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Biomass thinning in strips as an alternative to conventional selective thinning in biomass-dense forests

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Cover: Footage from the *Smallwood project*, featuring biomass thinning in 1- to 2-meter wide strips by Christian Höök.

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Abstract

In Northern Europe, novel thinning methods are being explored to find a balance between the biomass extraction required to meet the rising demand for renewable energy and the maintenance of ecological integrity. This thesis synthesises findings from three studies: two conducted in Southern Sweden, which focussed on the utility of biomass thinning (BT) techniques in strips, and one based on Swedish National Forest Inventory data, to pinpoint the biomass-dense forests (BDFs) where these BT methods could be implemented. The first study evaluated how BT impacts the growth and development of the forest remaining post-thinning. The findings revealed that BT, when implemented in 1- to 2-m wide strips, does not compromise the growth of the remaining target trees and may reduce the damage associated with commercial thinning (CT). The second study examined how BT influences spatial tree diversity, which is a critical factor for forest diversity and resilience. The results indicated that BT in strips fosters higher spatial tree diversity than traditional CT. The third study investigated the potential for biomass extraction from BDFs across Sweden. The research identified 1.4 million ha of Swedish forests that are currently classified as BDF, where some type of BT could be implemented. Furthermore, the findings suggest that sediment and moraine soils within mesic and mesic-moist moisture categories are the optimal targets for BDF management. The various findings presented in this thesis suggest that BT in strips can be an effective strategy for sustainable biomass production. However, the presented evidence also highlights the need for long-term research and consideration of regional variation before widespread implementation. This thesis contributes to the understanding of sustainable forestry practices that align with Sweden's renewable energy goals as well as the broader European Union sustainability framework.

Keywords: *Stand development, whole-tree harvest, small-tree harvesting, thinning, boom-corridor, species mingling, spatial tree diversity, biomass dense forest, biomass, bioenergy.*

Biomassagallring i korridorer som ett alternativ till traditionella selektiv gallring i biomassatäta skogar

Abstract

I Norra Europa utforskas nya gallringsmetoder för att hitta en balans mellan att öka biomassautvinning till förnybar energi samtidigt som den ekologiska balansen bibehålls. Denna avhandling är en synopsis av resultaten från tre studier: två genomfördes i södra Sverige, med fokus på biomassagallrings (BT) tekniker, och en studie baserad på data från den svenska Riksskogstaxeringen som fokuserar på att identifiera biomassatäta skogar (BDF) där geometrisk BT kan implementeras. Den första studien utvärderar effekten av geometrisk BT på tillväxten och utvecklingen av kvarvarande träd efter gallring. Den visar att BT implementerat i 1 till 2 meter breda korridorer, inte kompromissar tillväxten hos målträden och kan minska förekomsten av skador förknippade med kommersiell gallring (CT). Den andra studien undersöker effekten av geometrisk BT på rumslig träddiversitet, vilket är en kritisk faktor för skogens mångfald och resistens mot störningar. Resultaten indikerar att BT i korridorer främjar högre rumslig träddiversitet och resistens än CT. Den tredje studien undersöker potentialen för biomassautvinning från BDF i Sverige. Studien visar på att 1,4 miljoner hektar av svensk skog kan klassificeras som BDF, där olika typer av BT skulle kunna implementeras. Jordarterna morän och sediment i kombination med markfuktighetsklass frisk och frisk fuktig indikeras som mest optimal för BDF-förvaltning. Sammanfattningsvis indikerar avhandlingen att geometrisk BT kan vara en effektiv strategi för hållbar biomassaproduktion utan att kompromissa skogstillväxt eller mångfald. Avhandlingen belyser samtidigt behovet av långsiktig forskning och hänsyn till regionala variationer innan en bred implementering kan rekommenderas. Denna avhandling bidrar till förståelsen av hållbara skogsbruksmetoder som är i linje med Sveriges mål för förnybar energi inom ramen för Europeiska unionens hållbarhetsmål.

Nyckelord: *Beståndsutveckling, helträdsavverkning, avverkning av små träd, gallring, krankorridors gallring, art blandning, rumslig träd diversitet, biomasstäta skogar, biomassa, bioenergi.*

Dedication

To My Beloved Family:

Your unwavering love, endless support, and sacrifices have been the cornerstone of my academic journey. Your encouragement and belief in my abilities have been my guiding light through the highs and lows of my educational pursuit. This dissertation is dedicated to you, with deepest gratitude and love.

Photo: Christian Höök

Contents

List of publications

This thesis is based on the work contained in the following studies, referred to by Roman numerals in the text:

I. Becs, A., Kuglerová, L., Bergström, D., Holmström, E., Egnell, G., 2024. Development of crop trees after different thinning methods in mixed Norway spruce (*Picea abies* L.) and Birch (*Betula spp*.) forests in Southern Sweden. For. Ecol. Manag. 566, 122055. (Published)

II. Becs, A., Bergström, D., Egnell, G., Pommerening, A., 2024. 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? Can. J. For. Res. 54(4): 447-456. (Published)

III. Becs, A., Bergström, D., Egnell, G., Matisons, R., and Kuglerová, L. Factors that influence occurrence of biomass-dense forests in Sweden. (Submitted/manuscript)

Studies I-II are reproduced with the permission of the publishers.

The contribution of Artis Becs to the studies included in this thesis was as follows:

I. Planned the study together with the co-authors. Assisted the SLU Tönnersjöheden research station team during fieldwork period. Performed the analysis and wrote the manuscript with input from co-authors.

II. Planned the study together with the co-authors. Conducted the fieldwork in collaboration with the fieldwork assistant at the time, Joel Jensen. Performed the analysis and wrote the manuscript with input from co-authors.

III. Planned the study together with the co-authors. Prepared the data and performed the analysis. Wrote the manuscript with input from co-authors.

List of figures

Abbreviations

BAI	Mean annual basal area increment
BDF	Biomass-dense forests
BT	Biomass thinning
BT_{1m}	Biomass thinning in 1-metre wide strips between extraction racks
BT_{2m}	Biomass thinning in 2-metre wide strips between extraction racks
BT_{sel}	Selective biomass thinning in 1-metre wide strips between extraction racks
CSR	Complete spatial randomness
CT	Commercial thinning
dbh	Diameter at breast height
FSC	Forest Stewardship Council
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LM	Linear model
M	Species mingling index
NFI	National Forest Inventory
ODt	Oven-dry metric tonnes
PCT	Pre-commercial thinning
PEFC	Programme for the Endorsement of Forest Certification
R	Spatial aggregation index

RF	Random Forest model
RQ	Research questions
T	Size differentiation index
UT	Unthinned
VI	Mean annual volume increment
yr	Year

1. Introduction

To address climate change and maintain the global temperature rise at a maximum of 1.5 C°, the Intergovernmental Panel on Climate Change (IPCC) outlined multiple strategies in 2018. These strategies encompass sustainable energy adoption, land use optimisation, and socio-economic advancement. The IPCC report also highlights key pathways, more specifically “Pathway 2”, “Pathway 3”, and “Pathway 4”, which permit the limited use of fossil fuels. In these scenarios, energy production from biological feedstocks with carbon capture and storage was identified as a viable method to achieve the set climate objectives (IPCC, 2018).

Driven by the potential social and environmental impacts of climate change, as well as the obligations of the Paris Agreement, the European Union has established a binding target to achieve at least a 42.5% share of renewable energy in final energy consumption by 2030. These climate targets served as the basis for Renewable Energy Directive, which specifies forest biomass as an accepted renewable energy source (2023/2413/EU). This classification means that European countries with large forestry sectors can set more ambitious climate goals than other Member States. This applies to countries like Sweden, which has a well-developed forest sector, a well-developed network of hydroelectric power stations, and a history of farsighted decision-making to reduce dependence on oil following the “Oil crisis” of the 1970s (Ericsson et al., 2004). In the last 40 years, the share of oil in the Swedish energy market has decreased dramatically while the supply of energy from biofuels has tripled (SEA, 2021). Currently, the shares of biofuels and fossil fuels (oil, natural gas, and coal) in total energy production in Sweden are 26.5% and 26.3%, respectively (Fig. 1), with approximately 75% of the biofuels used in Sweden originating from the forest (SEA, 2021). These factors have helped Sweden set the ambitious national goal of becoming a net zero emitter of greenhouse gases (GHGs) by 2045 (Klimatlag 2017:720).

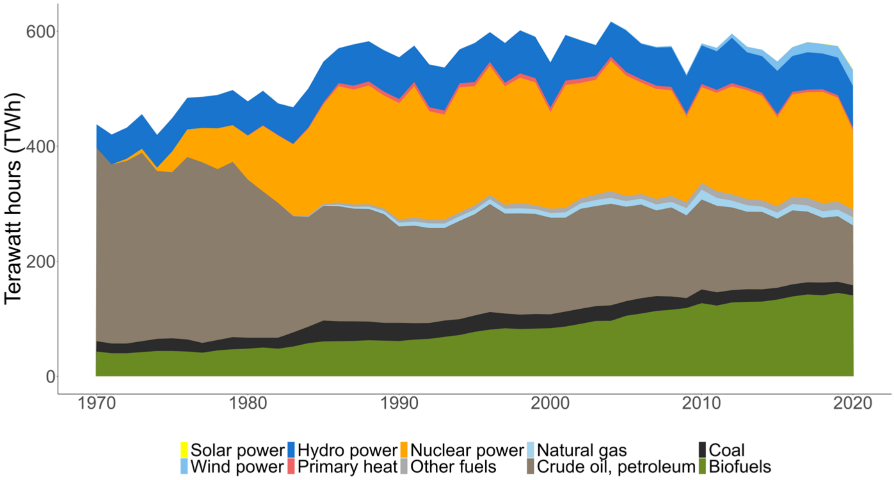

Figure 1. The shares of different feedstocks in the total energy supply of Sweden from 1970 to 2020. Source: SEA, 2021.

To effectively continue phasing out fossil fuels, it is crucial for both established and emerging energy providers to increase the share of bio-based feedstocks in energy production. This includes the sustainable utilisation of logging residues, e.g., tree tops, branches and stumps, which could yield an additional 20 terawatt-hours (TWh) of wood-based biofuels annually (Börjesson et al., 2017). However, the Swedish Energy Agency (2015) has noted that the current utilisation rate of forest biomass, which is extracted following traditional forest management practices, is nearing the sustainable limit. As a result, Swedish forest managers will need to implement some changes in their practices if Sweden is to achieve the ambitious climate goals which have been set forth. Thus, this thesis investigates the potential contribution of harvesting small-diameter trees for energy production while ensuring the continued availability of economically valuable forest products, such as sawn timber and pulpwood.

1.1 Forests in Sweden

Sweden has a wide range of climate and soil conditions due to a wide latitude range (55°N to 69°N). This variation in latitude significantly affects the mean volume annual increment, which is 4.9 cubic metres (m^3) per hectare (ha^{-1}), with regional variations ranging from 3.1 m^3 ha^{-1} in Northern Norrland, 5 m^3 ha^{-1} in Southern Norrland, 5.6 m^3 ha^{-1} in Svealand, to 6.7 m^3 ha^{-1} in the southernmost region, Götaland. However, more than half of the 23.5 million hectares (ha) of "productive forestland[1]" are located in the northern regions (Swedish NFI, 2023). Productive forestland in Sweden has a total growing stock of 3348 million m^3. The harvested volume of timber in 2022 amounted to 96.9 million m^3, which consisted of final felling (65.1 million m^3 from 0.25 million ha), commercial thinning (CT: 21 million m^3 from 0.29 million ha), and pre-commercial thinning (PCT: 1.4 million m^3 from 0.26 million ha; Swedish NFI, 2023).

The two dominant tree species in the managed forests of Sweden are Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.), which together account for 78.7% of growing stock (individual shares of 39.8% and 38.9%, respectively). After these two dominant species, the silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrh.) also have a noticeable share in the growing stock (a joint share of 13%; Swedish NFI, 2023). Norway spruce and Scots pine are mainly regenerated by planting "improved seedlings[2]" on scarified soils due to the importance for the forest industry. Therefore, around 418 million conifer seedlings were planted over 210 000 ha of Swedish forests in 2022 (SFA, 2023). Unlike conifer species, birch (*Betula spp.*) and other broadleaved trees, such as common aspen (*Populus tremula* L.), primarily regenerate through natural regeneration (Götmark et al., 2005; Hynynen et al., 2010; Karlsson et al., 2002; Latva-Karjanmaa et al., 2003; Lidman et al., 2023; Myking et al., 2011; Nilsson et al., 2002; Worrell, 1995). As a result, the regenerated forests in Sweden are rarely pure monocultures, with around 20% of the standing volume consisting of broadleaved trees (Swedish NFI, 2023).

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[1]Land primarily dedicated to forestry characterised by production of at least 1 m^3 solid under bark wood ha^{-1} yr^{-1}.

[2]Seedlings that have been selectively bred to exhibit desirable traits such as faster growth, increased resistance to diseases and pests, better wood quality, and improved adaptability to various environmental conditions.

1.2 Forest management in Sweden

At present, the most commonly used forest management system in Sweden is even-aged forestry. This approach involves a sequence of operations that begins with final felling, followed by mechanical soil scarification (with disc trenching being most popular) and forest re-planting, after which selective thinnings are carried out at specific time points (Fig. 2). Typically, both soil scarification and forest re-planting occur three years after final felling to minimise the length of the regeneration period. In Sweden, planting seedlings from plant nurseries onto scarified soil accounts for 84% of the regenerated area. Other regeneration methods, such as direct seeding and natural regeneration beneath seed or shelter trees, are employed on 10% and 4% of the regenerated area, respectively. Additionally, approximately 2% of the regenerated area is not subjected to any regeneration measures (SFA, 2023).

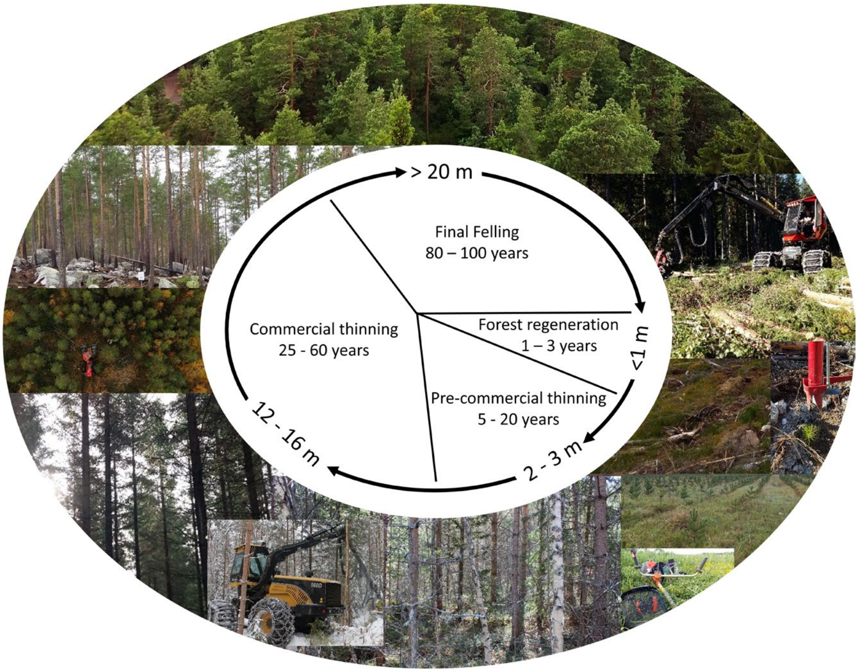

Figure 2. An illustration of the cycle associated with even-aged forestry systems, including specific actions taken at certain tree heights (in metres) and time points. The cycle starts with final felling, which is followed by several activities: forest regeneration (i.e., soil scarification and planting); pre-commercial thinning; and commercial thinning until the next final felling.

The guidelines for planting conifers can vary among forest managers. However, the general planting density typically ranges from 2000 to 2500 trees ha^{-1}, with any variation mainly depending on the tree species (Hallsby, 2013; SFA, 2019). The purpose of soil scarification is to provide an environment with conditions that are favourable to the establishment and growth of seedlings. However, soil scarification also promotes the natural regeneration of broadleaved species by improving the conditions for naturally-dispersed seeds from neighbouring forests or retained trees to germinate (Karlsson et al., 2002; Lidman et al., 2023; Sarvas, 1948). The preservation of retained trees after final felling are stipulated by the Forest Act of 1994 as well as various forest certification standards, notably, the Forest Stewardship Council (FSC, 2019) and the Programme for the Endorsement of Forest Certification (PEFC SWE 002:4). In addition to seed germination, certain broadleaved species, such as birch and aspen, can regenerate naturally from the stumps or roots that remain after harvesting (Hynynen et al., 2010; Myking et al., 2011; Nilsson et al., 2002; Worrell, 1995). Thus, after soil scarification, as many as 10000 naturally regenerated trees ha^{-1} can occur in post-felling forests (Nilsson et al., 2002).

To mitigate the effects of sporadic natural regeneration, selective thinning is used to remove lower-quality trees in a bid to reduce competition and promote the growth of high-quality planted conifers (Ara et al., 2022; Holmström et al., 2016; Nilsson et al., 2010; Peltola et al., 2002; Bergquist et al., 2016; Eriksson and Karlsson, 1997). The initial selective thinning, i.e., PCT, is conducted early in the development of a forest, more specifically, when the regenerated trees are small and around 2 to 3 m in height (Roberge et al., 2020; Fahlvik, 2005; Lundqvist et al., 2014). Most forest managers will perform this type of thinning rather early, when it is more cost-effective and simpler to cut smaller-diameter trees using motor-manual equipment (Ligne. 2004).

