Assessing the effects of stand dynamics on stem growth allocation of individual Scots pine trees

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Abstract

Forest management alters the growing conditions and thus further development of trees. However, quantitative assessment of forest management on tree growth has been demanding as methodologies for capturing changes comprehensively in space and time have been lacking. Terrestrial laser scanning (TLS) has shown to be capable of providing three-dimensional (3D) tree stem reconstructions required for revealing differences between stem forms and growth allocation. In this study, we used TLS-based 3D reconstructions of tree stems to investigate how forest management (i.e., varying thinning treatments and the following growth effects) has affected stem size and form of Scots pine (*Pinus sylvestris* L.) trees. The results showed that intensive thinning resulted in more stem volume and therefore total biomass allocation and carbon uptake compared to the moderate thinning. Scots pines growing in plots from which suppressed trees were removed (i.e., thinning from below) had larger bottom part of stems (i.e., volume accumulated more below 50% of tree height) compared to Scots pines growing in plots from which part of the dominant trees had been removed (i.e., thinning from above). Furthermore, intensive thinning, especially from below, produced less variation in relative stem attributes characterizing stem size and form. Thus, it can be concluded that thinning intensity, type, and the following growth effects have an impact on post-thinning stem growth as well as stem form of individual Scots pine trees. Our study presented detailed measurements on post-thinning growth of Scots pines that have been laborious or impracticable before the emergence of TLS technology. Moreover, TLS-based stem reconstructions provided variety of attributes characterizing stem growth allocation that have not traditionally been feasible to obtain. The study demonstrated that TLS technology can be used to generate new knowledge for supporting forest management and silviculture as well as improving ecological understanding of boreal forests.

Keywords: growth and yield, forest management, silviculture, terrestrial laser scanning, ground-based LiDAR

Introduction

Allocation of photosynthesis products between different parts of a tree define their development. If resources are limited, trees first channel them towards respiration and sustaining existing parts, producing fine roots and seed (i.e. reproduction), height growth and only then growth in diameter at breast height (1.3 m, DBH). Competition of resources (e.g. light, water, nutrients) between trees also affects development of different tree parts. Thus, differences in the allocation of photosynthesis products within a tree and competition between trees result in variation in tree architecture.

In thinning, as a part of forest management, competition within a population is regulated as part of the trees are removed. Therefore, ecologically thinning is aimed at improving growing conditions (i.e., light, temperature, water, nutrients) of remaining trees and economically to maximize the net present value of a stand by decreasing the opportunity costs of the capital. Especially when part of shadowing leaf mass is removed in thinning, the amount of light is increased, and growth of remaining trees is enhanced (White 1980). Additionally, increase in the amount of nutrients, especially in nitrogen, have been demonstrated after thinning in Scots pine (*Pinus sylvestris* L.) stands due to logging residue (Kimmins & Scoullar 1983, Kukkola & Mälkönen 1997). The development and profitability of forestry can be affected through thinning intensity, type (i.e. selection of the remaining and removing trees) as well as timing. More intensive thinning signifies fewer remaining trees and decrease in standing volume (Mäkinen & Isomäki 2004a).

Intermediate and suppressed trees can expect to benefit from thinning more than co-dominant and dominant trees as growing conditions are improved and competition decreased (i.e. more light) for trees in lower canopy layers. Mäkinen & Isomäki (2004c) reported that relative growth of basal area after thinning was independent of tree size, but it was the largest among intermediate and suppressed trees compared to co-dominant and dominant trees. Conversely, height growth of trees in forests with low tree density is typically smaller than in forests with normal tree density. Especially in Scots pine stands growth of dominant height can temporarily decline (during 25 years on average) after heavy thinning from below (Mäkinen & Isomäki 2004a). Thinning affects the forest structure and relationship between the remaining trees. For example, intensive thinning homogenized DBH distributions in Scots pine stands as dense forests have respectively larger variation in DBH (Mäkinen & Isomäki (2004c). Similarly, it has been shown that DBH growth is affected by tree density and the available space, for example, according to Savill & Sandels (1983) more spacing (i.e. less trees per ha) increased DBH growth.

Studies on diameter growth along the stem of conifers reveal that width of annual rings in the most top part of a stem is relatively narrow but increases linearly with leaf volume (i.e. lower stem part) (Farrar 1961, Kozlowski 1971). In these studies, it has been shown that in dominant

and open-grown trees the annual ring thickens near the bottom of a stem whereas in suppressed trees the ring throughout the stem is thinner than in dominant trees. Farrar (1961) reported increasing annual ring growth in the bottom part of a stem after thinning while growth in top part of a stem (i.e. within crown) was comparable to the situation before thinning. Similarly, Valinger (1992) demonstrated that thinning promoted diameter growth in the bottom part of a stem and decreased height growth. Mäkinen & Isomäki (2004b), on the other hand, demonstrated that diameter growth of Norway spruce (*Pica abies* (L.) H. Karst) concentrated on top part of a stem in dense forests whereas in forests where trees had more space available, diameter growth was similar in different heights along a stem.

When impacts of thinning intensity were assessed through attributes characterizing stem form of Scots pine trees, Mäkinen & Isomäki (2004c) reported that height/diameter ratio decreased and stem taper (i.e. DBH – diameter at 6 m height) increased when thinning intensity increased from unthinned to light, moderate, and heavy thinning (i.e. average basal area after the thinning treatment compared to the state before thinning ≥95%, 80-94%, 65-79%, and ≤64% of control plots, respectively). Similarly, crown height and crown ratio were significantly different between thinning intensities (Mäkinen & Isomäki 2004c). The thinning intensities, even the heavy thinning, studied in Mäkinen & Isomäki (2004c) correspond approximately thinning intensities applied nowadays in Finland (Rantala 2011).

In addition to different thinning intensities, thinning type defines what kind of trees are removed and most importantly left to grow. In thinning from below, intermediate and suppressed as well as overgrown trees are removed in order to increase the volume growth of the remaining trees whereas in thinning from above dominant and overgrown trees are removed. At stand level, thinning from above increased basal area and volume growth in Scots pine stands compared to thinning from below whereas thinning from below increased growth of dominant height more than thinning from above (Vuokila 1977). Similarly, Mielikäinen & Valkonen (1991) reported that thinning from above resulted in 4-8% more volume growth in Scot pine stands than thinning from below. Furthermore, Eriksson & Karlsson (1997) illustrated that thinning from above did not decrease volume growth in Scots pine stands in comparison with thinning from below.

Growing conditions are, thus, dependent on tree density that affects growth and structure of trees (Harper 1977) whereas changes in height and diameter growth alter stem form and taper. Therefore, understanding changes in stem form and taper enable assessing the effects of thinning on future growth as well as possible susceptibility of snow and wind damage of remaining trees. However, studies reviewed above were only based on a limited number of observations and the observations used were only able to capture limited changes along a stem. Observations included only DBH, diameter at 6-m height, and tree height measured with calipers and clinometers. Differences in stem volume were predicted using allometric equations that are incapable of considering variation in stem form. Thus, our understanding how forest management affects stem form and volume allocation is still rather limited.

Terrestrial laser scanning (TLS) has proven to non-destructively provide three-dimensional (3D) information on tree stems (Liang et al. 2014, Kankare et al. 2013, Raumonen et al. 2013, Saarinen et al. 2017) that has not been possible with calipers or measurement tape. Individual

trees can be detected from a TLS-based point cloud through identification of circular shapes (Aschoff et al. 2004, Maas et al. 2008) or clusters of points (Cabo et al. 2018, Zhang et al. 2019). Points from individual trees can then be utilized in reconstructing the entire architectural structure of a tree (Raumonen et al. 2013, Hackenberg et al. 2014) or only the stem (Liang et al. 2011, Heinzel & Huber 2017). When acquisition and preprocessing of TLS data are carried out thoroughly, millimeter-level details can be observed from TLS point clouds (Wilkes et al. 2017, Liang et al. 2018). This enables accurate geometrical tree reconstruction (Hackenberg et al. 2014). In applications related to boreal forests, TLS has been utilized in quantifying stem growth and changes in stem taper (Luoma et al. 2019), reparametrizing an existing taper curve model (Saarinen et al. 2019), and assessing timber quality (Pyörälä et al. 2019). In Central Europe, on the other hand, impacts of silviculture on stem form of Norway spruce (Jacobs et al. 2019) and European beech (Juchheim et al. 2017, Georgi et al. 2018, Noyer et al. 2019) have been studied. In Juchheim et al. (2017) and Georgi et al. (2018), several attributes characterizing stem size and form were generated from TLS point clouds (e.g. tree height, DBH, stem volume, crown-base height, height-diameter ratio, taper, lean, and sweep) of which most are attributes that have been generated also from traditional measurements. However, as shown by Jacobs et al. (2019) and Saarinen et al. (2019), taper curve is possible to obtain from TLS point clouds and it enables generation of unconventional attributes that may be used in revealing differences in the stem development and stem growth allocation.

