

How do different thinning methods influence spatial tree diversity in mixed forest stands of planted Norway spruce (*Picea abies* L.) and naturally regenerated birch (*Betula* spp.) in southern Sweden?

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Abstract

Forest biomass has become a viable alternative energy source for replacing fossil fuels, particularly after the European Union acknowledged its sustainability status. To reach zero net greenhouse gas emissions by 2045 in Sweden, new efficient methods of biomass extraction, such as geometrical biomass thinnings, are being explored and tested. These machine-based methods involve the extraction of above-ground biomass in narrow, 1–2 m-wide strips between extraction racks. While evidence-based optimization of biomass extraction mostly focuses on time- and cost-efficiency and on stand growth, criteria such as tree diversity are often overlooked. However, with ongoing climate change, tree diversity is crucial to strengthening the resilience and productivity of future forests, which also enhance the provision of ecosystem services and overall biological diversity. Therefore, we studied the effects of different biomass thinning strategies on spatial tree diversity in southern Sweden using nearest-neighbour summary statistics. We found scientific evidence that different geometrical designs of biomass thinning. Hence, in mixed conifer-broadleaved forests, biomass thinning in 1 or 2 m-wide strips is recommended for maintaining spatial tree diversity.

Key words: biomass, geometrical thinning, boom-corridor, species mingling, spatial tree diversity

1. Introduction

Forest biomass is an alternative energy source that is in high demand in Sweden (Ericsson et al. 2004; Swedish Energy Agency (SEA) 2021). However, the forest industry often experiences that conventional biomass thinning (BT_{conv}) from below, where the whole above-ground tree biomass is extracted is too expensive and time-consuming in stem- and biomassrich young forests (Bergström et al. 2010; Bergström et al. 2022). The reason for this is that traditionally the most common first commercial thinning (CT) method in Fennoscandia is selective thinning from below, which aims to optimize tree growth by removing dominated, lower quality trees and leaving desirable (target) trees with more growth and quality potential in the forest (Helms 1998; Nilsson et al. 2010). Currently, researchers in Fennoscandia are exploring geometrical biomass thinning (BT) methods as an alternative to conventional selective thinnings (first CT and BT_{conv}). Geometrical BT is performed with a multi-tree accumulating felling/harvester head, cutting all trees into narrow (1-2 m wide and 10 m long) strips between extraction racks,

where the harvester crane creates a linear strip that is cut away from the extraction racks in pre-determined directions (Fig. 1; Bergström et al. 2007; Bergström 2009). In theory, this method allows for a more varied forest structure than conventional selective thinnings because none of the tree species receives preferential treatment in the thinning operation, unlike the situation in conventional selective thinnings, where the species of planted trees are preferentially promoted on the site.

Traditionally, fast-growing broadleaved species such as silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrh.) are removed down to the level permitted by the forest certification scheme in pre-commercial (PCT) and CT thinnings in Swedish rotation forestry. Optimising the volume production of residual Norway spruce (*Picea abies* L.) is the main reason for this behaviour (Tham 1988; Johansson 2001; Fahlvik 2005; Lundqvist et al. 2014). Another, less important reason traditionally put forward in favour of removing broadleaves is whipping damage, which can potentially be caused by slender birch trees growing in close proximity to **Fig. 1.** Schematic representation of treatments. (A) Conventional biomass thinning (BT_{conv}) from below. (B) Strict biomass thinning (BT) in strips of 1 or 2 m wide. (C) Selective biomass thinning (BT_{sel}) in 1 m-wide strips where the harvester operator has the liberty to adjust the direction and angle of the strip.



Norway spruce. This damage occasionally arises when wind whips birch stems and branches against spruce branches and stems, causing wounds and scars that may affect the growth and quality of spruce trees (Fahlvik et al. 2011). However, this motivation for removing broadleaves in conifer forests has recently been challenged (Linden 2003; Pukkala et al. 2016; Nevalainen 2017).

With ongoing climate change and changing forest policies, diversity has become crucial to strengthening the resilience and productivity of future forests. At the same time, tree diversity also enhances the provision of ecosystem goods and services (Fries et al. 1997; Carey 2003; Pommerening 2023). Therefore, increasingly, thinning methods are improved and new ones are developed that promote species diversity and size inequality as well as mimic natural processes and structures.