Later in the development of a forest, i.e., when trees reach around 12-16 m in height, thinning processes become fully mechanised and are referred to as CT (Broman et al., 2018; Roberge et al., 2020; Fig. 2). The mechanisation of CT increases the efficiency of thinning operations and generates early financial returns through the harvesting of products for the forest industry, primarily small-sawn timber and pulpwood, both of which have minimum size-quality requirements (Biometria, 2024). Due to the cost of extraction, smaller-diameter trees that do not meet these minimal size-quality requirements are often left on-site following thinning (Bergström, 2009; Bergström et al., 2010; Chang et al., 2023).

These selective thinning practices (i.e., PCT and CT) have evolved to focus on stem wood production, namely, sawn timber and pulpwood, for traditional forest industries such as sawmills and pulp mills. However, the growing demand for wood-based biomass for energy production as well as biogenic carbon for other industries may challenge these established thinning methods.

1.3 Biomass-dense forests in Sweden

Currently, biomass-dense forests (BDFs) in Sweden, which are characterised by trees ranging from 3-12 m in height, a mean diameter at breast height (dbh) under 15 cm, a stem volume of less than 0.12 m^3 per tree, and above-ground biomass density exceeding 30 oven-dry tonnes (ODt) ha^{-1}, cover slightly under 3 million ha (Fig. 3; Swedish NFI, 2023). The area of this type of forest has been relatively stable since the publication of the New Forest Act of 1994, which positioned PCT as a voluntary forest management activity (Roberge et al., 2020).

Figure 3. Area covered by biomass-dense forests (BDFs) in Sweden since the New Forest Act come into force (1994-2020). BDF describes forestland covered by trees with heights between 3-12 m, a dbh of < 15 cm, a stem volume < 0.12 m^3 $tree^{-1}$, and an above-ground biomass density >30 ODt ha^{-1}. Source: Swedish NFI, 2023.

In this context, the site properties that favour natural regeneration could be theorised to hold a major role in BDF development. While the southern regions of Sweden, such as Götaland and Svealand, generally provide more fertile conditions and higher annual growths compared to northern regions (Swedish NFI, 2023), the actual distribution of BDFs presents a contrasting picture. Remarkably, about 65% of Swedish BDFs are located in the northern regions of Northern Norrland and Southern Norrland (Fig. 4; Fernandez-Lacruz et al., 2015); this suggests that factors other than site fertility, such as local characteristics and forest management strategies, might significantly influence the occurrence of BDFs.

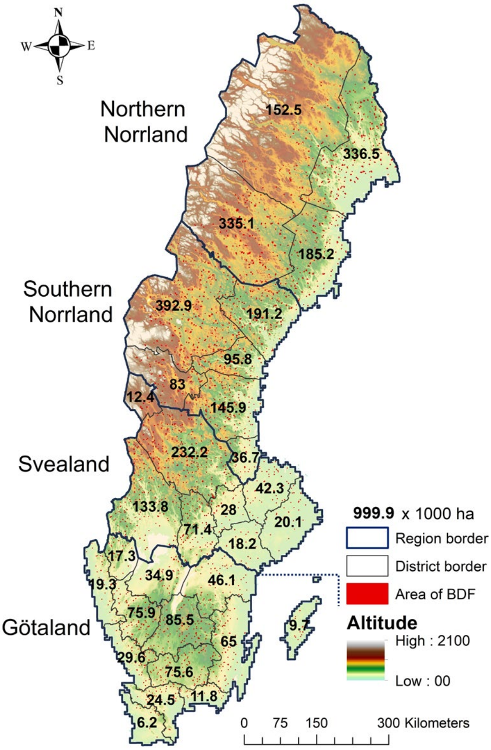

Figure 4. Distribution of biomass-dense forests across Swedish districts as of 2020. Source: Swedish NFI 2023.

Northern forests are predominantly managed by large commercial enterprises, while smaller private forest owners own about 80% of forestland in Götaland (Roberge et al., 2020). This ownership disparity may cause between-region variations in forest management practices and could contribute to the observed BDF distribution (Fig. 4). A notable forest management difference that could influence the occurrence of BDFs is the practice of selective thinnings. Although widely regarded as a financially sound strategy for sustainable forest management in Sweden, many areas are either not thinned or thinned too late; this dynamic is in stark contrast to the recommended stand development principles (Bergquist et al., 2016; Roberge et al., 2020). This is particularly true for PCT, which lacks immediate financial incentives; furthermore, the 1994 decision to classify the PCT as a voluntary measure further emphasises this aspect (Roberge et al., 2020). Therefore, it is hypothesised that this voluntary application of PCT has reduced PCT activities and, consequently, increased the share of young forests characterised by high stem and biomass density (Bergquist et al., 2016; Fernandez-Lacruz et al., 2015). The decline in PCT activities up until the 2000s (Fig. 5) might have contributed to the slight increase in the area of BDFs noticed in 2016 (Fig. 3; Swedish NFI, 2023; Roberge et al., 2020). However, the decline in PCT activities can also be attributed to a reduction in final felling areas in the 1970s, which directly resulted in fewer forests that are eligible for PCT in later years (Fig. 5; Swedish NFI, 2023).

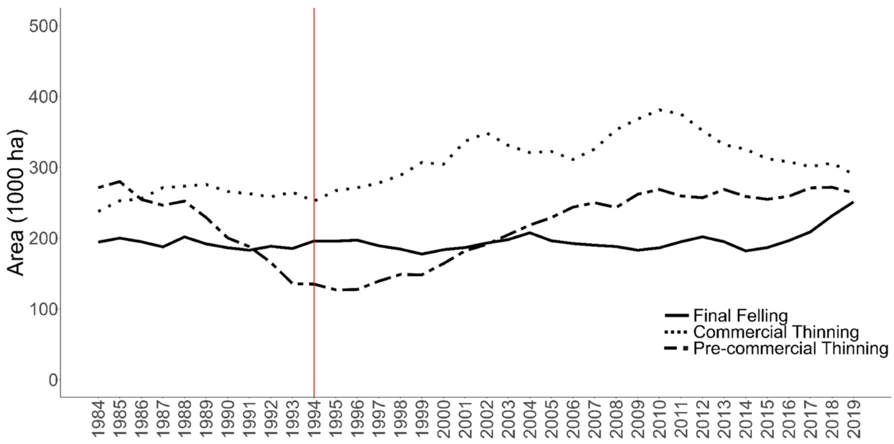

Figure 5. Area of forestland subjected to pre-commercial thinning, commercial thinning, and final felling, presented year-by-year, across Sweden between 1984-2019. The vertical (red) line shows the point at which the New Forest Act of 1994 was implemented. Source: Swedish NFI, 2023.

While the significant costs and limited short-term benefits of selective thinnings, particularly PCT and early CT, might discourage some forest managers from implementing these silvicultural measures in a timely manner, it is still possible to increase revenue associated with CT. For example, modifying the timing of CT, or the approach, either by delaying it or by conducting it from above, can improve early profits from CT. Delayed CT allows the forest to mature until most trees reach a size that is favourable for the forestry market, which will thereby increase revenue before final felling (Agestam, 2009). However, this method can temporarily compromise the resilience of a forest to wind and snow damage due to the removal of supportive trees (Gardiner et al., 1997; Pukkala et al., 2016; Ruel et al., 2001; Valinger, 1996; Wallentin and Nilsson, 2014). Another approach is CT performed from above, which focusses on harvesting larger, more valuable trees, leaving smaller, lower-quality trees to grow and develop prior to final felling. Although this approach yields higher immediate financial returns, it can compromise future growth by leaving lower-quality trees, which are avoided when CT is performed from below. Therefore, CT from above is rarely practised in traditional Swedish forestry due to concerns over long-term impacts (Agestam, 2009; Nilsson et al., 2010).

Based on what was discussed in the preceding paragraphs, new thinning methods could incentivise current forest managers to apply timely thinnings if the extraction of trees would be cost-efficient and the timber could be utilised as fuelwood without compromising long-term stand development (Bergström, 2009; Bergström et al., 2012, 2010; Bergström and Di Fulvio, 2014; De la Fuente et al., 2022; Nuutinen et al., 2021).

1.4 Alternative forest management options

Researchers have explored various geometrical thinning strategies in field experiments – such as harvesting in corridors, lines, rows, and strips – to reduce thinning costs and, more recently, to meet the growing demand for wood-based biomass for energy purposes. The results generally indicate minor growth differences when the residual stand is compared to CT in coniferous forests (*Scots pine*; Bucht and Elfving, 1977; Elfving, 1985; Karlsson et al., 2013; Mäkinen et al., 2006; Nuutinen and Miina, 2023; Segtowich et al., 2023; Pettersson, 1986; *Norway spruce*; Elfving, 1985; Mäkinen et al., 2006). This suggests that geometrical thinning strategies are a feasible option to reduce the costs of biomass extraction in forests with high tree densities.

A biomass extraction approach that has recently received significant attention is biomass thinning (BT) in 1- to 2-m wide strips, also known as “boom-corridor” thinning. This method involves creating narrow, approximately 1-m wide strips that are perpendicular to the extraction racks (i.e., strip roads), with the length of each “boom-corridor” corresponding to the reach of a crane (usually around 10 m). This approach is also compatible with various thinning patterns (Fig. 6; Bergström, 2009).

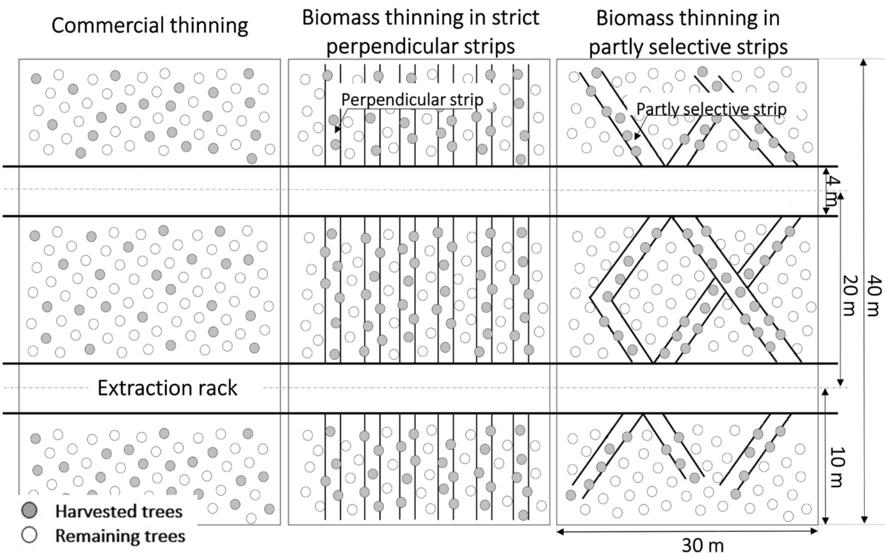

Figure 6. A schematic illustration of biomass thinning in strips between extraction racks (i.e., strip-roads).

The primary difference between traditional selective thinning (i.e., PCT and CT) and BT in strips is that the former aims to preserve as many target species, typically planted conifers, as possible. In contrast, BT in strips employs a geometrical approach that shows a lower degree of selection when compared to traditional methods. Although traditional thinning methods could theoretically be used to create more mixed forests, these methods have not been successful due to the general objective of producing timber with higher market demand, which is traditionally conifer timber in Sweden. However, there is a growing shift towards recognising the value of forest diversity throughout the entire cycle of forest management, rather than just at later stages of development (Andersson et al., 2023). Therefore, adopting BT in strips, a less selective approach, could reduce the preference for conifers over broadleaves and potentially result in earlier income from thinning and a more diverse forest structure (Ahnlund Ulvcrona et al., 2017; Bergström, 2009). This approach could also potentially reduce the thinning frequency over the forest rotation period because one BT replaces both PCT and the first CT. Furthermore, BT could lower harvest-related GHG emissions (De la Fuente et al., 2022), reduce the risk of root rot spread in the remaining stand, which is strongly linked to the number of thinnings (Blomquist et al., 2023; Vollbrecht, 1994), as well as decrease operational costs (Bergström and Di Fulvio, 2014; Jundén et al., 2013; Sängstuvall et al., 2012). Overall, the application of BT offers more feedstock to the industry, and thereby, more wood-based products to the market.

Nevertheless, the extraction of whole above-ground biomass, as applied in BT in strips, is associated with certain risks. For example, the extraction of whole above-ground biomass substantially decreases the nutrients in the remaining forest, even if the extraction is moderate (i.e., branches and treetops; Hakkila et al., 1997). In stands dominated by Norway spruce, whole-tree harvesting – when compared to conventional cut-to-length extraction – has been shown to significantly decrease basal area and volume increment, as well as deviation from the expected mean height (Egnell, 2011; Helmisaari et al., 2011; Jacobson et al., 2000; Nord-Larsen, 2002). Therefore, before recommending BT in strips to forest managers, it is crucial to understand how this method affects the growth and structure of the remaining stand and individual target trees at different stages of forest rotation to avoid compromising future forest production and development.

2. Objectives and research questions

The primary objective of this thesis is to assess whether the introduction of BT in strips is a feasible management option in Swedish forestry to fulfil the increased demand for wood-based biomass without jeopardising the production of traditional forest products, namely, sawn timber and pulpwood.

Moreover, the thesis aims to provide forest owners and managers with insights into alternative strategies that would be relevant for forest sites that have been neglected in forest management or are naturally predisposed to evolution into BDF. The framework and focus areas of Studies I-III are depicted in Figure 7.

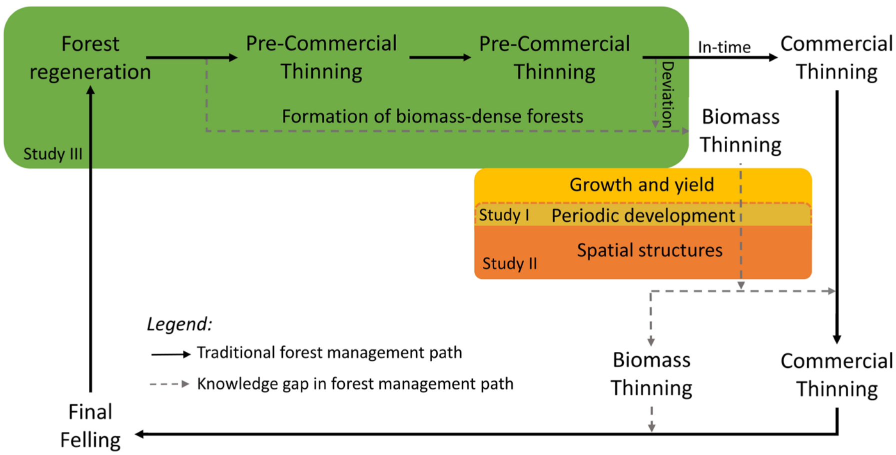

Figure 7. Conceptual framework of the research underlying this thesis. The figure illustrates how the individual projects are interconnected to forest management. Different colours represent each individual project: yellow for Study I, orange for Study II, and green for Study III.

Studies I and II present new scientific evidence about how BT in strips affects mixed Norway spruce and birch forests observed five to six years post-thinning at the target tree level, as well as whether this practice leads to changes in post-thinning spatial diversity. This focus strongly contrasts the case in prior studies, which predominantly examine the stand as a single group of trees or focus on changes immediately after thinning (Bucht and Elfving 1977; Elfving 1985; Pettersson 1986; Mäkinen et al. 2006), species composition (Ahnlund Ulvcrona et al., 2017), and the environmental impacts of thinning operations (De la Fuente et al., 2022). The continuous analysis of post-thinning operations offers deeper insight into the long-term developmental trajectories of stands, and thus expands our understanding of how BT practices influence forest over longer time period.

Study III seeks to describe the natural processes and factors, which contribute to the occurrence of BDFs. This understanding is crucial for pinpointing potential locations for the implementation of BT in strips in tandem with existing forest management practices.

The research questions (RQs) related to Studies I-III are:

I. How do different thinning methods affect the development of the target trees in mixed Norway spruce and birch forests?
II. How do different thinning methods influence spatial tree diversity in mixed forest stands of planted Norway spruce and naturally regenerated birch?
III. Which factors have the most pivotal influence on the occurrence of biomass-dense forests in Sweden under the current forest management practices?

3. Materials and Methods

The research presented in this thesis utilised field data from a long-term thinning experiment (Studies I and II) and data from the Swedish National Forest Inventory (NFI) related to BDFs (Study III) to address the RQs. The long-term thinning experiment was established between 2013-2015 in Southern Sweden, while the analysis in Study III was based on Swedish NFI data from 2016-2020. A brief overview of the materials and methods used in Studies I, II, and III is provided in this section (Section 3). For more detailed information, please refer to the corresponding studies.

3.1 Study design utilised in Studies I and II

The first and second RQs were addressed using data representing three sites, or blocks, with similar site conditions from the long-term thinning experiment in Southern Sweden (Table 1 of Study I). Each of the selected sites had Norway spruce as the dominant tree species, planted at a density of 2000 trees ha^{-1}. However, a significant number of naturally regenerated broadleaves had colonised the plantations; therefore, the actual total tree density ranged from 5800 to 11800 trees ha^{-1}. Silver and downy birch were the dominant naturally regenerated broadleaved species; from here on, both birch species are referred to as birch unless stated otherwise.

The experimental plots were rectangular-shaped and varied in size from 0.1-0.12 ha, and were surrounded by a 5-m wide buffer zone. Treatments were randomly assigned to the plots and replicated at all three sites. For all treatments other than unthinned (UT), 4-m wide extraction racks were established with a 20-m distance between each extraction rack. Next, CT from below and BT in 1- to 2-m wide strips was applied (Fig. 6).

