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Effects of Elevation and Wind on the Growth of *Pinus cembra* L. in a Subalpine Afforestation

By

H. KRONFUSS[1)] & W.M. HAVRANEK[1)]

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Summary

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To improve avalanche protection, research on an afforestation project of a steep sunny slope of former pasture land in the Sellrain valley, Tyrol was initiated. Data of this project were analysed to investigate interactions of tree growth and climate, especially of temperature and wind.

Experimental plots were arranged along an elevational gradient from 1700m (valley bottom) to 1900m a.s.l. Annual height growth of *Pinus cembra* L. decreased with altitude by about 5-6% per 100m corresponding to the decrease in length of the growing season. Only in the uppermost 30 metres of the afforestation area did height growth decrease disproportionately fast. Among climatic parameters only wind speed was negatively and highly correlated with height growth. Wind speed at 1900m was more than twice as high as at 1800 and 1730m. However, wind did not cause acute damage (e.g., abrasion, winter desiccation) but seemed to influence growth indirectly by altering microclimate.

Overheating of plant organs and the soil by strong radiation on sunny slopes can be reduced by wind and, as a consequence, optimum temperatures for growth and for photosynthetic production occur less frequently than in the less wind-exposed lower experimental plots. As soon as stand closure occurs, the forest lifts the wind field and thus reduces the negative effects of wind on growth.

Introduction

The community St. Sigmund in the Sellrain valley, Tyrol, has been endangered by avalanches and land slides for centuries. The reason for this constant threat is the clear-cutting of the former forest in order to use the sunny slopes for grazing by cattle, sheep and goats. After disastrous avalanches in 1951

[1)] Forstliche Bundesversuchsanstalt, Rennweg 1, A-6020 Innsbruck, Austria. e-mail: fbva.aiatr@magnet.at

and 1954 and after the failure of a pilot reforestation project, a broad based research project was initiated in 1965. The aims were first to develop proper methods for a successful establishment of a forest stand on a steep, sunny slope covered with grass and heath and second to establish management techniques to sustain such protection forests at high elevation. Therefore investigations focussed on interactions of climate and tree physiology, changes in soil and soil biological characteristics, and aspects of forest yield. In this paper, the relations between tree growth and climate parameters are presented.

Material and Methods

The afforested area is above the village Haggen near St. Sigmund in the Sellrain valley, Tyrol (47°13'N, 11°06'E) and extends from the valley bottom (1700m) to 1950m a.s.l. Exposition and angle of the slope are SSW, and 35°, respectively. Permanent experimental plots were installed in the year 1975 at 1730, 1800, 1870, and 1900 m.

Podsolic brown soil with humus horizons originating from foliated gneiss and mica schist bedrock developed into brown earth by grazing and hay-making over centuries. The vegetation at the beginning of the afforestation consisted of heath and grassland (Callunetum, Nardetum alpigenum). The stand was thinned in the years 1983 and 1995. The state of the trees in the year 1993 is depicted for three experimental plots in table 1.

Table 1. Stem numbers per hectare, and means (of 40 trees per plot) for projected crown area, stem diameter at 1/3 stem height, etc. in 1993, 10 years after the first thinning.

Altitude of experimental plot	1730m	1800m	1900m
Stocking: stems / ha	6044	9762	7592
Projected crown area, m²	1.94	1.72	1.33
Stem (H/3) diameter, cm	8.17	7.98	6.02
Root collar diameter, cm	13.95	13.8	10.25
Stem volume, dm³	19.86	18.0	6.8
Height/Diameter ratio	56	54	46

Onset time, seasonal course, and the end of height growth (means of 40 trees) at the experimental plots at 1730, 1800, 1870 and 1900 m were measured annually from 1970 through 1995. The length of the growing season was defined as from the beginning to the end of the annual growth of the leader. Diameter growth of stem and root collar were measured every fifth year.