Previous studies have revealed that more broadleaved trees remain in the forest stand after BT in strips (Bergström 2009; Sängstuvall et al. 2012; Jundén et al. 2013; Bergström and Di Fulvio 2014; Ahnlund Ulvcrona et al. 2017). In addition, the introduction of BT in forest management could potentially decrease the overall number of thinnings conducted over the forest rotation, if PCT and first CT are replaced by BT. A reduction in the number of thinnings has the potential to decrease not only overall management costs but also harvest-related greenhouse gas emissions (de la Fuente et al. 2022). Reducing the number of thinning operations may also decrease the risk of root rot in the remaining stand, which is highly correlated with the number of thinnings (Vollbrecht 1994; Blomquist et al. 2023).

So far, studies on geometrical BT involving the comparison with conventional thinning methods (CT or BT_{conv}) have mostly focused on growth (Bucht and Elfving 1977; Elfving 1985; Pettersson 1986; Mäkinen et al. 2006), species composition (Ahnlund Ulvcrona et al. 2017), and environmental impact (de la Fuente et al. 2022). To our knowledge, no study has so far analyzed the effect different biomass thinning strategies, including different variants of BT in strips, have on spatial forest structure. Therefore, we used data from experimental sites in southern Sweden to analyze the spatial diversity of trees (i.e., location diversity of trees, spatial tree species diversity, and spatial diversity of tree sizes) following different thinning strategies. We compared untinned (UT) and conventional biomass thinning (BT_{conv}) with systematic early release from density-induced competition using biomass thinning (BT) in strips and the effect of this method on tree location diversity, spatial species diversity, and spatial size diversity. We applied nearest-neighbour summary statistics (NNSS), which have been developed in previous studies by Clark and Evans (1954), Pielou (1977), Gadow (1993), and Pommerening and Grabarnik (2019). Such spatial diversity indices accurately quantify the spatial arrangement and heterogeneity of tree patterns, which are important for the aforementioned ecological traits, and even detect sub-

Site	Location	Year of planting	Soil type	Soil moisture	Altitude	Site index*
Erikstad	57°1″39″N 13°55″56″E	1994	Morain	Mesic	175	37
Stretelid	57°0'8″N 14°2'36″E	1996	Morain	Mesic	160	34
Torared	56°39″56″N 13°6″33″E	1987	Morain	Mesic	118	32

 Table 1. Location, site, and stand characteristics of the experimental sites used in this study.

*Mean height of dominant Norway spruce trees at the age of 100 years.

tle changes in forest structure. We hypothesized (i) that all sites, irrespective of treatment, were likely to exhibit regular spatial tree dispersion at this relatively young stage of stand development (~30 years) as a consequence of the legacy of the planting methods recommended by the Swedish Forest Agency¹ (Hallsby 2013; Skogsstyrelsen 2019), which were implemented when the stands were replanted. We also hypothesized (ii) that the UT and geometrical BT strategies resulted in high species mingling and low species segregation as compared to BT_{conv} , since the aim of BT_{conv} was to leave as many Norway spruce trees on site as possible, and (iii) the BT_{conv} strategy resulted in smaller size inequalities as compared to the UT and BT in strips, since the majority of broadleaved trees was removed.

2. Material and methods

2.1. Site characteristics

A long-term experiment with five treatments was established in southern Sweden on three sites with fertile moraine soils and homogeneous site conditions (Table 1). On all selected sites, Norway spruce plantations were established with a planting density of 2000 seedlings ha⁻¹. However, soon after, a high number of naturally regenerated broadleaves had colonized the plantations, and, as a consequence, their numbers added to the total tree density, ranging from 5800 to 11,800 trees ha⁻¹ before thinnings commenced. Birch was the dominant naturally regenerated broadleaved species.

2.2. Study design

The experimental plots were rectangular with side lengths of 30 m \times 40 m surrounded by a 5 m-wide buffer zone. For all treatments but the unthinned (UT) control, 4 mwide extraction racks were established with a 20 m distance between extraction racks. Conventional biomass thinning (BT_{conv}) and biomass thinning (BT) in strips (in other publications also known as boom-corridor thinning, see e.g., Bergström 2009; Bergström et al. 2010; Ahnlund Ulvcrona et al. 2017; Nuutinen et al. 2021) were then applied between the extraction racks (Fig. 1). The specifications of these treatments were as follows:

UT: unthinned (control) plot without tree removal.