The locations and directions of strips for BT were marked in the field beforehand. The treatments had the following specifications:

UT – Unthinned plot without tree removal;

CT – Commercial thinning performed between the extraction racks in which the above-ground biomass of individual trees is harvested from below. The primary goal of the thinning was to retain approximately 1000-planted Norway spruce trees on-site. In Studies I and II, this thinning practice is referred to as conventional biomass thinning, denoted as: BT_{conv};

BT_{1m} – Strict geometrical harvesting of all trees in a 1-m wide and 10-m long harvesting strip which starts at the extraction rack centre and runs 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. No tree species receives preferential treatment during harvesting;

BT_{2m} – Strict geometrical harvesting of all trees in a 2-m wide and 10-m long harvesting strip which starts at the extraction rack centre and runs perpendicular to the extraction rack. There are two strips on either side of the extraction rack, the distance between neighbouring strips is 5 m. No tree species receives preferential treatment during harvesting;

BT_{sel} – Semi-selective geometrical harvesting in 1-m wide and 10-m long harvesting strips with flexible placement. The harvester operator is tasked with harvesting one strip in each direction from the extraction rack at an angle of roughly 90 to 60 degrees, with the objective of retaining as many spruce trees as possible on-site and to achieve full crane depth.

Key stand data concerning the remaining and harvested stands directly after treatments are summarised as mean values among the experimental sites in Figure 8 and Table 2 of Study I.

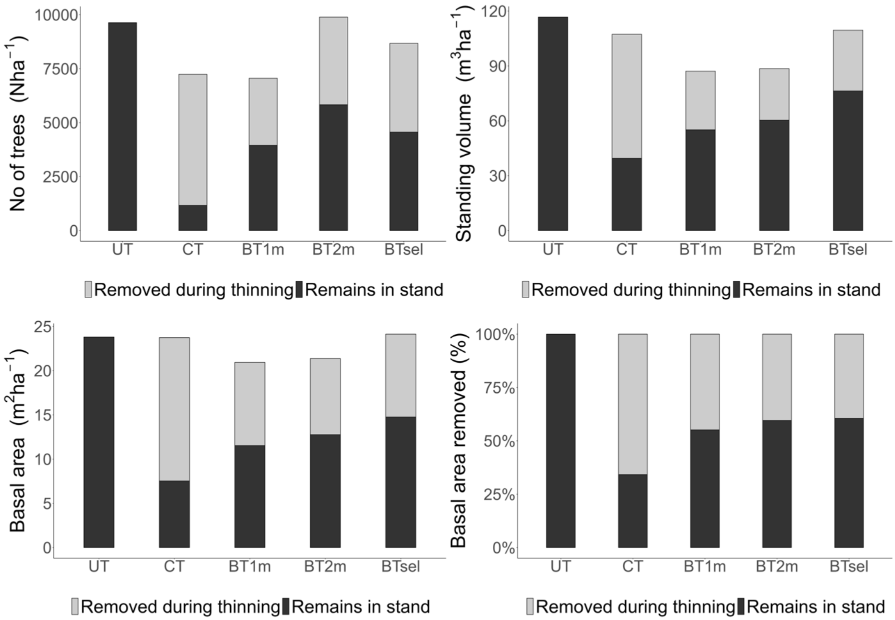

Figure 8. Mean stand data of all the remaining and removed trees after/during different treatments for three experimental sites in southern Sweden. The treatments are unthinned (UT), commercial thinning (CT), biomass thinning in 1-metre wide strips (BT_{1m}), biomass thinning in 2-metre wide strips (BT_{2m}), and selective biomass thinning in 1-metre wide strips (BT_{sel}).

3.2 Data analysis for Study I

To address the first RQ, data from remaining undamaged trees at the study sites five to six years after silvicultural treatment were analysed. All of the measured trees were categorised into three groups (i.e., cohorts in Study I).

The first group included all of the remaining target trees without visible damages, which in Study I were referred to as "all crop trees"; in this thesis, this group is referred to as "*all target trees*". The second group, which was referred to as "500-largest crop trees" in Study I, is referred to as "*target trees for final felling*" in this thesis; this group included the 500-largest target trees without visible damages based on dbh, corresponding to 500 trees ha^{-1}, that were expected to remain until final felling. The third group, was referred as "crop trees from 501 to 900" in Study I, but referred to as "*target trees for the next thinning*" in this thesis, includes 400 trees ha^{-1} without visible damages that are likely to be harvested during the next thinning.

Linear models (LMs) from the `stats` package in R studio (R Core Team, 2022) were used to analyse how different treatments (Section 3.1) influence the response variables. These variables encompassed the periodic development of target trees, including mean annual volume increment (VI, m^3 ha^{-1} yr^{-1}), mean annual basal area increment (BAI, m^2 ha^{-1} yr^{-1}), and proportion of new damages since the first thinning.

In these models, the differences between treatments were assessed using a multiple pairwise comparison of means, performed using a Tukey post-hoc test (`emmeans` package; Lenth, 2022). In all analyses, the threshold for statistical significance was $p < 0.05$.

3.3 Data analysis for Study II

To address the second RQ, data from the long-term BT experiment in Southern Sweden with five different treatments were used. The individual tree locations in the experimental plots were measured using the PosTex system (version 2.3) developed by Haglöf AB (Lämås, 2010).

The analyses utilised in Study II concerned tree species and size, along with the spatial diversity of tree location. Spatial tree location diversity was expressed using the spatial aggregation index (R) presented by Clark and Evans (1954). The R, which compares the mean observed distances between trees and the nearest neighbour with the expected distances between trees under the condition of complete spatial randomness (CSR). An index value R greater than 1 indicates a stand that approaches a regular point pattern. Conversely, an index value R under 1 suggests that a stand demonstrates a trend towards clustering. In the case where R is ~ 1, the observed pattern of tree locations is close to CSR.

The spatial diversity of tree species was quantified using the species mingling index (M; Gadow 1993; Aguirre et al., 2003), which defines the mean heterospecific (i.e., different species) fraction of trees among the four nearest neighbours of a given reference tree (Pommerening and Grabarnik, 2019). The value of M falls between 0 and 1. An M value of 0 indicates low interactions between different tree species, while an M value of 1 indicates high interactions between different tree species. The M can also be expressed as discrete mingling values of 0, 0.25, 0.5, 0.75, or 1.0. These values indicate different intensities of interaction between different tree species around a given reference tree based on the number of different tree species surrounding it (Pommerening and Grabarnik, 2019).

Spatial tree size diversity was quantified using the size differentiation index (T), initially defined by Gadow (1993). This index expresses the relative size differences among the four nearest neighbours of a reference tree. This index T also takes values between 0 and 1; cases in which T is equal to 0 imply that all of the neighbouring trees are equal in size, while a value of 1 implies that neighbouring trees substantially differ in size. A more detailed interpretation guideline for T index values is provided in Table 3 of Study II.

An linear mixed-effects model from `lme4` package (Bates et al., 2015) was used to analyse the variance among response variables, namely, the spatial diversity of tree locations, tree species, and tree size. Different treatments (Section 3.1) were incorporated as explanatory variables, with the site considered a random effect. The differences between treatments were assessed using a multiple pairwise comparison of means (`emmeans` package; Lenth, 2022), with the threshold for statistical significance set as $p < 0.05$.

3.4 Study design for Study III

3.4.1 Data acquisition for Study III

In Study III, data from the Swedish NFI were used to analyse factors influencing the occurrence of BDFs in Sweden under the current forest management practices. Study III employed the response variable of weighted yield of biomass ha^{-1} from BDF, henceforth referred to as BDF biomass yield ha^{-1}. In Study III, BDF was defined as any productive forestland with:

1. mean tree height between 3-12 m;
2. all trees having a diameter at breast height (1.3 m) <15 cm;
3. all trees having a stem volume <0.12 m^3;
4. weighted above ground biomass >30 ODt ha^{-1}:

A total of 13 explanatory variables (i.e., predictors) were obtained from the Swedish NFI database (Table 2 of Study III). The explanatory variables that were predominantly related to landscape and topographic features (region, altitude, slope) are referred as "landscape properties" throughout this thesis based on the terminology applied in Study III. The explanatory variables related to stand properties (stand age, dominant tree species) and management-related aspects (thinning activities, forest ownership structure, and proximity to road) are referred to as "forest management settings" throughout this thesis. Finally, the predictor variables linked to soil characteristics and site productivity, i.e., site index, soil moisture, soil type, and soil depth, are referred to as "site properties" throughout this thesis.

3.4.2 Data analysis for Study III

The first objective of Study III was to understand the importance of various explanatory variables (Table 2 of Study III) on BDF occurrence across Sweden. Without defining any specific hypotheses, the focus was to assess the impact of explanatory variables using a Random Forest (RF) model (`randomForest` package; Liaw and Wiener, 2002).

Study III also examined how forest management settings and site properties influence the occurrence of BDFs. In this study, two separate LMs (`stats` package; R Core Team, 2022) were used for each region (Fig. 4), as delineated in the Swedish NFI. The regional division was implemented based on previously reported results, which have indicated significant regional variation in BDF area and growing stocks; both of these variables generally increase from south to north (Fernandez-Lacruz et al., 2015).

In each LM, BDF biomass yield ha^{-1} served as the response variable, with the forest management settings and site properties as explanatory variables. Because both LMs included the same response variable, the statistical significance, which was determined based on *p*-values, was adjusted by *Bonferroni* correction. To assess the differences between categories of explanatory variables, a multiple pairwise comparison of means was conducted using the Tukey post-hoc test (`emmeans` package; Lenth, 2022).

4. Results and Discussion

The following sections will address each RQ individually, with a focus on the results that the author has deemed significant. In case of further interest, each of the appended studies will provide a more comprehensive discussion.

4.1 Research question I:

How do different thinning methods affect the development of the target trees in mixed Norway spruce and birch forests?

The main finding of Study I was that the type of treatment does not significantly affect the periodic development of the target trees in terms of mean volume increment, mean basal area increment, and proportion of new damages (Fig. 9). Although not a statistically significant result, CT yielded a higher proportion of new damages in the group *all target trees* when compared to UT (3.4-times), $BT_{1\,m}$ (3.4-times), $BT_{2\,m}$ (2.3-times), and BT_{sel} (1.4-times). A similar trend was also observed for *target trees for final felling* and *target trees for next thinning*. Additionally, the proportions of new damages showed the largest degree of variation across the experimental sites when compared to all the other measured response variables (Fig. 9).

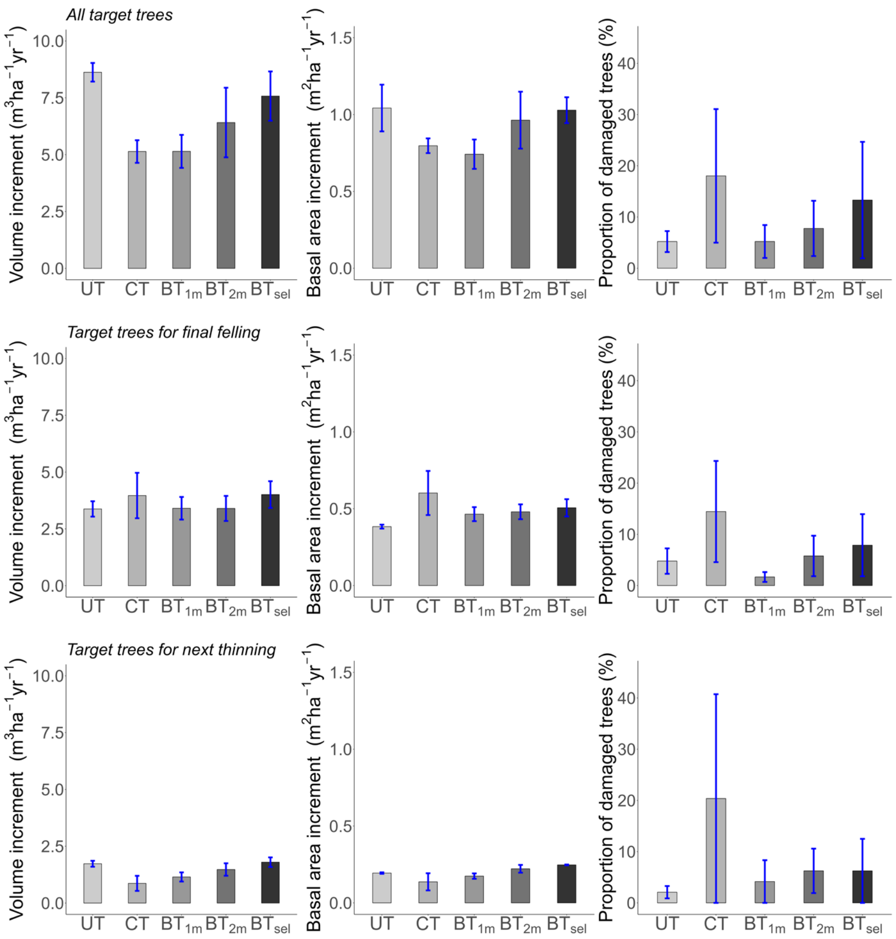

Figure 9. Stand development during the 5-6 years after different treatments for three groups of target tees in the residual stand, i.e., *all target trees*, *target trees for final felling*, and *target trees for next thinning*. The results for the different response variables across different treatments and study sites (n=3) are presented as mean values ± standard error. No significant differences among treatments were found. The treatments are unthinned (UT), commercial thinning (CT), biomass thinning in 1-m wide strips (BT_{1m}), biomass thinning in 2-m wide strips (BT_{2m}), and selective biomass thinning in 1-m wide strips (BT_{sel}).

Although the tested variables did not show significant differences among the selected target trees, the proportion of new damages demonstrated more pronounced differences for the various tested treatments (Fig. 9). More specifically, CT and BT_{sel} resulted in a greater number of new damages post-thinning relative to the other treatments across all three groups of target trees. Strict BT in strips (BT_{1m} and BT_{2m}) and UT resulted in the fewest new damages, especially in *target trees for next thinning* (Fig. 9). The reasons for these differences could be inherent variability in stand properties, such as the number of remaining trees and standing volume, immediately after the treatment (Ahnlund Ulvcrona et al., 2017). In addition, differences in thinning strength could influence the observed results. The thinning strength (i.e., BA removed) in Torared and Erikstad during CT exceeded 70% (Table 2 of Study I). Another contributing factor, alongside thinning strength, could be high tree density prior to treatment (Fig. 8). This density may lead to competition for light, which – in turn – restricts the ability of birch and spruce to develop robust crowns; this dynamic is especially relevant for birch trees, which are highly light-demanding. Consequently, this results in trees with tall, slender trunks and elevated crowns (Hynynen et al., 2010; Hynynen, 1993), which may increase vulnerability to damage from wind and snow after thinning. This suggests that birches may suffer most when stands with high tree densities undergo thinning. However, the data show that fewer birches were retained post-CT (Fig. 10), which was the thinning practice with the highest damage rate (Fig. 9). Therefore, based on extensive research into how thinning strength is related to wind and snow damage (Pellikka and Järvenpää, 2003; Ruel et al., 2001; Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014), it is reasonable to assume that the severe wind damage that occurred shortly after CT was most likely a result of the higher thinning intensity (Fig. 8).

While different BT methods can be assessed using various criteria, including the growth and stand productivity metrics applied in Study I, the crucial aspect of spatial tree diversity is often overlooked in conventional forest management. This aspect was included in Study II because the thinning design and intensity used may result in various distances between neighbouring trees. These differences in remaining distances between neighbouring trees influence forest resilience to wind disturbances due to the loss of support from neighbouring trees (Gardiner et al., 1997). Therefore, the next section of this thesis will evaluate how various treatments influence the aspect of spatial tree diversity.

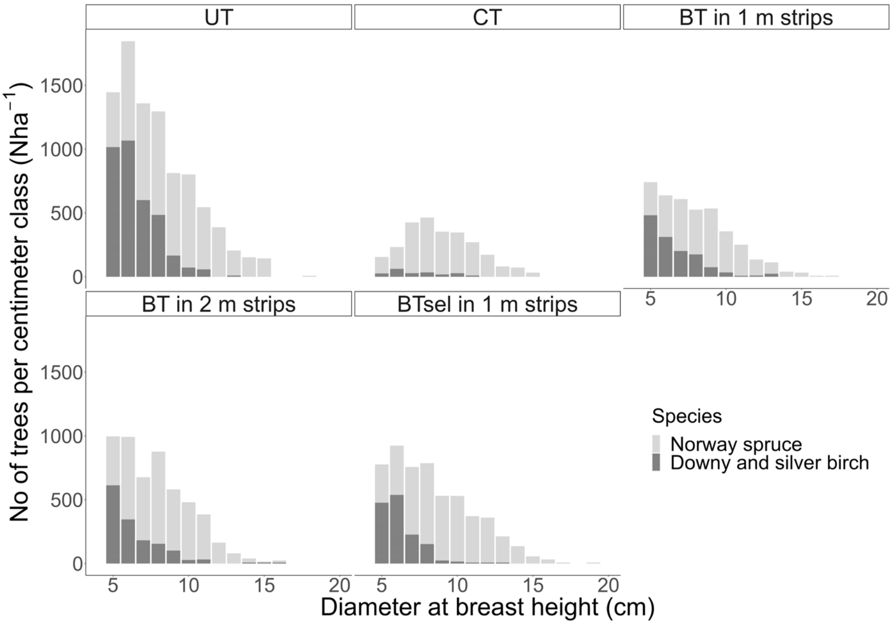

Figure 10. Diameter distribution of Norway spruce, along with downy and silver birch, for all target trees across all study sites (n=3) following different treatments. The treatments are: unthinned (UT); commercial thinning (CT); biomass thinning in 1-m wide strips (BT_{1m}); biomass thinning in 2-m wide strips (BT_{2m}); and selective biomass thinning in 1-m wide strips (BT_{sel}).

4.2 Research question II:

How do different thinning methods influence spatial tree diversity in mixed forest stands of planted Norway spruce and naturally regenerated birch?

The thinning methods of UT, CT, and strict BT in strips (BT_{1m} and BT_{2m}) yielded significantly different spatial aggregation index values. The results from Study II indicate that both UT and CT result in a more regular distribution of trees, as measured by the spatial aggregation index, while strict BT in strips is slightly associated with the tendency for trees to cluster (Fig. 11). In this context, the distances between the neighbouring trees following CT is likely longer than that caused by BT due to the lower number of remaining trees post-CT (Fig. 8).

