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Glass domes with adjustable windows: A novel technique for exposing juvenile forest stands to elevated CO_2 concentration

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Abstract

We present a new technological approach for *in situ* investigation of long-term impacts of elevated CO_2 concentration (EC) on juvenile forests characterised by an intensive community level and canopy closure phase. Construction of the glass domes is based on the properties of earlier tested open-top chambers (OTCs). An air climatisation device together with an adjustable window system, that forms the shell cover of the domes, is able to keep the required [CO_2] in both time and spatial scales with the relatively small consumption of supplied CO_2. This is achieved by half-closing the windows on the windward side. We evidenced good coupling of treated trees to the atmosphere, including mutual interactions among trees. The semi-open design of the domes moderates the problems of strong wind, humidity, and temperature gradients associated with OTCs. The frequency distributions of the environmental variations within the domes indicate that: air temperature is maintained within the ambient range ±1.0 °C for *ca.* 80 % of the time, and changes in the relative air humidity vary from −15 to 0 % for *ca.* 82 % of the time. The most important chamber effect is associated with the penetration of solar irradiance, which is reduced by 26 % compared to the open condition outside the domes. The dimensions of the domes are 10×10 m in length and 7 m high in the central part. The experiment was done in three identical stands of twelve-year-old Norway spruce trees. The 56 trees are planted at two different spacings to estimate the impacts of stand spatial structure in relation to EC.

Additional key words: experimental facility; gas exposure technique; long-term experiment; Norway spruce; *Picea abies*.

Introduction

Forests cover about one-third of the land area and forest ecosystems represent the final stage of many terrestrial ecosystems; thus they are a very important part of the global biosphere (Eamus and Jarvis 1989). The role of forests in the global carbon budget is extremely important (Olson *et al.* 1983) because of the longevity of forest trees and the importance of forest stands as a large sink for atmospheric CO_2 (Malhi *et al.* 1999). Until recently, the role of rainforests in the global CO_2 budget was considered to be of the greatest significance. However, new studies stress the significance of the temperate and boreal forests (Dixon *et al.* 1994, Malhi *et al.* 1999). Because of the possible crucial role of forests as important sinks for atmospheric CO_2 over a long period (Dixon *et al.* 1994), in comparison to other types of ecosystems, experimental investigation and simulation is essential. However, experiments with trees, and especially with whole forest stands, are fraught with technical and methodological difficulties (Allen *et al.* 1992, Hileman *et al.* 1992). Papers describing the impacts of elevated CO_2 concentration (EC) on mountain forests are rare (Pontailler *et al.* 1998). However, long-term experiments to observe development of forest stands, effects of canopy closure and within canopy responses (*e.g.*, formation of vertical differences of assimilatory apparatus) are needed to evaluate effects of EC.

During the last decades, several plant exposure systems have been developed for treatment of plants in an

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atmosphere with various gas compositions (reviewed in detail by Allen *et al.* 1992). These systems involve different degrees of interference with important natural microclimatological conditions, such as wind-flow, radiation, and thermal energy exchange. Because of the size, longevity, and root-zone volume of trees, open-top chambers (OTCs) (Hileman *et al.* 1992, Janouš *et al.* 1996, De Angelis and Scarascia-Mugnozza 1998, Clark *et al.* 2000) and free-air CO_2 enrichment (FACE) systems (McLeod *et al.* 1985, Hendrey *et al.* 1999) are the most useful facilities for the investigation of impacts of EC on forest trees and stands. Nevertheless, closed top chambers are also used for specific climatic conditions (Kellomäki *et al.* 2000).

