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Growth response of Douglas fir to the first early and delayed thinning

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Abstract

Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) is considered one of the most promising introduced tree species for use in forestry in Central Europe. The formation of vital and stable forest stands with a certain share of Douglas fir (DF) requires the application of appropriate silvicultural measures, such as thinning. The article evaluates the growth response of DF to the initial experimental thinning. Eight stands were analysed on nutrient-rich sites in the three forest vegetation zones (*Querceto-Fagetum*, *Fagetum*, *Abieto-Fagetum*). The analysis includes both stands dominated by DF and stands where DF is only interspersed. The thinning was applied when the dominant tree height ranged from 5 to 20 m. A dominant tree height of 10 m was used as the threshold to define well-timed thinning. The data were analysed using Bayesian hierarchical modelling, and generalized hierarchical models were employed. DF promising trees responded to early thinning with significant acceleration of radial growth, leading to improvements in height-to-diameter ratio (HDR) and crown ratio (CR) parameters. The response of DF promising trees to delayed thinning was negligible. Neither early nor delayed thinning had a detectable effect on height growth of the DF promising trees. The result confirms the necessity of initiating thinning for DF stands at the stage of thickets. The thinning should ideally begin when the dominant tree height is between 4 to 5 meters. At this stage, it is possible to positively influence diameter growth and mitigate the deterioration of individual tree stability as well as the stability of the whole stand.

Key words: *Pseudotsuga menziesii* [Mirb.] Franco; diameter increment; height-to-diameter ratio; crown ratio; Bayesian inference

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1. Introduction

In recent years, forests in the Czech Republic have been struggling with extensive calamities, primarily in spruce and pine stands (MZe 2022). Given the scenarios of climate change, it will be necessary to consider the spectrum of introduced tree species as a potential partial (but not predominant) replacement for the receding commercial tree species. Douglas fir is considered one of the most promising non-native tree species in central Europe (Thomas et al. 2022; Nicolescu et al. 2023). In the species composition of forests in the Czech Republic it is represented by less than 0.3%. Douglas fir is known for its rapid growth rate, which allows for relatively quick harvesting cycles compared to many native European species. This can lead to higher timber yields over shorter time frames, contributing to increased productivity in forestry operations (Kantor 2008; Kantor & Mareš 2009; Tauchman et al. 2010; Podrázský et al. 2013; Kubeček et al. 2014; Podrázský et al. 2016; Mondek & Baláš 2019; Remeš et al. 2020). The wood of Douglas fir is valued for its strength, durability, and versatility (Tauchman et al. 2010; Zeidler et al. 2022). It is commonly used in construction, woodworking, and furniture making due to its excellent structural properties and attractive appearance. Its dimensional stability and resistance to decay make it particularly suitable for outdoor applications.

Douglas fir exhibits a wide range of adaptability to different soil types and climatic conditions (Eckhart et al. 2019), making it well-suited for planting in various regions across the Czech Republic. It can thrive in both lowland and upland sites. Douglas fir has demonstrated good tolerance to drought conditions once established (Eilmann & Rigling 2012; Rais et al. 2014; Mondek et al. 2021; Elfstrom & Powers 2023), making it a resilient option for forest plantations in regions prone

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to periodic water shortages or climate variability. The ecological impacts of Douglas fir are in general not as severe as those of other exotic tree species (Schmid et al. 2014). The Douglas fir has relatively small impact on the biodiversity of ground vegetation, which is comparable to natural communities within its forests (Kubeček et al. 2014; Thomas et al. 2022; Glatthorn et al. 2023). In contrast, the cultivation of Douglas fir may lead to higher soil nitrification (Podrázský et al. 2014; Matějka et al. 2015; Zeller et al. 2019; Podrázský et al. 2020).

Significant reductions in Douglas fir growth have been linked to needle casts caused by *Rhabdocline pseudotsugae* Syd. and *Phaeocryptopus gaeumanni* Petrak. However, compared to other non-native conifers, Douglas fir remains relatively unaffected by abiotic damage. Despite this resilience, climate warming and global plant movement are expected to hasten the introduction of pests from its native range (Roques et al. 2019). Additionally, Douglas fir is highly susceptible to browsing, almost to the same extent as silver fir (Konôpka et al. 2024). To protect Douglas fir, it is necessary to prevent browsing and concurrently reduce ruminating ungulate populations.

The current trend in forestry is the establishment and cultivation of species-diverse stands, which are expected to have higher resilience to the adverse effects of global climate change. It is also recommended to cultivate Douglas fir in mixtures to prevent monoculture cultivation of this introduced species (Thomas et al. 2022), aiming to eliminate its significant nutrient uptake during rapid growth, among other reasons (Kubeček et al. 2014; Mondek & Baláš 2019). However, Douglas fir is only partially shade-tolerant (Nicolescu et al. 2023), and there is a risk that on certain sites, it will be overgrown in mixtures with some native, faster-growing species in youth, leading to a deterioration in its quality and vitality or even its disappearance without adequate silvicultural interventions. Although Douglas fir is a fast-growing species, it may be outcompeted in the seedling and sapling stages (Frei et al. 2022), for example by silver birch on nutrient-rich sites or by Scots pine on nutrient-poor sites (Novák et al. 2019). Even in stands dominated by Douglas fir, the absence of stand thinning leads to the development of numerous unstable individuals (Dušek et al. 2018) with poorly developed crowns. Thinning management (incl. pruning) of Douglas fir stands should be optimised also from expected timber quantity and quality (Rais et al. 2020). One of the thinning effects is also support of higher carbon stock, as Coletta et al. (2016) found for low selective thinning in Douglas fir plantation in southern Italy.

The benefit of stand thinning is also seen in the improvement of the hydrological regime of stands and the increase in the availability of precipitation due to the reduction of stand interception. Thinning can promote drought adaptation in Douglas fir stands, but these effects dissipate over time (Elfstrom & Powers 2023). In addition, Vitali et al. (2018) point out that Douglas fir may be more stressed in a mixed stand during periods of drought than in an unmixed stand.