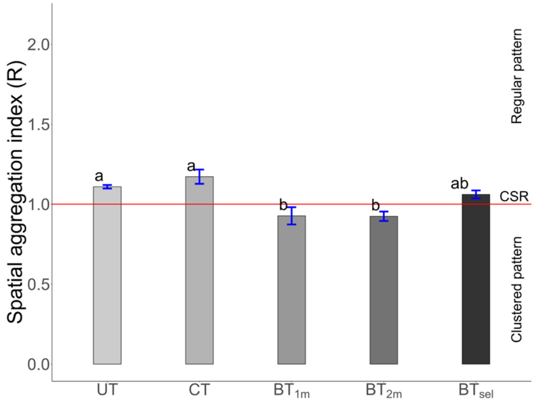

Figure 11. Spatial aggregation index (*R*) values associated with different treatments. The values of *R* for different treatments are presented as the mean values ± standard error across study sites (n=3). Different letters alongside the bars indicate significant between-treatment differences. The treatments are unthinned (UT), commercial thinning (CT), biomass thinning in 1-m wide strips (BT_{1m}), biomass thinning in 2-m wide strips (BT_{2m}), and selective biomass thinning in 1-m wide strips (BT_{sel}). *Note*: An R value >1 signifies a regular pattern of trees, an R value <1 suggests a clustering pattern, and an R value ≈ 1 implies tree distribution that is close to complete spatial randomness (CSR).

The treatments also showed significant differences in mean species mingling and mean tree size diversity (i.e., differentiation), with CT exhibiting significantly lower species mingling and tree size diversity compared to the other treatments (Fig. 12). The results also revealed that the species mingling and tree size diversity following BT in strips (BT_{1m}, BT_{2m}, and BT_{sel}) are similar to those observed for UT, yet greater than the species mingling and size diversity measured for CT.

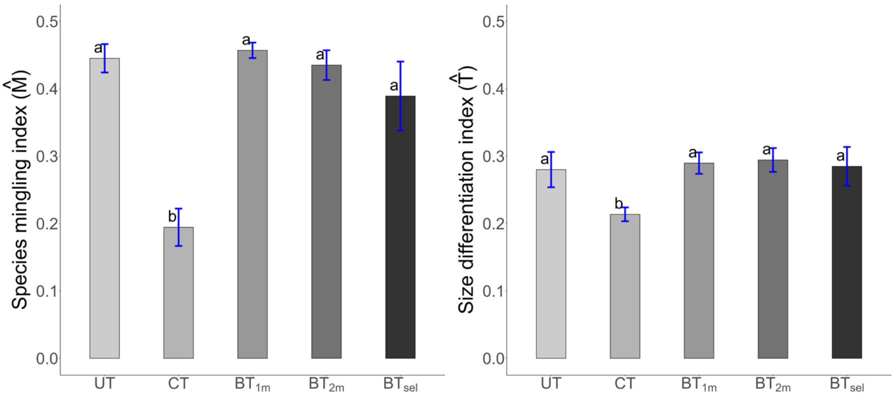

Figure 12. Species mingling ($\hat{M}$) and size differentiation ($\hat{T}$). Values for each index are presented as mean values ± standard error for different treatments across study sites (n=3). Different letters alongside the bars indicate significant between-treatment differences. The treatments are: unthinned (UT); commercial thinning (CT); biomass thinning in 1-m wide strips (BT_{1m}); biomass thinning in 2-m wide strips (BT_{2m}); and selective biomass thinning in 1-m wide strips (BT_{sel}). *Note*: $\hat{M}$ and $\hat{T}$ values of 0 indicate low interactions between different tree species and small size differences between neighbouring trees, whereas $\hat{M}$ and $\hat{T}$ values of 1 signify high interactions between different tree species and large size differences between neighbouring trees.

The differences in spatial aggregation, species mingling, and tree size diversity indices associated with the different treatments are most likely attributed to the general legacy of forest regeneration in Swedish forestry. More specifically, forests are typically regenerated as monocultures, with regular intervals between the planting of trees on scarified soil (Hallsby, 2013; SFA, 2019). In the case of CT, the legacy of planting and the objectives of thinning reduce the amount of naturally regenerated birch trees and preserve the high-quality planted Norway spruce; these dynamics can be expected to play an influential role in maintaining a regular pattern, low mingling index, and low tree size diversity. These findings support the hypothesis from Study II that all treatments would exhibit a regular spatial distribution of trees. Additionally, it was expected that BT in strips would translate to higher species mingling and tree size diversity relative to CT at this stage of stand development (approximately 30 years) when considering that the main objective of thinning was to remove the majority of broadleaved trees. Interestingly, stands where strict BT in strips (i.e., BT_{1m} and BT_{2m}) was performed demonstrated a slightly higher tendency towards complete spatial randomness (Fig. 11), higher mingling, and size diversity (Fig. 12).

The findings of species mingling and size diversity align with the work of Pommerening and Uria-Diez (2017) and Pommerening et al. (2020), with these researchers introducing the *mingling-size hypothesis* to describe the connection between these two indices. The association between the species mingling and size diversity suggests that forest managers who actively enhance species mingling during thinnings also tend to increase size diversity. The increased mingling-size diversity after BT likely stems from a greater number of broadleaved trees remaining between the strips following BT (Ahnlund Ulvcrona et al., 2017, Table 3 of Study I). This is because BT, when performed in strips, results in the preservation of a certain level of spatial diversity throughout the stand which is primarily driven by the natural regeneration of birch trees. This is further supported by empirical mingling distributions, i.e., BT in strips, particularly BT_{1m}, closely resembles the UT treatment in terms of empirical mingling distribution (Fig. 13). The empirical mingling distributions observed for UT and BT_{1m} treatments exhibited a bell-shaped curve which reached the maximum value at $M_i = 0.5$. Treatments BT_{2m} and BT_{sel} displayed an almost uniform mingling distribution, while the mingling distribution observed for CT was characterised by positive skewness with a maximum value at $M_i = 0$ (Fig. 13).

The various thinning methods explored in Studies I and II, along with other research, demonstrate numerous advantages when compared to BT in strips. These include an increase in broadleaved tree populations (Ahnlund Ulvcrona et al., 2017) and reduced carbon emissions from harvesting (De la Fuente et al., 2022). However, to incorporate BT in strips or other BT practices into traditional forest management, and thereby capitalise on the substantial potential of wood-based biomass (Fig. 3; Fernandez-Lacruz et al., 2015), it is essential to understand the occurrences of BDFs in Sweden. The following section of this thesis will discuss the key factors that may influence the occurrence of BDFs, and then pinpoint where BT practices could be implemented.

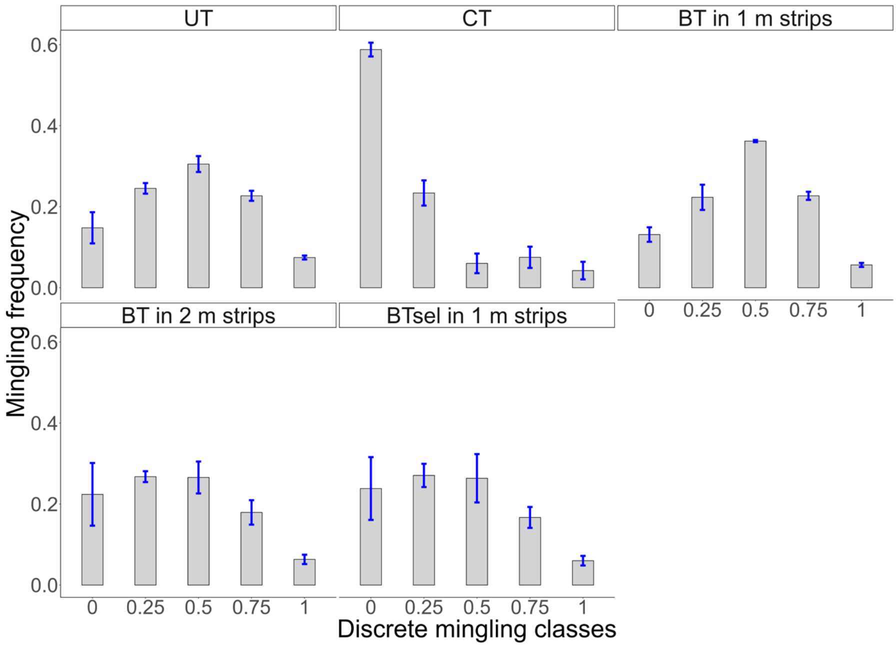

Figure 13. Mean empirical mingling distribution across different treatments. In the figure, a value of 0 represents "low mingling", i.e., four conspecific close neighbours, while a value of 1 represents "high mingling", i.e., four heterospecific close neighbours. The treatments are: unthinned (UT); commercial thinning (CT); 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.

4.3 Research question III:

Which factors have the most pivotal influence on the occurrence of biomass-dense forests in Sweden under the current forest management practices?

Stand age affects the occurrence of BDF both on the national, showing a 63% importance score in the RF model, and regional (Northern Norrland, Southern Norrland, Svealand, and Götaland) levels. This finding underscores the critical role of stand age in BDF occurrence, and is unsurprising when considering that stand age is inherently linked to forest maturity, which affects the accumulation of standing volume in forests classified as BDFs. These findings align with the observations of Fernandez-Lacruz et al. (2015), who noted an increase in the average age of BDF stands from south to north and from east to west.

The site index (importance score of 25%) was identified as the second most important predictor for BDF occurrence on a national scale (Fig. 5 of Study III). However, when comparing the relationship between site index and occurrence of BDFs, statistically significant trend was only identified in one region, namely, Svealand. Nonetheless, all four regions did show a positive, albeit non-statistically significant trend, indicating that BDF biomass yields ha^{-1} increase as site index increases.

Soil moisture class and soil type imparted a significant influence on BDF occurrence on a regional level, as shown in Table 4 of Study III. These findings suggest that soil characteristics play a crucial role in the occurrence and productivity of BDFs in regions, even though these factors showed rather low importance scores on the national level, i.e., 10% and 5%, respectively.

Interestingly, the regional analysis revealed that, soil moisture classes only have a significant effect on the occurrence of BDFs in Southern Norrland, where mesic-moist soils were linked to higher BDF biomass yields ha^{-1} than mesic soils. Study III results also indicate that mesic and mesic-moist soils generally support higher BDF biomass yields ha^{-1} compared to dry, moist, and wet soil moisture classes, especially in the northern regions (i.e., Northern Norrland and Southern Norrland; Fig. 14). Remarkably, in the southern regions (i.e., Svealand and Götaland) wet soils supported the highest BDF biomass yields ha^{-1}.

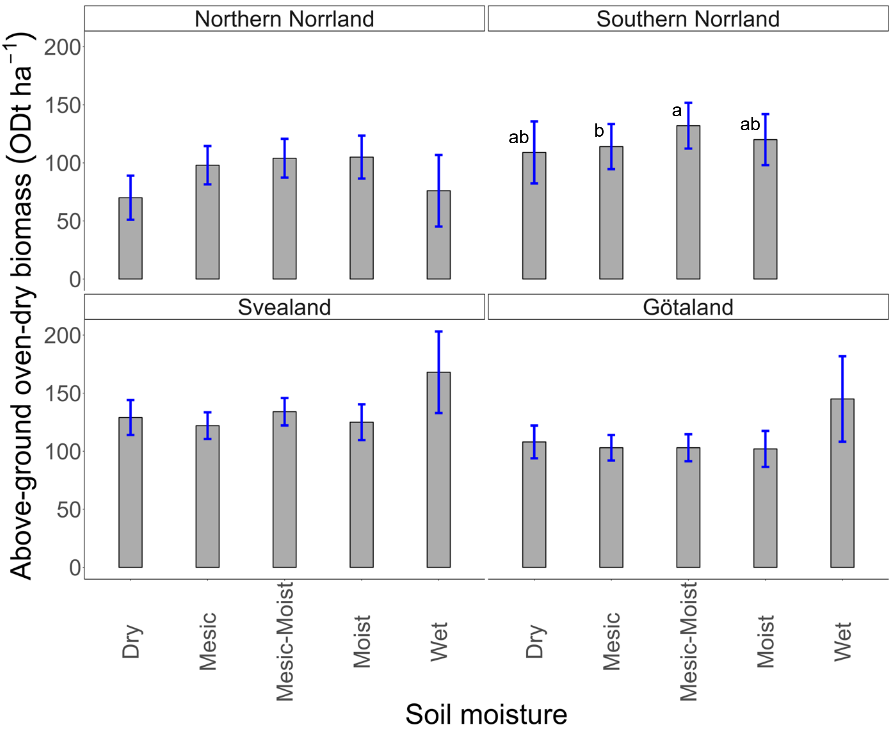

Figure 14. Regional distribution of biomass-dense forests (BDFs) by biomass yield (ODt ha^{-1}) according to soil moisture class. The values of biomass yield (ODt ha^{-1}) for each soil moisture class are presented as mean values ± standard error. Superscript letters indicate significant differences between categories, as calculated using Tukey's multiple comparison test.

The results of Study III demonstrated that soil type exerts a significant influence on the biomass yields associated with BDFs in Northern Norrland and, to a lesser extent, in Svealand. Peatlands were consistently identified as the soil type with the highest biomass yield ha^{-1} across all regions. Notably, BDFs situated on peat and sediment soils yielded significantly greater amounts of biomass than BDFs on moraine soils; this difference was only observed in Northern Norrland (Fig. 15).

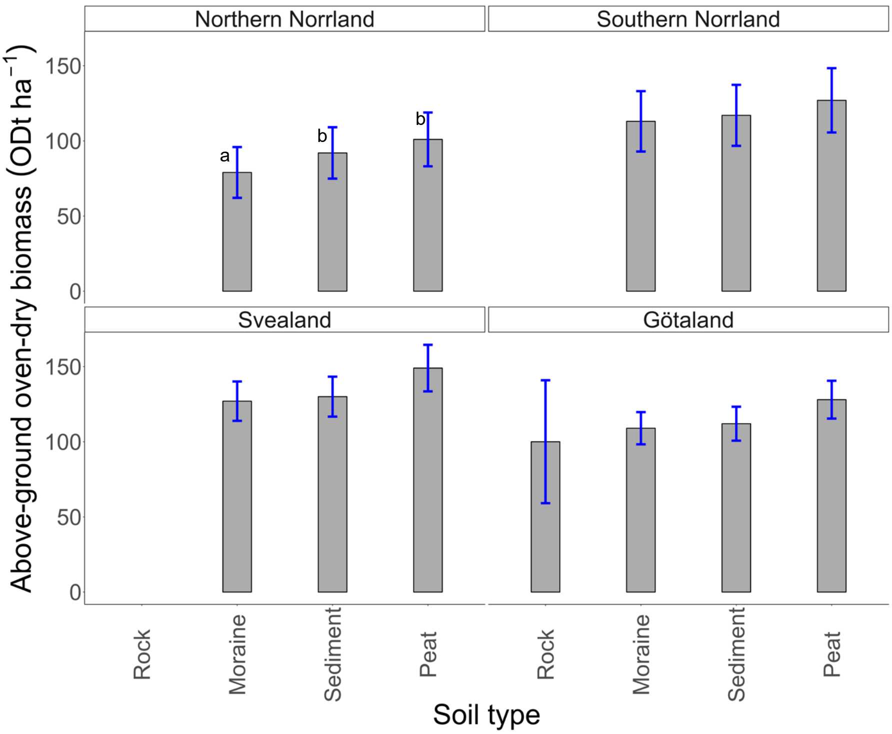

Figure 15. The biomass yields (ODt ha^{-1}) associated with BDFs across various Swedish regions, categorised by soil type. The values of biomass yield (ODt ha^{-1}) for each soil type class are presented as mean values ± standard error. Superscript letters indicate significant differences between categories, as calculated by Tukey's multiple comparison test.

These rather unexpected results, that wet and peat soils are associated with significant biomass yields when considering BDFs (Fig. 14 and Fig. 15), could be attributed to the fact that wet and peat soils are often characterised by a low site index and, therefore, low productivity (Crawford et al., 2021; Hägglund and Lundmark, 1977; Swedish NFI, 2023). As a result, forests on these soils tend to be generally not prioritised in active forest management. Consequently, forests on these sites are likely to remain intact for extended periods, and – as an extension – accumulate more biomass during their longer lifespan (Table 1S of Study III). However, it should be noted that the low productivity associated with these sites (Crawford et al., 2021; Hägglund and Lundmark, 1977; Swedish NFI, 2023) means that these types of forest are unlikely to reach out of our definition of BDF, i.e., dbh < 15 cm, due to limited growth potential.

Mesic-moist soils may be of greater interest to forest managers using BT methods because these sites are characterised by a higher water content, which is favourable for seed germination during the initial stages of natural forest regeneration (Götmark et al., 2005; Lidman et al., 2023). This may well translate to effective biomass extraction from these BDFs, which will show high initial tree density (Bergström, 2009; Bergström and Di Fulvio, 2014). This soil moisture class (i.e., mesic-moist) represents the category accounting for the second-largest area of BDFs in Sweden (Table 4 and Table 6 of Study III).

When considering that thinning typically results in decreased stand-level biomass, as reported by Gizachew et al. (2012), Gizachew and Brunner (2011), Holmström et al. (2016), and Nilsson et al. (2010), it is not surprising that the results show higher biomass yields ha^{-1} in BDF sites which had not been subjected to PCT (Table 3 of Study III). Based on these findings, it is plausible to hypothesise that sites with a lower site index, such as those situated on wet, moist, and peat soils, may be under-managed and overlooked by forest managers (Table 1S of Study III). Consequently, these sites exhibit higher biomass yields ha^{-1} than other sites because they have not been subjected to common silvicultural practices. Data observations from Study III partly support this line of reasoning, and reveal a preference for PCT on sites with higher growth potential (Table 1S of Study III). The tendency to implement PCT on more productive sites likely stems from the understanding that forests characterised by a higher site index should be prioritised for PCT due to enhanced natural regeneration. This preference to apply PCT to more fertile sites (Table 1S of Study III) with higher growth potential warrants further investigation into how certain behavioural factors influence management decisions.