Climatic variables (Table 2) were recorded from 1975 through 1995 with a standard weather station in the centre of the afforestation area at 1800m a.s.l. (for details see KRONFUSS 1997). For the vegetation period (mid-May through September), temperature was also recorded at 1730m and 1900m for the periods 1980-1994, and wind speed at 6m aboveground was recorded for the periods 1980-1986.

Results and Discussion

The cumulative height growth of *Pinus cembra* trees was recorded over a 25-year period along an elevational gradient from 1730m to 2000m a.s.l. (Fig. 1A). Height growth decreased moderately from 100% at 1730m to 94% at 1800m and to 89% at 1870m, but showed a dramatic decrease to 62% within the uppermost 30 metres of the afforestation area, between 1870m and 1900m. The data for 2000m

Table 2. Macroclimatic data for the afforestation area "Haggen" (1800m) measured for the period 1975-1995 and presented here as 20-year-means.

Radiation: Loss of potential radiation by horizontal shielding	30.4 %
Possible sunshine hours per year	3093 hrs
Actual mean of annual sunshine hours	1426 hrs
Actual mean of sunshine hours during vegetation period	682 hrs
Mean sum of global radiation during vegetation period	69 $kWhm^{-2}$
Air temperature (annual mean/absolute max/min measured)	3.2°/ 29.7/-28.0°C
Mean of vegetation period (mid-May through Sept.)	9.0°C
Wind speed (Mean of vegetation period, 6m above ground)	1.17 ms^{-1}
Relative humidity, annual mean	71 %
Precipitation: annual mean / mean during vegetation period	909 / 517mm
Snow cover (mean duration / max. / min)	169 / 205 / 120 days
Snow depth (mean / max. / min)	0.79 / 1.50 / 0.30 m

are from an afforestation area on a north-exposed slope at the opposite side of the valley for which no other data are available. They are included here to demonstrate the strong effect that reduced radiation has on growth on a north-exposed compared to a south-exposed slope (cf. TURNER 1971). Similarly reduced height growth has been reported for naturally regenerated *P. cembra* on a WNW- slope at 1985m (closed forest) and 2194m (kampfzone) in Obergurgl, Tyrol (OSWALD 1963).

Compared to height growth, diameter growth was reduced less with increasing elevation, while stem volume decreased dramatically (Table 1). Height to diameter ratios decreased slightly with elevation.

Mean height growth along the elevational gradient decreased to a similar degree as the mean length of the growing season. Changes in growing season length with elevation were largely due to the later onset of the spring; the end of the growing season in autumn was similar for all plots (Table 3).

At 1730m the growing season started earlier due to higher air temperatures than at 1900m. On average the air temperature in May and June was 0.5°C higher at 1730 than at 1900m during 1980-1994. In July and August this difference was smaller (+0.2°C) and in September the air temperature was even 0.2°C lower at 1730 than at 1900m.

The air temperature at 1730m was only 0.2°C higher on average than at 1800 and 1900m during the vegetation period. This temperature decrease with elevation is much smaller than the normal adiabatic temperature decrease of 0.65°C per 100m, but is typical for the well known "warm slope zone" in alpine valleys (AULITZKY 1961a). Nevertheless, the shortening of the growing period may explain the decrease in height growth from the valley up to 1870m but it cannot explain the sharp decline between 1870 and 1900m. Year-to-year fluctuations in annual growth did not correlate with the mean temperature of the current vegetation

Table 3. Mean tree height in the year 1995 compared to the length of the growing season of *Pinus cembra* for the period 1978-1990 at the experimental plots. Numbers in brackets give the percentage of base values at 1730m.

Altitude of experimental plot	1730m	1800m	1870m	1900m
Tree height in 1995 in meters	5.13 (100)	4.84 (94)	4.56 (89)	3.21 (62)
Mean growing season in days	112 (100)	107 (95)	101 (90)	99 (88)
Mean date of beginning / end	30-04/20-08	03-05/18-08		11-05/18-08
Earliest / latest beginning	13-04/11-05	15-04/16-05		24-04/23-05
Earliest / latest end	03-08/31-08	31-07/29-08		01-08/30-08

period, but showed some correspondence to that of the previous year (Fig. 1B, C). This may be expected since the initiation of primordia in the bud of pines takes place in the previous year and only extension growth of the predetermined stem unit occurs in the current year. Similar results were noted by MÄKINEN 1998 in *Pinus sylvestris*.

