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Comparing wood production and carbon sequestration after extreme thinnings in boreal Scots pine stands

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ABSTRACT

Fennoscandian studies of thinning responses are usually limited to low thinning with moderate intensities. We studied here intermediate commercial thinning of different types (low, crown/normal, crown/strict, where respectively mostly intermediate and suppressed trees, mostly dominant and co-dominant trees, and only dominant trees were removed) and intensities (moderate and heavy) in Scots pine (*Pinus sylvestris* L.) dominated stands. We analysed their responses in terms of wood production and carbon balance. We investigated three stands in Southern and Middle Finland at the stage of second or third commercial thinning (age 34–50 years). We observed their development for fifteen years, and then we further simulated it with MOTTI stand simulator until final felling (scheduled either at age 65 or 80 years). We considered various variables of interest related to the thinning outputs, volume production after thinning, simulated final felling, and carbon balance. For all variables of interest, there were negligible differences across thinning types, and strong ones across thinning intensities. Thinning removals were significantly higher in heavy than moderate treatments, although only crown heavy thinnings had significantly higher sawlog output than low moderate. Volume growth post thinning during the 15-years observation was highest in unthinned plots, followed by moderate and then heavy treatments. For both total standing volume at simulated final fellings and carbon balance at any times, there was a similar descending trend from unthinned to moderate to heavy treatments. Concluding, the results suggest that crown/normal thinning could be applied with moderate intensity as alternative to low thinning, while heavy thinnings do not provide commercial benefits in Scots pine stands. Heavy intermediate thinnings in Scots pine stands provides lower total carbon accumulation during rotation, and early higher wood products (although not necessarily in terms of sawlogs) at the expense of later ones. Moderate thinning reached on site carbon neutrality after 5-years, while heavy thinning after 15 years.

1. Introduction

Forests are important global carbon (C) sinks that annually sequester an estimated 2.4 Gt of C from the atmosphere (Pan et al., 2011). The boreal forest is one of the largest terrestrial biomes and about two thirds of its area is under some form of management, mostly for wood production (Gauthier et al., 2015). In the Nordic countries of Europe, Scots pine (*Pinus sylvestris* L.) is one the most important tree species of the boreal forest and thus its management can be very important for the global C cycle. The forest C cycle is characterized by a biological (forest ecosystem) and industrial (forest products) cycle (Gower, 2003). The biological C cycle is driven by climate and is influenced by both natural disturbances and silvicultural activities, while the industrial cycle by the nature of the forest products (Ameray et al., 2021). Mankind is ultimately controlling both those aspects, either directly (through forest management) or indirectly (through nitrogen deposition) (Magnani et al., 2007). Intensive forest management (based on activities such as mechanized soil preparation, fertilization, use of genetic improved material, and pre-commercial thinning, likely leading to pure stands and shorter rotation length), increases C sequestration in the short-term, but it may be less effective in the long-term than lower intensity silviculture (which may rely on species mixture, less operations, and longer rotations) (Ameray et al., 2021).

Traditionally, the aim of forest management was to maximise the

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timber wood production and its profitability, and thinning was one of the main forest management activities to reach such goals. Thinning removes a portion of stand stocking, resulting in more growing space for the remaining trees. The aim is generally to accelerate their diameter and volume growth for increased net yield of higher quality wood (Assmann, 1970; Mäkinen and Isomäki, 2004a, 2004b; Zeide, 2001). Thinnings can be also used to affect the species composition and stand structure, to increase the profitability of forest management by providing cutting incomes long before the final felling, and to improve the external quality of stems and vitality of the remaining trees.

On the other hand, thinnings may also have harmful effects on stand development and vitality. Heavy thinnings may considerably reduce gross yield during rotation, depending on stand development phase and tree species (Eriksson and Karlsson, 1997; Mäkinen and Isomäki, 2004a, 2004b). Biotic and abiotic damage risks can also increase during the first years after thinning (Jactel et al., 2009). Trees are exposed to wind and snow damages, before they have adapted to wider spacing by strengthening their crown, stem and root system (Laiho, 1987; Persson, 1975; Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014). Thinnings can notably promote the root rot damage caused by *Heterobasidion* species. After thinning the fresh stump surfaces can be infected by airborne spores enabling the vegetative spread of the fungus to adjacent trees through root contacts and grafts (e.g. (Piri and Korhonen, 2008; Swedjemark and Stenlid, 1993). Thus, in practice, heavy thinnings are not recommended in the Finnish silvicultural guidelines (Rantala, 2011).

Thinnings can be carried out with different approaches to reach different aims. Low thinning (otherwise known as thinning from below) has been the prevailing thinning type in Fennoscandia (Wallentin, 2007). Low thinning favours larger trees in the growing stock, and smaller trees are removed primarily from the lower canopy, i.e. suppressed and intermediate trees. On the other hand, crown thinning (otherwise known as thinning from above) removes primarily dominant and co-dominants trees, increasing immediate harvesting incomes and the number of sawlog-sized trees during rotation (Mielikäinen and Valkonen, 1991). In the Finnish silvicultural guidelines crown thinning has been recently introduced to a be suitable type for well-managed conifer stands in intermediate thinnings (e.g. 2nd and 3rd commercial thinning) (Rantala, 2011). The effects of thinnings types on stand development are much less studied than the effect of timing and intensity. In Scots pine stands, post-thinning volume increment of crown thinning has found to be 3% greater (Vuokila, 1977), about 7.5% greater (Mielikäinen and Valkonen, 1991; Niemistö et al., 2018) or at the same level as after low thinnings (Eriksson and Karlsson, 1997; Nilsson et al., 2010a). However, (Pettersson, 2008) has found 10% lower volume increment for Scots pine after crown thinning compared to low thinning. For another important conifer in the Nordic countries, Norway spruce (*Picea abies* (L.) Karst) crown thinnings have resulted in lower volume increment (Eriksson and Karlsson, 1997; Mielikäinen and Valkonen, 1991; Nilsson et al., 2010a) or same level than low thinning (Vuokila, 1977).

