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Norway spruce production and static stability in IUFRO thinning experiments in the Czech Republic

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Abstract: Despite recent issues, Norway spruce remains the most important commercial tree species which might be demanded henceforth for its broadly utilizable wood. Even before foresters faced both the bark beetle outbreaks and spruce decline, spruce monospecific stands were known to be prone also to other damage due to snow and wind. On this basis, measures that help prevent such failures were looked for, which resulted in the establishment of international IUFRO experimental series focused on impacts of different thinning regimes on stability and production of spruce stands. The thinning treatments differed in numbers of trees removed and retained on the site when dominant height of crop trees was reached or allowable cut in non-crop trees was accumulated. Also effects of different width of skid trails were tested. The study summarizes the results from the two IUFRO experiments in the Czech Republic. Effects of thinning regimes on spruce were found positive though thinning reduced the total volume production of wood while improving crop-tree stability which enhanced production safety. Different widths of skid trails had no effect on wood increment. Early thinning of spruce can be used to prevent their damage. No such measure, however, can alleviate the spruce decline.

Keywords: *Picea abies*; early thinning; stand stability; slenderness ratio; total volume production

Thinning of forest stands is accounted a silvicultural measure that helps establish and maintain the most important stand properties such as performance of tree individuals and production characteristics. Norway spruce (*Picea abies* /L./ Karst.) is still the most important commercial tree species that grows in many site conditions ranging from floodplain to mountainous spruce types of forest in the Czech Republic. Considerable damage to monospecific spruce stands due to both snow and wind forced foresters and researchers to revise a currently applied thinning approach focusing on both volume and quality of production; the innovative measures should also improve production safety and maintain other services of forest. Besides effects of thinning, also the impact of initial density and spacing of plants was studied (Korpeľ, Saniga 1995).

There were 14 European countries which established totally 29 IUFRO thinning experimental series at the beginning of the 1970s. The objective of the experiments was to get the knowledge of relationships between different thinning regimes and forest stand productivity, wood quality and static stability at both the stand and individual tree levels. In 2005, only 11 experiments were maintained without discontinuation of the stand measurement.

In the Czech Republic, three experimental thinning series were established in accordance with the IUFRO international project focusing on spruce production and stability that were expected to be affected by silvicultural measures (Abetz 1977). Long-term observations, however, were carried out only in two of them, Machov (IUFRO 14) in eastern Bohemia (Chroust 1981) and Vítkov (IUFRO 13) in northern Moravia (Pařez 1981). Both were mea-

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sured annually until 2010 (IUFRO 13) and 2011 (IUFRO 14). In 2013–2014, both experimental observations were terminated due to salvage cutting by private owners. Some preliminary results from these experiments were published (Slodičák et al. 2005, Slodičák, Novák 2006, 2007; Horák, Novák 2009; Dušek et al. 2015).

The objective of this study is to add a final analysis of data and also summarize the results from both IUFRO experimental series with thinning expected to influence spruce stand stability and production. Considering a working hypothesis, we supposed an improved safety of production, which includes lower threat of snow load and wind, when heavy thinning is conducted in young spruce stands.

MATERIAL AND METHODS

Study sites. The experimental site IUFRO 13-Vítkov (Pařez 1981) was established in 8-year-old monospecific Norway spruce stand with dominant height of 3.5 m in 1971. The stands were planted regularly on afforested agricultural land with the initial density of 2 500 plants per hectare. The site classification unit was beech with fir [*Abieto-Fagetum fraxinosum humidum* according to Viewegh et al. (2003)] on moist-to-wet gleyic Cambisol with dominant *Athyrium filix-femina* at an altitude of 600 m a.s.l.

The experimental site IUFRO 14-Machov (Chroust 1981) was established in 6-year-old monospecific Norway spruce stand with dominant height of 1.2 m. The stand density was initially more than three times higher (7 700 plants·ha^{-1}) compared to IUFRO 13. Prior to the research plot establishment, the density was, therefore, reduced to comparable 2 500 plants·ha^{-1}. The site classification unit was beech with spruce [*Piceeto-Fagetum illimerosum acidophilum* according to Viewegh et al. (2003)] on compacted acid gleyic Luvisol at an altitude of 700 m a.s.l. Some trees suffered from bark-stripping damage by deer in the 1980s (15 years old stand).