Both these systems can be used for studying natural vegetation *in situ* in natural sunlight and in conditions close to the natural environment. Climate in OTCs tracks the dynamics of temperature, humidity, irradiance, and rainfall experienced by unenclosed areas (Janouš *et al.* 1996, De Angelis and Scarascia-Mugnozza 1998). Generally, OTCs are too small to allow investigation at the ecosystem or community level (Janouš *et al.* 1996). De Angelis and Scarascia-Mugnozza (1998) presented an application of large OTCs (4 m in diameter, 6 m in height) on an evergreen "*macchia*" ecosystem. FACE systems include mutual interactions between individual plants, which are generally well coupled to the atmosphere (Hendrey *et al.* 1999). Poor coupling may result in a substantial shift of the driving variables for gas exchange and lead to substantially different fluxes of water vapour and CO_2. At present, FACE systems include complex feedback control (McLeod *et al.* 1985) that reduces solving the problems of spatial gradients and short-term variability in [CO_2] (Hendrey *et al.* 1999). The main disadvantage of these systems is a large volume of consumed CO_2, its high price, and lower applicability in mountain conditions.

In this paper, we present a new technological approach—glass domes with adjustable windows. Two domes (dimensions 10×10×7 m) were built to simulate the long-term impacts of EC (ambient *plus* 350 μmol mol^{-1}) on mountain stands of Norway spruce. Stands of twelve-year-old trees were artificially established at two different densities to estimate the impacts of stand spatial structure and canopy closure processes on responses to EC.

Materials and methods

The domes are located at the experimental research site Bílý Kříž (Beskydy Mts., 49°33'N, 18°32'E, 908 m a.s.l., NE of the Czech Republic). The geological bedrock is formed by Mesozoic Godula sandstone (flysch type), with ferric podzols. The climate is cool (annual mean temperature 4.9 °C), humid with high precipitation (mean 1 100 mm). The average number of days with snow cover is 160.

There are three identical, artificially established pure stands of twelve-year-old Norway spruce trees. Two domes cover two of these plots; the third area was established as an open control (C) plot. One dome contains ambient [CO_2] (AC-variant), the second dome contains elevated [CO_2] (ambient *plus* 350 μmol mol^{-1}) (EC-variant). The total number of trees in each area is 56, of which 26 form a buffer zone. The mean size of the spruce trees was 1.6±0.1 m of height and 23±2 mm of diameter at 0.3 m at time of planting. The trees were planted at two different densities with projected leaf area index in the more open areas of 0.8 to 0.9, while it was *ca.* 1.7 in the denser areas at the beginning of the experiment. Reasons for this stand structure pattern are (*1*) to reach canopy closure quickly, and (*2*) to estimate the impacts of stand spatial structure and competition for growing space on the responses to EC.

The dimensions of the glass domes (Fig. 1*A,B*) are 10×10 m in length and 7 m high in the central part. The domes are anchored on a concrete base (depth 0.9 m), and include a massive iron frame (approximate mass: 17 000 kg) with movable windows. These 72 windows are constructed from safety glass (6.0 mm thick). The opening of the windows on the different sides and at different heights is mutually independent (see Fig. 1*B* for details). Fully closed and fully open (angle 90°) positions of the windows can be achieved automatically. Using manual control, the positions can be adjusted in 10° steps.

The main requirements for the maintenance of constant EC and minimising of environmental modifications inside the domes are ensured by both a system of adjustable windows and an air climatisation device (Fig. 1*A,B*). The positioning of windows is automatic and depends on wind speed and its direction. Limited escape of added [CO_2] is achieved by half-closing the windows on the windward side. The windows at all levels and sides are fully open for the wind velocities lower than 3.0 m s^{-1}, while they are fully closed for velocities higher than 20.0 m s^{-1}. Average values of 12-min reading are used to control operation of the window mechanism.

The climatisation device of the each dome consists of four radial fans (model *RNH 400*, *Janka*, Czech Republic) with volumetric rates of airflow 1.2 m^3 s^{-1}. The air flows in through ducts and is distributed by eight ventilating inlets with lamellae for vertical and horizontal routing of the air. The air inlets are situated 0.4 m above the ground. In addition, two auxiliary fans (500 W, *Janka*, Czech Republic) located within each dome supply turbulent mixing of the air (Fig. 1*B*) and are automatically switched on during the daytime (07:00–19:00). The