It should be emphasised that it is not the mean air temperature but the actual air temperature at a given time which affects the various processes in plants. For instance the strong depressions in annual growth at 1730 and 1800m in 1991 (arrow in Fig.1B) cannot be explained by different mean temperatures but could have been caused both by the exceptionally dry summer of 1990 and by frost damage in May, a time when growth had already resumed at the lower elevations but not at 1900m.

There was a surprising increase in annual height growth at the uppermost 30 metres (1900m) during the last 6 years of records. We hypothesise that this increase in growth was due to the closure of the stand and hence to an improved microclimate with less wind exposure. In the following we analyse the data available to support this hypothesis.

Apart from mechanical damage, wind induces physiological and developmental responses in trees (see review by TELEWSKI 1995). In the afforestation area at Haggen no acute wind damage has been observed and chronic wind stress produced just a weak indication of wind-flags in a few trees at the 1900m plot. From other investigations it is well known, that snow deposition is poor on wind exposed sites, and in consequence snow may not protect needles from winter desiccation and roots from deep soil frost (AULITZKY 1961b, HADLEY & SMITH 1986). In general, wind speed at Haggen was measured only during the vegetation period, and only from 1990-1994 it was measured for the whole year at a height of 8m above the ground at 1700 m, the bottom of the valley. On average the difference between the wind speed in winter (2.9 ms^{-1}) and during the vegetation period (2.6 ms^{-1}) was only 10% during these 5 years. Unfortunately no data on differences in snow deposition along the altitude gradient are available because it was impossible to reach the upper part of the afforestation due to the danger of avalanches.

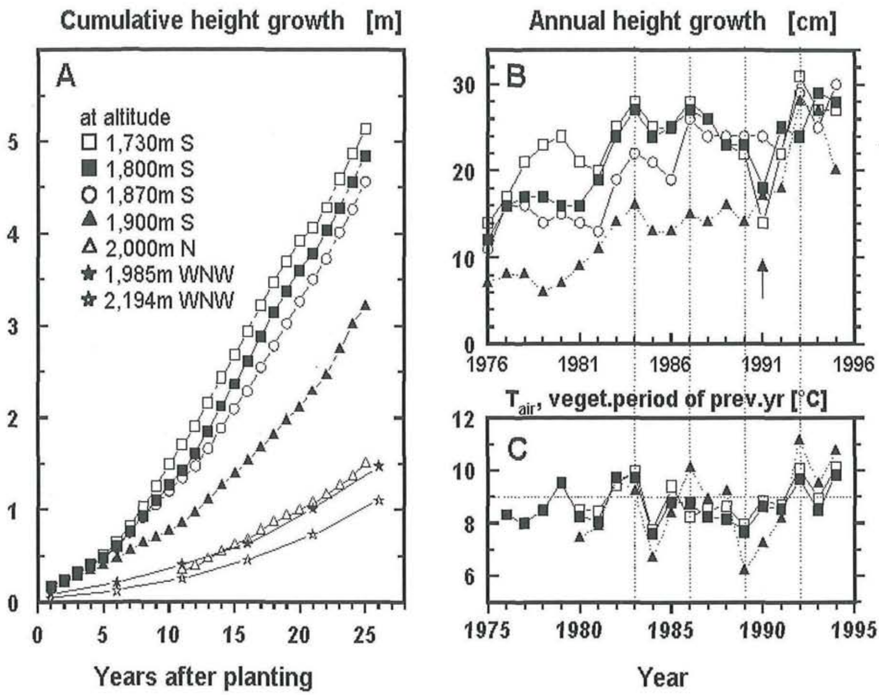

Fig. 1. A. Cumulative height growth of young *P. cembra* during a 25-year period after plantation at different altitudes and expositions at Haggen, and of naturally regenerated seedlings at a WNW-slope at Obergurgl (data from OSWALD 1963). B: Annual height growth of *P. cembra* trees for the years 1976-1995 compared to (C) the mean air temperatures of previous year's vegetation period. (years 1975-1994) at 1730 and 1800 and 1900m. (For arrow see text).