Experimental and treatment design. The experiments were established and measured according to IUFRO methods (Abetz 1977; Herbstritt et al. 2006). The Vítkov experiment was established as a completely randomized block design with two blocks, five treatments and one replication of a treatment per block. The area of a particular plot was 0.10 ha. The last thinning according to IUFRO prescriptions was conducted in the stand reaching a dominant height of 27.5 m in 2008.

The Machov experiment was established as a completely randomized design with five treatments and two replications per treatment. One plot of control treatment and one plot of treatment 3 were excluded from the analysis due to different and possibly inappropriate manner of their establishment. The last thinning according to IUFRO prescriptions was conducted in the stand reaching a dominant height of 22.5 m in 2008 (Figure 1).

Both experiments consisted of these treatments:

1 – Control without thinning, only wind-thrown and dry trees were removed.

2 – Early heavy thinning from below when the dominant heights of 10 m (1 200 trees·ha^{-1} were left), 12.5 m (900 trees·ha^{-1} were left) and 15 m (700 trees·ha^{-1} were left) were reached. The last thinning was conducted when dominant height reached 27.5 m and 400 trees·ha^{-1} were left on the site.

3 – The second and third thinning from below were delayed so as to obtain merchantable wood assortments from the stand with 20-meter and 22.5-meter dominant height (900 and

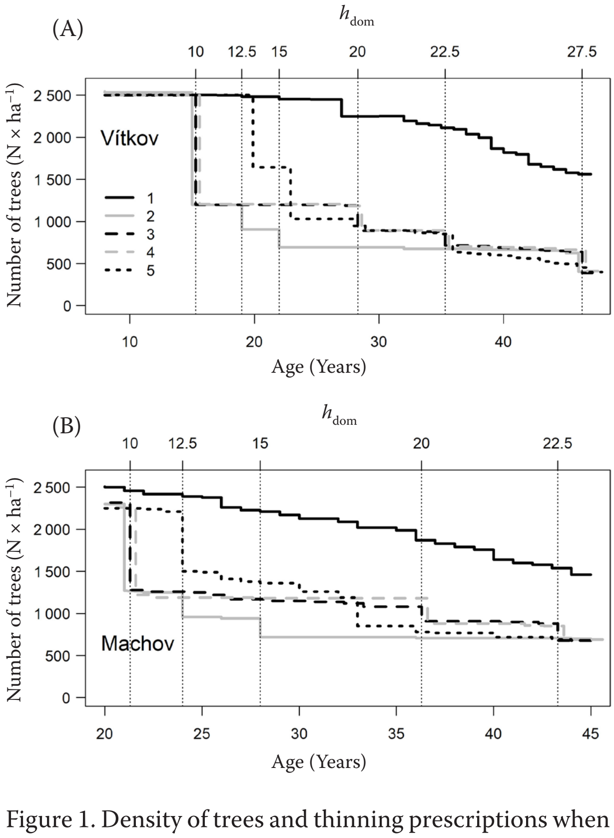

Figure 1. Density of trees and thinning prescriptions when the height of dominant trees (h_{dom}) according to IUFRO methodology was reached in the treatments (see Material and Methods)

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700 trees·ha^{-1} were left, respectively). The last thinning was conducted when dominant height was 27.5 m and 400 trees·ha^{-1} were left on the site. The treatment included a 3.5-meter skid trail.

4 – The same thinning prescription as in item 3 but a 5-meter skid trail was used. The wider the trail, the less damage to trees left can be expected.

5 – The treatment called "commercial" where the thinning schedule is no longer based on dominant heights. The thinning from above was conducted if 60 m^3·ha^{-1} of available wood accumulated in non-crop trees with DBH (diameter at breast height) exceeding 12 cm; these could be removed while all crop trees were left on the site.

Data collection. The experiments were measured annually until 2010 (Vítkov) and 2011 (Machov). Stem diameters of all trees were measured using a calliper. Tree heights of 30 trees per plot (represented the whole range of stem diameters) were measured using a Blume-Leiss hypsometer (Carl Leiss, Germany). In Vítkov experiment, the last mensuration was conducted at the age of 47 years in 2010; the dominant height was 28–29 m. Four years later, the experiment was terminated due to salvage cutting.