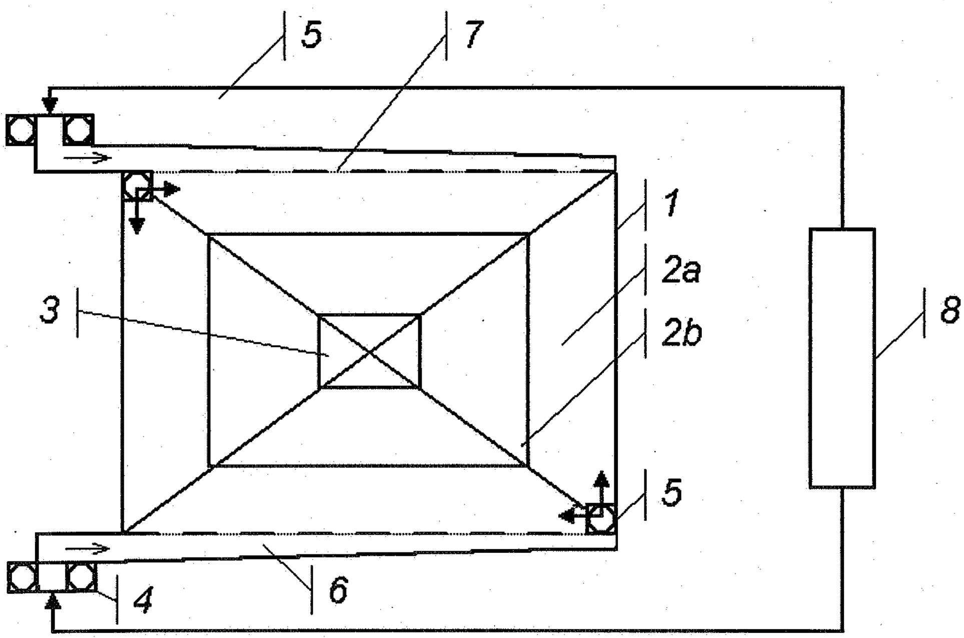

Fig. 1. *A* (*top*): Photograph of glass domes at Experimental Research Site Bílý Kříž (49°33'N, 18°32'E, 908 m a.s.l.), Czech Republic. *B* (*bottom*): Scheme of the glass domes with adjustable windows: *1* – fixed glass wall (2.0 m high). *2* – glass walls formed by the system of adjustable windows with closing wind limits of 3.0 (*2a*) and 10.0 (*2b*) m s^{-1}. *3* – fixed glass top (1 m^2). *4* – radial fans. The air enters *via* chimneys (3 m), so that warm air near the ground is not introduced. *5* – routable auxiliary fans (500 W) for turbulent mixing. *6* – air ducts. 7 – ventilating inlets with routing lamellae. *8* – CO_2 storage tank with vaporiser.

fans and the air ducts are acoustically insulated, such that the ambient noise does not exceed 35 dB.

The air in the domes contains an ambient atmospheric [CO_2] or ambient *plus* 350 μmol mol^{-1} (*i.e.*, *ca.* 700 μmol mol^{-1}). To attain this [CO_2] enrichment, the dome is fed with 1 500 cm^3 s^{-1} of pure CO_2 from a storage tank (Fig. 1*B*) with a capacity of 17 000 kg (*Linde*, Czech Republic). There is continuous (24 h per day) enrichment from April till November. The total annual consumption of CO_2 is *ca.* 90 000 kg per year.

Selected environmental variables are measured identically inside both the domes and at the open control plot. The [CO_2] in the atmosphere is measured automatically at two levels (0.8 and 3.0 m). These measurements are made in both the dense and sparse areas of the stands. Mixed samples of air from four different points are analysed by an absolute infrared gas analyser (*WMA-2*, *PP Systems*, UK). A net of 12 photosynthetically active radiation (PAR) sensors (photodiodes *BPW-21*, 400-700 nm, *Siemens*) is used for an investigation of the PAR regime within the stands. Temperature and relative air humidity sensors *RHA1* (*Delta-T Devices*, UK) are installed in the central part 2 m above the soil surface. In addition, four shaded resistance sensors (*Pt1000*) for detail analysis are situated 0.7 m above the soil surface at a distance of 0.1 m from the tree stems. Readings are taken every 30 s and averaged over 30 min and stored on a data logger (*Delta-T*, UK).

