Long-Term Results of a Field Experiment in Conifer Mixed Regenerations

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Keywords:	Regeneration, Drettinge method, Scots pine, Norway spruce, Clearcut, Shelterwood

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Abstract

A national regeneration experiment was established across the boreal forest of Sweden. This study presents the regeneration results of the combination method, the so-called Drettinge method, which aims to evaluate the establishment of mixtures of naturally regenerated Scots pine (*Pinus sylvestris* L.) and planted Norway spruce (*Picea abies* L. Karst.). In the experiment, two different regeneration approaches were compared: (i) planting on clearfelled areas and (ii) a combination of planting and natural regeneration using shelter trees. About 133 stemsha^{-1} of Scots pine trees were retained in the shelterwood and no trees were retained in the clearcut. Planting was performed in both treatments with 2000 - 2500 Norway spruce seedlings ha^{-1}. Each of the established plots was further divided into two sub-treatments, treated with either soil scarification or no soil scarification. Ten (10) sites across the south to central of Sweden were analysed for this study. Stem density, basal area proportions and volume production were analysed across the treatments in both regions. The results from this study show that the treatments resulted in a Norway spruce-dominated stand on the sites in the south. At the same time, the sites in the central region were mainly spruce-pine mixtures. Natural regeneration of birch was abundant in both regions. The volume production was similar to the basal area production in both regions. The shelterwood treatments resulted in lower basal area and volume in both regions. Scarification had a limited effect on the stand variables. The stands in clearcut treatments often outperformed the stands in the shelterwood treatments in both regions. Based on the results of this study, it is evident that the combination method was not successful in achieving the desired outcome of establishing mixed forests of Scots pine and Norway spruce, particularly in the southern sites. Consequently, there is a need for further development of the combination method to effectively promote the creation of mixed forests, thereby ensuring sustainable forest management practices.

Keywords: Regeneration, Drettinge method, Scots pine, Norway spruce, Clearcut, Shelterwood.

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Abbreviations

The following abbreviations are used in this thesis:

CCF	Continous Cover Forestry
CN	Clearcut Non-scarified
CS	Clearcut Scarified
DBH	Diameter at Breast Height (1.3m)
FAO	The Food and Agriculture Organization of the United Nations
Silvsys	Silvicultural system (Clearcut or Shelterwood)
PCT	Pre-commercial thinning
Pine	Scots pine
Siteprep	Site preparation (Soil scarified or Non-scarified)
SN	Shelterwood Non-scarified
Spruce	Norway spruce
SS	Shelterwood Scarified

1. INTRODUCTION

Over time, sustainable forest management has gained prominence in the boreal biome. One possible way to achieve this is by growing trees in mixtures (Forrester, 2014). However, the boreal forest of Sweden is mainly dominated by even-aged forests of Norway spruce (*Picea abies L. Karst*), thereafter called (spruce), and Scots pine (*Pinus sylvestris L.*), thereafter called (pine). Both species have been managed by clearcutting to achieve sustainable wood production (Berg *et al.* 2017; Gauthier *et al.* 2015; Nilsson *et al.* 2001). Recently, monocultures have been debated as vulnerable to varying disturbances from climatic change (Ruiz-Pérez & Vico 2020; Venäläinen *et al*. 2020).

For the past two decades, expanding forestry practices and adaptive silvicultural practices have become imperative due to the pressures of climate change on forest ecosystems (Hof *et al.* 2017; Montoro Girona *et al.* 2018). Continuous cover variants of natural regeneration and shelterwood systems are silvicultural alternatives to clearcutting and can seemingly tackle these climatic change concerns (Kern *et al.* 2017). Furthermore, growing trees in mixtures have been reported to be better adapted and resilient to a wide range of these disturbances (Huuskonen *et al.* 2021; Felton *et al.* 2016) and can provide several ranges of ecosystem services (Lodin 2020) when compared to monocultures (Bauhus *et al.* 2017). Spruce and Pine are Sweden's two most common conifer species, both economically and ecologically (Kellomäki *et al.* 2008). However, very little attention has been given to the regeneration of these species in combination.