The Machov experiment was terminated after being harvested by a new private owner at the age of 48 years in 2013. The last mensuration was conducted two years earlier as the stand dominant height reached ca. 24–25 m.

Data analysis. The mean DBH was expressed as the mean quadratic diameter related to stem with mean basal area (d_g) according to Formula (1):

$$d_g = \sqrt{\frac{\sum d_i^2}{n}} \quad (1)$$

where:
d_i – DBH;
n – number of trees.

Based on the measured heights and DBHs, regression parameters of height curves were calculated using Formula (2) (Näslund 1937):

$$h = \frac{d^2}{\left(\alpha + \beta \times d\right)^2} + 1.3 \quad (2)$$

where:
h – height
d – DBH;
α, β – regression coefficients.

Based on the calculated height curves, height and slenderness ratio of mean stem and dominant stem for 200 thickest trees per ha (i.e. 20 trees per plot) were calculated. Mean periodical basal area (*mBA*) as the thinning intensity (Pretzsch 2009) was calculated according to Formula (3):

$$mBA = \frac{\frac{pBA_1 + kBA_1}{2} \times per_1 + \frac{pBA + kBA_2}{2} \times per_2 + \ldots + \frac{pBA_n + kBA_n}{2} \times per_n}{per_1 + per_2 + \ldots + per_n} \quad (3)$$

where:
pBA – initial basal area at the beginning of inventory period;
kBA – the basal area at the end of inventory period;
per – years in particular periods between the inventories.

Both standing volume and total volume production of inside-bark wood below the 7-cm sawlog top diameter (e.g. see Domke et al. 2013) were estimated according to Korsuň (1961). The volume production of the inside-bark sawlog was also calculated for trees with volumes exceeding 0.7 and 0.5 m^3. Both planned cuttings and salvage cuttings were included in the calculation of total volume production.

To verify the influence of experimental thinning on particular mensurational and production characteristics, ANOVA model (Formula (4)) for block design was used:

$$y = \alpha + treatment \times \beta 1 + block \times \beta 2 + \varepsilon\, N\left(0, \sigma\right) \quad (4)$$

where:
y – dependent variable;
α – absolute term;
treatment – experimental treatment;
$\beta 1$ – parameter for experimental treatment;
block – locality;
$\beta 2$ – parameter for block;
ε – normally distributed errors;
σ – variance.

The following four linear orthogonal (i.e. mutually independent) contrasts were formulated:

L1 – test of difference between the control and the mean of all thinned treatments;

L2 – test of difference between the mean of treatments 2, 3 and 4 (where a crucial parameter for thinning was the reached dominant height) and the "commercial thinning" in treatment 5;

L3 – test of difference between treatment 2 (with early thinning) and the mean of treatments 3 and 4 where thinning was delayed;

L4 – test of difference between treatments 3 and 4 with the same thinning prescription and skid trails of different width.

Due to the unbalanced experimental design, a restricted maximum likelihood method (REML) was

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used. All dependent variables (except the slenderness ratio) were logarithmically transformed, thus the differences between the treatments (defined by the contrasts) can be expressed as proportion (percentage). Statistical language R (Version 3.6.3, 2020) with nlme library (Pinheiro et al. 2020) was used for calculations of all tests.

RESULTS

All results described in this section are based on 2010 data from IUFRO 13 at the age of 47 years with height of 200 dominant trees (h_{200}) 28–29 m and 2011 data from IUFRO 14 at the age of 46 years with h_{200} 24–25 m.

The mean stem diameter (d_g) was 28% lower in unthinned control compared to thinned treatments (contrast L1, $P < 0.001$). Treatments 2, 3 and 4 showed 6% thicker d_g compared to the "commercial" treatment 5 (L2, $P = 0.02$). The early thinning increased d_g as treatment 2 showed a 5% thicker value compared to delayed-thinning treatments 3 and 4 (L3, $P = 0.09$). The differences between treatments 3 and 4 accounted for less than 2% (L4, $P = 0.49$). The unthinned dominant stem diameter (d_{200}) was also lower than the thinned treatments as it showed a 13% reduction (L1, $P < 0.001$). The d_{200} of treatments 2, 3 and 4 were ca. 1% lower compared to treatment 5 (L2, $P = 0.86$). Treatment 2 d_{200} showed ca. 6% thicker values compared to treatments 3 and 4 (L3, $P = 0.41$). The difference between treatment 3 and 4 accounted for less than 1% (L4, $P = 0.41$, Figure 2).