Understanding differences in tree architecture based on quantitative information is still limited, although theoretical understanding exists on the effects of forest management and resultant growing conditions on allocation between height and diameter growth of trees. However, detailed information on stem form and size has not been available for studies investigating the effects of both thinning intensity and type. Therefore, the objective of the study is to investigate the effects of intensity and type of thinning on post-thinning stem growth of Scots pine trees. Various attributes characterizing stem form and size (e.g. tapering) were generated from TLS-based point clouds for indicating differences in stem growth allocation. Theoretical premises based on previous studies on growth and yield led to a main hypothesis that thinning intensity and type produce differing stem form and size. It was further divided to following research questions: **(1)** how thinning intensity affects volume and woody biomass allocation as well as tapering along a stem; **(2)** how thinning type affects volume and woody biomass allocation as well as tapering along a stem; and **(3)** how thinning intensity and thinning type affect variation in stem form and size.

Materials and methods

Study site and data acquisition

The research was conducted in southern Finland in three study sites (Palomäki, Pollari, and Vesijako) (Figure 1) established and maintained by Natural Resources Institute Finland (Luke). Study site in Palomäki was established in 2005 whereas study sites in Pollari and Vesijako in 2006. The study sites are located in the same vegetation zone namely southern Boreal forest zone at relative flat terrain, the elevation is 135 m, 155 m, and 120 m above sea level in

Palomäki, Pollari, and Vesijako, respectively. Furthermore, the temperature sum is 1195, 1130, and 1256 degree days in Palomäki, Pollari, and Vesijako, respectively. Each study site is characterized as mesic heath forest (i.e., Myrtillus forest site type according to Cajander (1909)) and includes nine rectangular sample plots with size varying from 1000 m^2 to 1200 m^2 resulting in total of 27 sample plots.

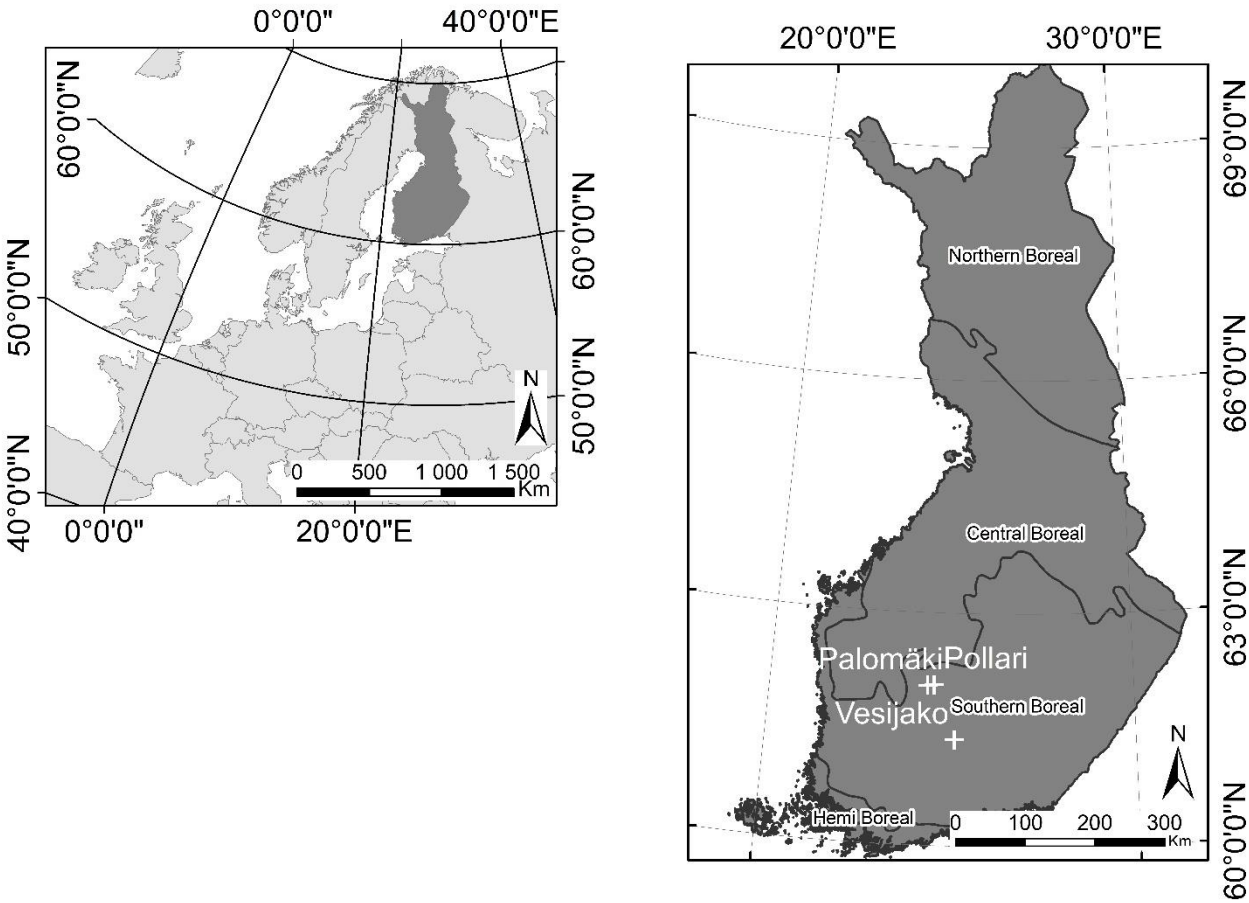

Figure 1. Location of three study sites namely Palomäki, Pollari, and Vesijako and vegetation zones in Finland.

The experimental design of the study sites includes two levels of thinning intensity and three thinning types resulting in six different thinning treatments, namely i) moderate thinning from below, ii) moderate thinning from above, iii) moderate systematic thinning from above, iv) intensive thinning from below, v) intensive thinning from above, and vi) intensive systematic thinning from above, as well as a control plot where no thinning has been carried out since the establishment. Moderate thinning refers to prevailing thinning guidelines applied in Finland (Rantala 2011) whereas intensive thinning corresponds 50% lower remaining basal area (m^2/ha) than in the plots with moderate thinning intensity. Regarding thinning types, small and suppressed trees as well as unsound and damaged trees (e.g. crooked, forked) were first removed from plots where thinning from below or above was carried out. Furthermore, suppressed and co-dominant tree were removed in thinning from below whereas mostly dominant trees were removed in thinning from above, but also maintaining regular spatial distribution of trees. In systematic thinning from above, on the other hand, only dominant trees

were removed and small, suppressed trees were left to grow and regularity of spatial distribution of remaining trees was not emphasized similarly to other thinning types, although large gaps were avoided.

Table 1. Minimum, mean, maximum, and standard deviation (std) of tree-level attributes for each study site at the year of establishment before treatments (First measurement) and last measurement. DBH = diameter at breast height.

		First measurement (2005-2006)		
		Palomäki	**Pollari**	**Vesijako**
DBH (cm)	min	6.3	6.6	5.4
	mean	15.8	14.2	17.2
	max	29.8	25.3	31.6
	std	4.1	3.2	4.9
Height (m)	min	9.6	8.0	8.5
	mean	15.8	13.4	16.5
	max	20.9	17.4	23.0
	std	1.7	1.3	2.2
Volume (dm^3)	min	16.9	16.8	10.3
	mean	169.6	115.5	213.5
	max	623.0	387.7	783.6
	std	96.1	58.4	126.0
		Last measurement (2018-2019)		
		Palomäki	**Pollari**	**Vesijako**
DBH (cm)	min	7.9	7.6	6.5
	mean	20.0	19.2	21.3
	max	36.4	30.1	34.4
	std	4.9	3.9	4.9
Height (m)	min	12.9	8.4	13.7
	mean	20.3	18.5	22.0
	max	26.6	23.5	223.7
	std	2.1	1.7	8.9
Volume (dm^3)	min	33.1	21.3	20.9
	mean	332.9	275.4	394.2
	max	1146.2	762.4	1266.4
	std	183.5	124.2	184.3

At the time of establishment, plots were measured, and thinning treatments were performed (Niemistö et al. manuscript). The study sites have been re-measured three times after the establishment, the latest measurements were carried out in October 2018 in study site Pollari whereas study sites Palomäki and Vesijako were measured in April 2019. Thus, the time after the thinning treatments and the period for growth response on the remaining trees was 13 years in Palomäki and 12 in Pollari and Vesijako. Tree species, DBH from two perpendicular

directions, crown layer, and health status were recorded from each tree within a plot for each measurement time. Each sample plot includes also 22 sample trees, on average, from which tree height, crown base height, and height of the lowest dead branch have been measured. Development of tree-level attributes are presented in Table 1 for each study site and in Table 2 for each thinning treatment.