Results and discussion

[CO_2] distribution: In the dome with ambient air, the [CO_2] closely follows the uninfluenced reference value (355±5.8 μmol mol^{-1}) throughout the year. A moderate increase of elevated atmospheric [CO_2] in the lower part of the E-dome was observed. The increase of [CO_2] occurred especially in the dense part of the plot (Fig. 2).

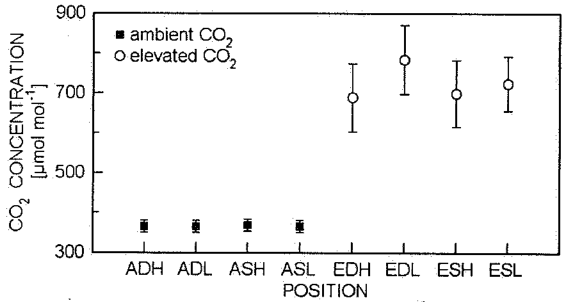

Fig. 2. Spatial variation of [CO_2] within the ambient (AC) and elevated (EC) CO_2 concentration domes throughout the vegetation season (May–September). A (E) letters represent ambient (elevated) variants, D (S) – dense (sparse) density plot, H (L) – high = 3.0 m (low = 0.8 m) position. Error bars are standard deviations.

The target [CO_2] (700 μmol mol^{-1}) was maintained for *ca.* 72 % of the time within the range 600-800 μmol mol^{-1} throughout the vegetation season. Low [CO_2], under 600 μmol mol^{-1} (*ca.* 10 % of the time), reflects situations of CO_2 deficiency in the storage tank, its supplementation or loss of electrical energy for operation of the fans. Because of the solubility of CO_2 in water, slight decreases (*ca.* 5 %) of EC occurred during the rain. High [CO_2], above 800 μmol mol^{-1} (*ca.* 18 % of the time), were mainly caused by the accumulation of [CO_2] in the lower part of the dome (*ca.* 13 %) or by overpressure of the liquefied CO_2 in the full storage tank.

During ten typical sunny days in July (1998), [CO_2] fluctuations gave a mean value of 724±52 μmol mol^{-1} (*n* = 960). Moreover, estimation of [CO_2] isolines (values not shown) showed small differences in the horizontal dimension; the difference between maximal and minimal values was 50 μmol mol^{-1} at 0.6 m and 30 μmol mol^{-1} at 1.5 and 2.5 m above the ground.

PAR: The iron frames of the domes (*ca.* 10 % of the total reduction), the glass of windows, and their instantaneous angle-to-the sunrays reduced irradiance. Average penetration of PAR was 74±3 % during three summer months (Fig. 3). With the optimal window inclination to direct sun rays from the south side, penetration reached values of 78±3 %. The change in penetration during the day was not statistically significant. Because of the penetration of direct solar beams and the high proportion of direct diffuse radiation through the open windows, no significant changes in the spectral composition (UV/PAR ratio) were observed inside the domes. No statistically significant ($p > 0.05$) differences of PAR were observed between the domes with AC and EC.

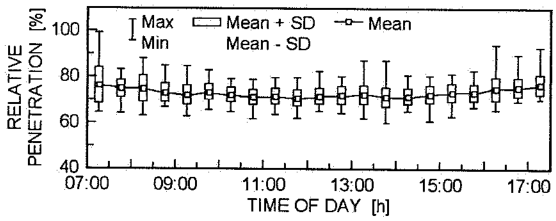

Fig. 3. Daily course of PAR penetration throughout three summer months (June–August) with an automatic regime controlling movement of windows.

Air temperature: Differences between the average air temperatures in the AC- and EC-domes, as well as inside and outside the domes, were not statistically significant ($p > 0.05$). The calculated difference was 0.2 °C (s.d. = 1.2) for the three summer months, when the chamber effect would be expected to be largest. The air temperature within the domes was maintained within the ambient range ±1.0 °C for 84 % of the time (Fig. 4*A*). The detailed analysis showed the maximal frequency distribution (*ca.* 48 % of the time) in the range 0.5-1.0 °C during the summer nights, while it was *ca.* 25 % of the time in the range from –0.5 to 0 °C during the summer days. The extreme air temperature decreases within the domes (from –4.0 to –4.5 °C) were observed during the noon as the result of maximal solar radiation. The maximal increase of 2.5-3.0 °C shown in Fig. 4*A* resulted from maximal soil radiation efflux during the nights.