Most of the previous studies literature has considered low thinning with a rather low intensity compared to today's commercial forests. This is due to changes in practical forest operations and the mechanization of timber harvesting, which has led to an increase in intensity and a decrease in numbers of thinnings throughout the stand cycle/rotation. Decades ago, the current moderate thinning would be classified as heavy, and the experiments were established with varying thinning intensities lower than today's intensive practices. For example, in Mäkinen and Isomäki (2004a) (2004b) the most intensive thinning treatment removed around 42% of basal area, not far from current thinning guidelines suggesting approximately one third of basal area (Äijälä et al., 2019). Thus, there is lack of empirical results of the effects of heavy thinnings according to current standards (i.e., removing much more than 30–40% of basal area), especially with different tree selection methods.

Heavy thinnings could be carried out with different aims, such as increasing immediate cutting incomes, diversifying the forest structure, transforming an even-aged stand to continuous cover forest management, and rehabilitating partially damaged stands. Thinning of higher intensity than in prevailing practices result in the removal of many of the largest trees, and increased unevenness of the remaining stands. They have been found to reduce the stand gross yield, especially after thinning, but also throughout the rotation (e.g., Eriksson and Karlsson, 1997; Mäkinen and Isomäki, 2004a, 2004b).

The effect has been greater for pine than for spruce, especially in young stands. As the stand become more mature, the ability of pine to react to thinning decreased, but in the more mature spruce stands the result was the opposite, where the intensification of thinning did not reduce the volume growth (Mäkinen and Isomäki, 2004a, 2004b). Additionally, alternative thinning methods such as crown thinning have been studied much more narrowly in terms of different intensity and timing (e.g. Eriksson and Karlsson, 1997; Nilsson et al., 2010a). More research-based information is clearly needed to study heavy thinnings, both in terms of thinning types and intensity.

For these reasons, no experimental result was available for stands treated with heavy thinnings and at the same time carried out with different approaches. Growth model-based studies of the profitability of forest management showed that stands should be intensively thinned when the main stand has reached sawlog tree dimensions (Fransson et al., 2019; Hyytiäinen and Tahvonen, 2002). In addition, transitional felling in even-aged forests aimed at continuous cover forest must be carried out extensively in order for any undergrowth to recover or the forest to regenerate from emerging seedlings (Äijälä et al., 2019). Currently, even if the intensive thinnings results in higher immediate cutting revenues, less is known on the long-term effects on the profitability and carbon sequestration throughout the full rotation.

The aim of this study was to analyse the effects of different thinning on the growth dynamics of mature Scots pine stands carried out with different intensities, namely moderate and heavy, and different types, namely low and crown thinning, the latter with normal (where mostly dominant and co-dominant trees were removed) and strict strategies (where only dominant trees were removed). We observed the stands for 15 years from the thinning, and then simulated forest development until final felling. Our hypothesis was that the various treatments would have significantly different effects on wood volume production and carbon balance, both in the observed and simulated period. Previous tree-level analyses in the same stands for a shorter period identified significant higher tree growth in heavy than moderate intensity, and only small differences across thinning types (Bianchi et al., 2022).

2. Materials and methods

2.1. Study material

The study material consisted of three thinning experiments in southern and middle Finland (Table 1). They were established in 2005–2008 by Finnish Forest Research Institute (Metla) and currently maintained by Natural Resources Institute Finland (Luke). The experimental stands were originally planted with Scots pine, on sites classified as sub-mesic *Myrtillus* forest site type (Cajander, 1949), or fresh heath (Tonteri et al., 1990). The temperature sum (the sum of degree-days above 5 °C) ranged from 1192 to 1256 d.d. according to the mean for the years 1980–2010, as averages estimated from the Finnish Metereological Institute for those municipalities. The stands were at the stage of second or third commercial thinning, on average 42 years old (Table 1). Stand densities before treatment were on average 1264 trees per hectare with basal area weighted mean diameter 17.7 cm, and dominant height 17.3 m.

Rectangular plots were established in each stand, from eight to twelve plots (Table 1). Plot size varied from 1000 m^2 to 1200 m^2. Each plot was surrounded by a buffer zone 5–10 m wide, treated similarly as

Table 1
Mean characteristics of experiments at time of first measurement. Site index was calculated according to Vuokila and Väliaho (1980), as the dominant height of the stand at 100 years. D_w is mean diameter, basal area weighted.

Stand	No. of plots	Coordinates (WGS84)	Temperature sum (degree days)	Site index	Age (years)	Dominant height (m)	Stem number (N ha^{-1})	Basal area (m^2 ha^{-1})	D_w (cm)	Volume (m^3 ha^{-1})
P112	10	62°03.5′N 24°20.0′E	1195	29.7	41	17.6	1359	27.4	17.6	219
P113	8	62°04.2′N 24°30.6′E	1195	28.9	34	15.1	1386	23.0	15.5	160
P114	9	61°22.3′N 25°06.5′E	1256	27.9	50	19.1	1096	27.6	19.6	239

Table 2
Stand characteristics after thinning treatments. The values presented are mean ± standard deviations. D_w is mean diameter basal area weighted, H_{dom} is the mean height of the 100 largest trees per hectare, Thinning ratio is the ratio of D_w after and before treatment.