Table 2. Minimum, mean, maximum, and standard deviation (std) of tree-level attributes for each treatment at the year of establishment before treatments (First measurement) and last measurement. DBH = diameter at breast height.

		First measurement (2005-2006)						
		Moderate below	**Moderate above**	**Moderate systematic**	**Intensive below**	**Intensive above**	**Intensive systematic**	**No treatment**
DBH (cm)	min	5.7	6.3	5.5	5.4	6.7	5.4	5.8
	mean	15.8	15.2	15.4	15.9	15.6	15.4	15.4
	max	28.2	28.6	29.5	29.8	31.6	31.0	30.7
	std	3.9	3.9	4.1	4.3	4.0	4.4	4.6
Height (m)	min	8.8	10.7	8.0	8.5	9.6	9.2	9.7
	mean	15.5	15.2	14.8	15.5	14.9	14.9	14.7
	max	19.9	19.3	22.3	20.9	19.8	22.2	23.0
	std	2.0	1.4	2.0	2.2	1.9	2.6	2.6
Volume (dm^3)	min	13.0	18.8	12.7	10.7	16.9	10.3	13.0
	mean	164.9	151.8	153.8	170.8	157.5	160.2	160.5
	max	549.4	583.8	689.8	623.0	679.9	704.4	783.6
	std	91.1	86.3	93.5	106.2	92.5	111.2	119.7
		Last measurement (2018-2019)						
		Moderate below	**Moderate above**	**Moderate systematic**	**Intensive below**	**Intensive above**	**Intensive systematic**	**No treatment**
DBH (cm)	min	13.4	9.1	7.6	17.9	13.1	10.7	6.5
	mean	22.2	19.3	18.8	26.4	21.1	20.8	18.7
	max	35.3	32.3	33.9	36.4	31.1	35.3	34.4
	std	3.7	4.3	4.2	3.9	3.5	4.3	5.0
Height (m)	min	14.7	15.6	8.4	18.2	14.9	13.6	13.2
	mean	21.2	20.4	19.4	21.2	19.1	19.6	20.6
	max	25.9	25.2	26.0	25.3	24.1	25.9	223.7
	std	2.1	1.6	2.2	1.7	1.5	2.8	10.3
Volume (dm^3)	min	116.6	51.0	21.3	231.9	103.9	61.6	22.9
	mean	408.3	306.4	282.5	563.8	335.2	347.0	299.4
	max	1050.8	923.3	1039.5	1146.2	815.6	1050.8	1266.4
	std	160.3	145.6	137.2	202.5	125.4	173.3	190.8

TLS data acquisition was carried out with Trimble TX5 3D laser scanner (Trible Navigation Limited, USA) for all three study sites between September and October 2018. Eight scans were place to each sample plot, the scan setup is depicted in Figure 2, and scan resolution of point distance approximately 6.3 mm at 10-m distance was used. Artificial constant sized spheres (i.e. diameter of 198 mm) were placed around sample plots and used as reference objects for registering the eight scans onto a single, aligned coordinate system. The registration was carried out with FARO Scene software (version 2018) with a mean distance error of 2.9 mm and standard deviation 1.2 mm, mean horizontal error was 1.3 mm (standard deviation 0.4 mm) and mean vertical error 2.3 mm (standard deviation 1.2 mm).

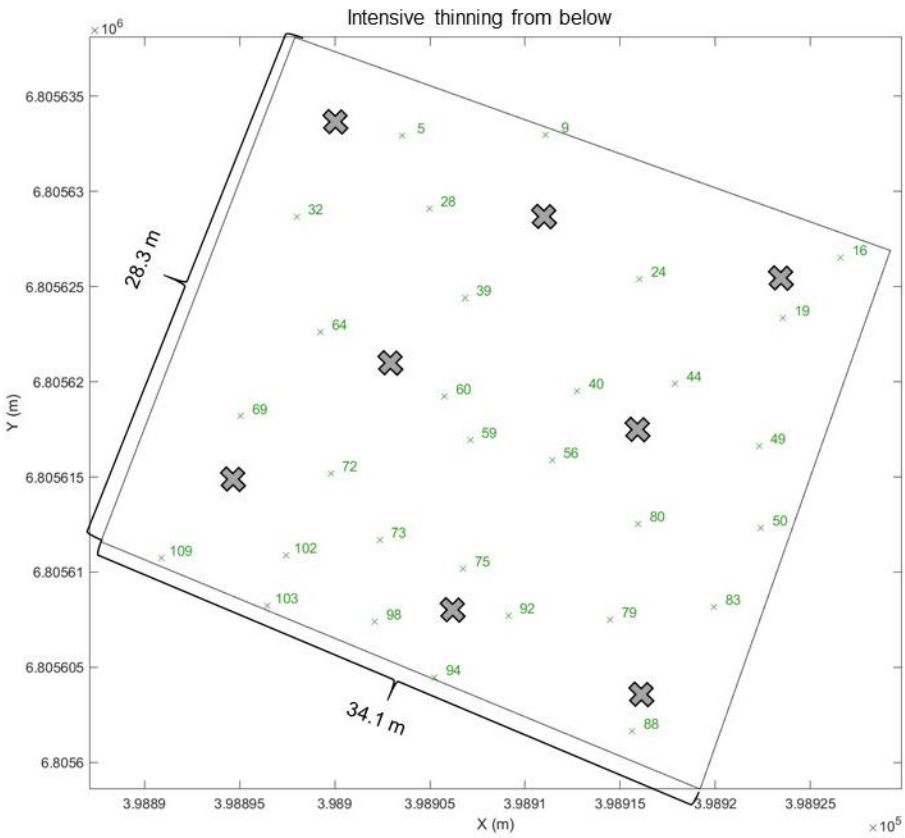

Figure 2. Scan design of eight scans (denoted as x) per an example sample plot thinned intensively from below. X and y axes present the coordinates of the sample plot in EUREF-FIN.

In addition to TLS data, aerial images were obtained by using an unmanned aerial vehicle (UAV) with Gryphon Dynamics quadcopter frame. Two Sony A7R II digital cameras that had CMOS sensor of 42.4 MP, with a Sony FE 35mm f/2.8 ZA Carl Zeiss Sonnar T* lens, were mounted on the UAV in +15° and -15° angles. Images was acquired in every two seconds and image locations were recorded for each image. The flights were carried out on October 2, 2018. For each study site, eight ground control points (GCPs) were placed and measured. Flying height of 140 m and a flying speed of 5 m/s was selected for all the flights, resulting in 1.6 cm ground sampling distance. Total of 639, 614 and 663 images were captured for study site Palomäki, Pollari, and Vesijako, respectively, resulting in 93 % and 75 % forward and side

overlaps, respectively. Photogrammetric processing of aerial images was carried out following the workflow as presented in Viljanen et al. (2018). The processing produced photogrammetric point clouds for each study site with point density of 804 points/m^2, 976 points/m^2, and 1030 points/m^2 for Palomäki, Pollari, and Vesijako, respectively.