During wintertime, the windows were fully open and the snow cover inside the domes was *ca.* 70 % compared to outside. The air temperature within the domes was significantly higher ($p < 0.01$) than outside during the three winter months (December-February): positive changes in the range of 0-4.0 °C occurred for 60 % of the time (Fig. 4*B*). The negative changes (from –10.0 to –8.0 °C) with a maximum difference up to –9.2 °C accounted for only 0.7 % of the time. In contrast, the increases of above 4 °C were observed for 1.6 % of the time with a maximum difference up to 10.4 °C.

In correspondence, slightly higher soil temperatures (by 0.5 °C) were recorded within the domes compared to the open control plot in summer. Differences between day and night were not significant in this respect.

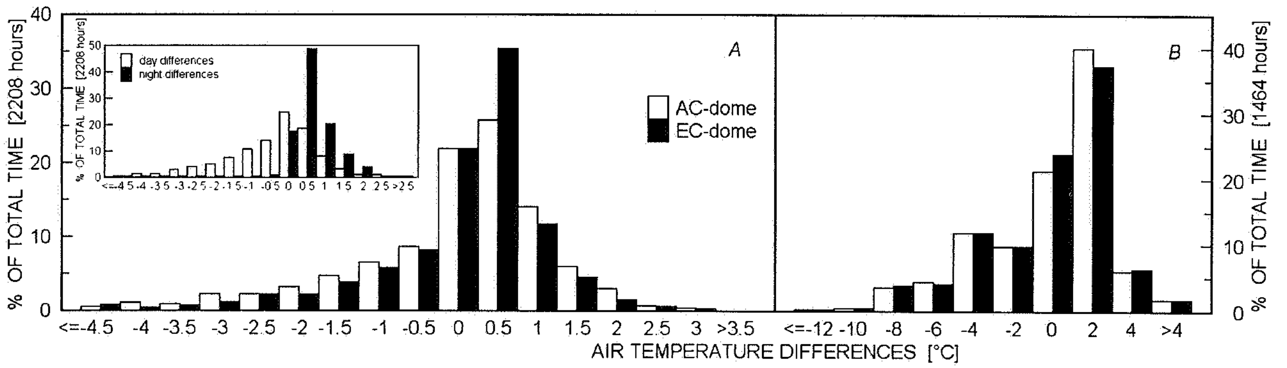

Fig. 4. *A*: Frequency distribution of the mean air temperature differences between inside and outside of the domes and their distributions during days and nights throughout three summer months (June–August). *B*: Frequency distribution of the differences of the mean air temperature between inside and outside the domes throughout three winter months (December–February).

Relative air humidity inside the spheres was modified according to the daily course of air temperature (values not shown). The relative air humidity inside the domes was significantly ($p < 0.05$) lower than outside (Fig. 5).

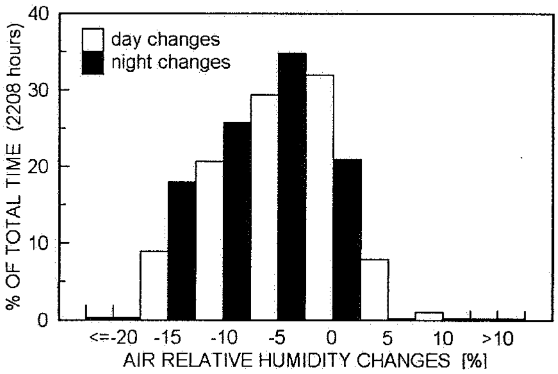

Fig. 5. Frequency distribution of the relative air humidity changes between inside and outside the domes throughout three summer months (June–August).