Treatment	Control	Low moderate	Low heavy	Crown/normal moderate	Crown/normal heavy	Crown/strict moderate	Crown/strict heavy
Plots	3	3	3	4	4	5	5
Stem number (ha-1)	1337 ± 86	628 ± 4	289 ± 59	937 ± 250	461 ± 103	1067 ± 161	520 ± 182
Basal area (m2 ha-1)	27.7 ± 7.2	19.0 ± 0.1	8.7 ± 0.6	17.9 ± 1.6	8.7 ± 0.5	17.9 ± 1.3	8.6 ± 0.7
Dw (cm)	17.8 ± 3.4	18.7 ± 2.4	20.4 ± 2.7	16.1 ± 1.7	16.5 ± 2.5	16.9 ± 1.9	15.7 ± 3.0
Hdom (m)	17.5 ± 3.6	17.3 ± 1.4	17.5 ± 1.5	16.6 ± 2.1	16.0 ± 1.8	16.5 ± 1.3	16.3 ± 2.6
Thinning ratio	NA	1.07 ± 0.03	1.13 ± 0.03	0.94 ± 0.01	0.93 ± 0.07	0.97 ± 0.02	0.87 ± 0.02
Thinning removals (m3 ha-1)	NA	80.0 ± 47.7	142.6 ± 42.9	72.1 ± 10.5	118.9 ± 28.8	61.4 ± 23.1	144.2 ± 47.7
Removed sawlogs (m3 ha-1)	NA	6.9 ± 1.4	24.0 ± 17.3	15.9 ± 6.4	28.7 ± 12.8	20.0 ± 14.8	47.5 ± 43.6
Removed pulpwood (m^3 ha^{-1})	NA	70.5 ± 45.3	114.7 ± 27.5	54.1 ± 12.5	87.3 ± 18.7	39.8 ± 13.5	94.0 ± 20.5

the plot area. Experimental design included two factors: three level of thinning types (i. low thinning, ii. crown thinning with normal strategy, iii. crown thinning with strict strategy); and two level of intensity (i. moderate, and ii. heavy). In addition, in each experiment was included one unthinned plot. The six different treatments were replicated from one to two times in each stand using a randomized block design.

Regarding the thinning types, in the low thinning and crown thinning with normal strategy (henceforth "crown/normal"), unsound or damaged trees (crooked, forked etc.) were first removed. Thereafter, in low thinning, suppressed and intermediate trees were removed, while in crown thinning, mostly dominant and co-dominant trees were removed, however aiming at maintaining regular spatial distribution of the trees throughout the plots. In crown thinning with strict strategy (henceforth "crown/strict") only dominant trees were removed, unsound or damaged trees (crooked, forked etc.) trees were left to grow, and regularity of spatial distribution of remaining trees was not emphasized as much as in other thinning types. However, large openings were avoided. When we refer to "crown" thinning, we intend both normal and strict strategy. For details about the crown classes used here, please refer to (Ashton and Kelty, 2018).

For the thinning intensity we considered: moderate intensity, according to prevailing thinning guidelines applied in Finland (Äijälä et al., 2019) and heavy intensity corresponding to 50% of the remaining stand basal area than in the moderate thinning. On average, the basal area before thinning was 26.2 m^2 ha^{-1}, and after moderate and heavy thinnings the remaining basal area was 18.0 m^2 ha^{-1} (31% removed) and 8.7 m^2 ha^{-1} (67% removed) respectively. Mortality after treatments was low on all in all cases without significant differences: in terms of basal area, mean 0.42 ± 0.38 m2 ha^{-1} after the first 5-years.

2.2. Measurements

At the establishment of the experiments, plots were measured and then thinned. Then three more measurements were carried out after successive five-year periods. In one stand (P112), the first two periods were 6 and 4 years, but all data were scaled to five-year intervals with simple linear imputation. Tree species, location, diameter at breast height ($d_{1.3}$) in two rectangular directions, and any damage were recorded for each tree on the plot. Sample trees were systematically selected during inventory, based on the number of trees in the plot and aiming that around 34 samples were selected before thinning treatments. Of those, on average 22 were left growing after treatment. Sample trees were measured for tree height and crown base (using Vertex®), and stem diameter at 6 m height (d_6) (using an electronic calliper mounted on telescopic pole).

The dominant height was calculated as the mean height of the 100 largest trees per hectare. The height of the non-sampled tally trees were predicted using the height curve of Näslund (1936), fitted for each plot on the sample trees measurements. Stem volume of the sample trees was calculated using volume functions based on measured stem diameters ($d_{1.3}$, d_6) and tree height (Laasasenaho, 1982). The volume of non-sampled tally trees was calculated based on smoothing functions ($v/d_{1.3}^2 = a0 + a1\ d_{1.3} + a2\ d_{1.3}^2$), fitted for each plot on the sample trees measurements. Such operations were carried out using Luke's KPL software (Heinonen, 1994).

Thinning ratio was calculated as the ratio of mean diameter basal area weighted after and before treatment. The merchantable stem volume in thinnings was calculated using the assortment rules widely applied in Finland. For pulpwood, we used minimum length of 3.0 m and minimum top diameter of 7.0 cm. For sawlogs, minimum sawlog length 3.1 m and minimum top diameter over bark was at the minimum 14.5 cm, increasing progressively with the increasing sawlog length. For the length of 4.3 m or more the minimum diameter was 20.5 cm. The assortment volumes were calculated according to tree dimensions and no sawlog reductions (i.e., expecting a lower quality than optimal due to form, branches, decay, and other issues) was assumed.

The dry weight of living biomass for both above ground and below ground compartments (stem, branches, needles and leaves, stumps, and roots larger than 1 cm) was based on models by Repola (2009, 2008). Loss of biomass due to the decomposition of dead biomass and logging residues, both originated after thinning, were considered in the analysis. Decomposition of above-ground biomass, including the stems and branches of dead trees, was estimated using the models of Mäkinen et al. (2006). The decomposition of the dead stumps and roots of Scots pine is faster than for the stems (e.g. Shorohova, Kapitsa and Vanha-Majamaa, 2008). Thus for the former we used the method described in Hynynen et al. (2015) and modified the stem wood decomposition model for the below-ground biomass compartments. The predicted percentage of the remaining biomass in the stump and roots 40 years after the tree's death was set to correspond with the results in the articles referenced above. Carbon content was then considered to be 0.5 of the biomass dry weight, and expressed as CO_2 equivalent (CO_2E Mg ha^{-1}).

