Glass domes with adjustable windows: A novel technique for exposing juvenile forest stands to elevated CO₂ concentration

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Abstract

We present a new technological approach for in situ investigation of long-term impacts of elevated CO₂ concentration (EC) on juvenile forest stands 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 [CO₂] in both time and spatial scales with the relatively small consumption of supplied CO₂. 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 CO₂ (Malhi et al. 1999). Until recently, the role of rainforests in the global CO₂ 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 CO₂ 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 CO₂ 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
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 CO₂ 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 CO₂. 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 [CO₂] (Hendrey et al. 1999). The main disadvantage of these systems is a large volume of consumed CO₂, 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 Bílá 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 1100 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 [CO₂] (AC-variant), the second dome contains elevated [CO₂] (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. 1A,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. 1B 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 climatization device (Fig. 1A,B). The positioning of windows is automatic and depends on wind speed and its direction. Limited escape of added [CO₂] 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 RH1 400, Janka, Czech Republic) with volumetric rates of airflow 1.2 m³ 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. 1B) 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 Klíž (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 m²). 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 – CO₂ 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.
1B) 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)
are 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 $[CO_2]$ oc-
curred 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.](image)

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. Be-
cause 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), $[CO_2]$ fluctua-
tions 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 penetra-
tion 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 dif-
fuse 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 sum-
mer months (June–August) with an automatic regime control-
ing movement of windows.](image)

**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 tempera-

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ture within the domes was maintained within the ambient range ±1.0 °C for 84% of the time (Fig. 4A). 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. 4A 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. 4B). 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.

![Graph A](image1.png)

**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).

![Graph B](image2.png)

**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).

Irrigation 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. 1B) creates a diffusive air move-
ment, auxiliary fans (5 in Fig. 1B) 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.

![Graph showing soil moisture content and precipitation](image)

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

<table>
<thead>
<tr>
<th>Physiological parameter</th>
<th>AC-dome</th>
<th>Control plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chl ((a+b))</td>
<td>0.41±0.05**</td>
<td>0.30±0.05**</td>
</tr>
<tr>
<td>Cars</td>
<td>0.08±0.01**</td>
<td>0.07±0.01**</td>
</tr>
<tr>
<td>Chl (a/b)</td>
<td>3.21±0.03**</td>
<td>3.31±0.05**</td>
</tr>
<tr>
<td>Chls/Cars</td>
<td>4.8±0.2**</td>
<td>4.1±0.2**</td>
</tr>
<tr>
<td>(F_o/F_m)</td>
<td>0.82±0.007**</td>
<td>0.80±0.007**</td>
</tr>
<tr>
<td>(P_n) [µmol(CO(_2)] m(^2) s(^{-1})</td>
<td>8.0±1.0</td>
<td>8.7±1.4</td>
</tr>
<tr>
<td>(γ) [µmol m(^{-2}) s(^{-1})</td>
<td>40.0±5.9</td>
<td>32.0±8.0</td>
</tr>
<tr>
<td>(E) [mm d(^{-1})] – sunny days</td>
<td>1.67±0.28**</td>
<td>0.46±0.09**</td>
</tr>
<tr>
<td>(E) [mm d(^{-1})] – cloudy days</td>
<td>0.26±0.23</td>
<td>0.09±0.07</td>
</tr>
<tr>
<td>SLA [cm(^2) g(^{-1})]</td>
<td>76±10</td>
<td>66±10</td>
</tr>
<tr>
<td>Tree height [m]</td>
<td>2.2±0.1</td>
<td>2.0±0.1</td>
</tr>
<tr>
<td>Stem diameter [cm]</td>
<td>3.8±0.1</td>
<td>3.7±0.2</td>
</tr>
<tr>
<td>Start of bud phenology</td>
<td>29 April – 12 May</td>
<td>29 April – 12 May</td>
</tr>
</tbody>
</table>

The needle contents of chlorophylls (Chl \(a\), Chl \(b\)) and total carotenoids (Cars) were determined (Lichten-thaler 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 \((F_o/F_m)\). 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 \((\leq 200\ \mu \text{mol m}^{-2} \text{s}^{-1})\) and high \((\geq 800\ \mu \text{mol m}^{-2} \text{s}^{-1})\) irradiances (Pokorny et al. 2001). Thus, the total stand transpiration of the AC- and C-plots, recalculated on the whole sap-
wood 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 [CO₂] 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 [CO₂] 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” (Janoš et al. 1996, Pontailler et al. 1998) and “large” (Allen et al. 1992, De Angelis and Scarrascia-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.

References


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