The results presented in Study III also indicate that certain tree species, such as Norway spruce, aspen, and birch, may positively influence the development of BDFs under current forest management settings and conditions. Surprisingly, BDF occurrence is prevalent in areas dominated by Norway spruce. Given the value attributed to Norway spruce by the Swedish forest industry, a higher frequency of PCT practices might be expected at these sites. However, the occurrence of BDFs in Norway spruce-dominated forests could be attributed to failed management objectives, particularly linked to PCT practices, or the extensive planting of Norway spruce in Sweden. Alternatively, it may related to the fact that Norway spruce is traditionally planted on more fertile soils with a higher site index (Swedish NFI, 2023), which was the second most important factor in the RF model. On the other hand, areas dominated by aspen and birch also achieved high biomass yields ha^{-1} (Table 3 of Study III). These findings concerning BDF occurrence on sites dominated by aspen and birch align with expectations, yet possibly present greater complexity to deciphering the dynamics that explain the occurrence of BDFs. These species exhibit sporadic natural regeneration and accelerated growth, which translates to a potential for overshadowing planted species such as Norway spruce and Scots pine (Hynynen, 1993; Hynynen et al., 2010; Tullus et al., 2012; Worrell, 1995). Thus, forest managers face the challenge of keeping pace with this rapid early growth, which may necessitate more frequent and efficient PCT operations to control the expansion of aspen and birch. Therefore, to avoid multiple PCTs, forest managers temporarily neglect stands already dominated by these species, with the intention of allowing them to reach a size and quality suitable for conducting CT. This approach aims to maximise profit from these stands, and therefore, forests dominated by birch and aspen often fall into the definition of BDFs.

For a comprehensive discussion of how additional variables, such as CT, forest ownership, and proximity to the road, along with specific landscape properties, influence BDF occurrence at the national scale, readers are directed to the manuscript of Study III.

4.4 Practical implications of findings

Based on what has been discussed thus far, the findings of the research underlying this thesis support the omission of early selective thinnings, such as PCT and the first CT, in favour of BT in strips. It is important to note that BT in strips does not adversely affect the growth and development of the remaining target trees, which will be subjected to subsequent CT and final felling (Study I). Moreover, BT in strips was found to contribute to enhancing a more diverse spatial structure of the remaining forest compared to the traditional CT (Study II). Implementing BT in BDFs, particularly those established on sediment and moraine soil types that fall under the mesic and mesic-moist classes (Study III), could be strategically advantageous for Swedish forest managers who are interested in BDF management.

The effective conversion of forests to BDFs could be achieved by promoting natural regeneration after final felling through soil preparation via disc trenching (Karlsson et al., 2002), and by delaying PCT (Holmström et al., 2016). Transferring all of the productive forestlands growing on sediment and moraine soil types which represent the mesic-moist soil moisture class to BDF management would increase the areas of BDFs in Northern Norrland, Southern Norrland, Svealand, and Götaland by 1.5 million ha, 1.2 million ha, 1.1. million ha, and 880 000 ha, respectively. However, the BDF management area can be expanded even further if forest managers were to transfer all productive forests on sediment and moraine soil types which also fall under the mesic soil moisture class to BDF management. This would further increase the area of BDFs in Northern Norrland, Southern Norrland, Svealand, and Götaland by 4.3 million ha, 3.9 million ha, 3.5 million ha, and 3.3 million ha, respectively.

Nevertheless, it is crucial to acknowledge that the findings of Studies I and II represent preliminary assessments of the medium-term effects of applying BT in strips to residual stands. Additionally, the research in Study III presents a theoretical scenario, e.g., what scale of operations could be achieved if forest managers were open to implementing BDF management through BT in strips. As such, further quantitative and qualitative research, for instance, the long-term impacts of BT operations on various site metrics and interviews with different forest managers, respectively, needs to be carried out so that stakeholders of Swedish forestry receive reliable recommendations for how to adapt their practices.

4.5 Constraints of the research presented in this thesis

Studies I and II investigated the effects of BT in strips on stand development and dynamics. The findings provided support that the application of this type of thinning would be relevant to Swedish forestry. Nonetheless, further long-term research across various site conditions and regions is essential to enhance our understanding of BT in strips and formulate more profound insights. This necessity for further empirical results stems from the fact that the examination of BT in strips (Studies I and II) occurred relatively soon after initial thinning, i.e., five to six years later, and the experimental stands were around 30 years of age. Consequently, these forests will not undergo harvesting for numerous decades, and at least one additional thinning is advisable. Therefore, tree development may be affected by both the current and forthcoming treatments.

The inherent variability of the remaining stand (Table 2 of Studies I and II), when considered together with the limited number of experimental sites ($n = 3$), may hinder the ability to detect statistically significant patterns, especially those related to irregular and unpredictable events like wind and snow damage. Thus, increasing the number of experimental sites could reduce this variability and improve the chances of identifying statistically significant trends.

Study II addressed aspects of tree species dynamics by examining the forest structures of the remaining forest. However, only post-treatment spatial data were available, which makes it difficult to determine whether spatial diversity among trees post-treatment differed significantly from the situation prior to treatment. Although it is plausible to assume that there could be minor variations between experimental sites before thinning (Mason et al., 2007), the current Swedish forestry practices, which prioritise uniformity in planting and thinning to optimise target tree growth (Nilsson et al., 2010; Hallsby, 2013), suggest that substantial pre-existing disparities are unlikely. Additionally, the decision to employ site replication was taken to mitigate this source of uncertainty.

Regarding Study III, certain explanatory variables, such as altitude, site index, soil moisture, and soil type, may exhibit high levels of correlation, which could lead to spurious associations that influence the results. Additionally, human behaviours (i.e., preference for thinning and road building), as highlighted in the same study, may further interact with the site-specific characteristics, a dynamic which further complicates efforts to decipher the factors that impact the occurrence of BDFs throughout Sweden.

To maintain continuity, a definition of BDF that was highly similar to the one coined by Fernandez-Lacruz et al. (2015) was adopted. However, this definition renders the material less useful for identifying sites suitable for rapid BDF development due to the discovered importance of stand age.

Furthermore, the Swedish NFI, which was utilised in Study III, provides comprehensive information at the national and regional levels. However, the scope of this data may limit the applicability and representativeness for smaller areas or specific forest types (e.g., BDFs). Nevertheless, it is well established that the Swedish NFI data represent the most extensive available source for capturing the full variation present in the Swedish landscape. The data set also offers methodologies and tools to mitigate some of these limitations, such as integrating field and remote sensing data and employing statistical methods and models to enhance spatial resolution and forest data coverage (Fridman et al., 2014).

5. Conclusions

This thesis provides insights into forest management using biomass thinning (BT) in 1- and 2-m wide strips in Southern Sweden, and highlights the development of biomass-dense forests (BDFs) in Sweden which could be subjected to BT in the future. The main findings of the research underlying this thesis are as follows:

1. Applying BT in 1- and 2-m wide strips does not affect the growth rates of the 900 largest and most valuable target trees. Thus, this method can be adopted in current forest management practices as an alternative to early commercial thinning, especially in forests with a high initial density of trees.
2. Biomass thinning in strips can enhance the spatial diversity of the remaining forest by creating more complex patterns of tree distribution, increasing the mingling of different species, and positively affecting tree size diversity among the remaining trees compared to early commercial thinning. Thus, the adoption of BT in 1- and 2-metre wide strips could potentially strengthen the resilience and increase the structural diversity of the remaining forest.
3. The occurrence of BDFs in Sweden is influenced by stand age, site productivity, dominant tree species, and pre-commercial thinning. Consequently, the total area of BDFs may be overestimated due to biomass accumulation on low productivity sites with lower thinning activates, particularly in wet and moist peat soils, which are less attractive to forest managers over the extended time period.
4. Productive forestlands representing mesic and mesic-moist soil moisture categories on sediment and moraine soil types, demonstrate potential for BDF expansion, with BT a possibility in the future.

6. Future research

Managing BDFs through BT in strips involves removing all of the above-ground biomass, an approach which carries certain risks. It is because prior the researcher have reported negative short- to medium-term growth responses as a result of whole-tree harvesting, which raises concerns about the long-term growth impacts of BT approach (Helmisaari et al., 2011; Jacobson et al., 2000; Nord-Larsen, 2002). However, there are certain indications from Egnell and Ulvcrona (2015) and Egnell (2011) that these effects may be short-lived. Therefore, these concerns should be further investigated to obtain a more reliable understanding of the long-term effects of BT in strips on soil nutrient levels, as well as how these thinning methods influence the growth rates of residual and future forests. Furthermore, continuing evaluations of how BT in strips can be refined to balance biomass extraction with nutrient retention (Bergström and Di Fulva, 2014) could be pivotal to ensuring truly sustainable forest management and production.

The replacement of traditional CT from below with BT in strips introduces a critical management dilemma, namely "*How to approach subsequent thinning operations*". The decision between continuing with CT or implementing a second BT is crucial because the trees remaining after the second thinning become the target population for final felling. While the outcomes of a second CT are well-documented (Nilsson et al., 2010), the trajectory of stand development and individual tree growth after a second BT remains largely unexplored. Financial implications will obviously influence decision-making, as the reduced density of residual target trees after CT could affect profitability (Kärhä et al., 2004). Forest managers may favour a second CT due to increased target tree numbers, which could potentially enhance profitability. However, this strategy involves harvesting smaller-diameter trees, which increases per-tree harvesting costs (Chang et al., 2023;

Eliasson et al., 2019) and potentially necessitates more intensive thinning efforts. Biomass thinning in strips, which results in more diverse spatial structures (Study II), appears to be beneficial to stand resilience towards wind and snow disturbances (Study I). However, the practice of BT may also intensify competition and lead to self-thinning, mortality, which can enhance biodiversity through small- to medium-diameter dead wood enrichment and may help to restore nutrients lost during whole-tree harvesting (Bergström and Di Fulvio, 2014; Hekkala et al., 2023; Jonsson et al., 2016; Marchetti, 2004). These complexities and potential benefits, while largely speculative, highlight an interesting research avenue for better understanding the implications of BT strategies over the full rotation period. More specifically, a few questions warrant deeper investigation. First, how does the implementation of a second BT in strips affect the growth and quality of target trees remaining for final felling in comparison to CT from below? Second, what are the economic and ecological trade-offs associated with different thinning strategies in terms of harvesting costs, risk of damage, and contributions to forest biodiversity?

Other aspects warranting further research include the impacts of BT in strips on public perceptions, reindeer herding, and recreational activities. For instance, the general public can be expected to express certain viewpoints on a new forest management method such as BT in strips. It is thus essential to explore their preferences, attitudes, and opinions regarding the aesthetic, environmental, and social impacts of BT in strips.

Furthermore, recreational activities in forests are an important issue in Swedish society; as such, it will be pertinent to examine how BT in strips could influence recreational activities through either direct impacts or implicit externalities. Future research could address how BT in strips affects forest amenities, accessibility, and appeal for various recreational pursuits, such as hiking, biking, hunting, and birdwatching.

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Popular science summary

In Sweden, forest biomass has been used as a renewable energy source to replace fossil fuels in energy production. This has become particularly evident following the European Union's endorsement of the sustainability of forest biomass in energy generation. At the moment, effective biomass extraction techniques are being explored so that Sweden can fulfil the national ambition of achieving net-zero greenhouse gas emissions by 2045. These techniques include geometrical biomass thinning in 1- to 2-m wide and roughly 10-m long strips between extraction racks (i.e., strip roads).

This thesis examines data from three experimental sites featuring mixed forests of Norway spruce and birch in Southern Sweden. The focus of the thesis is to compare how effective geometrical biomass thinning in strips is in relation to commercial thinning by evaluating the effects on residual trees over a period of five to six years post-thinning, with an emphasis on stand development.

The presented results indicate that strict geometrical biomass thinning, when executed in 1- to 2-m wide strips, does not adversely affect the growth and productivity of the top 900 target trees. In fact, it may confer the stand with some level of protection against damage, mainly that associated with wind and snow. Although not statistically significant, there was an observable trend of reduced new damage in areas subjected to strict geometrical biomass thinning or where no thinning was performed relative to commercial and semi-selective biomass thinning. Moreover, geometrical biomass thinning, especially when applied in a strict 1- or 2-m wide strips, fosters increased spatial heterogeneity among trees when compared to traditional practices. Therefore, the application of biomass thinning (in narrow strips) in mixed forests of coniferous and broadleaf species (i.e.,

spruce and birch) is a viable option that does not impede the development of the remaining trees.

At present, approximately 1.4 million ha of forests in Sweden are classified as biomass-dense forests where some type of biomass thinning could be implemented. Furthermore, an analysis of data from the Swedish National Forest Inventory suggests that mineral soils within the mesic-moist soil moisture class generally support higher biomass yield per hectare for forests classified as biomass-dense. Consequently, these soils are the optimal target for implementing geometrical biomass thinning in strips.

Nevertheless, while the research presented in this thesis offers promising initial findings, extensive long-term research across broader geographic regions is essential before these innovative thinning methods can be confidently recommended to forest managers across Northern Europe.

Populärvetenskaplig sammanfattning

I Sverige har skogsbiomassa använts som förnybar energikälla för att ersätta fossila bränslen. Intresset har ökat ytterligare efter Europeiska unionens inkluderade av skogligt biobränsle som en hållbar energikälla. Effektiva metoder för uttag av biomassa utforskas för att uppfylla Sveriges ambition att uppnå netto-noll växthusgasutsläpp till 2045. Bland dessa metoder finns geometrisk biomassagallring där alla träd avverkas längs 1-2 m breda och ungefär 10 m långa korridorer mellan stickvägarna.

Denna avhandling undersöker data från tre fältförsök i blandskog av gran och björk i södra Sverige. Fokus för avhandlingen är att jämföra kommersiell selektiv gallring med geometrisk gallring i korridorer och utvärdera hur de påverkar de kvarvarande träden under en period av fem till sex år efter gallring, med betoning på beståndets utveckling.

Resultaten indikerar att strikt geometrisk gallring, när genomförd i 1-2m breda korridorer, inte hindrar tillväxten eller utvecklingen för de 900 bästa träden. Faktum är att geometrisk gallring kan ge en viss nivå av skydd mot skador, främst orsakade av vind och snö. Även om det inte var statistiskt signifikant, fanns det en observerbar trend av minskade skador på försöksytor som gallrats geometriskt i korridorer och ogallrade försöksytor jämfört med ytor som gallrats med traditionella eller delvis selektiva gallringsmetoder. Dessutom främjar geometrisk gallring, särskilt när den tillämpas i 1 eller 2 m breda korridorer, ökad rumslig heterogenitet bland träd jämfört med traditionella metoder. Detta visar att biomassagallring i form av geometrisk gallring kan vara ett alternativ i stam- och biomassatäta blandskogar bestående av barr- och lövträd som inte hindrar de kvarvarande trädens utveckling.

För närvarande så är ungefär 1,4 millioner ha av skog i Sverige klassificerad som biomasstäta skogar där någon slags biomassagallring skulle kunna implementeras. Dessutom indikerar en analys av svenska Riksskogstaxeringens data att friska marker på mineraljord generellt resulterar i ett högre biomassa uttag per hektar för skogar som är klassificerade som biomasstäta. Följaktligen så är dessa marker bäst lämpade för implementering av geometrisk gallring i korridorer.

Även om resultatet i avhandlingen visar lovande initiala resultat så är storskalig långsiktig forskning som sträcker sig över geografiska regioner ovärderlig innan dessa innovativa metoder kan säkert rekommenderas till skogsägare och förvaltare i norra Europa.

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Development of crop trees after different thinning methods in mixed Norway spruce (*Picea abies* L.) and Birch (*Betula spp.*) forests in Southern Sweden

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ABSTRACT

In Northern Europe, novel thinning methods of small diameter trees are being tested to promote early competition release in young tree-dense forests at a low cost. These methods involve harvesting the whole above-ground tree biomass in 1 – 2 m wide strips between extraction racks (i.e. strip roads). Before recommending such methods to practical forestry, we need to know how the growth of remaining stand and individual trees perform at different stages of stand rotation to avoid compromising future forest production and the overall economy. Therefore, we analysed data from three Norway spruce dominated experimental sites in Southern Sweden with conventional selective biomass thinning (BT) versus geometrical BT in strips, where trees between extraction racks are cut in 1 – 2 m wide, ca. 10 m long strips (i.e. boom-corridor thinning) including unthinned reference treatment. To assess the thinning effect on the remaining stand, we analysed data from the remaining trees five to six years after thinning. We compared stand properties such as standing volume, diameter, height, basal area, volume increment, basal area increment and damages for different cohorts of the remaining trees. We found that BT in 1 – 2 m wide strips do not affect the growth and yield of the most important crop trees (i.e. the *500-largest crop trees* and the *next 400-largest crop trees*) and to some extent protect the remaining stand from damages. Although not statistically significant, we observed that for the cohort of the *500-largest crop trees*, the proportions of new damages were lower in unthinned treatment (4.8 %), and strict BT in 1 – 2 m wide strips (1.7 % and 5.8 % respectively) than in conventional BT (14.4 %) and semi-selective BT in 1 m wide strips (7.9 %). A similar pattern was seen for the *next 400-largest crop trees*. Thus, these short-term results suggests that BT in narrow strips of 1 – 2 m can be used in young tree-dense forests in Southern Sweden without compromising the development of the remaining crop trees. However, more long-term research on a broader geographical scale is required before we can fully recommend these novel-thinning methods to forest owners across the Northern Europe on a large scale.