1.1 Growth Dynamics of Norway spruce and Scots pine

Approximately 70% of the land in Sweden is covered by forest, with spruce accounting for a growing stock of ca. 1456 mln m^3 and pine 1382 mln m^3, with standing volumes of approximately 40% and 38%, of the total volume respectively (FRA 2020). Spruce is generally considered a late species in its succession as its initial growth accumulation is delayed but peaks over time (Lundmark 1988). Pine is traditionally considered a pioneer species due to its early establishment and fast initial growth (Engelmark & Hytteborn 1999; Lundmark 1988). Pine has been reported to have a higher level of stress tolerance to drought, windthrow, waterlogging, excessive acidity, and alkalinity (Baumgarten *et al.* 2019; Eilmann & Rigling 2012; Lebourgeois *et al.* 2012; Kelly & Connolly 2000; Lundmark 1988) whereas spruce reacts more sensitively to drought, uprooting and windthrow (van der Maaten-Theunissen *et al.* 2013; Levesque *et al.* 2013; Lebourgeois *et al.* 2012; Valinger & Fridman 2011).

The shade tolerance characteristics of spruce enable its needles to grow in less light conditions (Gebauer *et al.* 2011) when compared to pine with minimal shade tolerance (Engelmark & Hytteborn 1999). The volume production of pine has been reported to be higher than spruce on poor fertility sites deficient in nutrients and/or water (Bergh *et al*. 2010; Heiskanen & Mäkitalo 2002). Since the availability of nutrients is related to temperature, pine generally grows faster than spruce in northern Sweden. The initial growth of spruce has sometimes been found to be extremely slow in northern Sweden (Björkman 1953), and due to the general differences in growth between the two tree species, pine has been preferred when regenerating northern clearcuts. In contrast, spruce is believed to grow faster than pine in southern Sweden on intermediate and high fertility sites (SFA 2021). Recent research has however shown that pine grows equally well, if not better than spruce on intermediate soils (Lula *et al.* 2022). However, comparing the characteristics of these two species, it could be advantageous to grow them in combination.

1.2 Shelterwood System

The shelterwood system is a silvicultural method that involves the removal of mature trees in a series of operations. In this system, regeneration occurs beneath a protective canopy, which is later removed once the natural regeneration has become established (Mathews 1991).

The term “shelterwood” and “seed trees” are commonly associated with this system; their specific definitions can vary in different countries. Generally, “seed trees” are primarily focused on seed production and dispersal, while “shelterwood” serves the additional purpose of providing protection (smith *et al.* 1997) and ensures successful regeneration. The distinction between the two terms can also be established based on the number of trees per hectare. Typically, a seed tree stand consists of 50-150 trees per hectare, whereas a shelterwood stand tends to have more than 150 trees per hectare (Anon. 1995, Anon. 1996). However, in the context of this study, the term "shelterwood" was utilised. This is because the retained trees were meant to serve a dual purpose of dispersing seeds for regeneration and providing protection to the planted seedlings.

Shelterwood systems have been found to improve the growth conditions of seedlings during regeneration and increase the likelihood of seedlings' survival after clear-cutting (Pothier & Prévost 2008; Glöde & Sikström 2001). Regenerating using a dense-shelterwood approach promotes slow growth and reduces stem taper, resulting in uniform wood density. This uniformity in wood density improves the overall tree quality (Agestam *et al.* 1998; Ekö & Agestam 1994).

1.3 Regeneration and Soil Scarification

Regeneration enhanced with soil scarification is a key management practice in Sweden, especially for pine and spruce establishments. Several factors inhibit the survival and growth of forests during its regeneration phase (Burdett 1990), as it is the stage in which they are sensitive to pressure from browsing, frost, pine weevils, and vegetation competition (Johansson *et al*. 2013; Nilsson et al. 2010; Simard et al. 2003). However, seedlings' survival could be improved with soil scarification (Thiffault *et al.* 2017; Nilsson *et al.* 2010) and the tree species' morphophysiological and ecological traits (Pineda-García *et al.* 2011).