The aim of this paper is to evaluate the effect of experimental thinning and its timing on the diameter growth, height-to-diameter ratio, and crown ratio of Douglas fir. The growth of Douglas firs is being analysed in stands where they are dominant, as well as in mixed stands and stands where Douglas firs are only interspersed.

2. Material and methods

2.1. Experimental material and design

Thinning experiment of Douglas fir and its mixtures with other tree species were established at eight stands (localities) between 2010 and 2016. The stands originated from artificial regeneration and age of the stands at the first thinning ranged from 11 to 25 years (Table 1). For the purposes of evaluation, the experiment was divided into a treatment with early implemented thinning (up to a height of dominant trees of 10 m – 5 localities) and a treatment with delayed thinning (3 localities). At all localities, the soil type is Cambisol on nutrient-rich sites. The altitude ranges from 345 to 700 meters (Table 2). The representation of Douglas fir in the stand mixture was highly variable, ranging from 3 to 97% (Table 3).

The experimental design corresponds to a randomized block arrangement. At each localities, one plot was randomly selected for thinning, while the other served as a control. Before treatment assignment, promising trees were selected on both treatments (control and thinned), serving as a comparative set of tree individuals. The number of promising trees ranged from 780 to 1,400 individuals per hectare in timely thinned localities

Table 1. Experimental plots characteristics.

Locality	Abbreviation	Area (ha)	Year / Stand age of first thinning	Mean diameter of promising DF[1] (cm) (C / T)[2]	Mean height of promising DF[1] (cm) (C / T)[2]
Bílá Voda II	BV II.	2 × 0.025	2016 / 11	8.5 / 8.7	7.3 / 6.4
Hraničky	HRA	2 × 0.06	2016 / 11	12.1 / 12.7	8.6 / 8.9
Kajlovec	KA I.	2 × 0.01	2015 / 10	5.8 / 6.0	5.2 / 6.0
Kajlovec II	KA II.	2 × 0.02	2015 / 10	5.9 / 5.6	5.5 / 5.2
Libňatov	LIB	2 × 0.04	2016 / 11	7.7 / 7.6	6.3 / 6.1
Obora	OBO	2 × 0.04	2011 / 25	16.9 / 16.3	16.2 / 16.0
Vadětín	VA I.	2 × 0.04	2014 / 20	19.0 / 21.8	16.4 / 19.0
Vadětín II	VA II.	2 × 0.04	2014 / 20	22.7 / 18.8	20.1 / 16.7

Note: [1]DF – Douglas fir, [2]C / T – Control / Thinned.

Table 2. Site and environmental characteristics of the experimental stands.

Locality	Natural Forest Zone[1)]	Forest Site Type Complex[2)]	Altitude (m a.s.l.)	Bedrock	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	GPS Coordinates
Bílá Voda II	28	3B	370	gneiss	8–9	700–800	50.4417175N, 16.8903858E
Hraničky	28	5S	700	gneiss	5–6	900–1,000	50.3081833N, 16.9869175E
Kajlovec	29	4B	415	greywacke	8–9	600–700	49.8532506N, 17.8544694E
Kajlovec II	29	4B	415	greywacke	8–9	600–700	49.8455147N, 17.8523456E
Libňatov	23	3S	430	sandstone	8–9	700–800	50.4725425N, 16.0125667E
Obora	26	3H	345	marlstone	9–10	550–600	50.2489386N, 16.1185581E
Vadětín	26	4S	450	marlstone	6–7	700–800	49.9937839N, 16.4290911E
Vadětín II	26	4S	450	marlstone	6–7	700–800	49.9922789N, 16.4308367E

Note: [1)]NFZ: 23 – Podkrkonoší; 26 – Předhoří Orlických hor; 28 – Předhoří Hrubého Jeseníku; 29 – Nízký Jeseník; [2)]FSTC: 3B – *Querceto-Fagetum mesotrophicum*; 4B – *Fagetum mesotrophicum*; 3H – *Querceto-Fagetum illimerosum mesotrophicum*; 3S – *Querceto-Fagetum oligo-mesotrophicum*; 4S – *Fagetum oligo-mesotrophicum*; 5S – *Abieto-Fagetum oligo-mesotrophicum* (According to Viewegh et al. 2003).

Table 3. Tree species composition in experimental plots before first thinning.

Locality	Treatment	Year	Share of species (% of total basal area)																
			EB	SP	SB	SO	DF	SF	GW	ER	EA	SM	AB	SL	EL	TA	NS	PO	WP
BV II.	Control	2016		6.0	0.9		2.6	53.3			0.3	22.1		1.2	7.9		0.9		4.6
	Thinned			4.5	0.5		37.9	26.3	2.2			19.8		0.5	7.2		1.2		
HRA	Control	2016			0.1		63.4		1.3			1.5			4.8		28.8		
	Thinned				0.0		83.7	0.1	2.8			1.0			7.4		5.0		
KA I.	Control	2015	0.9		2.9	0.3	87.4					0.9				5.2	0.1	2.4	
	Thinned				2.6		94.8											2.6	
KA II.	Control	2015	15.6		16.1		68.3												
	Thinned				10.5		89.5												
LIB	Control	2016		7.5	0.1		88.6						0.1		3.5		0.3		
	Thinned			6.9	0.4		76.1			1.5					13.5		0.5		
OBO	Control	2011	0.7				93.5								4.3		1.6		
	Thinned						96.6								3.4				
VA I.	Control	2014	0.1	5.3			23.3								23.1		48.2		
	Thinned		0.6				47.0								14.6		37.9		
VA II.	Control	2014	4.5				52.8								9.5		33.2		
	Thinned		0.2				28.8								31.6		39.4		

