Influence of stand density, thinning and elevated CO_2 on stem wood density of spruce

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ABSTRACT: Stem wood density (SWD) of young Norway spruce trees (*Picea abies* [L.] Karst.) growing at ambient (**A** variant, 350 μmol(CO_2)/mol) and elevated (**E** variant, **A** + 350 μmol(CO_2)/mol) atmospheric CO_2 concentration inside of the glass domes with adjustable windows was estimated after six and eight years of the cultivation. Stand density of two subvariants (**s** – sparse with ca 5,000 trees/ha and **d** – dense with ca 10,000 trees/ha) and thinning impact (intensity of 27%) on SWD and its variation along the stem vertical profile were investigated. After six years of CO_2 fumigation, stems of sparse subvariant had about 10% lower values of SWD comparing to dense ones, although the difference was not statistically significant. In 2004 (two years after thinning), the SWD values were higher in all subvariants along the whole stem vertical profile. This increase was more obvious in **E** variant (about 6% in **d** subvariant and only 3% in **s** subvariant). The highest increase of SWD values was found in **Ed** subvariant, particularly in the middle stem part (about 8%, statistically significant increase).

Keywords: elevated CO_2; *Picea abies*; stand density; stem wood density; thinning

Stem wood density (SWD) is the most important determinant of the wood quality. It allows estimation of biomass and carbon mass contained in terrestrial vegetation (Fearnside 1997). The SWD is defined as the dry mass to fresh volume ratio and ranges typically within the interval from 0.1 to 1 g/cm^3 (Roderick 2001). SWD depends mainly on the cell size and the cell wall thickness. Specifically, SWD of forest trees is influenced by many factors. There are physical factors influencing SWD – weight of the crown, ice or snow loading. From the abiotic factors – soil moisture is recognized as a major factor controlling wood properties (Hansmann et al. 2002). Air temperature and soil type are the other significant factors (Roderick 2001), which depend on latitude and altitude. Thus SWD markedly decrease with latitude and altitude as well (Sopushynskyy et al. 2005). In response to nitrogen fertilization, SWD either declines or remains constant (Fearnside 1997).

Generally, SWD shows higher values compared to the branches (Panshin, De Zeeuw 1980). SWD of conifers varies directly with age in the radial direction and inversely with vertical direction. Thus, the highest SWD values occur in outer rings in lower stem parts and decreases from the bark inward and from the stem-base upward to the tree top (Panshin, De Zeeuw 1980).

In most cases, elevated CO_2 induce enhanced wood density. Compared to natural growing conditions, a doubling of air's CO_2 concentration would increase wood density of Norway spruce trees about 2–5% (Makinen et al. 2002). Kilpelainen et al. (2003) states that the increases in latewood density and maximum density in response to elevated CO_2

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may imply improvements in wood strength properties. Variations in environmental conditions induce unequal response of wood density to elevated CO_2. For example, at ambient temperatures, approximately 60% increase of the air's CO_2 concentration significantly enhance latewood density (by 27%) and maximum wood density (by 11%), while elevated-temperature conditions enhance less significantly latewood density (by 25%) and, in contrary, more significantly maximum wood density (by 15%) (Beismann et al. 2002). These changes lead to mean overall CO_2 – induced wood density increases of 2.8% at the ambient-temperature and 5.6% at the elevated-temperature (Beismann et al. 2002). Furthermore, elevated atmospheric CO_2 concentration increase wood toughness of spruce seedlings grown on acidic soils by 12 and 18% under low and high levels of nitrogen deposition, respectively. Elevated atmospheric CO_2 also increase the same mechanical wood properties in spruce seedlings grown on calcareous soils by about 17 and 14% under low and high levels of nitrogen deposition (Beismann et al. 2002).

The objectives of this study were:

(a) to evaluate an influence of elevated atmospheric CO_2 concentration on SWD,
(b) to describe the changes of SWD values along the stem vertical profile,
(c) to investigate changes of SWD with respect to stand density and thinning.

MATERIALS AND METHODS

Site and stand description: There were two variants of glass domes with adjustable windows (DAW) – ambient (**A**, 350 μmol(CO_2)/mol) and elevated (**E**, **A** + 350 μmol(CO_2)/mol) – established a for simulation of elevated atmospheric CO_2 concentration at the Experimental Research Site Bílý Kříž (Czech Republic, 49°30´N, 18°32´E, 908 m a.s.l.) in the Beskydy Mts. (for detail description see Urban et al. 2001).