Soil scarification is a vital silvicultural measure for the natural regeneration of pine and spruce on sites with a dense moss layer and a low amount of mineral soil (SFA 2021). Soil scarification can help improve the chances of successfully establishing a forest and ensure the long-term sustainability of the forest. In Sweden, pine regenerates better when the soil is scarified (Olsson *et al.* 1990). Most of the associated clearcuts are soil scarified prior to planting with methods that allows the natural regeneration of birch (*Betula pendula Roth, Betula pubescens Ehrh*) (Holmström *et al.* 2016; Holmström *et al*. 2017; Nilsson *et al.* 2010).

1.4 Drettinge Method/Combination Method

The Drettinge method combines naturally regenerated pine with planted spruce. This method is also known as the combination method (Karlsson & Örlander 2004). The method is practised on sites initially occupied by pine such that during final felling, shelter trees of pine are left and then planted with spruce seedlings with the objective of getting a mixed forest of naturally regenerated pine and planted spruce.

This method is mainly recommended on intermediate fertile soils where both species can grow well (Karlsson & Örlander 2004). The method could be used when the forest manager is uncertain about which tree species to regenerate. With the different biotic and abiotic threats to these species, combining the two species would give more options to forest owners and managers later in the rotation period. The findings of the study conducted by Strömberg *et al.* (2001) indicate that the utilisation of a combination of methods for regeneration involving natural regeneration and planting accounted for a relatively small proportion, approximately 10%, of the regenerated area in Sweden. The combination method could be included in continuous cover forest (CCF) methods. The regeneration result of the combination method has been evaluated 4 years after its establishment across sites in Sweden (Nilsson *et al*. 2006)

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1.5 Research Justification and Objectives

In Sweden, the use of natural regeneration with sheltertrees or seed trees as a method of forest regeneration is not commonly practised today. Instead, clearcutting has been the more common way of regenerating forests (Lämås 2017). However, there is an increased interest in continuous cover forestry (CCF) and using different management methods to increase admixtures and decrease risks. The Drettinge method should be carefully assessed to determine its suitability for wide use and applicability.

The aim of this study was to evaluate the long-term effect of the combination method of regeneration on stand composition and production. To investigate if the regeneration objective of creating a mixed forest can be achieved by using the combination method. Further on, I investigated, regardless of the outcome being monoculture or mixture, if the shelterwood had a negative impact on future growth. To address the above objectives, I hypothesised that:

1. Both silvicultural systems would result in a new generation of Norway spruce-Scots pine mixed forest stands in southern and central Sweden.
2. Both silvicultural systems would result in the same growth when comparing stand variables (basal area and volume) after 30 years.
3. Stand variables (stem density, basal area and volume) were positively affected by soil scarification in both silvicultural systems even after 30 years.

2. MATERIAL AND METHODS

2.1 Background of this study (Old study from the '90s)

The old Drettinge experiment was established between 1993 and 1997. The experimental setups was initiated in collaboration between the Swedish Forest Agency and the Swedish University of Agricultural Sciences (SLU). The Local personnel of the Regional Boards of forestry were saddled with managing the experimental plots over the first six years after establishment. Although there were some variations in site management and layout of the experiment, the differences were considered insignificant in influencing the result of the experiment. The sites were initially dominated by pine, spruce and a minor proportion of broadleaved species, mainly birch.