Note: EB – European beech; SP – Scots pine; SB – Silver birch; SO – Sessile oak; DF – Douglas fir; SF – Silver fir; GW – Goat willow; ER – European rowan; EA – European ash; SM – Sycamore maple; AB – Alder Buckthorn; SL – Small-leaved lime; EL – European larch; TA – Trembling aspen; NS – Norway spruce; PO – Poplar; WP – Eastern white pine.

and from 420 to 520 individuals in localities with delayed thinning. As promising trees, high-quality, desirable species individuals were selected without damage and with well-developed crowns, with the expectation that they would form the structural framework of the forest stands in the future. These promising trees were released from all competitors (1–3 individuals). In the stands where the height of dominant trees did not exceed 10 m, a crown thinning was applied. In other stands, the intervention took the form of low thinning. The first experimental thinning was carried out from 2011 to 2016 (Fig. 1–2, Table 1). In this study, only the growth response of promising Douglas fir trees is assessed.

2.2. Assessment of experimental material

Diameter at breast height (*DBH*), total height of trees (*H*) and height of crown base (*CB*) were measured annually. Subsequently, derived values were computed.

Mean annual diameter increment (*iDBH*):

$$iDBH = \frac{DBH_{tn} - DBH_{t0}}{n} \qquad [1]$$

where DBH_{t0} is diameter at breast height at the beginning of the period, DBH_{tn} is diameter at breast height at the end of the period and n is the number of years in the period.

Relative mean annual diameter increment (*riDBH*):

$$riDBH = \frac{\log(DBH_{tn}) - \log(DBH_{t0})}{n} \qquad [2]$$

where DBH_{t0} is diameter at breast height at the beginning of the period, DBH_{tn} is diameter at breast height at the end of the period, n is the number of years in the period and log is natural logarithm.

Height-to-diameter ratio (*HDR*):

$$HDR = \frac{H}{DBH} \qquad [3]$$

where H is tree height a DBH is diameter at breast height.

Crown ratio (*CR*):

$$CR = \frac{H - CB}{H} \qquad [4]$$

where H is tree height and CB is height of crown base.

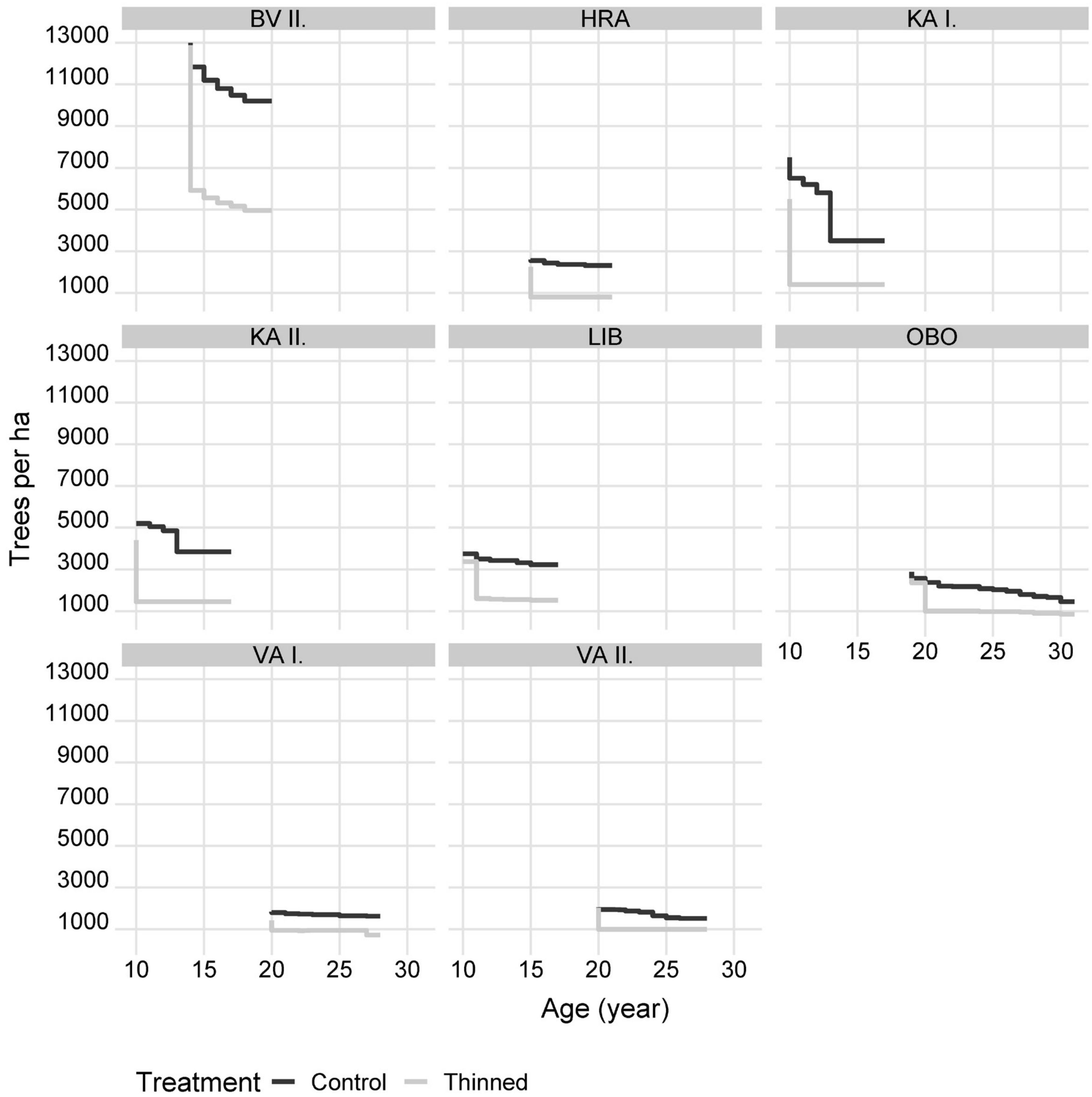

Fig. 1. Development of stand density of all trees by localities and treatments.