The mean stem slenderness ratio (h/d) showed less favourable, high values ranging between 94 (IUFRO 14) and 112 (IUFRO 13) in unthinned control which represented the mean difference of 25 compared to the other thinned treatments (L1, $P < 0.001$). The differences between the thinned treatments were negligible and the ratio values ranged between 76 and 84. Also the dominant stem slenderness ratio was the worst one in the unthinned treatment as it ranged between 77 (IUFRO 14) and 89 (IUFRO 13). The mean difference of 12 was the value exceeding the mean of the thinned treatments (L1, $P < 0.001$). The differences between the thinned treatments were negligible again (Figure 3, Table 1). The slenderness ratio of dominant trees increased with the mean basal area (mBA). Thinning proved a positive effect on the slenderness ratio of dominant trees (Figure 4).

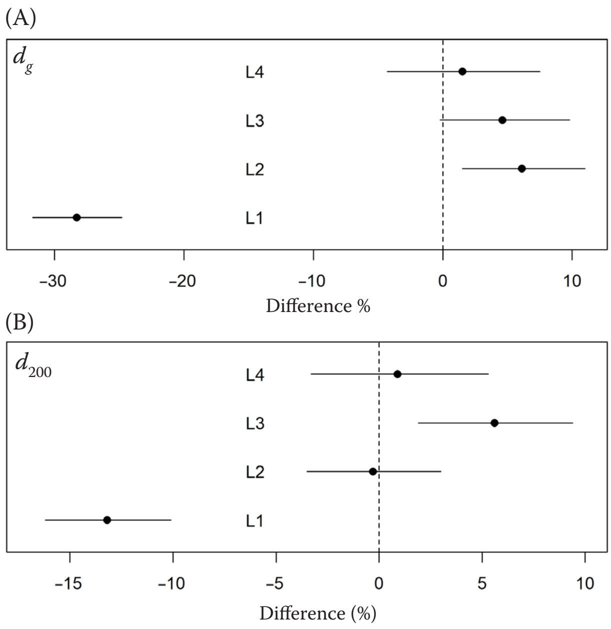

Figure 2. Percent differences in mean stem diameter (d_g) and stem diameter of dominant trees (d_{200}) for particular linear (orthogonal) contrasts with 95% confidence intervals

L1: treatment 1 – mean (treatments 2, 3, 4, 5); L2: mean (treatments 2, 3, 4) – treatment 5; L3: treatment 2 – mean (treatments 3, 4); L4: treatment 3 – treatment 4

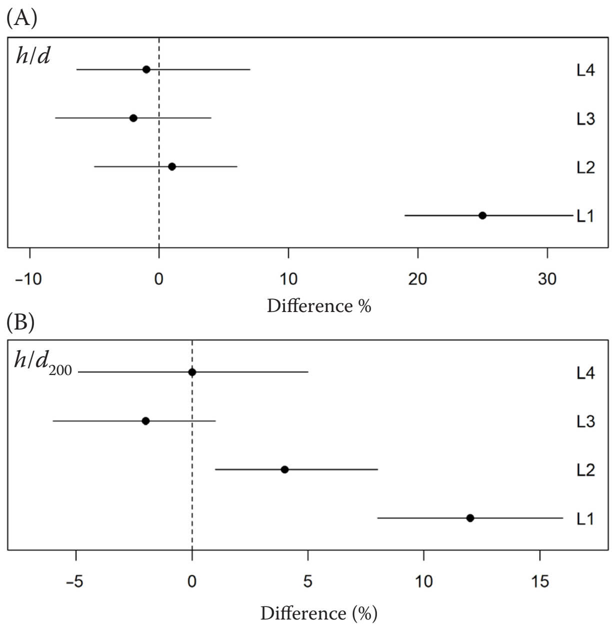

Figure 3. Differences in the slenderness ratio of mean stem (h/d) and dominant trees (h/d_{200}) for particular linear (orthogonal) contrasts with 95% confidence intervals

L1: treatment 1 – mean (treatments 2, 3, 4, 5); L2: mean (treatments 2, 3, 4) – treatment 5; L3: treatment 2 – mean (treatments 3, 4); L4: treatment 3 – treatment 4