The experimental plots were established on 22 sites in Sweden from Skåne in the south (56^{0}21'N, 15^{0}18'E) to Västerbotten in the north (64^{0}33 N, 18^{0}24'E). The experimental sites were designed with a split-plot harvesting treatment system of shelterwood and clearcut on the main plots (further on called silvicultural system) and with sub-plot treatments of site preparation in terms of scarification and non-scarification. The only form of site preparation in the non-scarification plots was the soil disturbance caused by the harvest operations. On every site, one part was harvested with clearcutting, and the other was left with pine shelterwood with an average density of about 133 stem ha-1. Each silvicultural system was then treated with scarification of one part and non-scarification of the other. Most of the sites were scarified with disc-trenching and some by patch scarification or mounding, both here referred to as the same treatment level. The scarification was mostly done on the sites 1 year after cutting, although there were some variations on the sites. Planting of 2000 – 2500 spruce seedlings per ha was applied on all the sites. The majority of the sites were planted 2-3 years after clearcutting, but some were planted the same year and one site was planted 1 year after clearcutting. The seedlings planted were 1-2 years old containerised seedlings and 4 years-old bare-rooted seedlings. The 4 years-old bare-rooted seedlings were for some sites in southern Sweden (Table 1). To further reduce pine weevil (*Hylobus abietis*) damage, the seedlings planted were treated with Permethrin, which was a commonly used pesticide in conifer plantations at that time.

Each experimental site was intended to be established on moderately fertile sites (blueberry-type or grass types according to the Swedish vegetation classification system (Hägglund & Lundmark 1977). The size of the experimental sites varied between 2 and 32ha. The treatment plots were 40 x 100m or 50 x 80m in size. All sites are in northern, central and southern Sweden on a growing soil of poor-medium fertility. The soil moisture class was mesic on most sites and dry on one site, with texture ranging from sandy-silty to silty-clay (Hägglund & Lundmark

1977). According to Morén and Perttu (1994) classification, the sum of the daily average temperature above 5^0C, degree days (dd) was about 800dd (North) and 1600dd (south). The dominant height at age 100 (site index) of the stands varied from T24 and G28 (Southern Sweden) and between T17 & T24 (Northern Sweden). The humus layer had a thickness of about (20-10cm) and (3-10cm) with field vegetation class of *Vaccinium myrtillus* or combinations of *V. myrtillus* and grass, without field layer or *Vaccinium vitis-idea* or herbs dominated (Hägglund & Lundmark 1977).

For further details about the so-called Drettinge method experiment setup, see Nilsson *et al.* (2006). Four to six years after establishment, the sites were measured to evaluate the regeneration results of this combination method (Nilsson *et al.* 2006). However, after the publication of the six years result, the experiment was abandoned and subsequently managed by the forest owners. At the time of this present study measurement, the shelterwood on all the sites had been removed, but the timing varies for all the sites. Unfortunately, there is no information on the timing of the shelterwood harvest and it might vary between sites.

Furthermore, all the stands have also been pre-commercially thinned (PCT). The directives of the PCTs are unknown except for one of the treatments in Leksberg (which was thinned in favour of birch). However, a common pre-commercial thinning practice in Sweden is thinning in favour of commercially valuable trees in this case spruce or pine.

Table 1. Characteristics of study sites showing the volume of retained shelterwood

Region	Site Name	Size (ha)	Longitude	Latitude	Site index (m)[a]	Clearcut year	Scarification Year	Planting year	Seedling type	Seedling age (yrs)	Vol. of retained trees (m^3ha)
South	Asa	15,3	14.8303389	57.139371	25-26	Mar 95	Nov 95	May 96	cont	1.5	110
South	Leksberg	3,5	13.7862142	58.670725	26	Apr 94	Nov 94	May 95	cont	2	114
South	Lonsboda	5,6	14.3504022	56.443959	28	Sept 95	Nov 95	Jun 96	Bare-root	4	125
South	Svenljunga	3	13.1464675	57.468919	22	Feb 94	Sept 94	Apr 95	Bare-root	4	73
South	Trollebo	2	15.28985	57.297481	28	May 95	Sept 95	Apr 96	cont	2	124
South	Uddevalla	3	11.952423	58.40822	20-24	Jan 95	May 96	Apr 96	Bare-root	4	119
Central	Karlstad	1,6	13.5277414	59.430904	26	Dec 94	Sept 95	May 96	cont	1	122
Central	Kvarndammen	32,4	16.8241342	59.223299	24-27	Apr 94	Oct 95	May 96	cont	1	93
Central	Rankkyttan	2,4	15.7537194	60.467153	23	Dec 94	May 95	Jun 95	cont	1.5	109
Central	Villboda	17	15.4629431	59.598487	24-26	Dec 94	Sept 95	Mai 96	cont	1	138