2.3. Simulations

The future development of the study plots was predicted with Motti stand simulator, developed at the Natural Resources Institute Finland (Luke). Motti is a forest management and decision support tool that consists of stand-level models and distance-independent individual-tree models for predicting stand dynamics structure (Hynynen et al., 2015; Salminen et al., 2005; Siipilehto et al., 2014). The growth and yield models of the Motti stand simulator are based on extensive empirical data covering all commercial tree species (Hynynen et al., 2002). The predicted responses to different forest management practices are based on empirical data which cover all common forest management practices applied in practical forestry in Finland over recent decades. Since crown and/or heavy thinning were less represented in practical forestry, there was still a possibility of higher biases in such situations. However, MOTTI has an established sound biological behaviour and enables responses from all type of thinning (Hynynen et al., 2014), so we expected low or negligible biases during a relatively short simulation period, especially starting 15 years after treatment. The simulation input was the measured tree-level information from the last measurement. The stand development was predicted for each plot until two different final felling scenarios (stand age 65 and 80 years), without additional thinnings. Same rules for the merchantable stem volume assortments were used also in Motti predictions (Huuskonen et al., 2020).

2.4. Statistical analysis

We investigated several variables of interest, using R Statistical software (R Core Team, 2023): (i) the thinning removals (m^3 ha^{-1}), further differentiated between saw logs and pulpwood; (ii) the volume growth post-thinning (m^3 ha^{-1} $year^{-1}$), as the difference in standing volume between successive measurements for the observation period only; (iii) the simulated final felling volume (m^3 ha^{-1}), as the standing volume at final felling, further differentiated between saw logs and pulpwood; (iv) the on-site carbon balance (CO_2E Mg ha^{-1}), as the difference between the carbon present at each measurement *m* and the carbon present in the standing biomass before harvesting. To determine the treatments effects on the variables of interest, we used the following linear mixed model with the package *lme4* (Bates et al., 2015):

$$Y_s = \beta_0 + \beta_1 * \text{Treatment} + \beta_2 * V_{\text{prethinning}} + \varepsilon_m + \varepsilon_s + \varepsilon_s + \varepsilon \quad (1)$$

Where Y_s is one of the variables of interest, standardized (i.e., mean set to 0 and standard deviation to 1); Treatment is one of the six combinations of type and intensity (with unthinned used as reference); $V_{\text{prethinning}}$ is the standing volume previous thinning for addressing variations in the initial state, standardized; β_n fixed coefficients estimated during model fitting; ε_m the random effect for each measurement interval *m*; ε_s the random effect for each stand *s*; ε_p the random effect for each plot *p*; and ε is the random error. The potential confounding effects due to different climate across different measurement periods, spatial correlation of plots within the same stand, and temporal correlation across the same plots repeatedly measured (only for volume growth and carbon balance), were accounted by using measurement, stand, and plot random effects respectively. For thinning removals, the control was low moderate thinning, for the other analyses, the unthinned plots. Each model results immediately pointed out which treatments were significantly different from control and the standardization of the numerical variables provided an easier understanding of the effect magnitude. To verify if the effects of the treatments were different from each other, we used an asymptotic Chi-squared statistic for a Wald-test-based comparison with the package *car* (Fox and Weisberg, 2019).

3. Results

3.1. Thinning outputs

3.1.1. Thinning ratio and stand structure

After the thinning, there were no differences in total remaining basal area between thinning types of the same intensity, while stand structure was notably different (Fig. 1). As already reported in Bianchi et al. (2022), low thinning increased mean diameter (i.e., thinning ratio was above 1) while crown thinning decreased it (i.e., thinning ratio was less than 1). Low heavy and crown/strict heavy thinning had respectively significantly higher ($p = 0.0420$) and significantly lower ($p = 0.0024$) thinning ratio than their moderate counterparts. Stand dominant height did not change after low thinning, and although in crown thinning it decreased slightly it was not significant.

3.1.2. Thinning removals

The removed stem volume during thinning was significantly lower in the moderate (68.1 m^3 ha^{-1} on average) than in the heavy thinning (almost double to 135.4 m^3 ha^{-1} on average) ($p < 0.0001$). There were no significant differences across types within the same intensity.

All treatments but crown/normal had significantly higher saw log output than low moderate thinning, ($p < 0.0001$). Crown heavy thinnings retrieved more sawlog than low heavy thinning ($p = 0.0305$), which in turn were not significantly different from crown moderate thinnings. Regarding pulpwood, it was higher in heavy thinnings than moderate one ($p < 0.0001$). Within heavy thinnings, it was weakly significantly higher in low heavy thinning ($p = 0.0617$), and there were no differences within moderate ones.

3.2. Wood production

3.2.1. Volume growth

Stand volume growth during the 15 observed years after thinning was on descending order from the unthinned plots to moderate to heavy thinnings (respectively 12.7, 10.5, and 7.0 m3 ha-1 year-1) ($p < 0.0001$) (Fig. 2). There were no significant differences across thinning types within the same intensity. Relative volume growth (i.e., per unit of standing volume) was slightly but significantly higher in heavy than moderate thinnings ($p < 0.0001$).

3.2.2. Simulated final felling

At the time of simulated final felling, either at 65 or 80 years, the standing volume was highest in unthinned plots ($p < 0.0001$). There were strong differences across intensities: moderately thinned stands had more standing volume than heavily thinned ones (Fig. 3, $p < 0.0001$), both in terms of sawlogs and pulpwood ($p < 0.0001$). Low moderate thinning had slightly more pulpwood than crown moderate thinnings ($p = 0.0131$).