Methods

Point clouds from TLS and UAV were combined for characterizing tree height and crown as comprehensively as possible. Individual tree detection and characterization from the combined point clouds followed the methodology presented by Yrttimaa et al. (2020) and Yrttimaa et al. (2019), respectively. The process included four steps: 1) point cloud normalization, 2) tree segmentation 3) point cloud classification, and 4) generation of tree-level attributes. The TLS point clouds were normalized (i.e. point heights were transformed to heights above ground) (1) using the *lasground* tool in LAStools software (Isenburg 2019) whereas RGB point clouds from UAV were normalized with digital terrain model (DTM) that is based on airborne laser scanning data and provided by National Land Survey of Finland. Canopy height models (CHMs) at a 20 cm resolution were generated from the normalized UAV point clouds to segment individual tree crowns (2). Variable Window Filter approach (Popescu & Wynne 2004) was used to identify the tree top positions, and Marker-Controlled Watershed Segmentation (Meyer & Beucher 1990) was applied to delineate the tree crown segments from the CHMs. The TLS point cloud was then split into tree-segments according to the extracted UAV crown segments using point-in-polygon approach. The tree-segmented TLS point clouds were then classified (3) into stem points and non-stem points. Points that represented planar, vertical, and cylindrical surfaces were classified as stem points while the rest of the points were classified as non-stem points. Finally, tree-level attributes such as DBH, height, stem volume, and taper curve were generated (4) for each tree. Tree height was measured from the UAV point cloud while taper curve was based on diameter measurements along the stem by fitting circles on horizontal stem point slices in every 20 cm. Initial diameter estimates were filtered by omitting clear outliers utilizing an iterative approach where diameters differing more than three median absolute deviation from the median diameter were omitted. Cubic spline curve was used to interpolate the missing diameters and to generate the taper curve. DBH was measured from the taper curve at the height of 1.3 m while stem volume was estimated using Huber formula by considering the stem as a sequence of vertical cylinders at 10 cm intervals.

Post-thinning stem growth was assessed between thinning treatments using TLS-derived tree attributes characterizing stem form and tapering. Used attributes and their descriptions are presented in Table 3. Form factor at breast height (ff), tapering (taper), and slenderness (slend) have been used in assessing stem form and were also included in this study. Cumulative volume (e.g. height at which 50% of stem volume accumulated (h_vol50), and volume percentiles (p10, .., p90)) enable more detailed quantitative assessment of stem tapering and volume allocation. Volume percentiles were defined as the height at which each percentage point of stem volume was accumulated. Furthermore, absolute and relative volume and tapering below and above 50% of tree height, represent attributes that can be generated from a taper curve. As taper curve

has been impractical to measure, these kinds of attributes have not been widely applied and can thus be considered novel in the field of growth and yield. Relative volume below and above 50% of tree height was obtained by dividing the absolute volume of part of a stem with total stem volume. Relative tapering, on the other hand, was produced through division of absolute tapering of bottom and top part of a stem by the diameter at the lowest point, in other words at 0 m and at 50% of tree height for relative tapering of bottom and top part of a stem, respectively. All of the attributes were generated for 2174 Scots pine trees within the 27 sample plots.

Table 3. Single tree attributes characterizing stem size and form.

Attribute (unit)	Abbreviation	Description
Diameter at breast height (cm)	DBH	Diameter at 1.3 m height from taper curve
Tree height (m)	H	The maximum height of 3D points
Stem volume (dm^3)	vol	Aggregated volume of cylinders obtained from taper curve
Volume bottom (dm^3)	vol_bottom	Volume below 50% of tree height
Volume top (dm^3)	vol_top	Volume above 50% of tree height
Relative volume	r_vol	vol_top / vol_bottom
Relative volume below 50% of tree height	r_vol_bottom	vol_bottom / vol
Relative volume above 50% of tree height	r_vol_top	vol_top / vol
Height at which 50% of total stem volume accumulated (m)	h_vol50	50% of the cumulative volume based on diameters from taper curve
Form quotient	formq	Diameter at 50% of tree height / DBH
Slenderness	slend	H / DBH
Form factor at breast height	ff	Stem volume / basal area at breast height * H
Form factor up to 50% of tree height	ff50	Stem volume up to 50% of tree height / basal are at 50% of tree height * 50% of tree height
Tapering (cm)	taper	DBH - diameter at 6 m
Tapering below 50% of tree height (cm)	taper_bottom	Diameter at 0 m height – diameter at 50% of tree height, from taper curve
Tapering above 50% of tree height (cm)	taper_top	Diameter at 50% of tree height – diameter at the top of a tree, from taper curve
Relative tapering below 50% of tree height	rel_taper_bottom	taper_bottom / diameter at 0 m height
Relative tapering above 50% of tree height	rel_taper_top	taper_top / diameter at 50% of tree height
Stem volume percentiles (m)	p10, p20, p30, …, p90	Height at which cumulative stem volume in every 10-percentage point accumulated by utilizing diameters from taper curve

One-way variance analyses (ANOVA) were carried out to evaluate differences in attributes characterizing growth allocation of a stem between the six thinning treatments, including two intensities (i.e. moderate and intensive) and three types (i.e. from below, from above, and systematic), as well as the control plots. The assumption of variance homogeneity was tested

with Levene's test. If it was not met, Kruskal-Wallis test was applied instead of ANOVA to reveal the significant differences ($p < 0.01$). Furthermore, if significant differences ($p < 0.01$) between the seven categories (i.e. six treatments and control) were found either Tukey Honest Significant Differences test for ANOVA or paired Wilcoxon test for Kruskal-Wallis was used to reveal the differences between groups.

To compare the taper curves after different thinning treatments that were carried out in 2005 for study site Palomäki and in 2006 in Pollari and Vesijako, diameters for all trees within each treatment was estimated with a smoothing cubic spline to relative heights of 1%, 2.5%, 5%, 7.5%, 10%, 15%, 20%, …, 95%, and 100% using the original taper curve measurements from TLS point clouds. This was carried out to normalize the differences in tree height. Finally, mean taper curve was calculated for each treatment together with its standard deviation.

As especially thinning type implicitly affects the size of the remaining trees (e.g. in thinning from below small trees were removed), we examined the basic statistics (i.e. minimum, mean, maximum, and standard deviation) of relative stem attributes, namely relative volume, relative volume below and above 50% tree height as well as relative tapering below and above 50% of tree height. These attributes disregard tree size and demonstrate more objectively the effects of different thinning treatment and can reveal the variation in the post-thinning growth.

As there are several levels of grouping (i.e. tree, sample plot, treatment) we were interested in testing the effects of these groups on stem attributes. Therefore, a nested two-level linear mixed-effects model (Equation 1) was fitted using Restricted Maximum Likelihood included in package nlme (Pinheiro et al. 2016) of the R-software (R Core Team, 2019).

$$y_{ijk} = x_{ijk\beta} + a_i^{(1)} + a_i^{(2)} x_{ijk}^{(2)} + c_{ij}^{(1)} + c_{ij}^{(2)} x_{ijk}^{(2)} + \epsilon_{ijk}, \quad (1)$$

where i, i = 1, …, M, refers to treatment, j, j = 1, …,n_i, to a plot, and k, k = 1, …,n_{ij}, to a tree, a_i and c_{ij} are normally distributed random effects for treatment and sample plot with mean zero and unknow, unrestricted variance-covariance matrix, and ϵ_{ij} is a residual error with mean zero and unknown variance. The random effects are independent across treatments and sample plots as well as residual errors are independent across trees.

Although taper curve for each tree was only available for one time point, field measurements before and after the thinning treatments were on hand. Post-thinning growth in DBH, height, and stem volume was calculated for all live trees that were in the sample plots during the last measurements. Additionally, difference in slenderness was assessed as a ratio between the first and last measurements to evaluate post-thinning growth. To evaluate if the growth of DBH, height, and stem volume as well as difference in slenderness varied statistically significantly (p-value<0.05) between thinning treatments, paired two-sided t-test was performed.

Results

When the effects of same thinning type (i.e. from below, from above, and systematic) but different intensity (i.e. moderate and intensive) on the stem attributes characterizing post-

thinning stem growth were compared, intensive thinning mainly produced larger attributes characterizing absolute tree size (Figure 3). Similarly, thinning from below (both moderate and intensive) mostly resulted in larger stem attributes characterizing absolute stem size compared to respective attributes caused by thinning from above and systematic with the same intensity (Figures 3). With intensive thinning, more trees were removed that ensured more resources for the remaining trees whereas with moderate thinning the resultant tree density was larger. Smaller trees were removed in thinnings from below and larger trees were left to grow whereas the situation was the opposite in thinnings from above and systematically. Thus, in addition to different growth effects, our findings about differences in absolute stem size between these thinning treatments is expected. Conversely, there was no apparent distinction in most of the realization of stem attributes between thinning from above and systematic with both moderate and intensive intensity. In relative attributes that disregard tree size, such as relative volumes and taperings, however, the difference between thinning intensity and type was smaller (Figure 3). There was a noticeable trend between moderate thinning types in stem volume percentiles, in other words in moderate systematic thinning and thinning from above stem volume percentiles were accumulated at lower heights of a stem compared to moderate thinning from below (Figure 4). Between intensive thinning types there was no such trend but intensive thinning from above, among the intensive thinnings, produced the lowest heights for stem volume percentile accumulation.