[a] Dominant height at age 100 years. Abbreviation: cont (Containerised)

2.2 Present Study

For this study, 10 sites (Fig. 1) were remeasured and analysed between the fall of 2022 and the winter of 2022. Hence the treatments in this study were delineated as: [1] Clearcut scarified (CS), [2] Clearcut non-scarified (CN), [3] Shelterwood scarified (SS) and [4] Shelterwood non-scarified (SN) (see Table 2). Six of the study sites, namely Asa, Svenljunga, Lonsboda, Uddevalla, Trollebo and Leksberg, are in southern Sweden. While Kvarndammen, Rankyttan, Karlstad and Villboda are located in central Sweden.

Table 2. Description of treatments applied on the sites.

Treatments	**Descriptions**
CS	Clearcut + Scarified
CN	Clearcut + Non-scarified
SS	Shelterwood + Scarified
SN	Shelterwood + Non-scarified

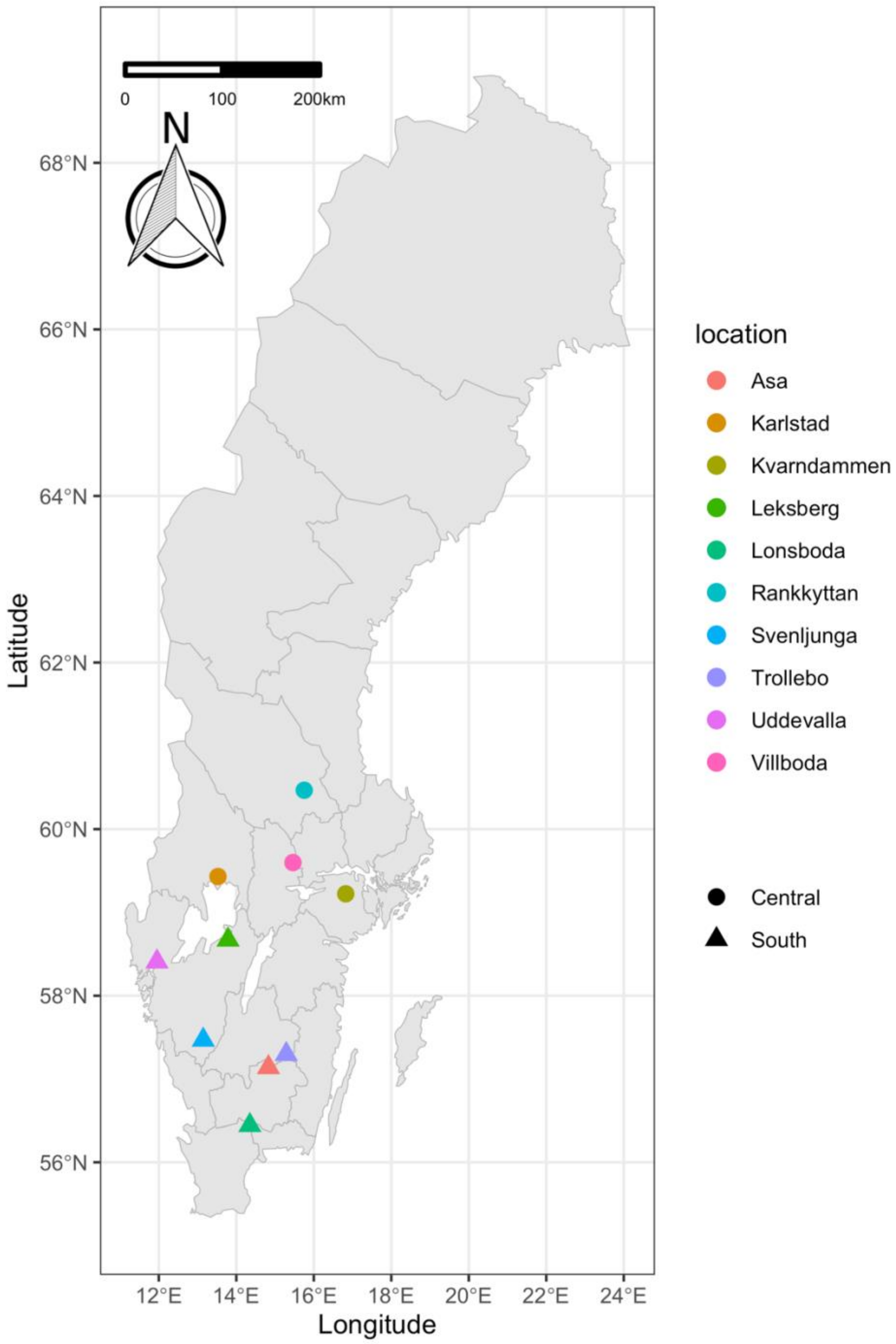

Figure 1. Map showing the location of the sites in south and central Sweden

2.3 Study Plots and Field Measurement

For the measurements, four circular sample plots with a radius of 5.64 m radius were randomly laid out in each treatment. The coordinates of the centre of all sample plots were mapped on a GPS. Within the boundary of each sample plot, all tree species and diameter at breast height (DBH) (1.3m) of the trees were recorded in the inventory (the callipered trees). On dense plots with much birch regeneration, a smaller subplot of 2.64m radius within the same 5.64m radius was established (sites Trollebo, Karlstad & Leksberg). Diameter was measured by cross-callipering the trees. Damages were registered according to the damaging agent and the position on the tree. Sample trees were selected for the tree height measurements, measuring their height and DBH. For every tree species in the circle