3.2.3. Carbon balance

For both the observation period and the simulated final felling, the on-site carbon balance was always highest in the unthinned plots ($p < 0.0001$, Fig. 4). For the thinned plots, it was always higher in

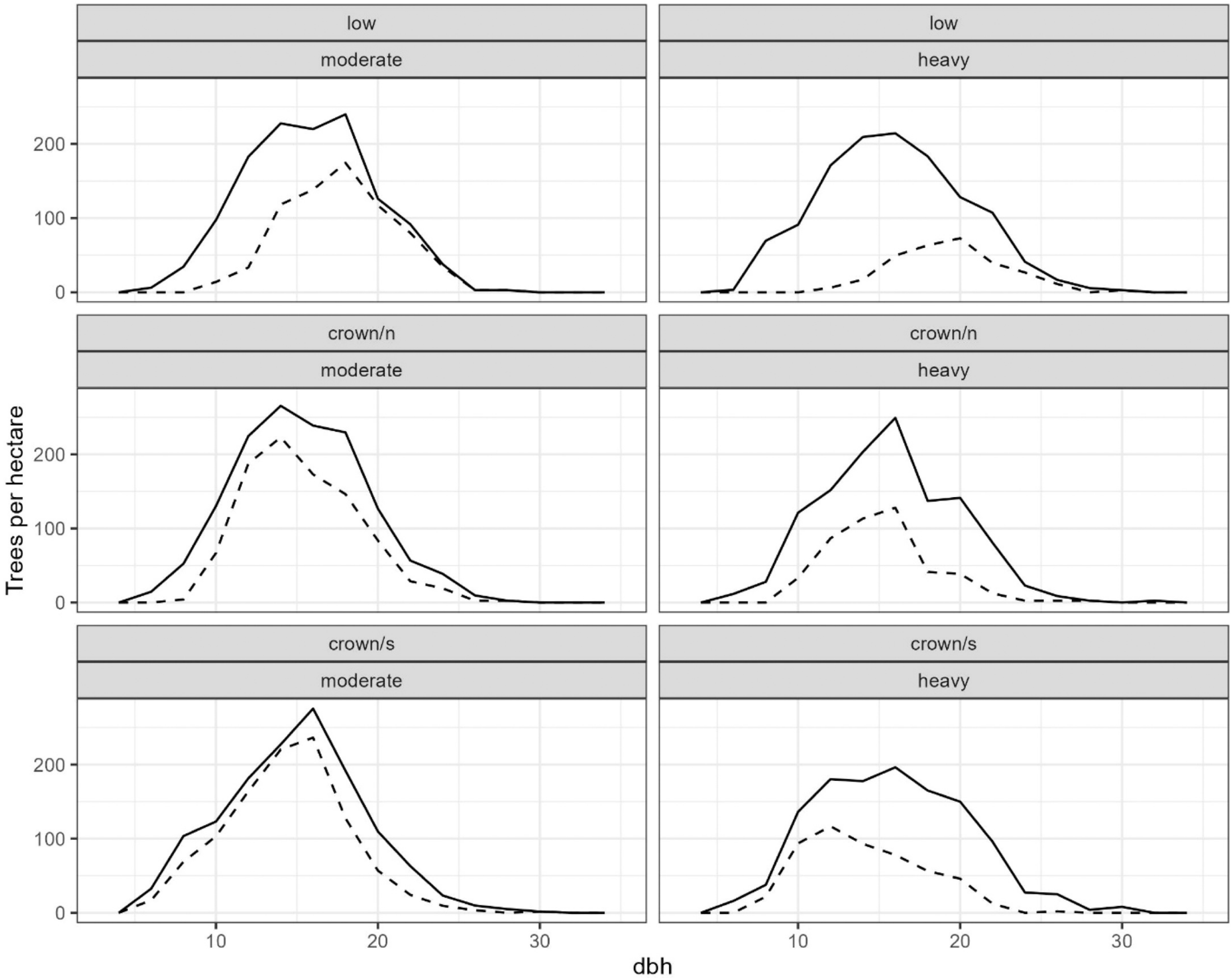

Fig. 1. Average diameter distributions (cm) by treatment: solid and dashed lines are respectively before and after thinning.

moderate than heavy intensities ($p < 0.0001$, Fig. 4). There were no significant differences across thinning types within the same intensity. Moderate thinnings reached neutral carbon balance (i.e., carbon accumulated thanks to growth after thinning compensated the carbon lost due to removals) already after 5 years on average, while intensive thinning had not yet reached it after 15 years on average.

4. Discussion

We assessed the effects of intermediate thinning (i.e., after first commercial thinning) of different intensity and types on the development of Scots pine stands. Previous studies on the effects of thinning (e. g. Eriksson and Karlsson, 1997; Mäkinen and Isomäki, 2004a, 2004b; Nilsson et al., 2010b) focused mainly on low thinning with light or moderate intensities. In this study we examined also heavy thinnings, in which around two-thirds of stand basal area were removed, and crown thinning with different approaches. The results were based on a relatively short study period (fifteen years after intervention), but they already showed differences in stand development. We obtained a more comprehensive view with the inclusion of future development predictions using Motti stand simulator software. It must be noted that the study stands were growing on more fertile sites than most of the pine stands in commercial forests in Finland.

4.1. Thinning outputs

Low thinning increased the mean diameter of the remaining stand, with heavy intensity even more significantly, while crown thinning decreased it. This was in line with previous studies (Vuokila, 1977; Eriksson and Karlsson, 1997) and resulted from the correct application of the guiding principles set for each method. Intensive thinnings doubled the removals of merchantable wood such that the average removals of moderate and intensive thinnings were 68.1 and 135.4 m^3 ha^{-1} respectively. Regarding assortments, crown thinning had a significantly higher sawlogs output compared to low thinning only when carried out with heavy intensity. The amount of sawlog is crucial for the cutting income, because its unit price is threefold compared with pulpwood (for Scots pine: sawlogs €67.0 m^{-3} and pulpwood €19.8 m^{-3}) (OSF, 2022). However, it should be noticed that in this study, no sawlog reduction models were used. According to Mehtätalo (2002) sawlog reductions are considerably high and dependent on tree diameter. We could expect lower sawlog recovery using low thinning than crown thinning due to the smaller size of the harvested trees. For example, for a pine tree of 20 cm in dbh, the sawlog reduction could exceed 60% while for a tree of 30 cm in dbh, the reduction it could drop to about 30% (Mehtätalo, 2002).