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Table 1. Experimental plots and treatment attributes at the end of observation period in 2010 (IUFRO 13-Vítkov, 47 years) and 2011 (IUFRO 14-Machov, 46 years)

Locality	Block	Treatment	N (trees·ha^{-1})	d_g (cm)	d_{200} (cm)	h (m)	h_{200} (m)	h/d	h/d_{200}
Machov	A	1	1 460	22.9	31.4	21.6	24.2	94	77
		2	700	30.0	36.9	23.8	25.0	79	68
		2	700	30.4	35.2	23.9	24.8	79	70
		3	680	29.7	35.2	24.2	25.7	82	73
		4	710	28.5	33.9	23.8	25.1	83	74
		4	690	28.3	32.8	23.7	24.9	84	76
		5	780	27.2	34.1	22.8	24.1	84	71
		5	680	27.9	34.3	22.9	24.1	82	70
Vítkov	B	1	1 470	23.6	32.3	26.3	28.6	111	89
		2	400	36.9	40.1	29.0	29.5	79	74
		3	380	34.2	37.0	27.6	28.0	81	76
		4	420	35.2	38.3	27.7	28.0	79	73
		5	500	33.1	39.8	25.5	26.6	77	67
	C	1	1 650	23.4	32.8	26.2	28.7	112	88
		2	410	35.7	39.1	28.8	29.4	81	75
		3	400	34.5	37.4	27.6	28.1	80	75
		4	400	34.3	37.8	27.5	27.9	80	74
		5	300	33.4	38.3	25.5	26.4	76	69

N – density of trees; d_g – mean stem diameter; d_{200} – diameter of 200 dominant trees; h – mean height of stand; h_{200} – height of 200 dominant trees; h/d – mean stem slenderness ratio; h/d_{200} – slenderness ratio of 200 dominant trees

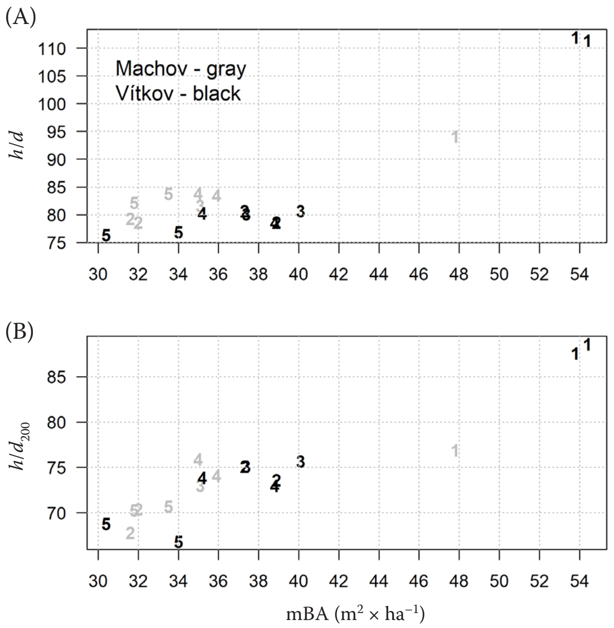

Figure 4. Relationship between mean basal area (*mBA*) and slenderness ratio of mean stem (h/d) and dominant trees (h/d_{200}); the letters denote the treatments

The greatest 61% higher *mBA* was reached in plots without thinning compared to the mean of thinned treatments (L1, $P < 0.001$). Basal area of "commercial" treatment 5 was 11% lower compared to treatments 2, 3 and 4 (L2, $P = 0.19$). Early heavy thinning in treatment 2 showed the 12% higher basal area than the mean of treatments 3 and 4 (L3. $P = 0.21$). The difference between treatments 3 and 4 accounted for less than 3% (L4, $P = 0.80$, Figure 5). The percentage differences in standing volumes were approximately in accordance with the differences in basal areas (Table 2).