Both variants of artificially established pure stands of Norway spruce (*Picea abies* [L.] Karst.) showed the identical arrangements of the tree spacing (Pokorný et al. 2001), which enabled to distinguish the two subvariants: sparse (**s**, ca 5,000 trees/ha) and dense (**d**, ca 10,000 trees/ha). Total number of trees per variant in each DAW was 56. The trees were planted at the age of 10–12 years in autumn 1996.

Sampling procedure: In 2002, the first schematic thinning (intensity of 27%) was carried out. After the two years, the next one (intensity of 35%) was performed. Thus, seven trees per subvariant, i.e. ambient/elevated sparse/dense, were analyzed in 2002 and 2004, respectively. SWD was obtained for chosen stem discs that were cut at the middle parts of internodial sections under the 3rd, 5th, and the 7th whorl (t_3, t_5, t_7), and in the one tenth of tree height ($Ht_{1/10}$) (Table 1). Fresh stem discs volume was measured as a volume of cylinder. Afterwards, stem discs were dried for 48 hours in 105°C. After drying, dry weight was precisely estimated (balance model 1405 B MP8-1, Sartorius, Germany). Then, SWD was calculated using the common formula for basic wood density calculation (Roderick 2001). SWD of the stem disc t_3 was assorted to block of internodial sections from the tree top to the t_3 section, SWD of t_5 disc to sections $t_4 + t_5$, SWD of t_7 disc to sections $t_6 + t_7$ and SWD of disc from 1/10 of H to internodial sections t_8 and below.

Methodology for stem volume calculation was based on the length of internodial section and its middle cross-sectional circle area measurement. SWD of tree was calculated as the weighted average (according to length of internodial sections).

Processing of statistical values: One-way and two-way ANOVA were used for detection of statistically significant differences (SSD, not significant = NS). All data were tested on normality and homoge-

Table 1. Position of stem discs in stem vertical profile grown in elevated (**E**) and ambient (**A**) concentration of CO_2 and sparse (**s**) and dense (**d**) subvariant; Ht – total tree height, $Ht_{3,5,7}$ – tree height from the tree base to the appropriate whorl (low index indicates whorl), $Ht_{1/10}$ – tree height in one tenth of the tree height. Numbers in bracket mean relative height

Subvariant (m)	2002				2004			
	As	**Ad**	**Es**	**Ed**	**As**	**Ad**	**Es**	**Ed**
Ht	3.66	3.37	3.23	3.27	4.36	4.59	5.62	4.94
Ht_3	2.09 (57%)	1.81 (54%)	1.85 (57%)	2.18 (67%)	2.73 (63%)	2.83 (62%)	3.13 (56%)	2.77 (56%)
Ht_5	1.45 (40%)	1.09 (32%)	1.42 (44%)	1.51 (46%)	2.08 (48%)	2.14 (47%)	2.43 (43%)	2.04 (41%)
Ht_7	0.87 (24%)	0.55 (16%)	0.79 (24%)	0.90 (28%)	1.26 (29%)	1.63 (36%)	1.51 (27%)	1.48 (30%)
$Ht_{1/10}$	0.37 (10%)	0.34 (10%)	0.32 (10%)	0.33 (10%)	0.44 (10%)	0.46 (10%)	0.56 (10%)	0.49 (10%)

neity (S-W and Lewene tests; differences were tested on the level α = 0.05). Scheffe and Duncan test were used for detection of SSD. Statistica software (StatSoft Inc., Tulsa USA) was performed for statistical analysis.