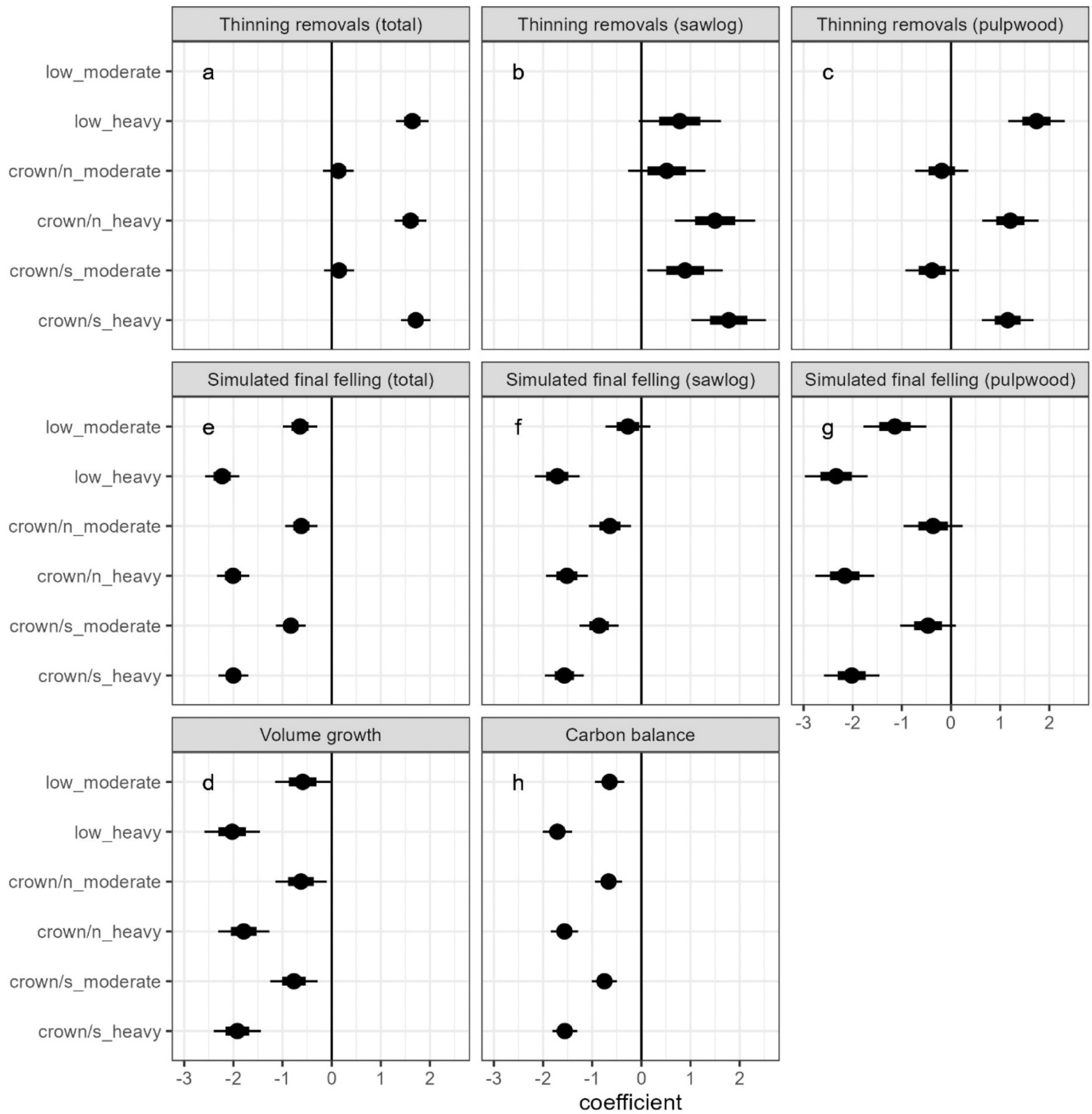

Fig. 2. Effects of treatments for all linear mixed models, using either low moderate (graphs a to c) or unthinned plot (graphs d to i) as contrast (i.e., the vertical solid line at x = 0), and after standardization of the numerical variables (i.e., mean set to 0 and standard deviation to 1). Points indicate the coefficient estimate, thick and narrow horizontal bars respectively one and two standard errors. Volume pre thinning was used to address potential variations in the initial state of plots and is not shown here.

4.2. Wood production

Our results showed that the amount and quality of post-thinning growing stock had a strong effect on the volume increment. The annual volume growth during the 15-years observed period after intensive thinnings was highest in the unthinned plots, then higher in moderate than heavy thinning type at any time, as in previous studies on Scots pine (Mäkinen and Isomäki, 2004a,b; Nilsson et al., 2010b). However, in the thinned plots, the relative growth response at stand level (i.e., the volume growth per unit of standing volume) was slightly higher after intensive than moderate thinnings. That meant that single growing trees increased their growth more after intensive thinning, as already shown from the first 10-years observation tree-level study in (Bianchi et al., 2022). Considering the thinning types, there were no differences within the same intensity. It seems that the removal of the larger trees in crown thinning did not deplete the stand growing potential more than in low thinning. Also other authors (Eriksson and Karlsson, 1997; Nilsson et al., 2010b; Niemistö et al., 2018) did not find differences in the observed post-thinning volume growth for low and crown thinning types for Scots pine. However, crown thinnings were carried out with moderate intensity and normal approach only. Contrasting results with higher volume increment in Scots pine stands after crown thinning has been reported by Vuokila (1977), with a 3% increase during first 10 years after thinning, and by Mielikäinen and Valkonen (1991), with 7.6% increase during 25 year observations of a thinned middle aged Scots pine stands and lower sawlog yield at the end of study period.