The total volume production (*TVP*) in the unthinned control treatment exceeded the thinned treatment production as it showed a 16% higher value (L1, $P = 0.001$). The "commercial" approach in treatment 5 reduced the *TVP* which was 7% lower compared to treatments 2–4 (L2, $P = 0.04$). The *TVP* differences between treatments 2, 3 and 4 were negligible. The *TVP* values increased with the mean basal area (Figure 6). The *TVP* accumulated

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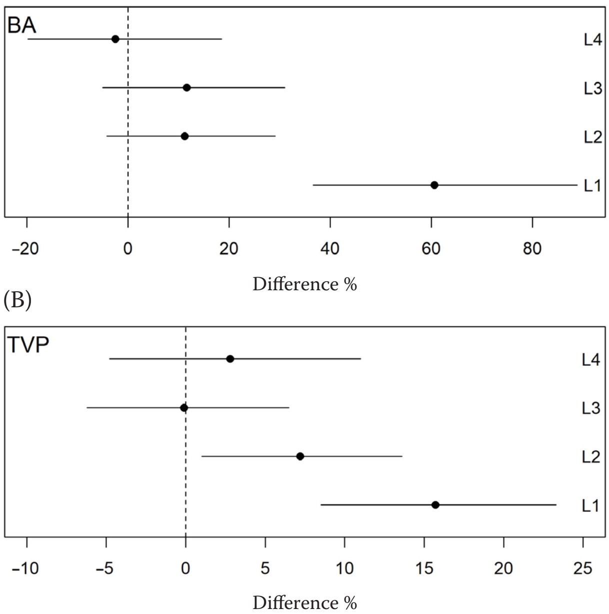

Figure 5. Percent differences in basal area (*BA*) and total volume production (*TVP*) for particular linear (orthogonal) contrasts with 95% confidence intervals

L1: treatment 1 – mean (treatments 2,3,4,5); L2: mean (treatments 2,3,4) – treatment 5; L3: treatment 2 – mean (treatments 3,4); L4: treatment 3 – treatment 4

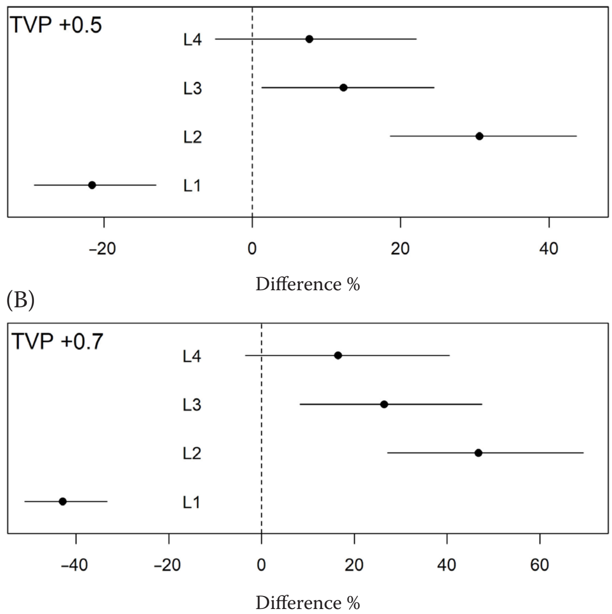

Figure 7. Percent differences in the total volume production of trees whose volume exceeded 0.5 m^3 ($TVP_{+0.5}$) and trees whose volume exceeded 0.7 m^3 ($TVP_{+0.7}$) for particular linear (orthogonal) contrasts with 95% confidence intervals

L1: treatment 1 – mean (treatments 2,3,4,5); L2: mean (treatments 2,3,4) – treatment 5; L3: treatment 2 – mean (treatments 3,4); L4: treatment 3 – treatment 4

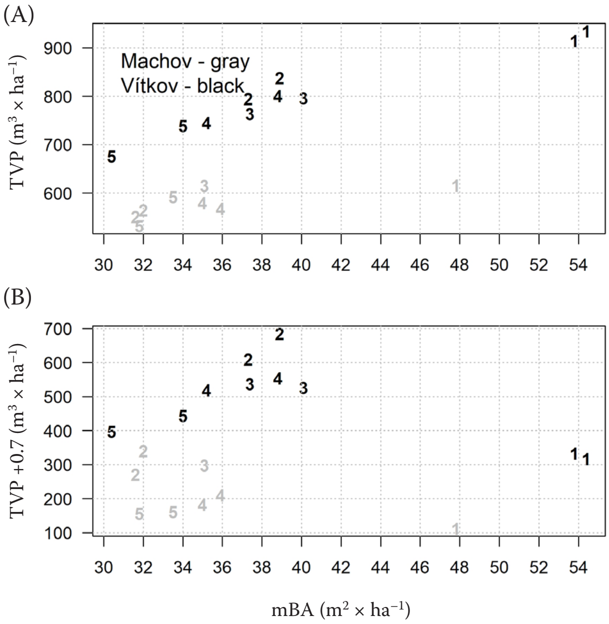

Figure 6. Relationship between mean basal area (*mBA*) and total volume production of all trees (*TVP*) and trees whose volume exceeded 0.7 m^3 ($TVP_{+0.7}$); the letters denote the treatments