plot, the two largest trees and the three closest trees to the centre of the plots were recorded. The height was measured with a vertex, with the display at breast height. Natural regeneration of Silver birch (*Betula pendula Roth*) and Downy birch (*Betula pubescens Ehrh*) were recorded in high observations, and both species, hereinafter referred to as (Birch) because they both exhibit similar phenological traits and are seldom separated in the practical forestry of Sweden (Holmström *et al.* 2017). Other tree species inventoried in this survey are Pedunculate oak (*Quercus robur L.),* European larch (*Larix decidua Mill.*), Willow (*Salix spp*.), Aspen (*Populus tremula L*.), Alder (*Alnus glutinosa L.) Gaertn.*, and Rowen (*Sorbus aucuparia L.*). Due to the fewer number of these tree species in the observations, they are hereafter delineated as “Others”. The data from the measurement were further analysed using R.

2.4 Estimated Variables

2.4.1 Height

The height of only the sample trees was used to estimate the height of the other callipered trees in each treatment. Using the function of Näslund (1936), the individual height of other callipered trees were calculated. The Näslund functions characteristics are as follows:

$$H = \left[\frac{d}{(\beta_0 + \beta_1 d)}\right]^{\varepsilon} + 1.3 \qquad (1)$$

Where:

H − expected tree height (cm) at a given diameter at breast height,

d − diameter (dcm) ,

$\beta_0, \ \beta_1$ – are the regression coefficients of the parameters to be estimated and

ε – an exponential parameter

To estimate the height for the callipered trees at a given diameter, the Näslund functions (equation 1) were adjusted for spruce, pine, birch and others with an exponential of (2, 3, 3, 3) respectively.