The thinning response hypothesis (e.g. Skovsgaard and Vanclay, 2008) states that thinning does not influence stand volume growth significantly for a wide species-specific range of intensities, whereas heavier thinning beyond that range reduces volume growth. For Spain, (Del Río et al., 2008) indicates a critical threshold of 84% of remaining basal area stand for a 5% growth decrease, while Ruiz-Peinado et al. (2016) lower values of 74% and 63% for a 6% and 8% decrease, respectively. In our case, 66% and 33% of remaining basal area showed a 17% and 45% decrease, respectively. The decrease in moderate

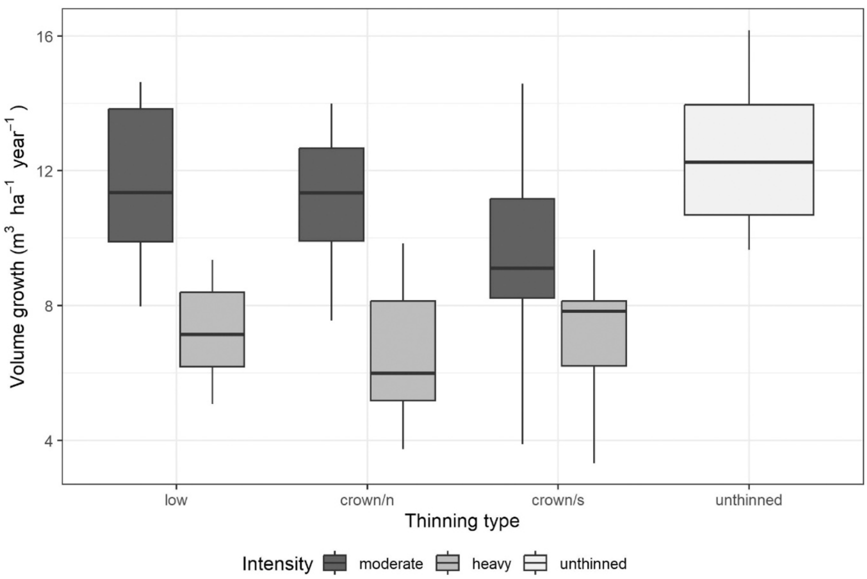

Fig. 3. Average volume growth post-thinning for all treatments over full observation period.

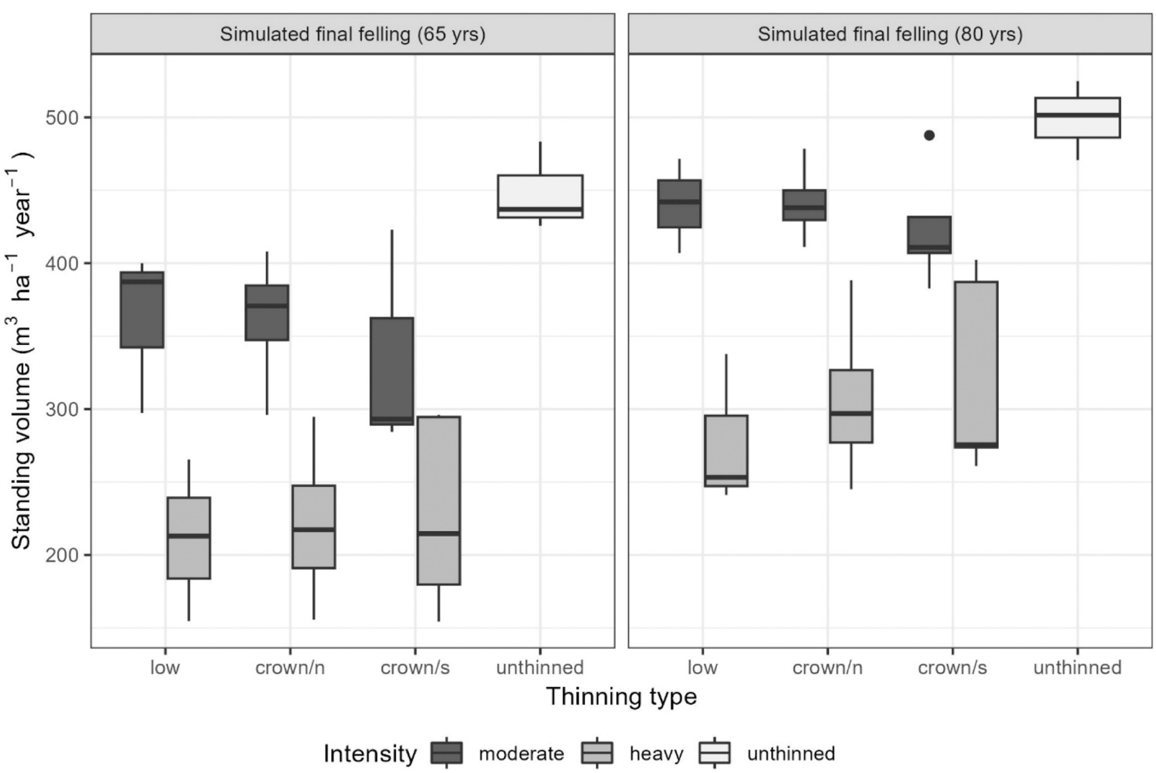

Fig. 4. Average simulated standing volume at final felling for two different rotation lengths.

thinning of the present study is lower than for the corresponding intensity from Ruiz-Peinado et al. (2016).

We did not observe significant temporal variations in growth rate after thinning. According to the results of Hynynen (1995), in Scots pine stands, 20% of total growth response is achieved during first five-years period since thinning, and 40% of growth response during the second. Earlier tree level results showed a slight reduction in growth rate in the second measurement period (Bianchi et al., 2022), likely balanced at plot level by having trees of larger size than the previous period.

Due to the lower standing stock and the lower growth after heavy thinning, it is no surprise that at simulated final felling, unthinned plots had highest total standing volume, followed by moderate and then heavy treatments. We need to highlight that we could set up only one control plot per stand.