- BT_{conv}: Conventional selective above-ground biomass thinning from below of individual trees between extraction racks. The main goal of the treatment is to leave as many planted Norway spruce trees on site as possible.
- BT_{1m} : Systematic thinning of all trees in 1 m-wide and 10 mlong strips starting at the extraction rack centre and running perpendicular to the extraction rack. There are two strips on either side of the extraction rack, and the distance between neighbouring strips is 3 m. None of the tree species has preferential treatment in the thinning operation.
- BT_{2m} : Systematic thinning of all trees in 2 m-wide and 10 mlong strips running from the extraction rack centre in a perpendicular direction to the extraction rack. There are two strips on either side of the extraction rack; the distance between neighbouring strips is 5 m. None of the tree species has preferential treatment in the thinning operation.
- BT_{sel} : Systematic and partly selective thinning in 1 m-wide and 10 m-long strips with flexible placement. The operator's task is to harvest one strip in each direction from the extraction rack roughly at a 90- to 60-degree angle, with the instruction to leave as many Norway spruce trees as possible on site and to achieve full crane depth. BT_{sel} is similar to the V-shape (chevron) thinning in North Americas, Britain, and Central Europe (Smith et al. 1997).

All five treatments were randomly assigned to the experimental plots and replicated three times at all three sites. Strip locations and directions were marked in the field beforehand. For selective BT, the locations for strips were marked beforehand, but the direction of the strip was decided by the harvester operator with the aim of leaving as many Norway spruce trees in the stand as possible. In all treatments, except in the unthinned (UT) control, complete trees (including branches and foliage but without roots) were removed from the experimental plot through the extraction racks (Fig. 1). A summary of stand structure characteristics is presented in Table 2.

2.3. Data collection and analysis

Five to six years after the treatments, within each plot, all trees with a stem diameter larger than 5 cm were crosscalipered at 1.3 m above ground, and the values were averaged to arrive at a consolidated measurement of diameter at breast height (dbh). In this study, only post-treatment data were available. The individual tree locations in the experimental plots were measured using the PosTex system (version 2.3) developed by Haglöf AB (Sweden). The PosTex system has

¹These guidelines include linear soil scarification, initial spacing ranging from 1.5 to 3 m between rows and from 1 to 2 m within rows, resulting in up to the 2500 seedlings per hectare depending on tree species.

Site	Treatment	Stem number (N ha ⁻¹)	Mean dbh (cm)	Mean height (m)	Top height (m)	Basal area (m² ha ⁻¹)	Volume $(m^3 ha^{-1})$
Erikstad	UT	4562	9.0	10.3	14.7	30.5	179.5
	СТ	745	14.9	12.3	16.7	13.2	82.8
	BT _{1m}	2163	10.6	12.3	20.8	19.4	122.0
	BT _{2m}	2620	9.7	10.1	13.8	19.3	108.8
	BT _{sel.}	2820	10.5	13.0	22.4	24.7	153.3
Stretelid	UT	4069	8.4	9.1	12.2	20.4	100.5
	СТ	1890	10.0	8.6	11.5	13.1	62.5
	BT _{1m}	1797	9.5	9.3	18.3	12.0	58.4
	BT _{2m}	1872	9.0	9.0	15.2	11.0	52.4
	BT _{sel.}	2440	8.9	9.0	19.3	13.7	14.2
Torared	UT	3679	9.8	11.5	22.8	29.9	193.3
	СТ	500	15.1	14.9	23.4	8.8	54.9
	BT _{1m}	2226	9.5	10.6	21.9	16.3	88.7
	BT_{2m}	2626	9.4	10.0	22.7	19.4	108.2
	BT _{sel.}	2322	10.3	12.2	21.7	20.9	135.0

Table 2. Summary of stand structure characteristics involving all trees with a stem diameter larger than5 cm from three sites in southern Sweden.

Note: The treatments referred to in this table are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m-wide strips (BT_{1m}), biomass thinning in 2 m-wide strips (BT_{2m}), and 1 m-wide selective biomass thinning (BT_{sel}) in strips.

an accuracy of about 30 cm for distances up to 10 m (Lämås 2010).