2.4.2 Volume

The volume of the individual tree species was estimated using Brandel's functions (1990) for large trees (DBH > 4.5cm) and Anderson (1954) for trees smaller in size (DBH < 4.5cm).

The Brandel and Anderson's function characteristics are as follows:

$$V = 10^{a} * D^{b} * (D + 20)^{c} * H^{d} * (H - 1.3)^{e} \quad (2)$$

$$V = 0.22 + 0.1086 * D^{2} + 0.01712 * D^{2} * H + 0.008905 * D * H^{2} \quad (3)$$

$$V = 0.22 + 0.1066 * D^{2} + 0.02085 * D^{2} * H + 0.008427 * D * H^{2} \quad (4)$$

$$V = 0.11 + 0.1302 * D^{2} + 0.01063 * D^{2} * H + 0.007981 * D * H^{2} \quad (5)$$

Where:

V – volume (dm^3) above stump for each sample tree,

D – diameter (dcm) at breast height,

H – Height (m) of the tree,

a, b, c, d, e – are coefficients which are species-specific and geographically dependent

The stem volume of each tree in the plots, where the height was measured and estimated, was calculated with specific functions for large trees (dbh > 4.5cm) of spruce, pine and birch using equation (2) and smaller trees (dbh < 4.5cm) of spruce, pine and birch using equations 3, 4 and 5 respectively. For other species, the birch function was used for other broadleaves, while the spruce function was used for other conifers (larch). The variables (stem density, basal area and volume) for each treatment plot were then calculated as the mean of the sample plots within each treatment.

2.5 Statistical Analysis

The new stand was considered a monoculture if one tree species had more than 75% of the basal area. The stand basal area was calculated as the mean percentage from the sample plots within each treatment plot. However, due to the differences in the treatments across the sites. A mixed-effect model using R package (lmer) was fitted to test the significant effects of the various treatments [silvicultural system (silvsys) & site preparation (siteprep)] and their interactions. The treatments were treated as a fixed effect and the sites as a random effect. A post-hoc Tukey test was further utilised to evaluate the differences between the various treatment with the R package (emmeans). All data processing in this study was done using R studio 1.4.1717.

3. RESULTS

3.1 Monoculture or Mixture

The result shows that only one of the stands in southern Sweden met the criteria for being classified as a mixed forest 30 years after regeneration, with less than 75% of the total basal area being of one tree species (Fig. 2). The shelterwood non-scarified (SS) treatment in Trollebo resulted in a spruce-birch mixture (Fig. 2). However, for the other treatment plots in southern Sweden, spruce basal area exceeded 75%, making the stands predominantly spruce-dominated. The only exception was the clearcut non-scarified (CN) treatment plot in Leksberg, where birch basal area was higher than 75%, giving a birch-dominated stand (Fig. 2). In central Sweden, most treatment plots resulted in mixed forest with few exceptions. In Kvarndammen & Karlstad, all the treatments resulted in a spruce-pine mixture except the shelterwood scarified (SS) treatment in Kvarndammen and clearcut scarified (CS) in Karlstad, which were spruce monocultures (Fig. 2). Pine-spruce mixtures were observed in clearcut non-scarified (CN) treatment in Rankkyttan and clearcut scarified treatment (CS) in Villboda (Fig. 2). The shelterwood scarified (SS) treatment in Rankkyttan was the only plot with a spruce-birch mixture in central Sweden (Fig. 2). A pine monoculture was present in the clearcut non-scarified (CN) treatment in Villboda (Fig. 2).