Based on the observation that there was no major winter desiccation damage and no increase in the number of forked trees as a result of leader damage in the uppermost zone (1870-1900m) with the highest wind speed, we conclude that wind did not cause major damage or endanger survival of trees. Nevertheless, wind exposure may have increased needle mortality at this site in winter (cf. HADLEY & SMITH 1986) and this reduction in needle mass, i.e. in photosynthetic area, would have contributed to the reduced growth rates during the following vegetation periods.

Wind also seems to have acted indirectly on growth conditions during the vegetation period by a general cooling of air, leaves, meristems and soil. Data from this afforestation area demonstrate that high mean wind speed during the vegetation period influenced mean air temperature at 1900m whereas low wind speed at 1730m had no effect on the temperature (Fig. 2A).

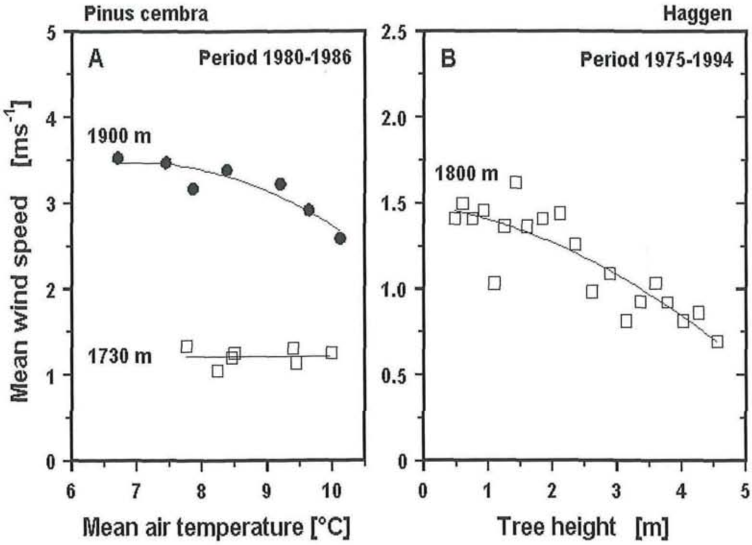

Fig. 2. (A): Relation between the mean air temperature and the mean wind speed during the vegetation period (years 1980-1986) at and 1900m;

(B): Decrease of the mean wind speed at increasing tree height. Wind speed was measured at a height of 6m above ground within the afforested plot at 1800m during the vegetation period of the years 1975-1994.

Long-term records of the wind speed at 1800m showed that as trees increased in height and stand development occurred, mean wind speed decreased (Fig. 2B). When the trees had grown to a mean height of 5m, the wind speed measured at 6m above ground was reduced by about 50% of the initial value at a tree height of 0.5m. This indicates a reduction of the wind speed within the afforestation and the lifting of the wind field above the trees. Wind measurements in another subalpine region in Tyrol revealed that already a small group of young *P. cembra* of about 2 metres in height reduced wind speed considerably and raised the wind field in the kampfzone where, without trees, high wind speeds occurred close to the ground (AULITZKY 1961c).