1. Introduction

In Sweden, transition away from fossil fuel dependence started after the oil crises in the 1970s. Apart from the introduction of nuclear power, this transition included an increased use of biomass for energy, where a major part of the biomass originates from forests (Ericsson et al., 2004; Swedish Energy Agency, 2021). This includes secondary residues from the forest industry (e.g. sawdust and bark) and primary residues available following logging operations in the forest – mainly discharged low quality round wood, branches and treetops. Although more of primary residues such as stump- and root-biomass can be harvested (Lundmark et al., 2015; Persson and Egnell, 2018; Persson, 2017; Walmsley and Godbold, 2010), the Swedish environmental objective of *"Sustainable Forests"* limits the extraction of these residues (i.e. stump- and root-biomass), because stumps following harvest provide coarse woody debris which is important for biodiversity and current stump

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harvest technologies can cause severe soil disturbances (De Jong et al., 2017). Furthermore, with current harvest technologies stump harvest is expensive (Lundmark et al., 2015), thus other biomass sources are likely to be necessary for the transition towards a fossil-free energy sector, especially at the European level.

The dominant silvicultural system in the managed forests in Northern Europe is the even-age management where final felling is followed by artificial regeneration through mechanical site preparation and planting, one or several pre-commercial thinnings (PCT), and one or several commercial thinnings (CT). The Swedish Forest Agency recommends early thinnings at a mean height of 2–3 m with selective PCT, using motor-manual brush-saw and leaving cut trees on site (Roberge et al. 2020). The fully mechanised first selective CT is usually recommended as thinning from below that extracts many small and few large low-quality trees, and performed when the stand reaches 12–16 m height (Broman et al. 2018; Roberge et al. 2020). In general, selective thinnings (i.e. PCT and CT) reduce competition for the economically important conifer species (Norway spruce *(Picea abies* L.) and Scots pine *(Pinus sylvestris* L.)) and thereby increase the tree growth and timber value of remaining trees (Ara et al., 2022; Bergquist et al. 2016; Eriksson and Karlsson, 1997; Holmström et al., 2016; Nilsson et al., 2010; Peltola et al., 2002; Zeide, 2001). Despite the high mechanisation of forest operations in Northern Europe (Roberge et. al., 2020; Sirén, 1998; Swedish NFI, 2019) the costs of selective thinnings are high (Eliasson et al., 2019) and low revenues associated with first CT may demotivate forest owners to conduct selective thinnings at the recommended time (Bergquist et al. 2016; Kärhä et al., 2004; Ligné et al., 2005; Pettersson et al. 2012).

With the aim to find ways to minimise costs associated with selective thinnings, new strategies of geometrical biomass thinning (BT) in strips have been studied in field experiments conducted throughout Europe, encompassing a variety of different tree species (Ahnlund Ulvcrona et al., 2017; Bergström et al., 2022; Nuutinen et al., 2021; Tolosana et al., 2024). Generally, studies focusing on geometrical thinning in corridors, lines, rows, or strips tend to reveal minimal growth differences when compared to selective CT in coniferous forests in Northern Europe (*Scots pine*; Bucht and Elfving, 1977; Elfving, 1985; Karlsson et al., 2013; Mäkinen et al., 2006; Nuutinen and Miina, 2023; Pettersson, 1986; Segtowich et al., 2023: ***Norway spruce***; Elfving, 1985; Mäkinen et al., 2006). This indicates that such methods could be an effective approach to optimise biomass extraction from young tree-dense forests. Recently, in Northern Europe, the most thoroughly studied geometrical thinning method is the BT in 1 – 2 m-wide and 10 m long strips between extraction racks using different geometrical thinning patterns (Fig. 1). This thinning method is also known as boom-corridor thinning (e.g. Ahnlund Ulvcrona et al., 2017; Bergström, 2009; Bergström et al., 2010; Nuutinen et al., 2021; Tolosana et al., 2024).

In young tree-dense forests, BT in strips could reduce the number of thinnings conducted over the rotation by replacing PCT and first CT with a single BT in strips. This thinning method could lower thinning costs (Bergström, 2009; Bergström et al., 2022, 2010, 2007; Di Fulvio et al., 2011), harvest-related carbon emissions (De la Fuente et al., 2022), and risk of root rot associated with high intensity of thinnings (Blomquist et al., 2023; Vollbrecht, 1994). Biomass thinning in strips can also increase the number of broadleaved trees that remain in the forest (Ahnlund Ulvcrona et al., 2017; Bergström, 2009) and enhance the complexity of forest stand structures (Becs et al., 2023), thus consequently improve the diversity of the remaining stand. However, this method is relatively novel and the evaluation of its effects on stand development have been carried out directly after the thinning and for all remaining trees as a single cohort (Ahnlund Ulvcrona et al., 2017; Bergström, 2009.; Bergström et al., 2022; Nuutinen et al., 2021). From what we know, limited research has so far examined the development of trees that are likely to remain until CT and final felling, separately. Further evaluations conducted several years since the thinning practices will give us more insights into the potential longer-term development trajectories of the remaining stands. Without knowledge about the development for the trees expected to remain until final harvest, the idea of replacing PCT and first CT with a single BT in strips cannot be conveyed to practical forestry.

Considering the large BT potential in Sweden with an estimated area of 2.1 – 9.8 M ha (Fernandez-Lacruz et al., 2015), we aim to analyse how different BT thinning methods affect the growth and development of

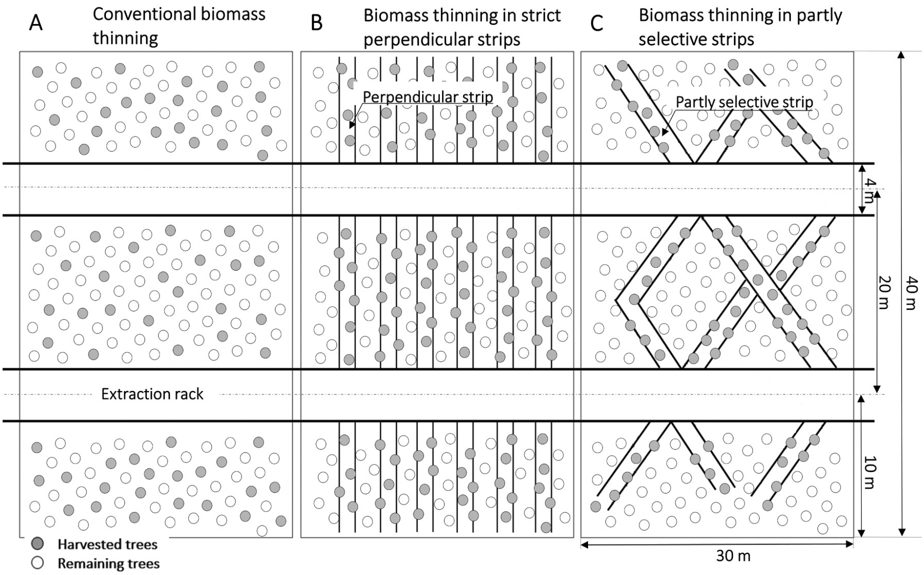

Fig. 1. Schematic representation of biomass thinnings. A: Conventional biomass thinning (BT_{conv}) from below. B: Strict biomass thinning (BT) in strips of 1 or 2 m wide. C: Selective biomass thinning (BT_{sel}) in 1 meter wide strips where the direction and angle of the strip was selected according to the thinning objectives.

three cohorts of remaining trees after thinnings. Based on data from a field experiment established in young tree-dense Norway--spruce-dominated forests in Southern Sweden we compare three types of BT in 1 – 2 m strips (i.e. strict BT in 1- and 2-m strips and semi-selective BT in 1-m strips) with the conventional biomass thinning (BT_{conv}) and untinned (UT) control as reference treatments. The analysed cohorts are all undamaged trees directly after the thinnings (*all crop trees)*, the 500 largest trees for final harvest (*500-largest crop trees)*, and the next 400 largest trees for second CT (*crop trees from 501 to 900)*. We expected no difference in growth and yield between the BT in 1 – 2 m strips and the BT_{conv} in spruce-birch mixtures for the cohort of *all crop trees* as previously reported in pine-birch mixtures (Nuutinen and Miina, 2023). However, we expected to experience some differences in growth and yield for cohort of *500-largest crop trees* and *crop trees from 501 to 900* because of the higher competition from the higher numbers of remaining trees following BT in 1 – 2 m strips (Ahnlund Ulvcrona et al., 2017).

2. Material and method

2.1. Study design

A long-term experiment with three treatments of BT in strips, along with two reference treatments, namely BT_{conv} (conventional thinning from below) and UT (unthinned) was established in Southern Sweden on three sites (i.e. blocks) with fertile moraine soil and similar site conditions (Table 1). All selected sites were Norway spruce plantations with a planting density of 2 000 trees ha^{-1}. A high number of naturally regenerated broadleaves such as *Betula spp., Salix spp., Populus tremula* L. *and Sorbus aucuparia* L. added to the total tree density ranging from 5 800–11 800 trees ha^{-1}. Birch (*Betula pendula* L. *and Betula pubescens* L.) was by far the dominating naturally regenerated species.

The experimental plots were rectangular, varying in size from 0.10 to 0.12 ha, surrounded by a 5 m wide buffer zone. Before the thinnings, diameter at breast height (dbh) was measured and trees were identified by species for all trees above 1.3 m in height. For all BT, but the UT control, 4 m wide extraction racks were established with 20 m distance in between extraction racks centreline. Conventional biomass thinnings (BT_{conv}) and BT in 1 – 2 m wide strips were then applied in between extraction racks (Fig. 1).

All treatments were randomly assigned to one experimental plot per site. The general guidelines of treatments as follows:

UT – Unthinned (control) plot without tree removal;

BT_{conv} – Conventional selective above-ground biomass harvesting from below of individual trees between extraction racks. The main goal for the treatment is to leave as many planted Norway spruce trees on site as possible;

BT_{1m} – Systematic harvesting of all trees in 1 m wide and 10 m long strips (i.e. harvesting 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 during the harvest;

BT_{2m} – Systematic harvesting of all trees in 2 m wide and 10 m long strips running from the extraction rack centre in 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 during the harvest;

BT_{sel} – Systematic and partly selective harvesting 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 90–60 degree angle with the liberty to leave as many Norway-spruce trees as possible on site and to achieve full crane depth. The BT_{sel} method is similar to the V-shaped (chevron) thinning method that is employed in North America, Britain, and Central Europe (Smith et al. 1997).

The detailed guidelines and description of thinning executions are described in Ahnlund Ulvcrona et al. (2017). Data of the remaining and harvested stand directly after the treatments including UT reference treatment is summarised in Table 2.

Immediately after thinning all remaining trees within an experimental plot were cross-calipered and recorded by species (*first inventory*). Trees with dbh ≥4.5 cm were tagged with individual ID number and the dbh position was marked for future measurements. Damages were recorded for all trees with individual ID. A detailed classification of the damages measured during the *first inventory* is presented in Appendix 1. In addition, height and height to the living crown were measured on sample trees. Two types of sample trees, among both spruce and birch trees, were sampled. The permanent G-type sample trees were selected from among the largest trees (based on dbh), and the temporal R-type sample trees were randomly chosen across diameter classes (class width 2 cm), with a higher selection probability for larger trees following a standard protocol at the Unit for Field-based Forest Research, SLU (Karlsson et al., 2012). The number of sample trees per experimental plot for each species ranged from 4 to 8 for G-type sample trees and from 12 to 16 for R-type sample trees. In total approximately 10 G-type and 30 R-type sample trees per experimental plot were selected. Additionally, for each birch sample tree, the bark thickness was measured to estimate the stem-volume using Brandel's (1990) functions 100–03.

Five to six years later the complete stand inventory was repeated in a *second inventory* following the same routine as the *first inventory*. Data from this second inventory form the basis for this study.

2.2. Data processing

Analyses were made for three different cohorts of undamaged trees, remaining directly after thinning. The first cohort included all remaining trees (dbh ≥ 4.5 cm at the *first inventory*) without visible damages directly after the thinning hereafter called *all crop trees*. The second cohort, *500-largest crop trees*, included the largest (based on dbh) undamaged post-thinning trees, corresponding to ~ 500 trees ha^{-1}, assuming these trees will remain until final felling. Based on 0.12 ha of experimental plot size in Erikstad and Torared, this were the 60 largest trees per experimental plot and the 50 largest trees in Stretelid, where the experimental plot size was 0.10 ha. The third cohort, *crop trees from 501 to 900* corresponding to ~ 400 undamaged post-thinning trees ha^{-1}, likely to be cut in a second CT. Based on experimental plot sizes this were the 48-largest trees per experimental plot in Erikstad and Torared and the 40-largest trees in Stretelid. The tree species composition based on the number of trees for each corresponding cohort is detailed in Table 3.

Mean height and stem-volume (m^3 ha^{-1}) were estimated based on

Table 1
Study site characteristics.

Site	GPS (DMS)	Year of planting	Soil type	Soil moisture	Soil texture	Altitude	Site index*
Erikstad	57°1′39"N 13°55′56"E	1994	Morain	Mesic	Sandy-silt	175	37
Stretelid	57°0′8"N 14°2′36"E	1996	Morain	Mesic	Sand	160	34
Torared	56°39′56"N 13°6′33"E	1987	Morain	Mesic	Sandy-silt	118	32

* Top height at age of 100 years of dominant Norway spruce trees (Hägglund and Lundmark, 1977)

Table 2
Stand data after different thinning treatments (including trees without ID number *i.e.* trees ≤ 4.5 cm in dbh; *left*), and data for the harvested trees (*right*), for three experimental sites in southern Sweden. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 m wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

Treatment	REMAINING STAND							REMOVED IN THINNING				Removed basal area (%)
	No of trees (N ha.1)	Volume (m^3 ha^{-1})	Mean dbh (cm)	Basal area (m^2 ha^{-1})	Top height (m)	Mean height (m)	Damaged trees* (N ha^{-1})	No of trees (N ha^{-1})	Volume (m^3 ha^{-1})	Mean dbh (cm)	Basal area (m^2 ha^{-1})	
Erikstad												
UT	11810	139.9	5.6	29	11.9	8.7	1080	0	0	0	0	0
BT_{conv}	845	35.6	9.7	6.3	11	10.6	435	6652	68.9	6.3	20.8	76.8
$BT_{1\ m}$	3340	67.8	7.1	13.2	11.1	9.4	928	2469	32.5	7.3	10.4	44.1
$BT_{2\ m}$	7281	66	5	14.4	10.7	8.1	201	4360	28.8	5.2	9.3	39.2
BT_{sel}	3807	91	7.6	17.4	11.8	9.8	697	3574	30.8	5.9	9.9	36.3
Stretelid												
UT	9934	61.4	4.5	15.7	8.6	7	170	0	0	0	0	0
BT_{conv}	1841	31.4	7.5	8.1	8.4	7.3	584	3779	31.3	5.2	8.1	50
$BT_{1\ m}$	3303	33.8	5.7	8.4	8.9	7.6	602	3303	24.9	5.1	6.8	44.7
$BT_{2\ m}$	4374	27.6	4.6	7.2	8.6	6.9	601	3537	16.4	4.3	5.1	41.5
BT_{sel}	4247	32.7	5.2	8.9	8.4	6.6	623	3344	24.7	5.1	6.7	42.9
Torared												
UT	7161	148.8	6.9	26.7	13	10.2	1266	0	0	0	0	0
BT_{conv}	817	51.6	11.3	8.2	12.3	12.6	17	7790	103.1	5.7	19.7	70.6
$BT_{1\ m}$	5203	63.8	5.6	13	11.7	9.1	284	3561	38.7	6.3	11	45.8
$BT_{2\ m}$	5844	87.5	6	16.7	12.9	9.8	205	4276	39.3	5.8	11.4	40.6
BT_{sel}	5649	105.4	6.4	18	13.8	10.9	206	5402	44.1	5.2	11.5	39

* Damages were recorded only for trees ≥4.5 cm in dbh

Table 3
Tree species composition of Norway spruce (S), birch (B), and Scots pine (P) across various cohorts within experimental plots. The numbers represent each species stem density as a proportion (%) of the total stem number. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 m wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

Treatment	All crop trees	500-largest crop trees	Crop trees from 501 to 900
UT	S61B39	S65B35	S74B26
BT_{conv}	S91B8P1	S91B7P2	S89B11
$BT_{1\ m}$	S66B34	S88B12	S73B27
$BT_{2\ m}$	S69B30P1	S90B8P2	S82B16P2
BT_{sel}	S72B28	S94B6	S93SB7

measured sample trees (G- and R-type) within species-specific 2-cm diameter classes and the total number of trees within that class. Stem-volume for sample trees were calculated with functions by Brandel (1990) using dbh, height, and height to the living crown for Norway spruce (function 100–02) and birch (function 100–03, also including bark thickness) as independent variables.

For diameter analysis, we used quadratic mean diameter (QMD, cm) where greater weight is assigned to larger trees (Eq. (1); Curtis and Marshall, 2000).

$$QMD = \sqrt{\frac{\sum dbh_i^2}{n}}. \tag{1}$$

In Eq. (1), dbh_i is cross-calipered mean diameter of each individual tree at breast height of the i^{th} tree, measured at 1.3 m above the ground, and n is the number of measured trees.

The basal area (BA, m^2 ha^{-1}) was estimated from cross-calipered dbh of individual trees based on the formula for the area of a circle. Mean annual volume increment (VI, m^3 ha^{-1} $year^{-1}$) was calculated as difference in standing volume between the second and first inventory cycles divided by the number of full growing seasons. In the same way, mean annual basal area increment (BAI, m^2 ha^{-1} $year^{-1}$) was calculated.