The calculated difference over three summer months was –8.0 % (s.d. = 5.3). Average decrease of the air humidity value by –9.6 % (s.d. = 4.8), with a minimum and maximum differences up to –19.3% and 7.5 %, respectively, was observed during summer nights. Whereas, the average decrease observed during summer days was 6.9 % (s.d. = 5.4) (min = 9.0, max = –19.4). The domes slightly but not significantly reduced air humidity during the driest periods (*ca.* 30 %) by –1.2 % (s.d. = 1.5).

Irigation system: Because of the window positioning, incoming precipitation is reduced. For this reason an artificial automatic watering system is provided. The six irrigation points are symmetrically placed in two lines, 2.5 m above both the stands. The system is based on comparison between the soil moisture in the open plot and inside both the domes. Resistive *VIRRIB* sensors (*AMET Co.*, Czech Republic) are used for the soil moisture measurement. The measurements are taken at 24-min intervals throughout the day. If the difference is greater than 5 %, water is provided for 3 min inside the domes and then it stops for 3 min. This cycle is repeated until the next soil moisture measurement indicates no further need. However, the soil humidity inside the domes was significantly ($p < 0.05$) higher than outside (Fig. 6). The changes of soil humidity over five months within the domes varied from –5.1 to 3 %.

Wind speed: There are two types of airflow within the domes. While the main fan system together with the air inlets (*4* and *7* in Fig. 1*B*) creates a diffusive air movement, auxiliary fans (*5* in Fig. 1*B*) create radial flows and turbulent mixing. Using a sonic anemometer (*Solent A1012R, Gill Instrument*, UK), wind speed in the layer close above the canopy varied from 1.0 to 2.5 m s^{-1} for 56 % of the daytime (Fig. 7). The mean value of wind is *ca.* 0.2 m s^{-1} during the nights when the auxiliary fans are switched off. These results are in good agreement with the wind speeds on the open plot. Differences between the two domes were not statistically significant.

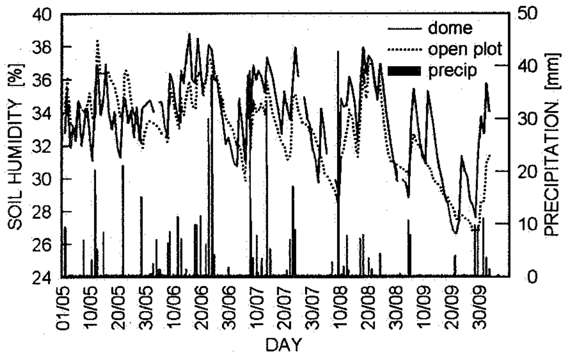

Fig. 6. Soil moisture content inside the domes and on the open control plot and daily precipitation throughout five months (May–September).

Physiological effects: The above mentioned differences in microclimatological conditions within the domes lead to changes of some physiological parameters of treated trees. Because no differences were observed between both domes and sampled trees at the beginning of the experiment (Marek *et al.* 2000), we presume that changes between trees in the C plot and AC dome reflect chamber effects of the dome, whereas comparison between trees in the domes with AC and EC demonstrates pure CO_2 effects.

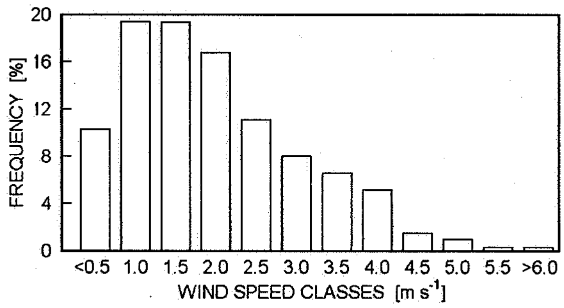

Fig. 7. Frequency distribution of the wind speed inside the domes (June–August) throughout the daytime in the layer close above the canopy (n = 600).

Table 1. Values (mean ± standard deviation) of selected physiological characteristics and their modification under the glass domes microclimate–chamber effects. Current needles were analysed at the end of the growing season 1999 for contents of chlorophyll (Chl) (a+b), total carotenoids (Cars), photochemical efficiency of photosystem 2 (F_V/F_M), net rate of CO_2 assimilation at saturating irradiance (P_{Nsat}), compensation irradiance (Γ_I), total stand transpiration (E) (values from June 1999), and specific leaf area (SLA). *, ** – significant at 95 and 99 %.