RESULTS AND DISCUSSION

After six years of the cultivation under two different CO_2 concentrations, **A** ambient and **E** elevated average stem wood density SWD was comparable in both variants (**A** > **E**, 358 versus 351 kg/m^3, NS). After schematic thinning (i.e. two years later), SWD increased about 60 kg/m^3 in **E** variant and 30 kg/m^3 in **A** variant (Fig. 1). Thus, SWD of young Norway spruce trees grown under elevated atmospheric CO_2 was higher on average about 6% comparing to ambient conditions (412 versus 390 kg/m^3, NS, $P = 0.055$). Thinning also affected the stem volume (increase about 13% in **E** variant) and stem biomass (increase about 17% in **E** variant). These results are consistent with the results of Makinen et al. (2002), who presented increase of SWD in Norway spruce trees up to 5% under the doubling of atmospheric CO_2 (results are from 12 year long experiment without the effect of thinning). A positive correlation between atmospheric CO_2 and SWD for *Pinus radiata* and *Pinus sylvestris* was also described by Hättenschwiler et al. (1996), Conroy et al. (1990), Ceulemans and Jach (2002). However, *Pinus taeda* did not respond to elevated CO_2 unambiguously. SWD of this species was increased (Doyle 1987) or decreased (Oren et al. 2001) and also remained stable (Murthy, Dougherty 1997; Telewski et al. 1999; Roderick 2001). These inconsistent results obtained for individual coniferous species can be also caused by differences in cultivation design and also in fumigation duration.

Presented values of SWD distinctively showed higher values (about 10%) for trees grown in more dense spacing (two times denser comparing to sparse one) for both investigated years (i.e. before and after thinning). Considering spacing of subvariants, the higher SWD values were observed in both **E** and **A** subvariants (**Es** > **As**, by 3%, NS; **Ed** > **Ad**, by 6%, SSD). This observation supports a phenomenon of the sink strength effect described by Urban (2003). SWD was found to be higher in **d** subvariant growing under elevated CO_2, therefore enhanced CO_2 effect seems to be forced by the stand density. The growth competition between trees of the **d** subvariant caused more probably sink strength, so the CO_2