In this study, we analyzed the spatial diversity of trees, including (i) location diversity of trees quantified by the Clark and Evans spatial aggregation index (R) (Clark and Evans 1954), (ii) spatial tree species diversity expressed as species mingling index (M) (Gadow 1993; Aguirre et al. 2003) and species segregation index (Ψ) (Pommerening and Uria-Diez 2017), and (iii) spatial tree size inequality quantified by the size differentiation index (T) (Gadow 1993) and the size segregation index (Υ) (Pommerening and Uria-Diez 2017). Data for silver birch and downy birch were lumped together in the analysis as the collective species "birch". The results of nonspatial characteristics applied to the data of this study have been reported in previous article, i.e., Ahnlund Ulvcrona et al. (2017) and in related studies by Bergström (2009), Sängstuvall et al. (2012), Jundén et al. (2013), and Bergström and Di Fulvio (2014).

2.3.1. Tree location diversity

To determine the spatial pattern of tree locations, we used the aggregation index, R, by Clark and Evans (1954), which compares the mean observed distances, \bar{r} , between trees and their first nearest neighbour with the expected distance, Er, under the condition of complete spatial randomness (CSR) of tree locations. The aggregation index is estimated according to eq. 1:

(1)
$$R = \frac{\tilde{r}}{\mathrm{E}r}$$
 with $\mathrm{E}r = \frac{1}{2 \times \sqrt{\frac{N}{A}}}, R \in [0, 2.1491]$

In eq. 1, *N* and *A* are the absolute number of trees and the experimental plot area, respectively. Index values of R > 1 indicate a tendency towards a regular point pattern, i.e., the

mean observed distance between a tree and its first nearest neighbour is larger than the corresponding mean distance expected according to CSR. This tendency has often been interpreted as being the result of a process of inhibition between plants. R < 1 points to a trend towards clustering or inhomogeneity, i.e., the mean observed first-neighbour distance is smaller than the corresponding distance expected when trees are randomly dispersed. This pattern is interpreted as being the result of mutual attraction between trees. In the case that $R \approx 1$, this indicates that the two distance measures are very similar in size, i.e., the observed pattern of tree locations is close to CSR. A theoretical maximum R is 2.1491 (Pommerening and Grabarnik 2019). Consequently, low values of R indicate high tree location diversity. Spatial characteristics are always affected by edge effects, since spatial information beyond the plot boundaries is unknown. To mitigate this effect, we applied the nearest-neighbour (NN1) edge correction method (Pommerening and Stoyan 2006).

2.3.2. Spatial tree species diversity

To analyze multivariate spatial species patterns involving k nearest neighbours, we applied the species mingling index, M, devised by Gadow (1993) and Aguirre et al. (2003). This index is defined as the mean heterospecific fraction of trees among the k nearest neighbours of a given tree i (Pommerening and Grabarnik 2019); see eq. 2.

(2)
$$M_i = \frac{1}{k} \sum_{j=1}^k \mathbf{1} (m_i \neq m_j), \ M_i \in [0, 1]$$

Here, m_i denotes the species of reference or subject tree *i* and m_j the species of the nearest neighbour trees, j = 1, ..., k. Indicator function 1() returns the value of 1, if the condition inside the round brackets is fulfilled, i.e., $1(m_i \neq m_j) = 1$,

Table 3. Interpretation of size differentiation index for different intervals.

T _i interval	Qualitative descriptor	Interpretation
[0.0, 0.3)	Weak	Smaller trees has at least 70% of the neighbouring tree size
[0.3, 0.5)	Moderate	Smaller trees has 50%–70% of the neighbouring tree size
[0.5, 0.7)	Strong	Smaller trees has 30%–50% of the neighbouring tree size
[0.7, 1.0)	Very strong	Smaller trees has less than 30% of the neighbouring tree size

otherwise it is $\mathbf{1}(m_i \neq m_i) = 0$. Due to the discrete nature of outcomes for a given k, there are only k + 1 possible values that M_i can take, i.e., 0/k, 1/k, ..., k/k (Pommerening and Grabarnik 2019). For example, for k = 4, M_i can only take the five discrete mingling values 0, 0.25, 0.5, 0.75, or 1.0. These discrete mingling values indicate the intensity of interaction with heterospecific trees of a given reference tree *i*, based on the number of heterospecific trees surrounding it. We experimented with different k values and found that k = 4 was the best compromise for all our plots. In addition, this choice allows for a better comparison with previous publications. A mingling value of 0 means low interaction with heterospecific trees, while an M_i value of 1 means high interaction with heterospecific trees. The calculation of the mean mingling of an experimental plot includes compensation for edge bias. Here we again followed Pommerening and Stoyan (2006) and used the NN1 estimator for deriving population mingling \dot{M} .