2.3. Statistical analysis

The data were analysed using a generalized hierarchical model in the following form:

$$y_{ijk} = \alpha + Thinning_i + Timing_j + Thinning_i \times \times Timing_j + Locality(Thinning)_{ik} \quad [5]$$

where y is the response variable (*DBH*, *iDBH*, *riDBH*, *H*, *HDR*, *CR*), *Thinning* is factor with two (i) levels (Control, Thinned) *Timing* is factor with two (j) levels (early thinned, delayed thinning), and *Locality* is blocking factor with eight (k) levels. The term *Thinning* × *Timing* denotes the interaction between *Thinning* and *Timing*. The term *Locality*(*Thinning*) reflects the hierarchical structure of experimental data (Thinning is nested in Locality). The response variables *DBH*, *iDBH*, *riDBH* and *HDR* were modelled with Gamma distribution and logarithmic link function. The *CR* was modelled with Beta distribution and logit link function and the *H* was modelled as normal distributed with identity link function.

Bayesian modelling tools were utilized for analysis due to their high flexibility. The brms library within the R statistical language was used. The brms library provides an interface to Stan, a probabilistic programming language for specifying and fitting Bayesian models via Markov Chain Monte Carlo (MCMC) methods. It provides extensive support for modelling a wide range of probability distributions and link functions (Bürkner 2017; Bürkner 2018). In the Bayesian models, default priors from the brms library were used. These are known as flat or weak priors, reflecting a lack of prior knowledge about the experimental data. Flat priors are often used when there is no strong prior information available, and they allow the data to primarily determine the posterior distribution.

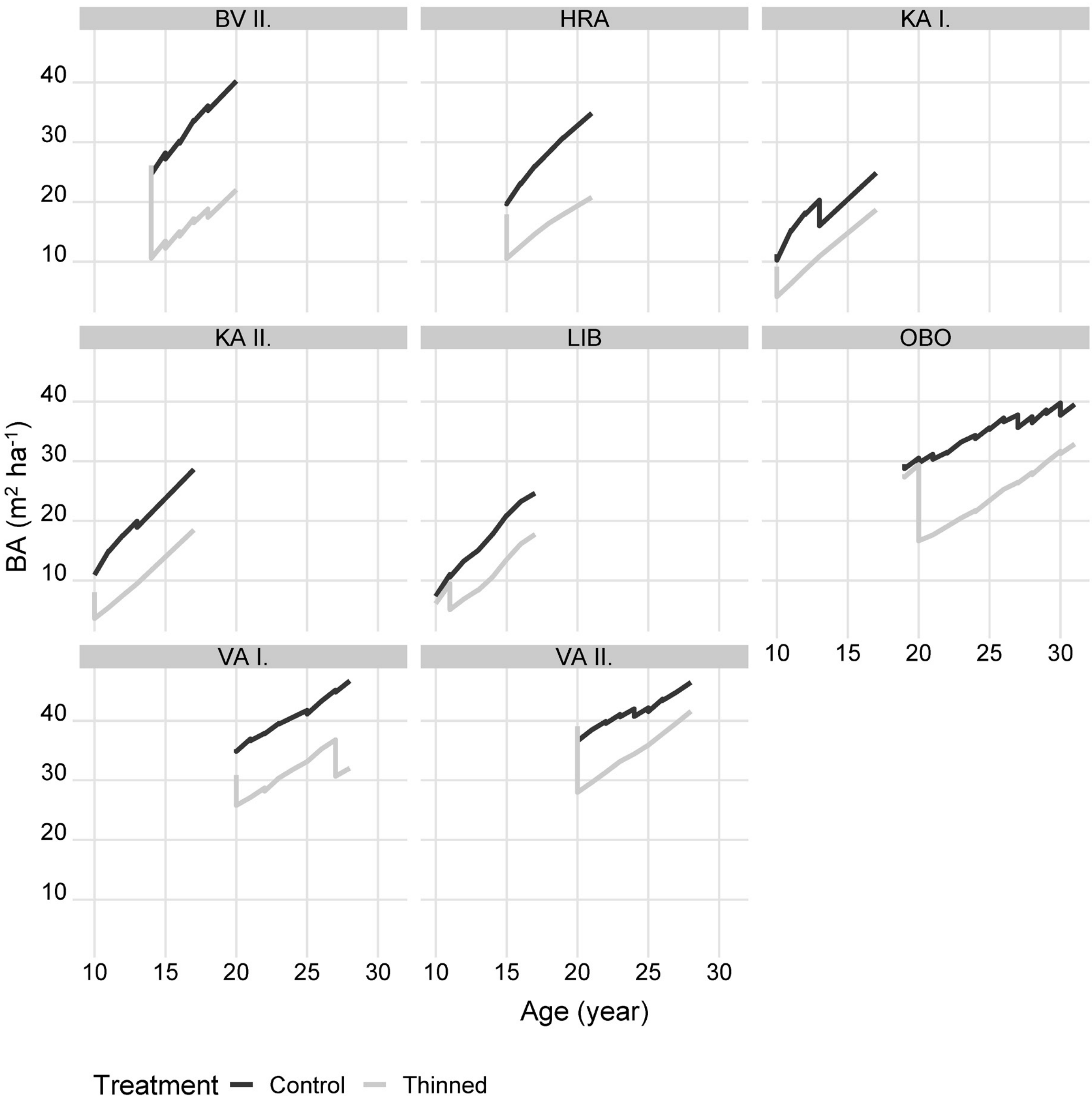

Fig. 2. Development of basal area of all trees by localities and treatments.