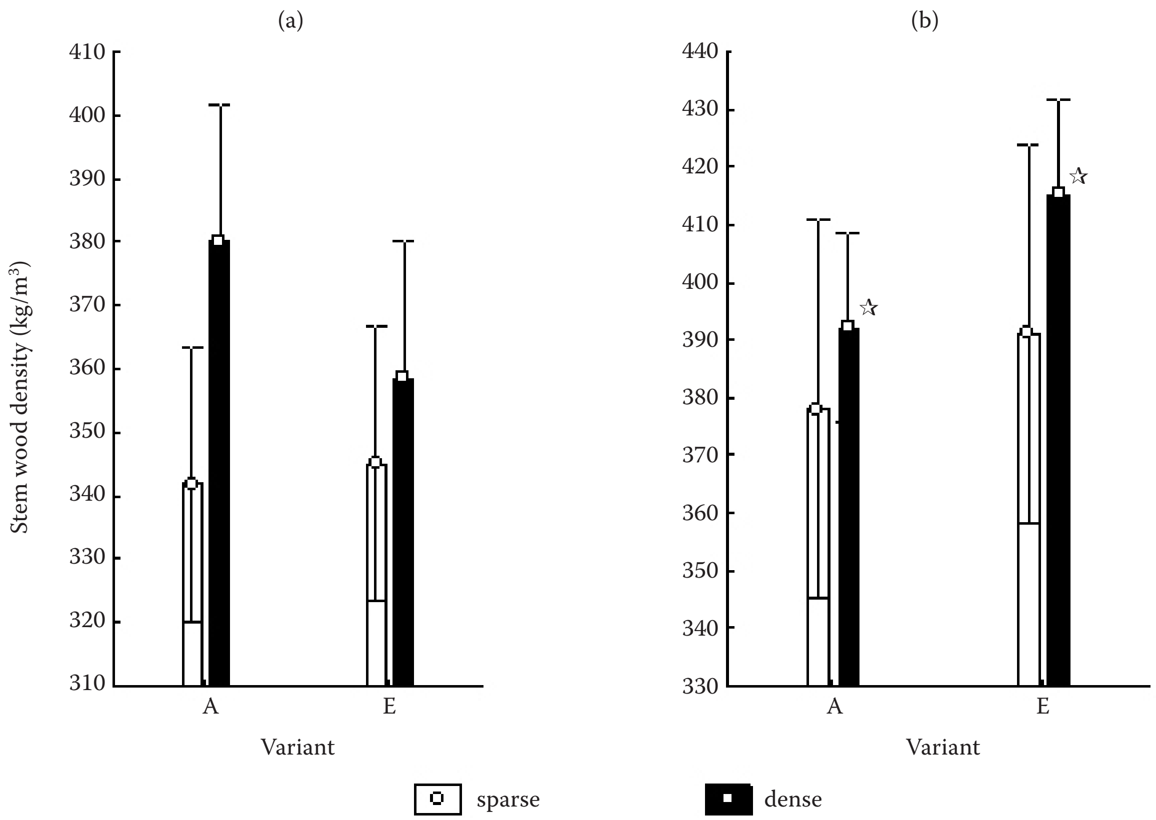

Fig. 1. Average stem wood density in elevated (**E**) and ambient (**A**) concentration of CO_2 and sparse (**s**) and dense (**d**) subvariant independent from vertical stem profile; (a) 2002, i.e. after 6 years of the cultivation and (b) 2004, i.e. after 8 years of the cultivation and 2 years after thinning. Stars denote statistical significant difference