Expected mingling, EM, describes mean mingling when the species are independently dispersed and show no correlation. EM is independent of the number of neighbour trees (Pommerening and Grabarnik 2019). Pommerening and Uria-Diez (2017) proposed combining \widehat{M} and EM in a single index, the species segregation index Ψ , see eq. 3.

(3)
$$\Psi = 1 - \frac{\widehat{M}}{EM} \Psi \in [-1, 1]$$

Consequently, if $\Psi \approx 0$, the tree species are independently dispersed. If $\Psi = 1$, the nearest neighbours and subject tree *i* always share the same species, which can be interpreted as an attraction of the same species. If all neighbours always tend to have a species different from that of the subject tree, Ψ is negative with a minimum of $\Psi \approx -1$. Such a result is thought to have been caused by the attraction of different species (Pommerening and Grabarnik 2019).

2.3.3. Spatial tree size diversity

According to Gadow (1993), size differentiation (eq. 4) is defined as the mean of the ratio of the sizes of the smaller and larger trees of the *k* nearest neighbours subtracted from one. Size differentiation produces continuous results between 0 and 1. T_i increases with increasing average size differences between neighbouring trees.

(4)
$$T_i = 1 - \frac{1}{k} \sum_{i=1}^k \frac{\min(m_i, m_j)}{\max(m_i, m_j)}, \ T_i \in [0, 1]$$

 $T_i = 0$ implies that neighbouring trees have equal size. m_i is the size of reference tree *i* and m_j denotes the size of neighbouring trees j = 1,..., k. In the context of this study, we selected tree stem diameter at breast height as a size variable. Interpretation guidelines are given in Table 3. Similar to the analysis of tree location patterns and species mingling, mean population size differentiation, \hat{T} , is estimated using the NN1 estimator, which compensates for spatial edge effects (Pommerening and Stoyan 2006).

Expected size differentiation, ET, gives mean size differentiation when the tree sizes are spatially independent, i.e., when there is no spatial correlation of tree sizes (Pommerening and Grabarnik 2019). In analogy to the species segregation index, Ψ , it is possible to define a size segregation index, Υ ; see eq. 5 (Pommerening and Uria-Diez 2017):

(5)
$$Y = 1 - \frac{\widehat{T}}{ET} Y \in [-1, 1]$$

If $\Upsilon = 0$, the tree sizes are independently dispersed and have no spatial correlation. If the sizes of the nearest neighbours and subject tree *i* tend to be always similar, $\Upsilon \approx 1$, indicating an aggregation of similar-sized trees. If all neighbours tend to always have sizes that are quite different from those of the subject tree, Υ is negative and approaches -1 in the extreme case. This describes a trend towards an aggregation of different sizes.

2.3.4. ANOVA and pairwise comparisons

We used a linear mixed model (lme4 package; Bates et al. 2015) and analysis of variance (basic anova stats package; R Core Team 2022) to study the effects of different treatments on the response variables. Response variables tested were the nearest-neighbour characteristics R, \widehat{M} , Ψ , \widehat{T} , and Υ . The site was used as a random effect and the treatment as an independent variable. The linear mixed model (eq. 6) applied in the analysis of variance was:

$$(6) X_{ij} = \mu + a_i + \beta_j + \varepsilon_{ij}$$

In eq. 6, X is the response variable $(R, \widehat{M}, \Psi, \widehat{T}, \text{ and } \Upsilon)$; *i*, *j* are indices of experimental site and treatment; $\mu_{0,...,3}$ are regression coefficients; and ε is a random error term. Treatment (a_i) and experimental site (β_j) are applied as fixed and random effects, respectively. To assess the differences between the treatments, we used a multiple pairwise comparison of means as provided by the Tukey's post-hoc test (emmean package; Lenth 2022). A significance level of $p \leq 0.05$ was chosen as the threshold for all analyses.

Table 4. Differences between the treatments in terms of aggregation (R, eq. 1), population mingling $(\widehat{M}, \text{ eq. 2})$, size differentiation $(\widehat{T}, \text{ eq. 4})$, species (Ψ , eq. 3), and size (Υ , eq. 5) segregation.