Bayesian inference provides a natural framework for quantifying uncertainty in parameter estimates and predictions. Instead of producing point estimates, Bayesian analysis yields probability distributions for parameters, allowing to assess the uncertainty associated with their estimates. Multilevel Bayesian models allow for the modelling of complex hierarchical structures in data, where observations are nested within multiple levels. This flexibility enables to account for dependencies and correlations among observations within the same group, leading to more accurate estimates and improved inference. Multilevel models (in both Bayesian and non-Bayesian approaches) incorporate shrinkage estimation, where parameter estimates at lower levels are "pulled" towards the overall mean or group-specific means. This helps to reduce the influence of noisy or extreme observations and improves the stability and robustness of the estimates.

3. Results

Early thinning resulted in significantly higher diameter growth of promising Douglas firs. In 2022, 6–11 years since the first thinning, the difference in measured diameter (DBH) between the control and thinned treatments was 2 cm in favour of the thinning treatment (Fig. 3). On the thinned treatment, the mean annual diameter increment was higher by 0.3 cm (Fig. 4), and the relative mean annual diameter increment was higher by 0.02 (approximately 2%) compared to the control (Fig. 5). In the case of delayed thinning, differences in the average diameter and annual diameter increment of promising Douglas firs were negligible (DBH = −0.2 cm, iDBH = 0.04 cm, and riDBH = 0.002, Fig. 3–5).

In the case of timely initiated stand thinning, a positive influence of the thinning on diameter increment is

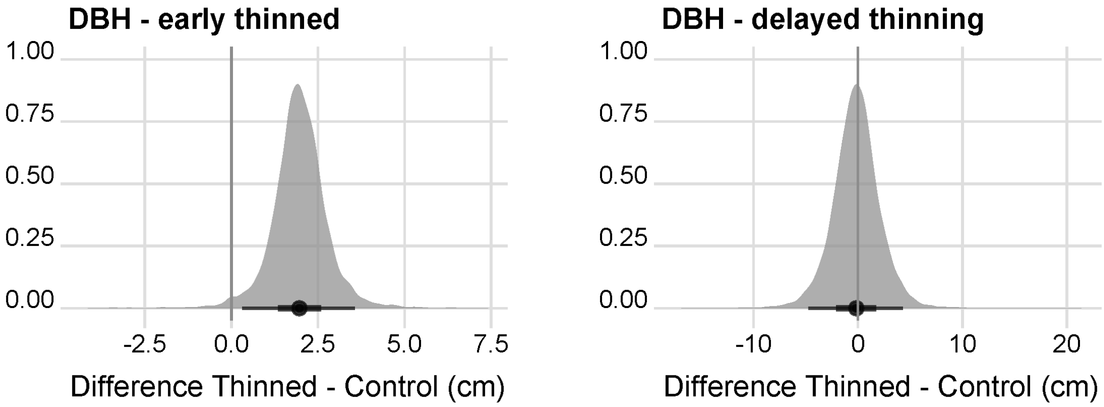

Fig. 3. Posterior density of probability of differences in the diameters at breast height (DBH) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

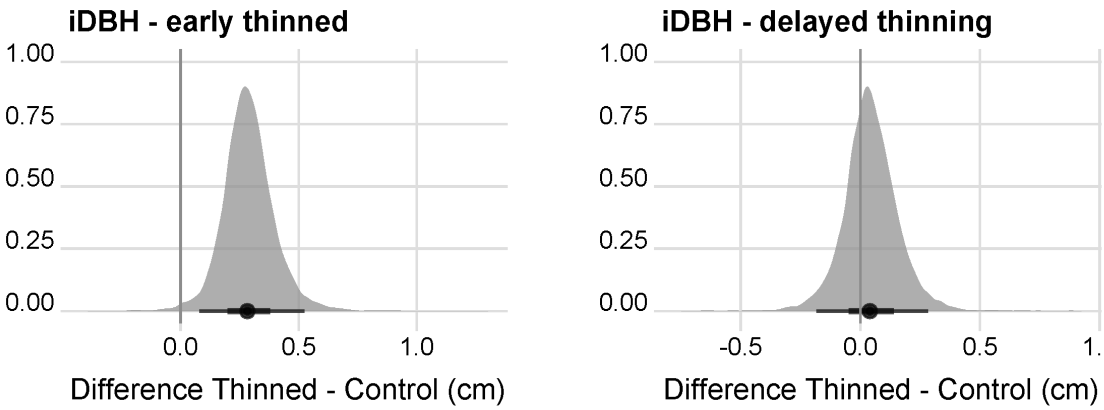

Fig. 4. Posterior density of probability of differences in the average annual growth increment of diameter at breast height (iDBH) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

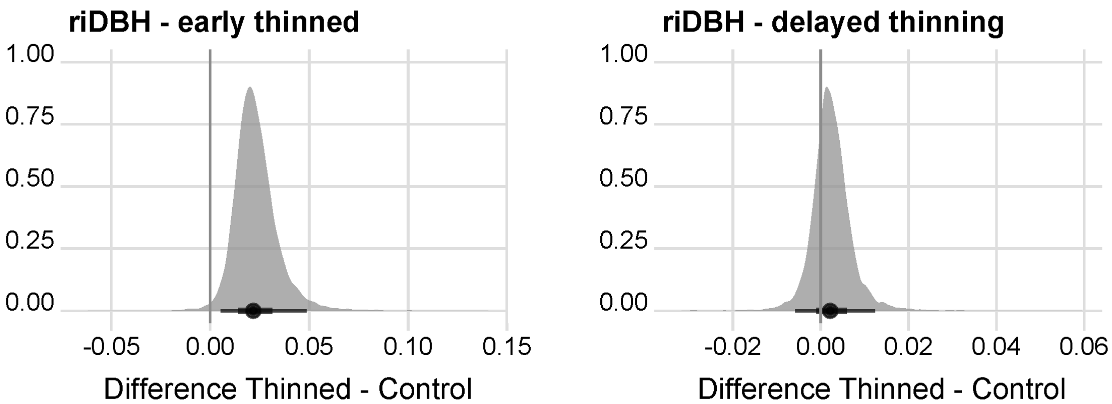

Fig. 5. Posterior density of probability of differences in the relative average annual growth increment of diameter at breast height (riDBH) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

apparent in all subsequent years. In the case of delayed thinning, the differences between the control and thinned treatments were inconclusive and rather mirrored the initial differences in mean tree diameters (and heights) in individual plots before the experimental thinning (Fig. 6).