Physiological parameter	AC-dome	Control plot
Chl (a+b)	0.41±0.05**	0.30 ±0.05**
Cars	0.08±0.01*	0.07±0.01*
Chl a/b	3.21±0.03**	3.31±0.05**
Chls/Cars	4.8±0.2**	4.1±0.2**
F_V/F_M	0.823±0.007**	0.801±0.007**
P_{Nsat} [μmol(CO_2) m^2 s^{-1}]	8.0±1.0	8.7±1.4
Γ_I [μmol m^2 s^{-1}]	40.0±5.0	32.0±8.0
E_t [mm d^{-1}] – sunny days	1.67±0.28**	0.46±0.09**
E_t [mm d^{-1}] – cloudy days	0.26±0.23	0.09±0.07
SLA [cm^2 g^{-1}]	76±10	66±10
Tree height [m]	2.2±0.1	2.0±0.1
Stem diameter [cm]	3.8±0.1	3.7±0.2
Start of bud phenology	29 April – 12 May	29 April – 12 May

The needle contents of chlorophylls (Chl a, Chl b) and total carotenoids (Cars) were determined (Lichtenthaler 1987). An increase of the Chl (a+b) content by 35 %, higher content of light-harvesting complexes (lower Chl a/b) by 3.1 %, and relatively lower content of protective carotenoids (Chls/Cars) by 18.5 % were recorded in current needles for trees inside AC-dome at the end of the growing season (Table 1). This is associated with a 2.7 % increase in photochemical yield of photosystem 2 (F_V/F_M). At the scale of whole shoot photosynthesis we did not observe any statistically significant differences (Table 1) between trees on the AC- and C-plots. Using the heat pulse method no differences were observed in the sap flux rate between the C- and AC-plots (Marek *et al.* 2000). Some differences among trees in specific sap flux values, *i.e.*, sap flux rate normalised by cross-sectional sapwood area, occurred under low (≤200 μmol m^{-2} s^{-1}) and high (≥800 μmol m^{-2} s^{-1}) irradiances (Pokorný *et al.* 2001). Thus, the total stand transpiration of the AC- and C-plots, recalculated on the whole sapwood area and stand area, was significantly different especially during sunny days (Table 1). Structural properties of specific leaf area, tree height, and stem diameter showed no significant differences after two years of growth in the dome. Additionally, there were no significant differences in bud phenology.

Conclusions: The effect of increasing [CO_2] on forest ecosystems is an environmental issue that requires carefully designed experiments and methodologies (Hileman *et al.* 1985, Allen *et al.* 1992, Hendrey *et al.* 1999, Malhi *et al.* 1999). Different effects of increasing [co_2] on juvenile and mature trees are known (Eamus and Jarvis 1989, Pontailler *et al.* 1998) but impacts of EC during the canopy closure phase and, subsequently, on the formation of sun and shade assimilation tissues are still open questions.

On the basis of microclimatic data for over two-years we show that glass domes with adjustable windows are suitable for the investigation of EC on juvenile forest stands. The constructional design allows satisfactory maintenance of EC, without sophisticated feedback control, that is comparable with "small" (Janouš *et al.* 1996, Pontailler *et al.* 1998) and "large" (Allen *et al.* 1992, De Angelis and Scarrascie-Mugnozza 1998) OTCs. The dome's dimensions enable treatment of juvenile Norway spruce trees over six vegetation seasons and through canopy closure.

The most important chamber effect is associated with the penetration of incident solar radiation. The PAR/UV ratio is significantly uninfluenced because of the high proportion of diffuse radiation inside the domes. However, the domes slightly protect trees against freezing stress and frost damages. Both the construction and concrete base of the domes have not influenced soil quality (pH, ion content). Thus, we conclude the glass dome with adjustable window system is a useful facility for the long-term investigation of EC in natural mountain forest ecosystems.

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