	Values of the tested response variables						
Treatments	R	\widehat{M}	Ψ	\widehat{T}	Υ		
UT	$1.11\pm0.02^{\text{a}}$	$0.45\pm0.04^{\text{a}}$	0.024 ± 0.02	0.280 ± 0.05^a	0.012 ± 0.01		
BT _{conv}	$1.17\pm0.08^{\text{a}}$	0.19 ± 0.05^{b}	-0.018 ± 0.06	0.214 ± 0.02^{b}	$\textbf{0.066} \pm \textbf{0.12}$		
BT _{1m}	0.93 ± 0.1^{b}	$0.46\pm0.02^{\text{a}}$	$\textbf{0.014} \pm \textbf{0.02}$	0.290 ± 0.03^{a}	$\textbf{0.003} \pm \textbf{0.002}$		
BT _{2m}	0.92 ± 0.05^{b}	$0.44\pm0.04^{\text{a}}$	$\textbf{0.057} \pm \textbf{0.1}$	0.294 ± 0.03^{a}	$\textbf{-0.002} \pm 0.01$		
BT _{sel}	1.06 ± 0.04^{ab}	$0.39\pm0.09^{\text{a}}$	$\textbf{0.026} \pm \textbf{0.02}$	0.285 ± 0.05^a	$\textbf{0.013} \pm \textbf{0.01}$		

Note: Values for each index are presented as mean (\pm SD) across study sites (n = 3) separately for different treatments. Different letters in the superscripts indicate significant differences between the treatments based on Tukey's multiple comparison test.

3. Results

3.1. Tree location diversity

The linear mixed model (eq. 6) showed that treatments (p = 0.001) had a significant impact on the spatial dispersion of trees. The results obtained for the Clark and Evans aggregation index, R (eq. 1) indicate that in the BT_{conv} (R = 1.17) plots, a markedly regular tree dispersion pattern could be identified. The significant differences in mean R values in terms of the different treatments UT, BT_{conv}, BT_{1m}, and BT_{2m} (p = 0.03 for UT vs. BT_{1m}, p = 0.04 for UT vs. BT_{2m}, p = 0.003 for BT_{conv} vs. BT_{1m}, p = 0.005 for BT_{conv} vs. BT_{2m}) suggest that the dispersion of trees in the BT_{1m} and BT_{2m} plots is closer to CSR compared to the BT_{conv} tretments (Table 4).

3.2. Spatial tree species diversity

The explanatory variable, treatment (p = 0.001), had a significant impact on mean population mingling, \hat{M} (eq. 2). All values of \widehat{M} were below 0.5, which is comparatively low but not unexpected in the context of Swedish forestry. \widehat{M} on average was lowest in BT_{conv} plots, i.e., 0.19. \widehat{M} on average was highest in BT_{1m} plots, i.e., 0.46 (Table 4). The empirical mingling distribution following UT and BT_{1m} treatments showed a bell shape with a maximum for $M_i = 0.5$. A nearly uniform mingling distribution was observed for treatments BT_{2m} and BT_{sel}. For BT_{conv}, the empirical mingling distribution resulted in the most interesting shape, i.e., in a (negative) exponential distribution with a maximum for $M_i = 0$ and a positive skew (Fig. 2). The significant differences in \widehat{M} in terms of the different treatments UT, BT_{conv} , BT_{1m} , BT_{2m} , and BT_{sel} (p = 0.001for UT vs. BT_{conv} , p = 0.001 for BT_{conv} vs. BT_{1m} , p = 0.01 for BT_{conv} vs. BT_{2m} , p = 0.01 for BT_{conv} vs. BT_{sel}) suggest that M of the residual trees after the biomass thinning in strict 1 and 2 m strips is closer to the UT plots, which had a nearly uniform mingling distribution (Table 4 and Fig. 2).

The different treatments (p = 0.664) tested in ANOVA (eq. 6) had no significant impact on species segregation, Ψ (eq. 3). Ψ was positive for the treatments UT, BT_{1m}, BT_{2m}, and BT_{sel}, i.e., there was an attraction of the same species. Ψ turned out to be negative for treatment BT_{conv}, i.e., there was an attraction of different species in the associated plots (Table 4). The strongest attraction of the same species occurred at the experimental plots related to the BT_{2m} treatment (0.057). The weakest attraction of the same species was observed

for BT_{conv} treatment (-0.018), where \widehat{M} was the lowest (Table 4).