The data does not highlight the influence of thinning on the height (H) of promising trees. Not even in the case of early intervention (Fig. 7). The positive effect of early thinning on diameter growth, coupled with the absence of support for height growth acceleration of promising trees, logically manifested in a reduction of height-

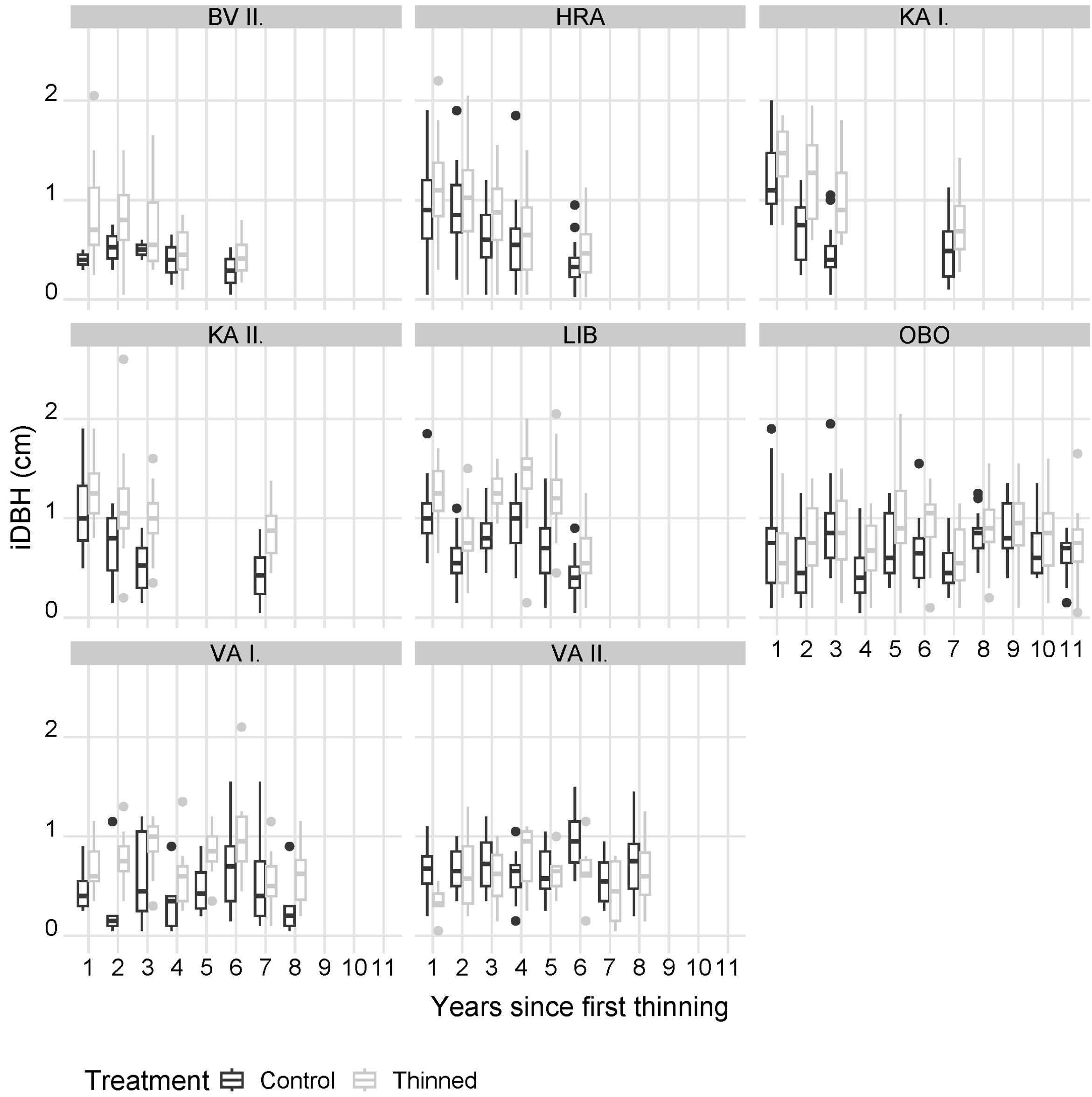

Fig. 6. Box plots of annual growth increment of diameter at breast height (iDBH) of promising Douglas fir trees by years since the first experimental thinning.

to-diameter ratio (HDR), which was 14 units lower in the thinned treatment compared to the control. In plots with delayed thinning, the effect of reducing HDR did not occur (Fig. 8).

Early thinning also resulted in more favourable crown ratio (CR) value, which was 12% higher in the thinned treatment compared to the control. Delayed thinning did not have a demonstrable effect on CR (Fig. 9).

4. Discussion

The experiments in our study were conducted in nutrient-rich sites within the three forest vegetation zones naturally dominated by oak, beech and fir. Our results demonstrated the positive impact of early thinning in young Douglas fir stands and their mixtures on increased diameter growth and improved stability of individual promising trees by reducing the height-to-diameter ratio (HDR) and slowing the shortening of their crowns. Additionally, our results indicate that crown thinning is suitable in young stands where the height of dominant trees does not exceed 10 m, ideally at a height of 4 to 5 m. However, in stands with delayed thinning, crown thinning poses a significant risk of reducing stand stability and may pose a risk of production loss. Delayed low thinning, at a stage when the upper stand height reached 15–20 m, did not lead to a significant increase in the diameter growth of promising Douglas-fir trees in our study. In these stands, the thinning was no longer able to improve the height-to-diameter ratio or crown ratio parameters of the released trees.

