in age. However, reassurance is needed that conductance values, usually measured on individual twigs, are representative for the canopy as a whole.

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