in trees with the volume exceeding 0.5 m^3 ($TVP_{+0.5}$, Figure 7) was the lowest in the unthinned treatment showing a 22% lower value compared to the thinned treatments (L1, $P < 0.001$). There was found also a 31% reduction of $TVP_{+0.5}$ in the "commercial" treatment 5 compared to the other thinned treatments 2, 3 and 4 (L2, $P < 0.001$). The early thinning showed 12% higher $TVP_{+0.5}$ than the delayed-thinning treatments 3 and 4 (L3, $P = 0.05$); the difference between treatment 3 and 4 accounted for 8% (L4, $P = 0.27$). In larger trees with volumes exceeding 0.7 m^3, $TVP_{+0.7}$ differences were found even greater (L1 = –43%, $P < 0.001$; L2 = +47 %, $P < 0.001$; L3 = +26 %, $P = 0.01$; L4 = +17 %, $P = 0.14$).

DISCUSSION

The last co-operative appraisal of all spruce thinning IUFROs experiments was done at the age of 30 years since the establishment of the experimental series (Herbstritt et al. 2006). It was observed that the stand density reduction according to the thinning prescriptions improved stand stability

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and accelerated diameter growth rate (Herbstritt et al. 2006). In studies dealing with Austrian (Neumann, Rössler 2012) and German (Hein et al. 2008) IUFROs, the same was concluded later.

As for the accelerated diameter increment and improved stem slenderness (i.e. lower *h*/*d* ratio), which is a good proxy for static stability, both these characteristics were found positive in many other studies dealing with the young spruce stands. Kuliešis and Saladis (1998) reported the improved spruce stand stability if thinned intensively at the age of 9–11 years. Štefančík et al. (2012) observed both higher diameter increment and improved static stability in 21-year-old naturally regenerated spruces thinned 4 years earlier. On the other hand, results from Norway (Gizachew, Brunner 2011) showed for spruce and pine that the basal area growth increases with stand density although slightly at higher densities. Also many other authors (Blackburn, Petty 1988; Rollinson 1988; Maccurrach 1991; Pettersson 1993; Mäkinen, Isomäki 2004, Gizachew et al. 2012, Katrevičs et al. 2018) reported a negative correlation between the stand density and diameter increment whereas height increment remained unaffected, which improved the stem slenderness thus impacting on the stand stability positively.

Other benefits resulting from heavy thinning were also found. For example Laurent et al. (2003) found that spruces became more resistant to drought over the six years following heavy thinning of 22-year old stand. This shows an importance of reduced competition for water and it also shows how the thinning of both water- and temperature-stressed spruces, which is likely the result of global climate change (Maracchi et al. 2005; Rennenberg et al. 2006; Tatarinov, Cienciala 2009; Allen et al. 2010; Lindner et al. 2010; Hlásny et al. 2011, 2014; Choat et al. 2012) is needed.

If the value of slenderness ratio exceeded 100, many authors (Milne 1995; Wang et al. 1998; Lekes, Dandul 2000) reported the low stability of spruce stands. Vicena (1964) reported 83 as critical and 79 as optimal values for the fir-beech vegetation zone where both our study sites belong to. Konôpka et al. (1987) and Navratil (1995) considered the *h*/*d* ratio exceeding 90 as critical one indicating a threat by snow load. Both IUFRO 13 (Vítkov) and IUFRO 14 (Machov) unthinned treatments showed the slenderness ratios of 100 and 90, respectively. From this point of view, the unthinned spruce stands are likely to be massively vulnerable to damage due to snow and wind. The trees support each other until the canopy is broken. Thinning in our experiments decreased the *h*/*d* ratio below the critical level, which confirmed the results from other experiments of IUFRO series (see Herbstritt et al. 2006, Hein et al. 2008). The time when the thinning was performed (i.e. in the young stage before the 10 m top height) is essential for obtaining these results (stable stands), because postponed thinning is ineffective from the stability point of view (Konôpka, Konôpka 2017) and may, on the contrary, lead to destabilization of stands (Wallentin, Nilsson 2014; Liziniewicz et al. 2016).