During the second inventory, new tree damages among the undamaged post-thinning trees were assessed and recorded using a binary classification system. Under this system, each tree was classified as either “damaged” or “undamaged”. In the statistical analyses the proportion of “*new damages*” per plot (%) were used. The motivation for this binary classification system stems from the observation that, over a period of five to six years, the most common damage type was attributed to wind and snow, i.e. no need for deeper analyses of the cause or type of damage.

2.3. *Statistical analysis*

2.3.1. *Analysis of stand data: number of trees, standing volume, height, diameter, and basal area*

A linear mixed model from `lme4` package (Bates et al., 2015) in R studio (R Core Team, 2022) was used to analyse the influence of different treatments on the response variables for tested cohorts of trees. Response variables tested were number of trees ha^{-1}, standing volume, mean height, QMD, and BA. Treatment was used as explanatory variable and site as random effect. The linear mixed model (Eq. (2)) applied in the analysis of variance was:

$$X_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \tag{2}$$

In Eq. (2), X is the response variable (number of trees ha^{-1}, standing volume, mean height, QMD and BA). The response variable, number of trees per hectare, was used only in analyses for the cohort of *all crop trees*. The μin Eq. (2) is the regression coefficient, a_i and β_j are treatment and site, which are applied as fixed and random effects, respectively. The ε in model is the random error term.

To assess the differences between the treatments, a multiple pairwise comparison of means was performed as provided by the Tukey post-hoc test (`emmeans` package; Lenth, 2022). A significance level of $p \leq 0.05$ was chosen as threshold for all analyses.

2.3.2. *Analysis of stand periodic development: mean volume increments, mean basal area increment, and proportion of new damages*

A linear model (Eq. (3)) from the basic `stats` package (R Core Team, 2022) was used to analyse periodic development variables, such as mean annual volume increment (VI, m^3 ha^{-1} $year^{-1}$), mean annual basal area increment (BAI, m^2 ha^{-1} $year^{-1}$), and proportion of new damages since the first thinning. These variables define the stand development over the 5–6 growing seasons. The different treatments were used as the explanatory variable. A linear mixed model as in the Eq.

(2) with site as a random factor was initially attempted, however the variance and standard deviation of statistical model for site variable in the third cohort, *crop trees from 501 to 900,* for the response variables VI and BAI was zero. This indicated that the site factor did not explain any variation in the data. Therefore, a simpler linear model without site was used. The linear model (Eq. (3)) applied in the analysis of variance was:

$$X_i = \mu + \alpha_i + \varepsilon_i \quad (3)$$

In Eq. (3), X is the response variable (VI, BAI, and proportion of new damages). The μin Eq. (3) is the regression coefficient, α_i is the explanatory variable i.e. treatment, and ε is the random error term. Similar to the linear mixed model (Eq. (2)) the differences between the treatments were assessed by a multiple pairwise comparison of means as provided by the Tukey post-hoc test and significance level of $p \leq 0.05$ was chosen as threshold for all analyses.

3. Results

3.1. Stand data: number of trees, standing volume, height, diameter, and basal area

For the cohort *all crop trees*, the treatments had a significant effect on the number of trees ($p = 0.005$), standing volume ($p = 0.002$), quadratic mean diameter (QMD, $p = 0.03$), and basal area (BA, $p = 0.005$). The UT plots resulted in significantly higher number of trees (3 039 trees ha^{-1}) and BA (21.8 m^2 ha^{-1}) than the BT_{conv} (891 trees ha^{-1}, $p = 0.005$; 10.7 m^2 ha^{-1}, $p = 0.006$) and $BT_{1\ m}$ (1 380 trees ha^{-1}, $p = 0.027$; 11.5 m^2 ha^{-1}, $p = 0.009$). Standing volume in UT control (127.1 m^3 ha^{-1}) was also significantly higher than the standing volume following BT_{conv} (62.5 m^3 ha^{-1}, $p = 0.004$), $BT_{1\ m}$ (64.7 m^3 ha^{-1}, $p = 0.005$), and $BT_{2\ m}$ (80.8 m^3 ha^{-1}, $p = 0.026$). The BT_{sel} (103.6 m^3 ha^{-1}) also resulted in significantly higher standing volume than the BT_{conv} ($p = 0.047$). Significantly lower QMD was found in UT control (9.6 cm, $p = 0.028$) and $BT_{2\ m}$ (9.9 cm, $p = 0.047$) compared to the BT_{conv} (12.9 cm; Table 4).

The treatment had no significant effect on any of the tested stand variables (i.e. the standing volume, height, diameter, and basal area) for the cohort of *500-largest crop trees*. For *crop trees from 501 to 900* treatments had a significant effect only on the QMD ($p = 0.034$). This effect was mostly driven by the close-to-significant difference ($p = 0.07$) between $BT_{1\ m}$ (QMD = 9.4 cm) and BT_{sel} (QMD = 11.3 cm; Fig. 2) when Tukey post-hoc test for the differences among individual treatments was applied.

3.2. Stand periodic development: mean volume increments, mean basal area increment, and proportion of new damages

The linear models (Eq. (3)) indicated that the treatment did not significantly affect the periodic development of the stand in any of the cohorts, including mean volume increment (VI), mean basal area increment (BAI), and the proportion of new damages (Table 4; Fig. 3). Although not statistically significant, the proportions of new damages was higher following BT_{conv} compared to UT (4-times), as well as compared to $BT_{1\ m}$ (10-times), $BT_{2\ m}$ (3-times), and BT_{sel} (2-times) for the cohort of the *500-largest crop trees*. A similar trend was observed also for the *501–900 crop trees*. Additionally, the variation in the proportions of new damages was the largest across the experimental sites compared to all the other measured response variables.

4. Discussion

Our results for *all crop trees* are as expected and consistent with previous findings by Nuutinen and Miina (2023), who reported that BT in 1 – 2 m strips (i.e. boom-corridors) did not result in growth or yield losses compared to conventional BT (BT_{conv}) in Scots pine-birch mixtures. Similarly, our findings in the spruce-birch mixtures showed that BT in 1 – 2 m strips had no significant effect on the cohort of *all crop trees* compared to BT_{conv}, except for the significant difference between $BT_{2\ m}$ and BT_{conv} for QMD (Table 4). However, when we compared the strict BT in 1 – 2 m strips ($BT_{1\ m}$ and $BT_{2\ m}$) to the unthinned (UT) control, we found a significant effect on the cohort of *all crop trees* in terms of the number of trees remaining, standing volume, and BA. These results are not surprising in the short term, considering the length of our follow-up study, which was five to six growing seasons after the thinning, and the differences in number of trees and standing volume retained following the different treatments (Table 2; Ahnlund Ulvcrona et al., 2017). Nevertheless, from the perspective of economical forest management, where high quality timber production (i.e. saw logs) is important, the key finding of this study was that the different thinning treatments did not affect stand variables (Fig. 2) and the periodic stand development (Fig. 3) for the *500-largest crop trees* over the first five- to six-year period. However, some variables, such as standing volume, BA (Fig. 2), and proportion of new damages (Fig. 3), showed more noticeable differences among the treatments for the *crop trees from 501 to 900*, but again none of these were significant. The absence of significant short-term effects for this cohort was surprising, given the difference in stand structure post-thinnings (Table 2; Fig. 4). These unexpected results could be attributed to the inherent variability of the remaining stand and when combined with the limited number of experimental sites, this variability may hinder our ability to detect statistically significant patterns. Increasing the number of experimental sites could mitigate this variability, especially for irregular and unpredictable events such as wind and snow damage, thus improving the chances of identifying statistically significant trends. Despite these challenges, the extensive research on the effects of wind and snow damage related to thinning intensities (Ruel et al., 2001; Urban et al., 1994; Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014; Tabbush and White, 1988) provides valuable insights regarding the damage risk during the post-thinning period, with a strong relationship between thinning intensity and damages.

While the design of the experiment may have affected the recognition of significant findings, it is notable that the BT_{conv} and BT_{sel} may lead to a higher occurrence of new damages across all three cohorts after thinning, compared to other treatments (Table 4, Fig. 3). The high stem

Table 4
Stand data after different thinning treatments for the cohort *all crop trees*. Mean values following different thinning treatments are presented as mean (±SE) across study sites (n=3). Different letters in the superscripts indicate significant differences between treatments based on Tukey's multiple comparison test. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 m wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

Treatment	No of trees (N ha^{-1})	Standing volume (m^3 ha^{-1})	Quadratic mean diameter (cm)	Mean height (m)	Basal area (m^2 ha^{-1})	Volume increment (m^3 ha^{-1} yr^{-1})	Basal area increment (m^2 ha^{-1} yr^{-1})	Proportion of damaged trees (%)
UT	3039^{a}±224	127.1^{a}±15.5	9.6^{a}±0.5	10.4±0.7	21.8^{a}±1.2	8.6±0.4	1.04±0.2	5±2
BT_{conv}	891^{b}±216	62.5^{bc}±9	12.9^{b}±2.8	12.3±2.1	10.7^{b}±0.9	5.1±0.5	0.8±0.1	18±13
$BT_{1\ m}$	1380^{b}±278	64.7^{bc}±13.6	10.3^{ab}±1	10.6±0.9	11.5^{b}±2.1	5.1±0.7	0.74±0.1	5±3
$BT_{2\ m}$	1859^{ab}±441	80.8^{bc}±24.2	9.9^{a}±0.2	9.7±0.4	14.6^{b}±3.8	6.4±1.5	0.96±0.2	8±5
BT_{sel}	1892^{ab}±234	103.6^{ab}±28.5	10.6^{ab}±0.5	11.2±1.2	17.1^{ab}±3.5	7.6±1	1.03±0.1	13±11

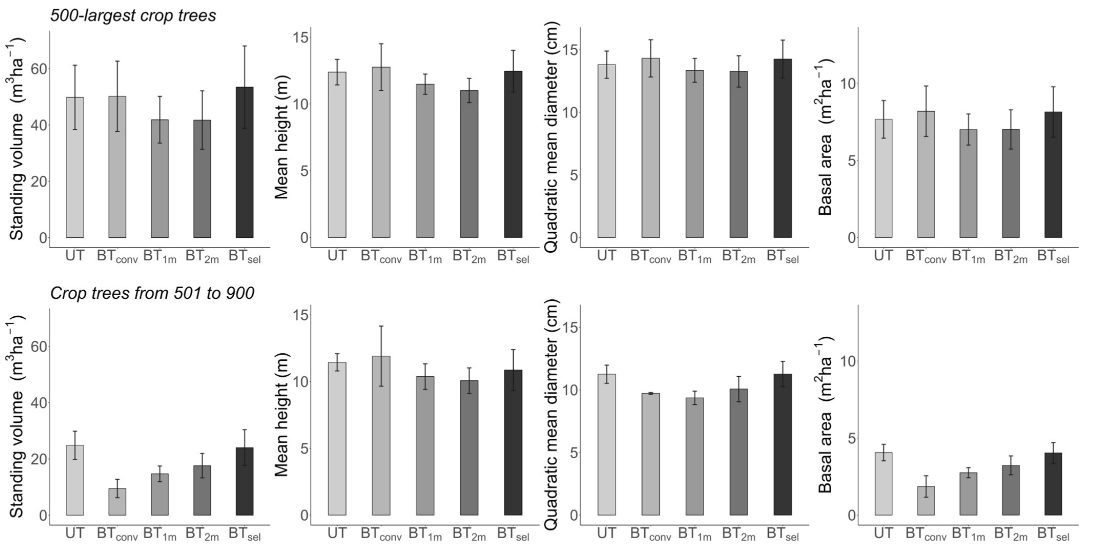

Fig. 2. Stand variables 5–6 years after different treatments for two cohorts in the residual stand, the *500-largest crop trees,* and the *crop trees from 501 to 900*. Mean values for different treatments are presented as mean (±SE) across study sites (n=3). No significant differences among treatments were found by statistical tests. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 meter wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

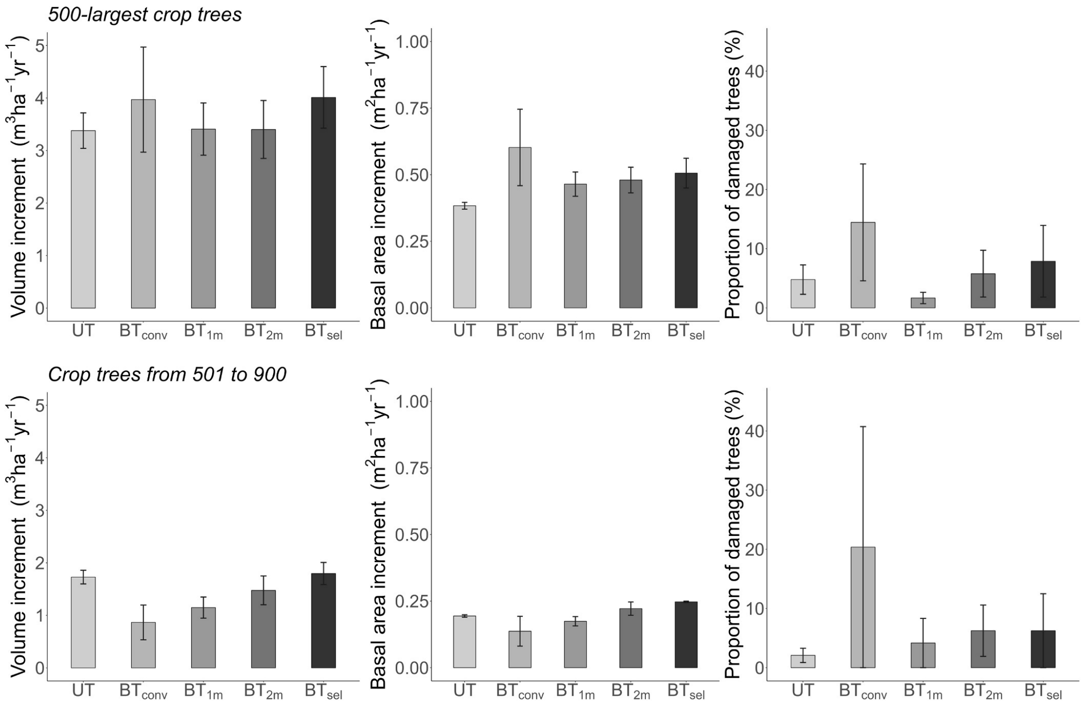

Fig. 3. Stand periodic development 5–6 years after different treatments for two cohorts in the residual stand, the *500-largest crop trees,* and the *crop trees from 501 to 900*. Mean values following different thinning treatments are presented as mean (±SE) across study sites (n=3). No significant differences among treatments were found by statistical tests. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 meter wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

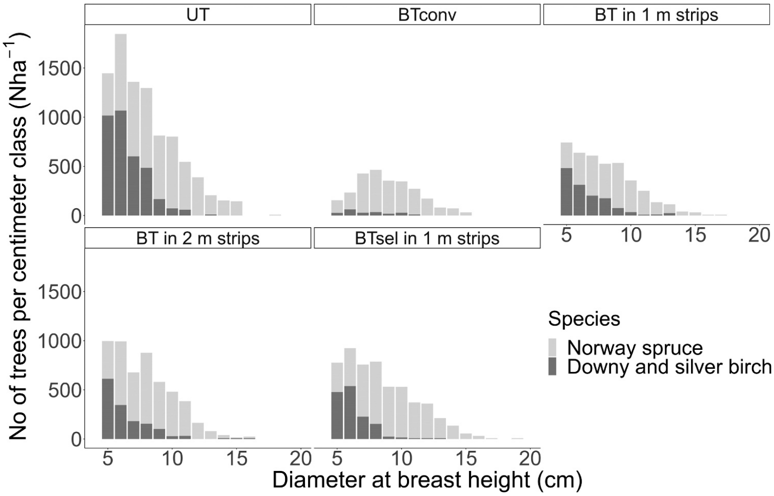

Fig. 4. Diameter distribution of Norway spruce, downy and silver birch for cohort of a*ll crop trees* across all study sites (n=3) following different thinning treatments. The thinning treatments are unthinned (UT), conventional biomass thinning (BT_{conv}), biomass thinning in 1 m wide strips ($BT_{1\ m}$), biomass thinning in 2 m wide strips ($BT_{2\ m}$), and selective biomass thinning in 1 m wide strips (BT_{sel}).

density before thinning (Table 2) may have affected the development of the crown and stem for both major tree species, i.e. Norway spruce and birch, making them susceptible to wind and snow disturbances after thinning (Hynynen et al., 2010; Hynynen, 1993). Silver birch can only maintain vitality and growth at a maximum density of around 600 trees ha^{-1}, but shade-tolerant Norway spruce could grow at a density of around 1400 trees ha^{-1} (Hynynen, 1993). This suggests that the birches have suffered most from the high tree densities. However, our data show that fewer birches were retained following BT_{conv}, the treatment with the highest damage rate, compared to all other treatments (Table 3; Fig. 4). Therefore, we assume that the severe wind damage that occurred shortly after the BT_{conv} at one of our study sites (Torared) was a result of the high thinning strength (70 % of BA and 90 % of the stems harvested, cf. Table 2), and this explains both the increase in damages in BT_{conv} and the large variation in the data (Fig. 3). This is supported by other studies showing a positive correlation between thinning strength and damages in the residual stand shortly after the thinnings (Ruel et al., 2001; Urban et al., 1994; Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014; Tabbush and White, 1988). High thinning intensity in BT_{conv}, resulted in longer distances between neighbouring trees compared to BT in strips (Becs et al., 2023), and this likely causes a temporarily decrease in stand resilience to wind damage by losing the neighbouring trees for support (Gardiner et al., 1997). In this sense, BT in strips is likely to be superior since the distance to neighbouring trees is kept short (Becs et al., 2023).