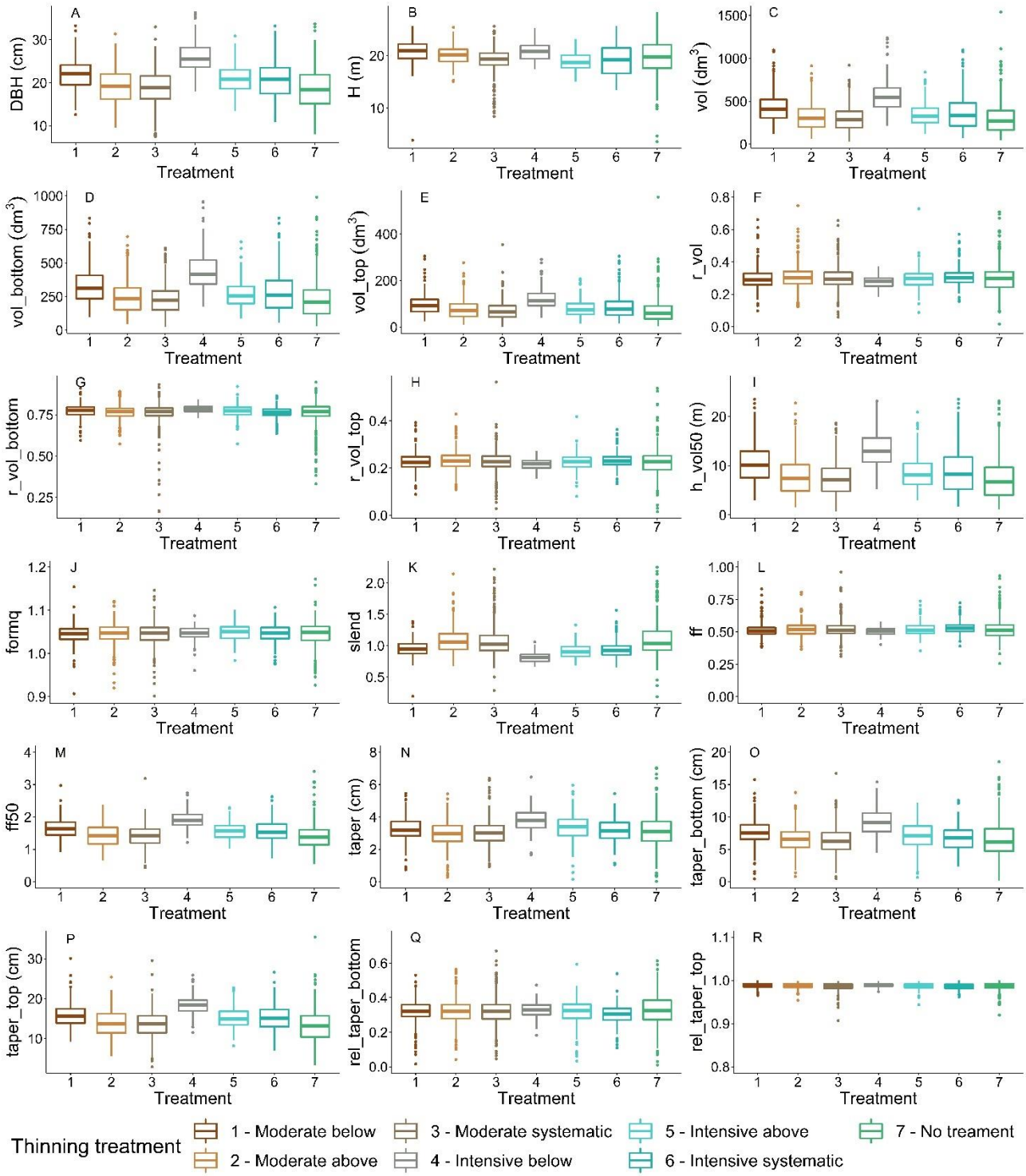

Figure 3. Stem attributes (i.e. diameter at breast height (A), tree height (B), stem volume (C), volume below 50% of tree height (D), volume above 50% of tree height (E), relative volume (F), relative volume below 50% of tree height (G), relative volume above 50% of tree height (H), height at which 50% of stem volume has accumulated (I), form quotient (J), slenderness (K), form factor at breast height (L), form factor up to 50% of tree height (M), tapering (N), tapering below 50% of tree height (O), tapering above 50% of tree height (P), relative tapering below 50% of tree height (Q), and relative tapering above 50% of tree height (R)) caused by

seven thinning treatments implemented in 2005-2006. Please refer to Table 3 for the descriptions of the attributes.

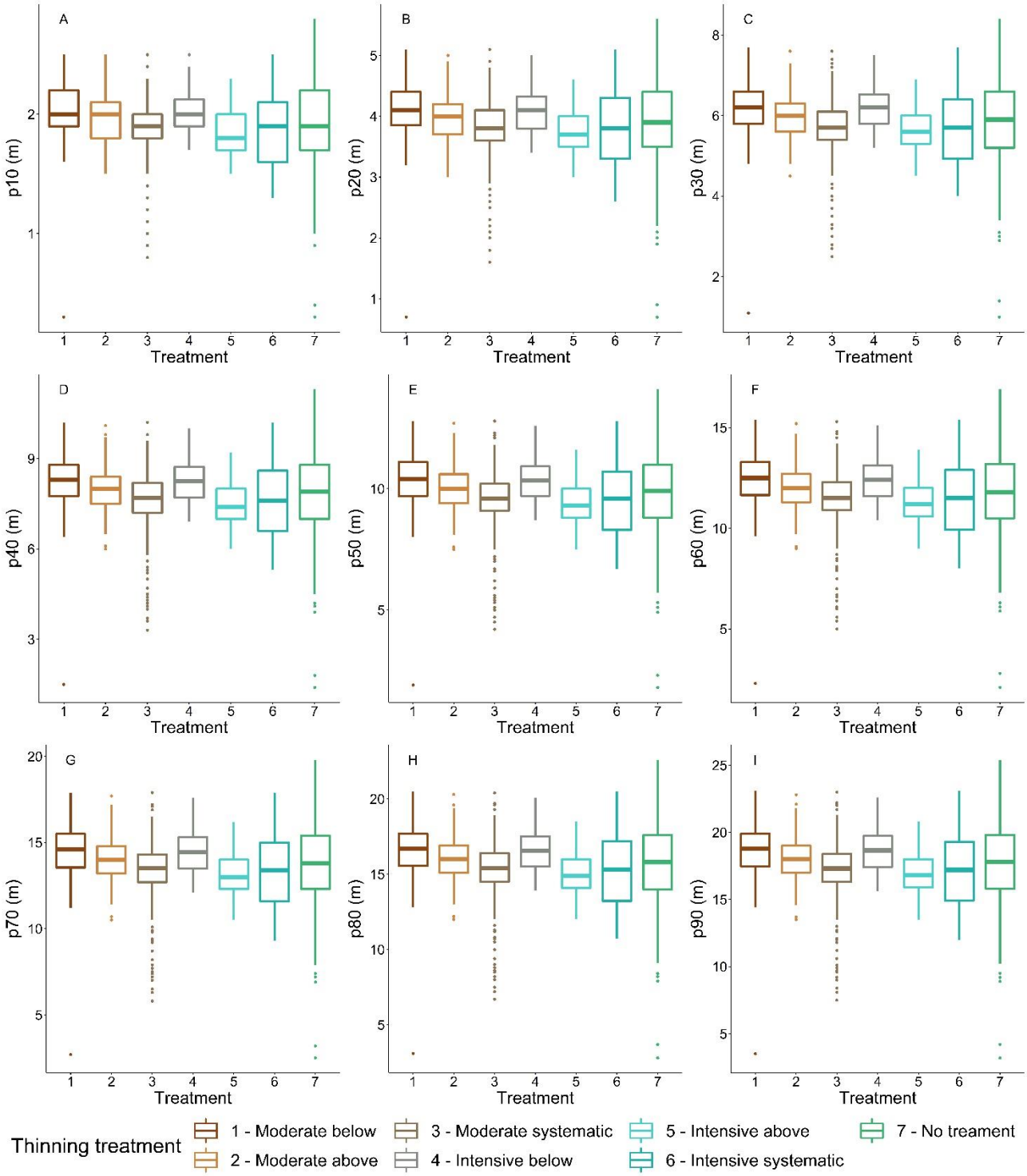

Figure 4. Differences caused by thinning treatments and 15-year growth to stem volume percentiles (i.e. height at which percentiles of volume accumulated; 10th: A, 20th: B, 30th: C, 40th: D, 50th: E, 60th: F, 70th: G., 80th: H, and 90th: I).