3.3. Spatial tree size diversity

Similar to species mingling, size differentiation, \hat{T} (eq. 4) was significantly affected by the treatment (p = 0.002) tested in Anova. The significant differences in \hat{T} in terms of the different treatments UT, BT_{conv} , BT_{1m} , BT_{2m} , and BT_{sel} (p = 0.01 for UT vs. BT_{conv} , p = 0.003 for BT_{conv} vs. BT_{1m} , p = 0.002 for BT_{conv} vs. BT_{2m} , p = 0.005 for BT_{conv} vs. BT_{sel}) suggest that the tree size inequalities after the biomass thinning in strips are similar to UT plots with higher size diversity compared to the BT_{conv} . The mean \hat{T} was lowest in the experimental plots where BT_{conv} was carried out, i.e., 0.214. On average, the highest value of \hat{T} was observed in the treatments where BT_{1m} and BT_{2m} were carried out, i.e., 0.290 and 0.294, respectively (Table 4). Here, the number of residual trees was also higher than in the experimental plots related to BT_{conv} treatment (Table 2).

The treatment did not have a significant impact (p = 0.598) on size segregation, Υ (eq. 5). The values of Υ were positive (indicating a tendency towards an attraction of similar sizes) for all treatments but BT_{2m}. The strongest attraction ($\Upsilon = 0.066$) of similar tree sizes occurred in the experimental plots associated with the BT_{conv} treatment. The strongest attraction ($\Upsilon = -0.002$) of different tree sizes was observed in BT_{2m} experimental plots (Table 4).

4. Discussion

The main goal of this study was to compare the effect of different biomass thinning patterns on spatial tree diversity, i.e., location diversity of trees, spatial tree species diversity, and spatial tree size diversity, which are likely to play a role in the development of novel and sustainable forest management practices (Pommerening 2002; Li et al. 2014; Bettinger and Tang 2015; Pommerening and Grabarnik 2019; Gadow et al. 2021). Although studies on the spatial diversity of trees in the context of traditional forestry are relatively few, earlier studies suggest that tree diversity fosters forest resilience and productivity and diversifies the provision of ecosystem goods and services. For example, diversity can increase carbon and nitrogen storage (Gamfeldt et al. 2013; Mack et al. 2021; Chen et al. 2023) and reduce soil acidification (Brandtberg et al. 2000; Paquette and Messier 2011).

Fig. 2. Mean empirical mingling distribution across different treatments. 0 represents "low mingling" with four conspecific nearest neighbours and 1 represents "high mingling" with four heterospecific nearest neighbours. The treatments referred to in this figure are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m-wide strips (BT_{1m}), biomass thinning in 2 m-wide strips (BT_{2m}), and 1 m wide selective biomass thinning (BT_{sel}) in strips.



The results both supported and rejected some of our hypotheses. Due to the legacy of a planting regime that followed the guidelines issued by the Swedish Forest Agency (Hallsby 2013; Skogsstyrelsen 2019), we expected that all treatments were likely to exhibit regular spatial tree dispersion at this relatively young stage of stand development (\sim 30 years). We found that unthinned (UT) and conventional biomass thinning (BT_{conv}) plots had a trend towards regular dispersal of trees according to the spatial aggregation index (R, eq. 1). This could be the result of a forest regeneration legacy in UT, which included the dense initial planting of Norway spruce and the effects of treatment strategies in BT_{conv}, such as the extraction of naturally regenerated birch trees and leaving behind as many Norway spruce trees as possible. Consequently, selective biomass thinning (BTsel) maintained a certain level of spatial diversity that originated from the natural regeneration of birch trees, which was reflected in the value of R = 1.06 and thus indicated a closer tendency to the CSR. A slight tendency towards clustering, as indicated by the values of R = 0.93 and R = 0.92 in strict-biomass thinning (BT_{1m} and BT_{2m}) in strips, might have been caused by the thinning design and by the fact that BT in strips were applied at 3 and 5 m intervals, respectively (Table 4). However, R values

in treatments where geometrical BT was performed can still be considered to be sufficiently close to R = 1.