4.3. Carbon

Due to the living biomass being the largest carbon stock (compared to standing and lying undecomposed deadwood), it was expected that the accumulated carbon followed similar dynamics to what previously discussed for standing volume. The on-site carbon balance decreased from unthinned to low to heavy thinning at all stages (Del Río et al.,

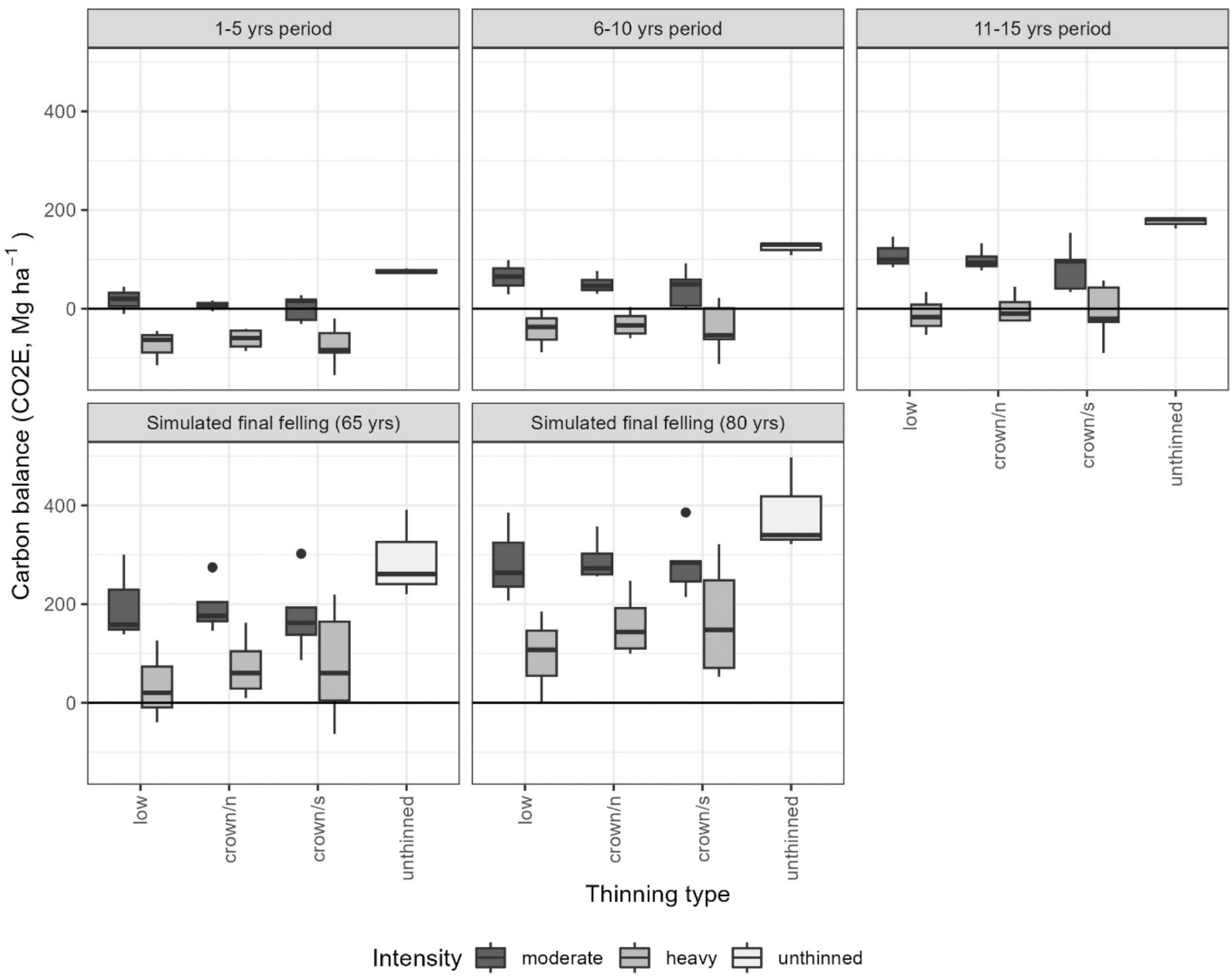

Fig. 5. Average carbon balance (difference between actual carbon and carbon before thinning) for each treatment and all observation periods, including simulations.

2017). Ruiz-Peinado et al. (2016), for Scots pine stands in Spain after repeated low thinnings with different intensities, found the total on-site C stock significantly lower with higher thinning intensity, again mainly due to the lower standing biomass component. Further, Węgiel and Polowy (2020) reports that for Scots pine about 80% of the standing biomass carbon accumulates in the stemwood.

Considering the timing, the carbon balance in moderate thinning reached neutrality already after 5 years in all types, while it took more than 15 years in the intensive thinning. Similarly, Aun et al. (2021) predicted that the woody carbon storage of Scots pine moderately thinned in Estonia will reach the preharvest level in four years after harvesting.

We did not find any differences across thinning types within the same intensity. Crown/strict thinning was not different from other moderate thinnings in terms of carbon balance as it was for timber volume. One reason could be the slightly lower total removals during thinning, which although not significantly in that analysis, may have positively impacted the carbon balance. We could not find in literature analyses related to carbon dynamics for crown thinning of Scots pine.

5. Conclusion

Our results showed that even if heavy thinnings resulted in higher sawlog removal than low moderate thinning, they also retained lower growing stock and lower standing volume increment. In turn, this provided lower volume and lower on-site carbon balance at the final felling. A comprehensive economic assessment of those trade-off should be carried out.

Our results also showed the interaction of time and thinning intensity to carbon accumulation. Moderate thinnings reached on-site neutral carbon balance (carbon accumulation in the forest compensated the carbon lost due to removals) already after 5 years, while intensive thinning will have needed more than 15 years.

Before gathering more data on future development of intensively thinned stands, we would still recommend using moderate intensities in Scots pine rotation forestry aimed at commercial production. However, our results showed that crown thinning could be used in intermediate thinnings without hindering the stand growth.

CRediT authorship contribution statement

PN: Conceptualization; SB, SH, JH: Data curation; SB, SH: Formal analysis; PN: Funding acquisition; SB, HS, PN, JH: Methodology; JH: Supervision; SB, PN; SH: Writing - original draft; SB, HS, PN, JH: Writing - review & editing.

Declaration of Competing Interest

The study was funded by Natural Resources Institute Finland (LUKE). We declare no conflicts of interest.

Data Availability

Data will be made available on request.

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