Although difference was not noticeable for all stem attributes between thinning treatments in Figures 3 and 4, Kruskal-Wallis test revealed statistically significant differences (p-value ≤ 0.001) in all other stem attributes except in form quotient (p-value = 0.7). However, it did not reveal between which treatments the differences occurred. Paired Wilcoxon test, however, showed statistically significant difference (p-value ≤ 0.01) in most of the stem attributes between thinning treatments (Table 4). When comparing the influence of thinning intensity on relative stem attributes only relative volume below 50% of tree height differed significantly between moderate and intensive thinning from below but not between moderate and intensive thinning from above or moderate and intensive systematic. The thinning type within same intensity affected relative volume below 50% of tree height from relative stem attributes; it differed between moderate from below and above as well as between intensive thinning from below and both above and systematic. Additionally, the significant difference was also found between intensive thinning from below and intensive systematic in relative volume above 50% of tree height as well as in relative tapering below and above 50% of tree height.

The taper curve depicts growth allocation of a stem and mean taper curve for each treatment with its standard deviation is presented in Figure 5. Larger diameters are visible for taper curves of intensive thinnings compared to moderate thinnings, in other words more volume and through that biomass can be expected to be allocated in stems in intensively thinned plots. Similarly, when thinning from below and above are compared, larger diameters are observed in bottom part of stem (i.e., below 50% relative height) in thinning from below indicating more stem growth allocation there. Furthermore, diameters in top part of taper curves (i.e., above 50% of relative height) are more similar between thinning treatments. Tapering in bottom and top parts of a stem was smaller in thinnings from above compared to thinnings from below (with both intensities) (Figure 3). Furthermore, tapering in both bottom and top parts of a stem were statistically significantly different between “Moderate below” and other moderate thinning types (i.e. “Moderate above” and “Moderate systematic) as well as “No treatment” (Table 4). Similar results were found between intensive thinning types (i.e. “Intensive below” vs “Intensive above” and “Intensive below” vs “Intensive systematic”). These results suggest thinning type affects tapering in different parts of a stem. Moreover, when tapering in bottom and top parts of a stem were compared between same thinning type (i.e. below, above, and systematically) and different intensity (i.e. moderate and intensive), there was statistically significant difference between same thinning type but different intensity also indicating the effects of thinning intensity on stem tapering.

Table 4. Statistically significant difference (p-value ≤ 0.01) caused by different thinning treatments and the following growth effect on the stem attributes characterizing post-thinning growth. DBH = diameter at breast height, H = tree height, vol = total stem volume, vol_bottom = volume below 50% of tree height, vol_top = volume above 50% of tree height, rel_vol = relative volume, rel_vol_bottom = relative volume below 50% of tree height, rel_vol_top = relative volume above 50% of tree height, h_vol50 = height at which 50% of stem volume accumulated, slend = slenderness, ff = form factor, ff50 = form factor up to 50% of tree height, taper = tapering, taper_bottom = tapering below 50% stem height, taper_top = tapering above

50% of tree height, rel_taper_bottom = relative tapering below 50% of tree height, rel_taper_top = relative tapering above 50% of tree height, p10, … p90 = cumulative stem volume in every 10 percentage point. Please refer to Table 3 for descriptions of the attributes.

Compared stem attributes caused by the thinning treatments and its growth response		**Attributes with statistically significant difference (p-value ≤ 0.01)**
Moderate below	Moderate above	DBH, H, vol, vol_bottom, vol_top, rel_vol_bottom, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Moderate below	Moderate systematic	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Moderate below	Intensive below	DBH, vol, vol_bottom, vol_top, rel_vol_bottom, h_vol50, slend, ff50, taper, taper_bottom, taper_top
Moderate below	Intensive above	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, ff50, p10,…,p90
Moderate below	Intensive systematic	DBH, H, vol, vol_bottom, vol_top, rel_vol_bottom, h_vol50, ff, ff50, taper_bottom, rel_taper_bottom, rel_taper_top, p10,…,p90
Moderate below	No treatment	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, taper_bottom, taper_top, ff50, p10,…,p90
Moderate above	Moderate systematic	H, p10, …, p90
Moderate above	Intensive below	DBH, H, vol, vol_bottom, vol_top, rel_vol, rel_vol_bottom, rel_vol_top, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Moderate above	Intensive above	DBH, H, vol_bottom, slend, ff50, taper, taper_bottom, taper_top, p10,…, p90
Moderate above	Intensive systematic	DBH, H, vol, vol_bottom, h_vol50, slend, ff, ff50, taper, taper_top, rel_taper_bottom, p10,…,p90
Moderate above	No treatment	vol_bottom, vol_top, h_vol50, taper_top
Moderate systematic	Intensive below	DBH, H, vol, vol_bottom, vol_top, rel_vol, rel_vol_bottom, rel_vol_top, h_vol50, slend, ff, ff50, taper, taper_bottom, taper_top, p10,…,p90
Moderate systematic	Intensive above	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Moderate systematic	Intensive systematic	DBH, vol, vol_bottom, vol_top, h_vol50, slend, ff, ff50, taper_bottom, taper_top, rel_taper_bottom
Moderate systematic	No treatment	H, p10, …, p90
Intensive below	Intensive above	DBH, H, vol, vol_bottom, vol_top, rel_vol_bottom, h_vol50, slend, taper, taper_bottom, taper_top, p10,…,p90
Intensive below	Intensive systematic	DBH, H, vol, vol_bottom, vol_top, rel_vol, rel_vol_bottom, rel_vol_top, h_vol50, slend, ff, ff50, taper, taper_bottom, taper_top, rel_taper_bottom, rel_taper_top, p10,…,p90
Intensive below	No treatment	DBH, H, vol, vol_bottom, vol_top, rel_bol_bottom, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Intensive above	Intensive systematic	ff, taper, rel_taper_bottom
Intensive above	No treatment	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, ff50, taper, taper_bottom, taper_top, p10,…,p90
Intensive systematic	No treatment	DBH, H, vol, vol_bottom, vol_top, h_vol50, slend, ff, ff50, taper_top, rel_taper_bottom, p10,…p90