This far, our results do not contradict the idea of omitting early selective thinnings, i.e. PCT and first CT, and instead practice BT in strips. However, the extraction of whole-above ground biomass as applied in BT in strips also entails some risks that should not be overlooked. For example, even at a moderate increase in biomass extraction following whole-tree harvest (including branches, treetops, and foliage) as it is practiced during the BT in strips comes at the cost of a substantial increase in nutrient export from the site with a potential risk for reduced growth in the residual stand (thinnigs) and subsequent stand (final felling; Hakkila et al., 1997). Indeed, decreased growth in the residual stand has been reported following whole-tree harvest in thinning of Norway spruce and Scots pine stands (Egnell and Ulvcrona, 2015; Helmisaari et al., 2011; Jacobson et al., 2000; Nord-Larsen, 2002). But the results are not consistent over all sites and there are studies showing no effect (Egnell and Leijon, 1997). All of these studies report short to medium term responses and concern has been raised for possible long-term effects on growth (Helmisaari et al., 2011). However, results presented by Egnell and Ulvcrona (2015) and Egnell (2011) suggest short-term effects in Scots pine and Norway spruce, and modelling results by Heikkilä et al., (2007) suggests only marginal growth losses over a rotation in Scots pine. Nevertheless, whole-tree harvest over full rotation period needs further attention (Kaarakka et al., 2014). Since the nutrient concentration is higher in foliage and finer branches (Mälkönen, 1976), on site defoliation has been suggested as a measure to counteract potential growth reductions and there is evidence that this has a counteracting effect both in thinnings (Nord-Larsen, 2002) and in final felling (Egnell and Leijon, 1999). Therefore, to lower the risks of production losses associated with whole-tree harvest, thinning and harvesting technologies that partly defoliates fine branches and needles has been evaluated (Bergström and Di Fulvio, 2014).

Besides the long-term production concerns, replacing the CT with BT in strips raises an important management question: how to conduct the next thinning. The suitable thinning methods in question could be either the traditional CT from below or a second BT in strips. This question is crucial because the trees remaining after the second thinning will include the crop trees for the final felling, i.e. high-quality trees with a high growth potential. Experiences of a second CT from below are well established and the expected outcomes are known in terms of stand development (Nilsson et al., 2010) when conventional even-aged forest management is practiced. However, the stand development and growth of individual trees following a second BT in strips are largely unknown. Additionally, costs and revenue from different thinning methods in later stages of forest management are also relevant factors to consider. This is particularly important because the lower density of remaining crop trees (Table 4) after the first conventional thinning (i.e. BT_{conv}), as observed in our study, may affect the marginal profitability in a subsequent CT (Kärhä et al., 2004). Considering the higher number of remaining trees (Table 4) following the BT in strips in this study, forest managers who are driven by profit may prefer the second thinning as CT from below. It will allow them to extract more trees and possibly generate higher profits due to the higher number of trees harvested. On the other hand, this also means that the trees with lower diameters (Table 4) will be harvested, which will increase the harvesting cost per tree (Chang et al., 2023; Eliasson et al., 2019). Moreover, it would also mean a higher thinning strength to meet the target number of crop trees for the final felling, which could increase the risk for damages from wind and snow (Gardiner et al., 1997; Ruel et al., 2001; Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014; Pukkala et al., 2016). Therefore, in order to lower potential risk of wind and snow damages for the crop trees, and keep the harvesting cost low, BT in strips could be a favourable option also in a second thinning.

While the short-term results following BT in strips indicate a promising increase in the diversity of remaining tree species (Ahnlund Ulvcrona et al., 2017; Table 3) and greater diversity in tree size contributing to a more complex spatial forest structure (Becs et al., 2023) it is cautious to consider the sustainability of these outcomes. Given the complex dynamics of competition levels post-BT in strips, which might be more complex than those following BT_{conv}. These complexities arises because the forest following BT in strips retains the understory trees that are not harvested during the thinning, which potentially creates a stratified canopy with multi-story competition. In the first-story canopy, the *500-largest crop trees* typically dominate while the *crop trees from 501 to 900* occupy the second-story. A study on the stand dynamics of mixed spruce-birch forests suggests that both species can coexist if their diameters and heights are similar (Fahlvik et al., 2005; Huuskonen et al., 2022). In the data for thinned stands presented here, the proportion of birch trees, with the potential to reach the final felling (first-story canopy), was highest following $BT_{1\ m}$, around 12 % (Table 3). However, trees in the second-story are likely to exhibit different and more complex competition dynamics due to the influence of the first-story canopy on the quantity and quality of light (Messier and Bellefleur, 1988). This competition for light and space in multi-storied forests often leads to more slender trees, which in turn affects the shape and size of the tree crown, crucial for future growth, particularly for light-demanding birch (Bergqvist, 1999; Brand, 1986; Greis and Kellomäki, 1981; Hynynen et al., 2010; Hynynen, 1993; Messier and Puttonen, 1995; Mård, 1996). Meanwhile, Norway spruce, being shade-tolerant, can adapt to a wide variety of light conditions and exhibit better growth also in the second-story canopy (Bergqvist, 1999; Hynynen et al., 2010; Hynynen, 1993; Nilsson, 1993). These properties may help spruce trees in the second-story canopy to grow and develop until the end of the rotation. Furthermore, BT in strips creates openings for the development of another story, likely to be occupied by light-demanding birch (Hynynen et al., 2010; Kuuluvainen and Aakala, 2011; Lidman et al., 2023). Given the presence of birch in the second-story canopy and potentially in the third-story, coupled with the intense struggle for sunlight within the spruce-dominated stand (Table 3), implementing BT in strips also in the second thinning may maintain the competition among the remaining trees. This is particularly true for the densely populated patches between the strips, which could result in an increased rate of mortality due to self-thinning processes that are akin to those observed in forests that have not been thinned (Nilsson et al., 2010). Although high mortality may be perceived as a loss in production and growth, it can also serve as a source of small to medium-diameter broadleaved coarse woody debris. This debris may help to restore nutrients lost during whole-tree harvesting, which could benefit both biodiversity and forest growth (Bergström and Di Fulvio, 2014; Hekkala et al., 2023; Jonsson et al., 2016; Marchetti, 2004).

5. Management implications

Our short-term results suggest that BT in strips (i.e. $BT_{1\ m}$, $BT_{2\ m}$, BT_{sel}) could be an alternative to a delayed and costly selective PCT or to an early selective CT and BT_{conv} in young tree-dense spruce-birch mixed forests in Southern Sweden. These thinning methods do not compromise the growth of the most relevant crop trees (i.e. the *500-largest crop trees* and the *next 400-largest crop trees*) five to six year post-thinning. Our results also indicate that BT in strips can reduce the risk of losing too many crop trees due to the high thinning strength associated with BT_{conv} from below in tree and biomass-dense young stands. Therefore, we suggest that more extensive, long-term research covering a wider geographical scale is needed before these novel-thinning methods can be fully recommended to forest owners throughout Northern Europe at a large scale.

CRediT authorship contribution statement

Gustaf Egnell: Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization. **Emma Holmström:** Writing – review & editing, Methodology, Conceptualization. **Dan Bergström:** Writing – review & editing, Supervision, Conceptualization. **Lenka Kuglerová:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Artis Becs:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1. Recorded causes of damages for trees above 4.5 cm in diameter at breast height. For each tree, no more than four instances of damages were recorded. If a tree exhibited more than four damages, the order of significance presented in the table was followed

Rank	Cause of damage in order of ranking	No of damage classes	Definition of damage classes
1	Dry and, or felled tree	3	Dry standing tree; Dry lying tree; Still living felled tree:
2	Stem breakage	3	Stem snapped in the upper part of the green crown; Stem snapped in the lower part of the green crown; Stem snapped below the green crown:
3	Dry top	3	Dry top < 20 cm; Dry top 20–50 cm; Dry top > 50 cm:

(*continued on next page*)

(*continued*)

Rank	Cause of damage in order of ranking	No of damage classes	Definition of damage classes
4	Deformed diameter at breast height	1	Stem deformation appears at breast height
5	Stem wound	3	Stem wound covering < 1/8 of the circumferences; Stem wound covering 1/8–14 of the circumferences; Stem wound covering > 1/4 of the circumferences;
6	Fungi damages	1	Visible signs of fungal fruiting body on the stem.
7	Leaning trees	1	E.g. snow bent
8	Tree fork	3	Tree fork in the lower part of the stem (lower 1/3); Tree fork in the central part of the stem (middle 1/3); Tree fork in the upper part of the stem (upper 1/3)
9	Root-rot	1	If only fruiting-body or rotten wood can be seen
10	Spike knot	3	Spike knot in the lower 1/3 of the stem; Spike knot in the middle 1/3 of the stem; Spike knot in the upper 1/3 of the stem:
11	Down grading of logs	1	E.g. crooked stem, course dry branches, stem damage with major effect on wood quality and thereby value
12	Suppressed tree	3	Tree with the green crown affected sideways; Tree with small crown below green crown of supressing trees; Previously suppressed tree where the green crown has potential to recover:

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II

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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, especially in 1 or 2 m-wide strips, resulted in higher spatial tree diversity compared to conventional biomass thinning. Hence, in mixed conifer-broadleaved forests, biomass thinning in 1 or 2 m-wide strips is recommended for maintaining spatial tree diversity.

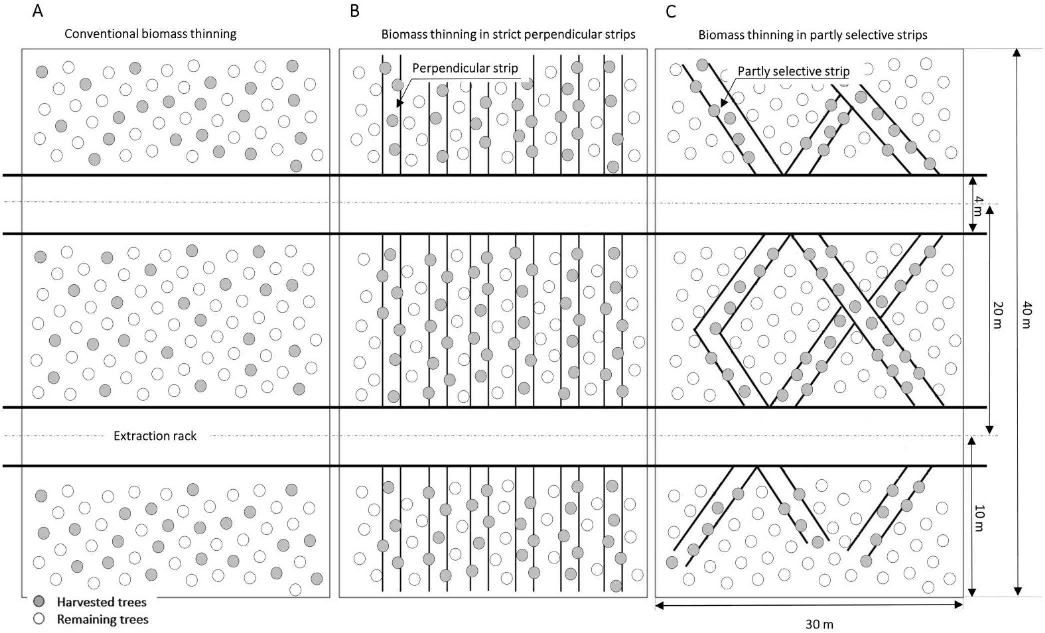
Key words: biomass, geometrical thinning, boom-corridor, species mingling, spatial tree diversity

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 biomass-rich 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 abi*es 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-

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

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

*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 Agency[1] (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 × 40 m surrounded by a 5 m-wide buffer zone. For all treatments but the unthinned (UT) control, 4 m-wide 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 m-long 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 m-long 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 cross-calipered 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

[1] These 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.

Table 2. Summary of stand structure characteristics involving all trees with a stem diameter larger than 5 cm from three sites in southern Sweden.

Site	Treatment	Stem number (N ha^{-1})	Mean dbh (cm)	Mean height (m)	Top height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Erikstad	UT	4562	9.0	10.3	14.7	30.5	179.5
	CT	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
	CT	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
	CT	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

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 non-spatial 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, $\mathbf{E}r$, under the condition of complete spatial randomness (CSR) of tree locations. The aggregation index is estimated according to eq. 1:

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

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.

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

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

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 $\mathbf{1}(m_i \neq m_j) = 0$. 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., $0/k, 1/k, \ldots, k/k$ (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 $\widehat{M}$.

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

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

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.

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

$T_i = 0$ 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 $j = 1, \ldots, k$. 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, $\widehat{T}$, is estimated using the NN1 estimator, which compensates for spatial edge effects (Pommerening and Stoyan 2006).

Expected size differentiation, $\mathbf{E}T$, 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):

$$(5) \qquad \Upsilon = 1 - \frac{\widehat{T}}{\mathbf{E}T} \Upsilon \in [-1, 1]$$

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, $\widehat{M}, \Psi$, $\widehat{T}$, 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:

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

In eq. 6, X is the response variable ($R, \widehat{M}, \Psi$, $\widehat{T}$, and Υ); i, j are indices of experimental site and treatment; $\mu_{0,\ldots,3}$ 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 ($\widehat{M}$, eq. 2), size differentiation ($\widehat{T}$, eq. 4), species (Ψ, eq. 3), and size (Υ, eq. 5) segregation.

Treatments	Values of the tested response variables				
	R	$\widehat{M}$	Ψ	$\widehat{T}$	Υ
UT	1.11 ± 0.02^{a}	0.45 ± 0.04^{a}	0.024 ± 0.02	0.280 ± 0.05^{a}	0.012 ± 0.01
BT_{conv}	1.17 ± 0.08^{a}	0.19 ± 0.05^{b}	-0.018 ± 0.06	0.214 ± 0.02^{b}	0.066 ± 0.12
BT_{1m}	0.93 ± 0.1^{b}	0.46 ± 0.02^{a}	0.014 ± 0.02	0.290 ± 0.03^{a}	0.003 ± 0.002
BT_{2m}	0.92 ± 0.05^{b}	0.44 ± 0.04^{a}	0.057 ± 0.1	0.294 ± 0.03^{a}	-0.002 ± 0.01
BT_{sel}	1.06 ± 0.04^{ab}	0.39 ± 0.09^{a}	0.026 ± 0.02	0.285 ± 0.05^{a}	0.013 ± 0.01

Note: Values for each index are presented as mean (±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, $\widehat{M}$ (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} ($p = 0.001$ for 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 $\widehat{M}$ 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

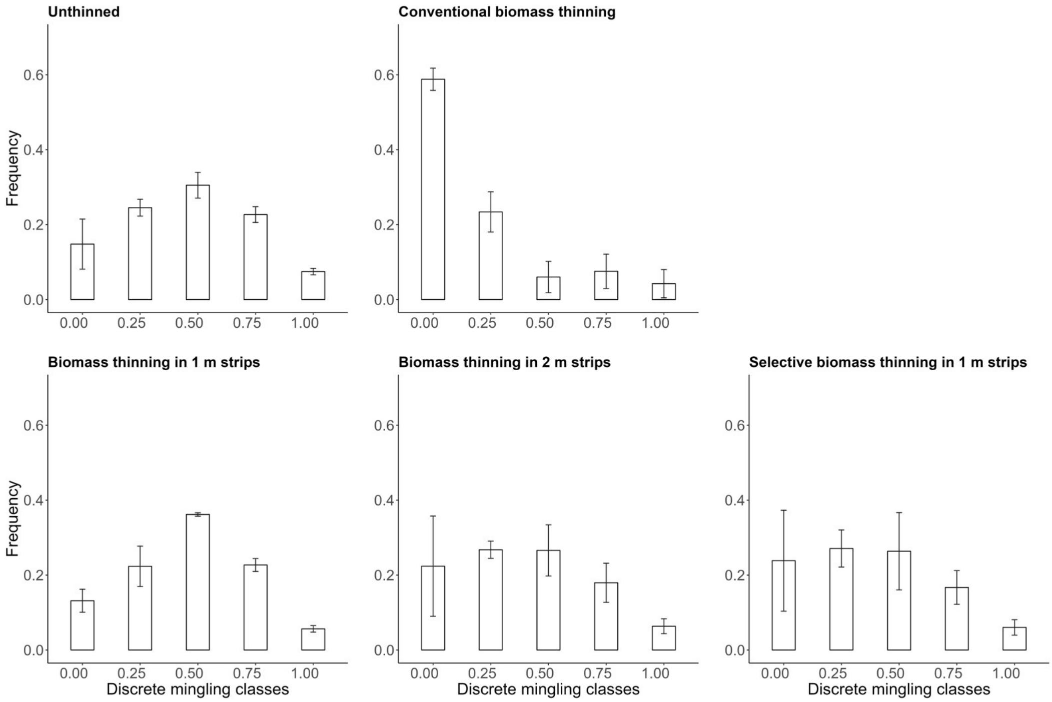
Similar to species mingling, size differentiation, $\widehat{T}$ (eq. 4) was significantly affected by the treatment ($p = 0.002$) tested in Anova. The significant differences in $\widehat{T}$ in terms of the different treatments UT, BT_{conv}, BT_{1m}, BT_{2m}, and BT_{sel} ($p = 0.01$ for UT vs. BT_{conv}, $p = 0.003$ 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 $\widehat{T}$ was lowest in the experimental plots where BT_{conv} was carried out, i.e., 0.214. On average, the highest value of $\widehat{T}$ 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 (~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 (BT_{sel}) 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 $\widehat{M}$ in experimental plots where geometrical BT strategies were performed compared to BT_{conv}. $\widehat{T}$ 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-m-wide 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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Competing interests

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

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This thesis explores the impacts of biomass thinning in strips on the growth and development of forests post-thinning and identifies biomass-dense forests where these methods could be implemented. The findings suggest that biomass thinning can be an effective strategy for biomass production without compromising short- to medium-term growth and development. Sediment and moraine soils within mesic and mesic-moist moisture classes could be optimal targets for applying these thinning methods in biomass-dense forests.

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