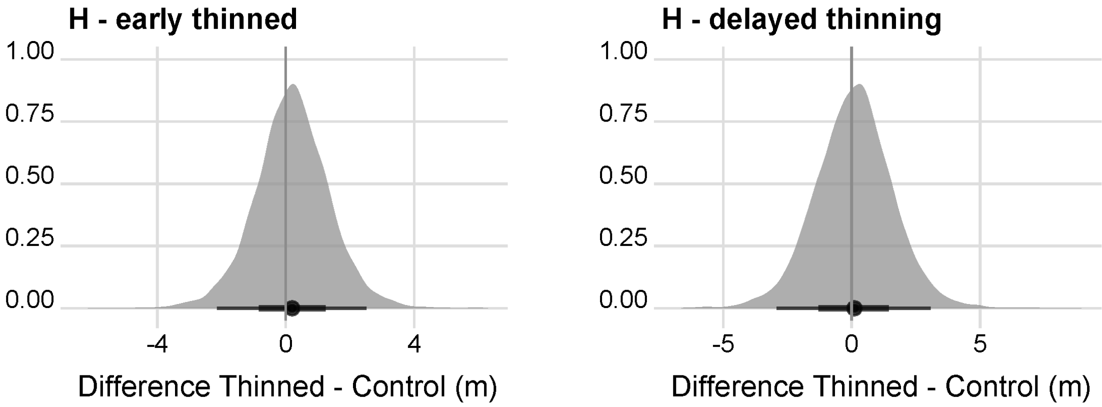

Fig. 7. Posterior density of probability of differences in the height (H) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

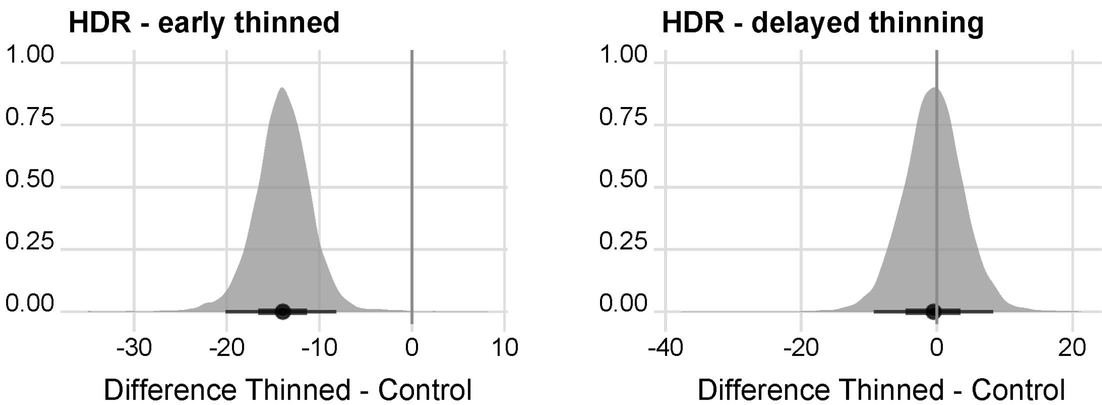

Fig. 8. Posterior density of probability of differences in the height-to-diameter ratio (HDR) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

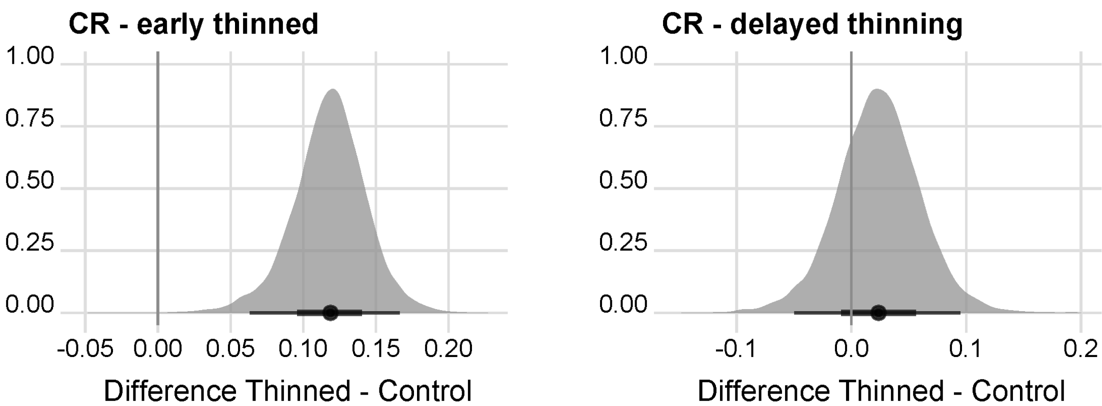

Fig. 9. Posterior density of probability of differences in the crown ratio (CR) of promising Douglas fir trees between experimental treatments in 2022, with 80% and 95% credible intervals.

First thinning as essential measure for right stand development (in case of growth and stability) is mentioned also by Cameron (2002). On the base of his review, optimal time for first thinning is around 10 years after full canopy closure (top height approx. 10 m), differentiated, of course, by growth conditions and method of stand establishment (natural or artificial regeneration, different spacing, etc.). Also Reukema (1975) recommend to start pre-commercial thinning in Douglas-fir stands at mean height 3–5 m (age of 10–15 years), whereas the thinning intensity depends on the required mean diameter when cutting the first commercially usable assortments. The confirmation of the good growth response of promising trees to release in our study is also consistent with the conclusions of Roberts & Harrington (2008), who investigated the effects of variable-density thinning in stands with Douglas fir. Filip et al. (2015) also notes the positive impact of thinning on the diameter growth of Douglas fir in mixed stands, even if such stands are affected by *Armillaria* ssp. or *Heterobasidion* sp. root diseases.