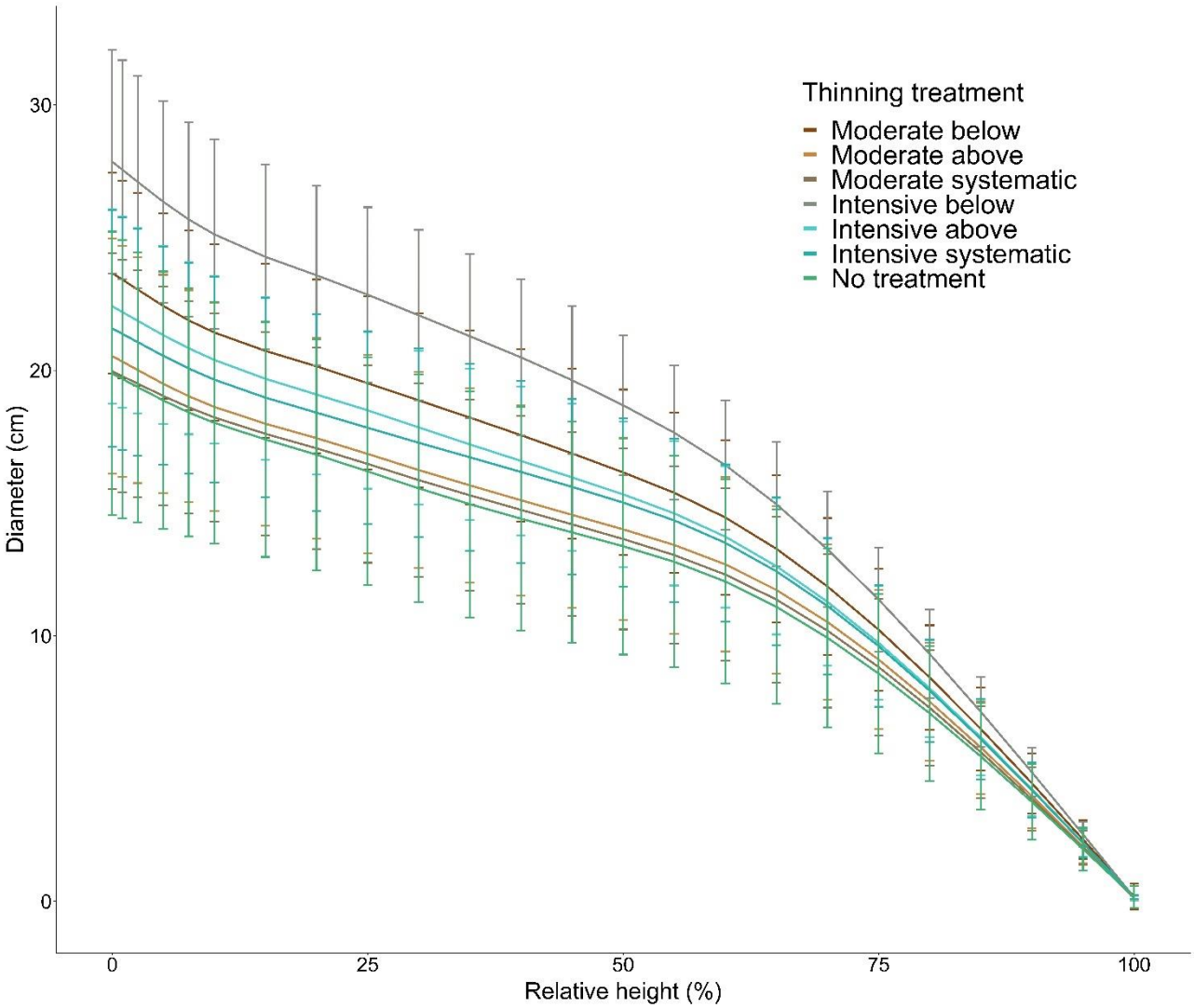

Figure 5. Mean taper curves with standard deviation (error bars) of each thinning treatment for relative heights.

Relative volume and tapering attributes were assessed separately through basic statistics to examine the variation in post-thinning growth of different thinning treatments. The relative attributes do not consider tree size that is implicitly included in thinning type (i.e. tree size affects which trees are removed). There were no clear differences between thinning treatments in relative volumes (i.e. relative volume, relative volume below and above 50% of tree height) or taperings (Figure 3) and no statistically significant difference was found (Table 4). More intensive thinnings (i.e. below, above, and systematic) mainly resulted in smaller standard deviation compared to the relative volume and tapering attributes of their corresponding moderate counterparts (Table 5). Only between moderate and intensive thinning from above the standard deviation of relative tapering above 50% of tree height was very similar, namely 0.006 and 0.007, respectively. When thinning type was compared, thinning from below produced smaller standard deviation than thinning from above and systematic thinning. Intensive thinning from below produced the smallest standard deviation in all of the relative

attributes characterizing volume and tapering whereas it was the largest in control plots (i.e. No treatment). This indicates that more intensive thinning and thinning from below generated smaller variation in relative stem size and tapering.

Table 5. Minimum, mean, maximum and standard deviation (std) of relative stem attributes namely relative volume (rel_vol), relative volume below 50% of tree height (rel_vol_bottom), relative volume above 50% of tree height (rel_vol_top), relative tapering below 50% of tree height (rel_taper_bottom), and relative tapering above 50% of tree height (rel_taper_top) between thinning treatments. Please refer to Table 3 for the descriptions of the attributes.

		Moderate below	Moderate above	Moderate systematic	Intensive below	Intensive above	Intensive systematic	No treatment
rel_vol	min	0.098	0.123	0.060	0.185	0.088	0.156	0.016
	mean	0.296	0.306	0.302	0.276	0.298	0.308	0.302
	max	0.661	0.748	1.345	0.373	0.728	0.571	1.154
	std	0.070	0.075	0.082	0.037	0.067	0.054	0.115
rel_vol_bottom	min	0.595	0.574	0.163	0.730	0.575	0.638	0.332
	mean	0.773	0.766	0.761	0.785	0.771	0.763	0.761
	max	0.912	0.892	0.933	0.844	0.922	0.864	0.948
	std	0.040	0.042	0.070	0.023	0.040	0.033	0.078
rel_vol_top	min	0.089	0.109	0.029	0.156	0.081	0.135	0.016
	mean	0.226	0.231	0.226	0.216	0.227	0.234	0.224
	max	0.393	0.429	0.564	0.272	0.418	0.364	0.538
	std	0.040	0.043	0.045	0.023	0.038	0.030	0.062
rel_taper_bottom	min	-0.237	-0.017	0.046	0.183	0.033	0.110	-0.453
	mean	0.316	0.318	0.317	0.326	0.314	0.301	0.324
	max	0.530	0.564	0.671	0.474	0.593	0.539	0.794
	std	0.084	0.077	0.076	0.049	0.074	0.054	0.113
rel_taper_top	min	0.567	0.954	0.907	0.974	0.944	0.961	0.335
	mean	0.986	0.987	0.986	0.989	0.986	0.986	0.984
	max	0.999	0.999	0.999	0.999	0.999	0.999	1.000
	std	0.028	0.006	0.009	0.005	0.007	0.007	0.035

Table 6. Variances obtained from linear mixed-effects models at tree, plot, and treatment level. Std = standard deviation.

Attribute (unit)	Tree $(\widehat{\mathbf{std}})^2$	Plot $(\widehat{\mathbf{std}})^2$	Treatment $(\widehat{\mathbf{std}})^2$	Residual $(\widehat{\mathbf{std}})^2$
Diameter at breast height (cm)	0.002	2.093	2.337	3.797
Tree height (m)	0.000	1.637	0.002	1.883
Stem volume (dm^3)	18.401	104.485	83.649	146.317
Volume bottom (dm^3)	0.024	81.838	69.110	112.760
Volume top (dm^3)	11.370	22.630	15.485	39.553
Ratio between volume above and below 50% of tree height	0.000	0.010	0.000	0.081
Ratio between volume below 50% of tree height and total volume	0.000	0.006	0.006	0.056
Ratio between volume above 50% of tree height and total volume	0.000	0.008	0.000	0.044
Height at which 50% of total stem volume accumulated (m)	0.001	2.196	1.532	3.249
Form quotient	0.003	0.003	0.000	0.025
Slenderness	0.000	0.048	0.103	0.199
Form factor at breast height	0.126	0.013	0.001	0.097
Form factor up to 50% of tree height	0.001	0.151	0.167	0.335
Tapering (cm)	0.000	0.147	0.203	0.872
Tapering below 50% of tree height (cm)	0.000	0.837	0.909	2.147
Tapering above 50% of tree height (cm)	0.002	1.541	1.587	3.163
Relative tapering below 50% of tree height	0.000	0.019	0.000	0.080
Relative tapering above 50% of tree height	0.018	0.001	0.000	0.007
Height at which 10% of stem volume accumulated (m)	0.000	0.164	0.000	0.190
Height at which 20% of stem volume accumulated (m)	0.000	0.328	0.000	0.377
Height at which 30% of stem volume accumulated (m)	0.000	0.492	0.000	0.565
Height at which 40% of stem volume accumulated (m)	0.000	0.656	0.000	0.754
Height at which 50% of stem volume accumulated (m)	0.000	0.819	0.001	0.942
Height at which 60% of stem volume accumulated (m)	0.000	0.983	0.001	1.130
Height at which 70% of stem volume accumulated (m)	0.000	1.147	0.001	1.319
Height at which 80% of stem volume accumulated (m)	0.000	1.310	0.001	1.507
Height at which 90% of stem volume accumulated (m)	0.000	1.474	0.001	1.695

Treatment- and plot-level variances were notably larger than tree-level variance for all other attributes except for volume above 50% of tree height, form quotient, form factor at breast height, and volume percentiles (Table 6), indicating that variation between trees can be explained by treatment and plot effects for most of the stem attributes. Plot-level variance, however, was larger than treatment-level variance for most of the attributes, treatment effects was only greater for DBH, slenderness, form factor up to 50% of tree height, tapering, as well as tapering below and above 50% of tree height. This indicates differences between plots within the same thinning treatment.