We were able to confirm our hypothesis regarding species mingling (\widehat{M} , eq. 2) and size differentiation (\widehat{T} , eq. 4). We predicted that UT and geometrical BT strategies (BT_{1m} , BT_{2m} , and BT_{sel}) would lead to higher species mingling and lesser size inequalities than BT_{conv}, as the latter favoured Norway spruce. We found a significantly higher value of M in experimental plots where geometrical BT strategies were performed compared to BT_{conv} . \hat{T} was also significantly higher in experimental plots where geometrical BT strategies were carried out compared to BT_{conv} (Table 4). While our results indicate that treatment designs influenced R, \widehat{M} , and \widehat{T} significantly (Table 4), strict BT treatments, especially BT_{1m} , showed more resemblance to the UT treatment in terms of the empirical mingling distribution (Fig. 2). However, we also expected that BT_{conv} would result in higher species (Ψ , eq. 3) and size (Υ , eq. 5) segregation than in treatments involving UT and geometrical BT, but we did not find any significant difference between the treatments.

In our study, the spatial diversity of trees may have slightly differed between the experimental plots before treatments (Mason et al. 2007). However, Swedish even-aged forest management aims for forest uniformity in planting and thinning in an attempt to optimize the growth of target trees (Nilsson et al. 2010; Hallsby 2013); therefore, large pre-existing differences are unlikely. Furthermore, to reduce this uncertainty, we used site replications (Table 1; Ahnlund Ulvcrona et al. 2017), and the site variable was assumed to have a random effect in the linear mixed model (eq. 6).

Our results provide a meaningful contribution to the discussion about how different thinning strategies affect the spatial diversity and species composition of mixed broadleaved-conifer forests in Sweden. They suggest making greater use of tree diversity characteristics that can provide more insightful information for achieving multi-purpose forest management than those characteristics that are used in traditional forest management. Traditional characteristics used in forestry, such as basal area, diameter distributions, volume, and height, do not provide sufficient information on diversity and ecosystem services (Felton et al. 2016).

Improving thinning and harvesting practices by monitoring forest structure can clearly enhance the resilience, productivity, and diversity of planted forests (Felton et al. 2016; Felton et al. 2022). Spatial forest structure, which can be quantified by spatial nearest neighbour summary characteristics as applied in this study, could therefore become a crucial criterion for evaluating the effect of thinning and harvesting methods (Pommerening 2002). Some studies have even taken a considerable step further by suggesting the use of structure-based forest management. In structure-based forest management, spatial nearest-neighbour characteristics, as applied in this study, play an even more active role. They are not only used for monitoring structural development but also for defining structural targets (Li et al. 2014; Bettinger and Tang 2015). As part of structure-based forest management, trees to be removed are identified in such a way that the spatial forest structure approaches the defined targets after the thinning. Nearest-neighbour indices are used here to advise which trees to leave behind and which to remove. Structure-based forest management, for example, gradually accelerated the development of a Pinus orientalis L. plantation towards a random dispersal pattern. The method also promoted the growth of target trees after 7 years significantly more compared to the control stands (Zhang et al. 2022). In this context, correlations between different measures of spatial forest structure and between indices representing the three aspects of diversity exist. They have been studied by Pommerening and Uria-Diez (2017) and Pommerening et al. (2020) who coined the term *mingling-size hypothesis* to describe this phenomenon. These correlations are intriguing and imply that forest managers who actively improve species mingling in thinnings usually also improve size inequality at the same time. Thus, these correlations simplify structure-based forest management.

5. Conclusions

Our findings showed that by conducting BT in 1- and 2-mwide strips, it is possible to improve the short-term dispersion of trees towards a more random pattern and to increase species mingling and size inequalities, even without an optimized approach where individual trees are selected for harvesting based on their spatial attributes or traditional characteristics (i.e., diameter, height, etc.). In forest stands with a high number of trees, strict 1- or 2-m-wide BT in strips can be beneficial not only for obtaining early profits (Bergström et al. 2010; Bergström et al. 2022) and for improving tree species diversity (Ahnlund Ulvcrona et al. 2017) but also for diversifying spatial stand structure.

One- and 2-m-wide BT applied in strips enhanced tree species mingling (\widehat{M}) , size inequalities (\widehat{T}) and reduced the likelihood of regular spatial patterns of trees (*R*). Therefore, different geometrical designs of biomass thinning, especially BT_{1m} and BT_{2m}, should be applied in mixed broadleaved conifer forests in Sweden to promote a higher diversity of trees.

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Data availability

Data collected and analyzed during this study are available from the corresponding author upon reasonable request.

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The authors have no competing financial or personal interests that may have affected this study.

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