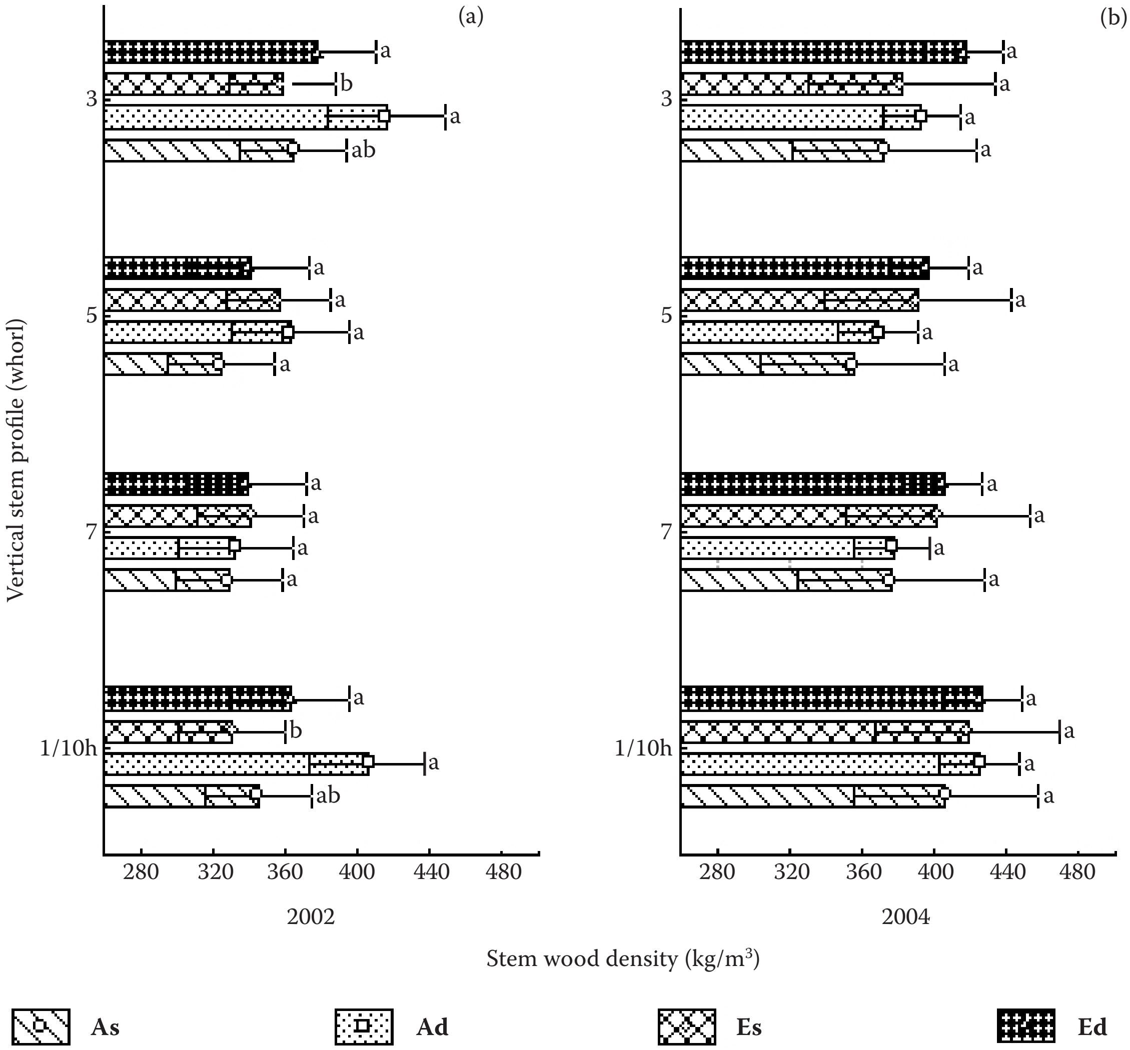

Fig. 2. Stem wood density in subvariants in elevated (**E**) and ambient (**A**) concentration of CO_2 and sparse (**s**) and dense (**d**) subvariant within vertical stem profile in (a) 2002 and (b) 2004. Whiskers denote standard deviation. Letters denote homogenous groups

effect was more obvious. These results are in accordance with findings of LINDSTROM (1996), who described strong effects of thinning on the Norway spruce trees SWD values.

SWD for European Norway spruce ranges on average within the interval 320–420 kg/m^3 (HAKKILA 1989). Thus, SWD values obtained in our experiment for elevated CO_2 treatment became close to upper interval limit of natural values.

Before the thinning, the SWD values alongside the whole stem as well as the stem biomass (SB) and stem volume (V), were comparable for both CO_2 variants. After thinning, the SWD values increased from 358 to 390 kg/m^3 in **A** variant and from 351 to 411 kg/m^3 in **E** variant. After the thinning, SSD were found among SWD values in the middle parts of the stem vertical profile (i.e. between 5 and 7 whorl). The average SWD in the upper part of the crown was 373 kg/m^3 in **A** variant compared to 346 kg/m^3 in **E** variant (Fig. 2). The highest SWD occurred at the stem-base and it was comparable with the SWD of upper part of the stem as pointed also PANSHIN et al. (1980).

Before the thinning, the average SWD at the stem base gained value of 388 and 367 kg/m^3 in **A** and **E** variants, respectively. After thinning, these values increased up to 393 and 417 kg/m^3, respectively.

CONCLUSION

The wood densities alongside the whole stem were comparable in the both ambient and elevated CO_2 treatments; therefore just elevated CO_2 had no significant effect on the stem wood density of Norway spruce after six years of cultivation. The thinning (tree reduction of 27%) resulted in the significant increase of the stem wood density along the whole stem vertical profile under elevated CO_2, especially in the middle part of stem. Participation of elevated CO_2 and thinning had a positive effect on stem wood density.

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Vliv hustoty porostu, prořezávky a zvýšené koncentrace CO_2 na hustotu dřeva kmene smrku

ABSTRAKT: Hustota dřeva kmene (SWD) byla stanovena u mladých jedinců smrku ztepilého (*Picea abies* [L.] Karst.) kultivovaných po dobu šesti a osmi let v přirozené (varianta **A**, 350 μmol(CO_2)mol) a zvýšené (varianta **E**, **A** + 350 μmol(CO_2)mol) vzdušné koncentraci CO_2 uvnitř lamelových komor. Byl zkoumán vliv rozdílných hustot porostu (subvarianty: **s** – řídká – 5 tisíc ks/ha a **d** – hustá – 10 tisíc ks/ha) a prořezávky (intenzita 27 %) na SWD a jeho změny v podélném profilu kmene. Po šesti letech fumigace CO_2 byly hodnoty SWD kmenů řídké subvarianty v průměru o 10 % nižší ve srovnání s hustou subvariantou. V r. 2004 (dva roky po prořezávce) byla SWD kmenů vyšší podél celého profilu kmene ve všech subvariantách. Tento nárůst byl výrazný především ve variantě **E** (v průměru o 6 % v husté subvariantě a o 3 % v řídké subvariantě). K nejvyššímu nárůstu hodnot SWD kmenů husté subvarianty **E** došlo ve střední části kmene (o 8 %, statisticky průkazný rozdíl).

Klíčová slova: zvýšená koncentrace CO_2; *Picea abies*; hustota porostu; hustota dřeva kmene; prořezávka

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