Our results is also in accordance with thinning systems for Douglas fir stands in Western Oregon published by Emmingham & Green (1984) – pre-commercial thinning before top height approx. 6 m. In poorly managed stands, silvicultural care is limited to removing the most unstable trees from the stand's understory. However, such intervention is unlikely to have a significant impact on the diameter growth of promising trees and will not prevent crown shortening.

Schütz et al. (2015) analysed thinning regimes applied in Douglas-fir stands in Switzerland. They found that social dominant trees are more or less untouched by thinning, i.e. these trees are self-dominanting. But mentioned study were done in stands planted with densities from 1.3 to 2.8 thousands trees per hectare, i.e. compare to our early thinned series considerably lower. In the case of unmixed even-aged stands of Douglas fir, Emmingham et al. (2007) recommend low thinning, especially given the fact that codominant and dominant individuals are the carriers of volume production. The importance of dominant Douglas fir trees on the rate of volume growth irrespective of thinning has also been pointed out by O'Hara (1988). These findings and recommendations are consistent with our results from experiments with delayed thinning.

Douglas fir as deeply rooted species (mainly compared to Norway spruce) is described as more resistant to abiotic damage (Mauer & Palátová 2012). However, this alone may not mean significantly less wind damage (Albrecht et al. 2013). The stability of individual trees is important, expressed in forestry management most often by the HDR value (Hanewinkel et al. 2011). Lower HDR, as a result of thinning or initial low spacing (or as combination of both), correlated with lower predisposition for snow (younger stands) or wind (mature stands) damage. It was documented in several studies from Douglas fir stands (Hein et al. 2008; Schelhaas 2008; Klädtke et al. 2012). Therefore, our results clearly confirmed that if thinning is to actively contribute to improving the stability of stands with Douglas fir, it must be carried out in time, i.e. before reaching the top height of 10 m.

Thinning in mixed stands with Douglas fir have a direct relationship with the rate of growth of the tree species, i.e. the rate of occupation of the habitat, the timing of growth culmination and the tolerance of the trees to shading. Although Douglas fir surpasses most Central-European native tree species in volume growth (Podrázský et al. 2013; Nicolescu et al. 2023), it can be outgrown by a wide range of (especially pioneer) tree species in the thickets stage (Radosevich et al. 2006; Cortini & Comeau 2008; Novák et al. 2019). On our experimental plots during the thickets stage, we observed significant overgrowth of Douglas fir by silver birch. In these mixtures, Douglas fir is rapidly suppressed, leading to crown reduction and worsening of the height-to-diameter ratio. Without adequate silvicultural support, there is a risk of its complete disappearance from the stand mixture. In mixed stands, Eberhard et al. (2021) suggest planting Douglas fir in mono-species patches, as productivity might decrease by up to 86% when it grows in association with highly competitive native tree species such as beech. Similarly, Frei et al. (2022) state that on productive beech sites, Douglas fir is strongly limited due to its low competitiveness compared to beech and fast-growing deciduous tree species.

The growth response of Douglas fir on the experiments was consistent across the sites and varied only due to the timing of the first thinning. However, it should be noted that our experiments are derived from a relatively narrow range of natural conditions within nutrient-rich sites in mid-altitude areas. In conditions of relatively nutrient-poor habitats in lowlands, Douglas fir in young stands faces strong competition pressure from Scots pine, which outpaces its growth. Due to the lower viability of Douglas fir in these sites during the early growth stages, we recommend based on our previous analyses (Dušek & Novák 2024), focusing silvicultural support only on the admixture of the highest quality Douglas fir individuals, with the prospect of subsequent artificial pruning and the formation of valuable assortments on *Fageto-Quercetum acidophilum* and *Pineto-Quercetum oligotrophicum* sites. Releasing a larger number of Douglas firs in mixtures with pine on nutrient-poor sites carries the risk of simultaneously thinning the pine, which can lead to the formation of epicormic shoots.

In accordance with the recommendations of Slodičák et al. (2014), the long-term goal of thinning in Douglas fir stands should be to achieve approximately 20% admixture of this species in the mature stage, which, given the growth characteristics of Douglas fir, will primarily consist of overstory individuals. Other desirable native promising tree species will be located at the stand and understory levels. The establishment of unmixed Douglas fir groups up to an area of 0.15–0.20 ha simplifies subsequent stand management, but the establishment of larger unmixed groups is undesirable.

5. Conclusions

The influence of the first experimental thinning on the promising trees of Douglas fir was affected by the timing of the thinning. In the case of early thinning (up to a height of 10 m of promising trees), an acceleration of the radial growth increment of the promising trees was recorded, along with more favourable (lower) values of HDR and higher values of CR. Early thinning did not significantly influence the height of the Douglas fir promising trees.

In the case of delayed thinning (where the height of the promising trees exceeded 15 m), no significant impact of the thinning on radial growth, HDR, and CR was observed. The result confirms earlier findings from spruce stands that after reaching the upper stand height of 10 m, silvicultural treatments cannot significantly increase the stability of individual trees.

We recommend initiating thinning of Douglas fir early. In dense natural regeneration stands, it is desirable to initiate the first release when the upper canopy height reaches 2 meters. In artificially regenerated stands, it is ideal to begin thinning when the upper canopy height reaches 4–5 meters. The upper canopy height of 10 meters can be considered as a critical threshold for implementing the first thinning. In pure stands of Douglas fir, the number of trees should be reduced to 1,200 trees per hectare after the first thinning. The number of promising Douglas fir in stand mixtures cannot be determined a priori and will vary depending on the composition of the stand mixture, quality of trees, and silvicultural objectives. We recommend restricting the fraction of Douglas fir admixtures to stands of native tree species to 20–30% at maximum. The thinning of Douglas fir in these stands aims to achieve full crown release of high-quality promising trees.

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