IUFRO 13 (Vítkov) showed the very high values of basal area, standing volume and *TVP*, which was attributable to the soil fertility of former agricultural site. The production capacity exceeded the yield table values for the site index +1, i.e. mean height of 36 m expected at the age of 100 years (Černý et al. 1996). Also tree dimensions after thinning achieved the values expected at the rotation age. Pape (1999a, 1999b) reported that heavy thinning (before the age of 30 years) removing 40% of the total basal area considerably enhanced diameter development without loss in volume production or reduction in the uniformity of wood. Also results from Pfister et al. (2007) suggest that appropriate combination of initial wide spacing with thinning from above may yield timber of similar quality compared to stand with denser spacing where thinning from below was conducted. A significant reduction in wood quality (larger knot dimensions) was reported for hundreds of individuals after a very strong reduction of density (or with low initial planting density) (Mäkinen, Hein 2006; Katrevičs et al. 2018).

In our experiments, it seems, therefore, that such stand could be allowed for harvesting, which happened as the salvage cut was conducted without important production loss in 2014. Besides, the first-generation spruces show more root and stem rot at the older age at these sites, which makes an economic income even lower if harvesting operations are "postponed" until the stand reaches the rotation maturity. These days, however, the whole Czech forestry sector faces a severe threat to large monospecific spruce stands due to drought and bark beetle outbreak, which affects the prices in the market negatively as too much spruce roundwood is available for selling. An increase of species diversity and establishment of mixed stands are the ef-

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ficient measures in the frame of adaptive strategy of forest ecosystem management (Mason et al. 2012). Even mixed stands need thinning for the reasons such as species composition maintenance, growth support of particular species and trees and also improved vigour and resilience against the harmful agents etc. (Bauhus et al. 2017). The appropriately applied thinning is one of the tools helping foresters to cope with climate change. To rely only on natural mechanisms regulating the effects of climate change is risky (Jandl et al. 2019).

Spruce stands stabilized by thinning might also be well-prepared if the future conversion to mixtures in the next rotation period is needed. The change of silvicultural management, from thinning from above or below to a group selection system which shows the highest mitigation efficiency against storm risk (Müller et al. 2019), is also more feasible.

CONCLUSION

(*i*) Thinning accelerated diameter increment and helped develop better parameters of slenderness ratio which improved the static stability of trees. The differences in the slenderness ratio between the thinned treatments were found negligible.

(*ii*) The unthinned treatment showed the largest basal area, standing volume and total volume production, whereas both mean diameter and mean stem volume were the lowest. The intensive thinning, therefore, reduced the total volume production (*TVP*), but improved its safety.

(*iii*) The very heavy early thinning from below in treatment 2 promoted development of the greatest standing volume and *TVP* in the large trees exceeding 0.5 m^3. This treatment is appropriate where trees are threatened by snow load and wind. The trees left on the site develop as large ones in a short time whereas logging and skidding operations are minimized.

(*iv*) The delayed first thinning from below in treatments 3 and 4 poses the advantage of the larger mean volume of removed trees. The differences between the treatments were negligible for all parameters studied – the wider skid trails in treatment 4 did not affect wood increment negatively. This thinning approach is appropriate for most sites excluding the extremely threatened sites such as water-logged ones.

(*v*) The "commercial" treatment 5 (thinning from above) showed both the lowest standing volume and *TVP*. Unlike the trees with appropriate slenderness ratio in upper story, the understory trees were found to be labile as they broke frequently thus increasing the need of salvage harvest. The production safety was, however, still better compared to the unthinned treatment.

(*vi*) It can be concluded that early thinning of spruce can be used as a mitigation measure against snow and wind damage in stands of middle to higher age. No such measure, however, can be expected to alleviate the spruce decline due to drought, bark beetle and honey fungus that occurs in forests in the Czech Republic nowadays.

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