Growth in DBH, height, and stem volume was calculated based on the first (before thinning treatment) and the last field measurements (Table 7). Additionally, difference in slenderness between first and last measurements was assessed. The largest growth in DBH and stem volume was found in intensive thinning from below, 7.4 cm and 314.6 dm^3, respectively, whereas in plots without thinning treatment had the largest height growth (i.e. 5.8 m). For moderate thinnings, difference in slenderness ratio was <1 whereas for intensive thinnings it was >1 indicating smaller difference in height-diameter ratio in denser plots. Height growth and difference in slenderness were mainly not significantly different (p-value > 0.05) between thinning treatments based on paired, two-sided t-test. In DBH growth, on the other hand, significant difference (p-value <0.05) was found between all other treatment except between moderate thinning from above and systematic. Similarly, volume growth between thinning treatments was mainly significantly different (p-value < 0.05), only between no treatment and both moderate above and systematic no statistically significant difference (p-value > 0.05) was observed.

Table 7. Mean growth with standard deviation (Std) in diameter at breast height (ΔDBH), height (ΔH), and stem volume (ΔVol) as well as mean difference with standard deviation in slenderness (Δslend) ratio between first and last field measurements.

		Moderate below	Moderate above	Moderate systematic	Intensive below	Intensive above	Intensive systematic	No treatment
ΔDBH (cm)	Mean	4.55	3.85 a	3.76 a	7.04	5.72	5.04	2.91
	Std	1.34	1.54	1.56	1.75	1.80	1.37	1.33
ΔH (m)	Mean	5.17 a	4.99 b	4.69 c d	4.78 b c e	4.26	4.73 d e	5.84 a b
	Std	0.69	0.78	0.97	1.11	1.10	1.11	9.71
ΔVol (dm^3)	Mean	203.50	153.44	139.94 a	314.55	187.90	230.78	132.13 a
	Std	82.70	78.20	71.92	114.77	74.04	86.77	78.36
Δslend (ratio)	Mean	0.95 a b	0.94 a c	0.95 b c	1.06 d	1.07 d	1.01	0.87
	Std	0.05	0.05	0.05	0.07	0.08	0.08	0.06

Note: The treatments marked with the same letter are not statistically significantly different (p-value > 0.05) between each other based on paired, two-sided t-test.

Discussion

The objective of this work was to examine how thinning intensity but also thinning type (i.e. from below, from above, and systematic) influenced post-thinning stem growth of Scots pine trees. The results showed that relative volume below 50% of tree height differed significantly between moderate and intensive thinning from below suggesting more volume and therefore woody biomass allocation in the bottom part of a stem, However, the relative tapering did not differ significantly between different thinning intensities (research question 1). Similarly, thinning type affected the relative volume below 50% of tree height and there was a significant difference between thinning from below and above implying more volume and woody biomass allocation in the bottom part of a stem. However, there was no significant difference in relative tapering between thinning types (research question 2). When assessing similarity of relative attributes, intensive thinning and especially intensive thinning from below led to the smallest variation in those attributes (research question 3). Thus, our hypothesis about thinning intensity and type affecting size and form of Scots pine trees can be accepted, although no clear difference in relative tapering was observed. Difference in relative stem volume, however, affects both stem size and form.

All the three study sites were located in the same vegetation zone and site type suggesting that the differences in stem attributes and through them growth allocation of stem was mainly due to thinning treatments and the following growth effects. The plot-level effects, however, were similar to or even larger than treatment-level effects based on the analyzed variances. These findings imply that despite to the comparable site type and vegetation zone there is variation between the plots within the same thinning treatment. This is most probably due to inconsistency in the earlier development of the stands (e.g. regeneration, tending of seedlings and saplings as well as the effects of first thinning, possible damage). Additionally, there were small differences in the elevation and thermal sum between study sites that can affect the growing conditions also after the thinning treatments.

Although several studies in Finland have concentrated on the effects of post-thinning growth, they have mainly examined what kind of impact stand density has on the development of DBH, height, volume, and tapering. However, the number of observations from each tree has been limited together with the number of sample trees (Peltola et al. 2002, Mäkinen & Isomäki 2004c, Mäkinen et al. 2005). Vuokila (1977) investigated how thinning from below and above affected stand growth. In their study they only concentrated on mean basal area per ha, mean volume per ha, and mean yield of timber assortments without investigating the effects on single trees. This study enabled quantitative analysis of multiple stem attributes derived from a taper curve based on dense diameter measurements from more than 2100 Scots pines. Previous studies investigating the effects of thinning on tree growth and structural development (Peltola et al. 2002, Mäkinen & Isomäki 2004c, Mäkinen et al. 2005) have only included fraction of trees compared to this study. Additionally, taper curves derived from TLS-based 3D point clouds enabled generating new attributes characterizing stem form and size that have formerly only been available through destructive measurements and thus provided novel and quantitative information about stem size and form (in both absolute and relative scale) for forest management and ecology. Furthermore, this study concentrated on relative attributes that

ignore the effects of absolute stem size (in contrast to absolute attributes in earlier studies) in which there was clear difference between thinning intensity as well as thinning type, especially with thinning from below. As stem size is inherently included in thinning type as in thinning from below small trees in size (height and DBH) are removed and the remaining trees are already bigger in size compared to thinning from above. Therefore, relative attributes enhance the assessment of the effects of thinning treatments.

Stem attributes have been generated from TLS-based point clouds to study the effects of thinning in Central Europe and Jacobs et al. (2019) reported smaller form factor with less competition whereas tapering in butt logs decreased when competition increase for Norway spruce in southern Germany. Our results did not reveal notable difference in form factor between moderate and intensive thinning whereas tapering below 50% of tree height was smaller for moderate thinnings than for intensive thinnings corroborating results by Jacobs et al. (2019). Georgi et al. (2018) found significant difference in tapering generated from TLS data between unmanaged and intensively managed beech stands. Most of their attributes were related to crown dimensions or height of branches similar to the study by Juchheim et al. (2017) who concentrated on crown expansion in both horizontal and vertical directions. However, there is still limited understanding of the holistic effects of thinning intensity and type on tree architecture in boreal forest conditions.

Intensive thinning expands the growing space of and reduces the competition between remaining trees allowing them to allocate the photosynthesis products not just sustaining respiration and existing parts but also for wood formation and growth. Correspondingly, thinning from below enhances the growing conditions of dominant and co-dominant trees as small and suppressed trees are removed and enables trees that are already in advanced position to boost their stem growth.

Conclusions

Taper curve characterizes stem dimensions, tapering, form, and especially volume allocation of an individual tree. Therefore, TLS point clouds were utilized in reconstructing stems and deriving taper curves for Scots pine trees growing in similar site conditions (e.g., same fertility based on vegetation) but with varying management history enabling us to investigate the effects of forest management (i.e. thinning) on the stem dimensions and the post-thinning growth effect. Our results showed that more intensive thinning than usually applied in Finland and the following stem growth effect led to larger bottom part of a stem (i.e. relative volume) of Scots pine trees. Similarly, more intensive thinning and the following growth effect caused larger Scots pine trees in size (i.e., DBH and volume) compared to moderate thinning. This indicates that sparse Scots pine stands (i.e., low number of stems) allocate growth especially in the bottom part of a stem. When volume allocation was compared between thinning type (i.e., from below, from above, or systematic), thinning from below resulted in more volume allocation in bottom part of a stem (i.e. relative volume).

Thus, it can be concluded that different thinning treatments and the resultant growth caused distinct stem size and form and more biomass was accumulated in individual stem of Scots

pines when intensive thinning or thinning from below is applied. Those thinning treatments lead to more growing space for the remaining trees and they can allocate their growth in stem instead of accessing light through height growth. TLS automatically provided detailed information for taper curves from more than 2100 Scots pines enabling creation of novel attributes characterizing post-thinning stem growth. The hypothesis that thinning intensity and type affect size and form of Scots pine trees was accepted as it was shown that intensive thinning and thinning from below produced more stem volume allocation in bottom part of stems as well as more similar stem size and form compared to moderate thinning or thinning from above.

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