For seven years of measurements at the Haggen experimental plots at 1730, 1800 and 1900m, height growth was highly and negatively correlated with the mean wind speed of the vegetation period (Fig. 3). The wind speed at 1900m was more than 2 times higher than that at 1730 and 1800m because the 1900 m plot was open to the NW to the neighbouring grassland - the prevailing wind direction. Therefore the wind could enter the uppermost zone of the afforestation area at full speed as long as the space between the young trees was open. It seems that the wind speed within the plot decreased in the early 1990ies as soon as stand closure was reached (cf. table 1, projected crown area of $1.33m^2$ indicates stand closure at a stem number of ca. 7600 stems ha^{-1}). This was presumably the main reason for the upward shift of the annual height growth at 1900m, close to the growth rates at the lower plots (Fig. 1B). However, only future measurements will prove whether this high growth rate continues.

Wind affected the growth of young trees in a Swiss afforestation at the upper altitudinal limit for tree growth in two very different ways (TURNER 1971): a mean wind speed of up to 2.5 ms^{-1} increased survival and growth at sites with low global radiation whereas on sites with strong radiation, comparable to our south-exposed slope, wind speeds higher than 1.5 ms^{-1} reduced growth of young *Larix decidua* and *Picea abies*. The annual height growth of these two species was even more strongly reduced (>50%) at a mean wind speed of 3.0 ms^{-1} than that in *P. cembra* of our experiment.

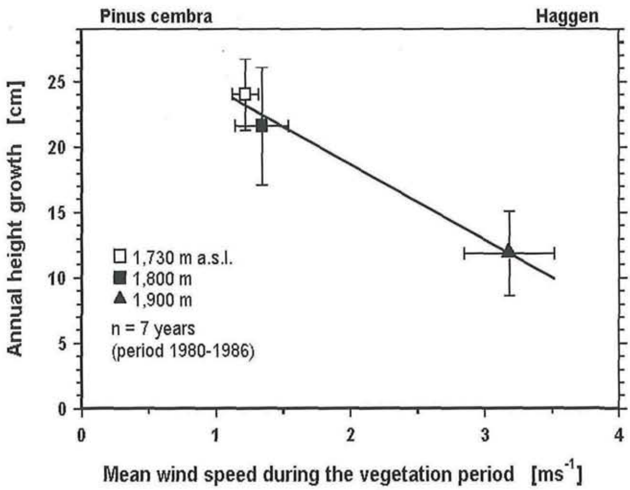

Fig. 3. Mean wind speed of the vegetation period measured for seven years at the experimental plots at 1730, 1800 and 1900m a.s.l. was strongly and negatively correlated with height growth.

Within the complex interaction of climate factors, temperature undoubtedly has to be considered as the major limiting factor in this extreme environment. Therefore any increase of plant or soil temperature above ambient air temperature (by strong radiation, overheating and little cooling by wind), or of the air temperature itself due to transfer of warm air mass by wind, will result in higher production and growth. This was confirmed by TURNER 1971 for soil temperature at the upper tree line where the mean exponential temperature (eT) of the soil surface during the vegetation period was much higher (5°eT) at sites with high radiation at low wind speed of 1.5 ms^{-1} than at sites with the same radiation and a mean wind speed of 3 ms^{-1}. It is well known that radiation raises meristem and leaf temperatures considerably above the air temperature under windless or low wind conditions (cf. TRANQUILLINI & TURNER 1961, HADLEY & SMITH 1987, GROSS 1989) and consequently also photosynthetic gain. Moreover, experiments in a wind tunnel under optimal soil water relations established that wind did not alter net photosynthesis nor transpiration substantially in *P. cembra*. (TRANQUILLINI 1969). These results and the fact that *P. cembra* occupies rather wind exposed sites with wind speeds >3 ms^{-1} during 30% of the vegetation period led CALDWELL 1970 to conclude that "during the growing season, wind probably is not a significant influence on developing *Pinus cembra* seedlings growing on exposed ridges above timberline". However, the results of the afforestation at Haggen where water generally did not seem to be a major limiting factor indicate a clear wind effect on height growth of *P. cembra* at least as long as the stand is not closed. Therefore, at 1900m, the afforested area may not have reached the upper limit of the climatic timberline yet. A stepwise extension of the forest to higher areas seems possible especially if wind protection is provided.

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