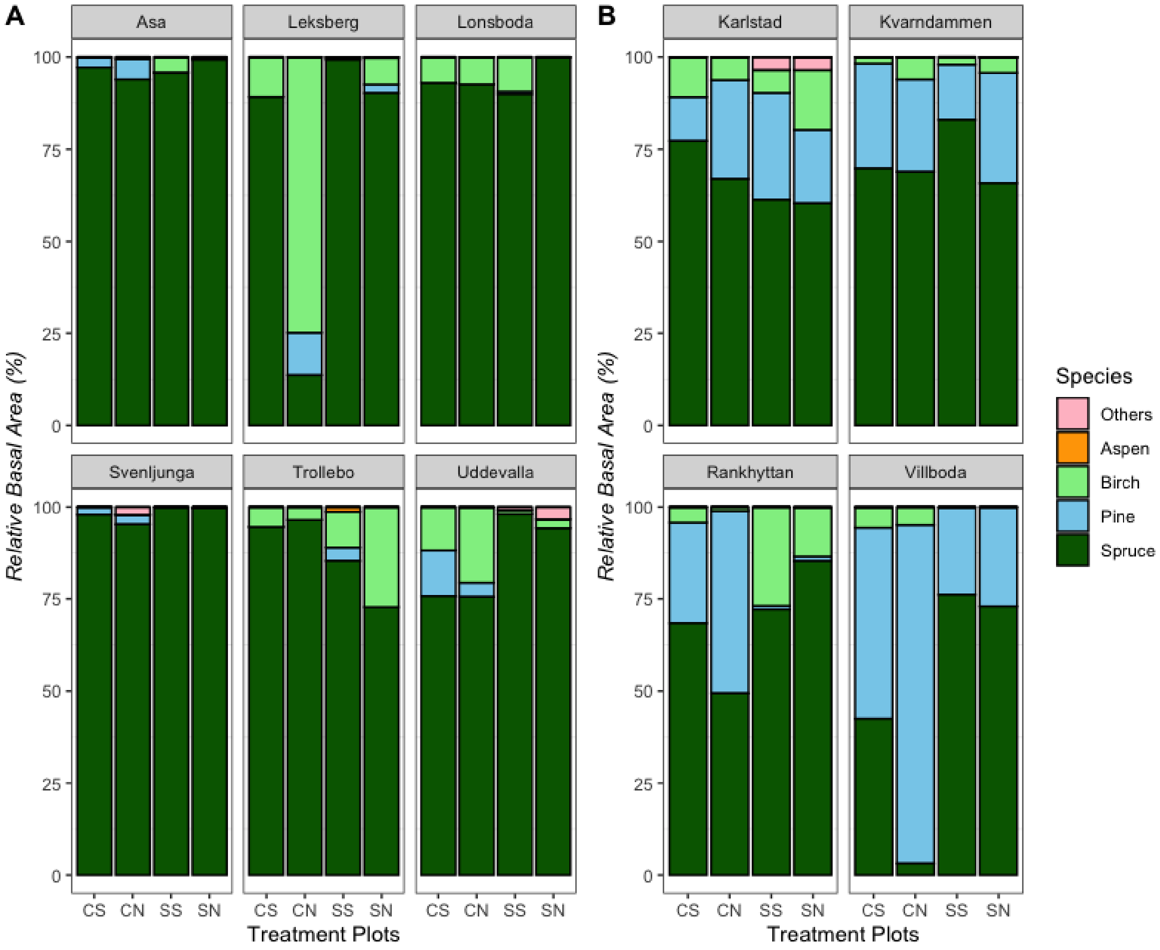

Figure 2. Percentage basal area across the sites in southern Sweden ***(A, left pane)*** *and central Sweden* ***(B, right pane)****. Key to abbreviations: CS (clearcut with soil scarification), CN (clearcut no soil scarification), SS (Shelterwood with soil scarification), SN (shelterwood no soil scarification)*

3.2 The treatment effects on stand variables

On the southern sites of the study area, spruce accounted for more than 50% of the total number of stems per hectare, whereas on the central sites, spruce had less than 50% of the total number of stems per hectare (Fig. 3)

The silvicultural systems, site preparation, and their interaction significantly affected stem density and volume production ($p < 0.05$). For the basal area, site preparation had a near-significant effect (p-value= 0.06), while the silvicultural systems and their interaction had a significant effect ($p < 0.05$) when both regions were analysed together (Supplementary Table 1).

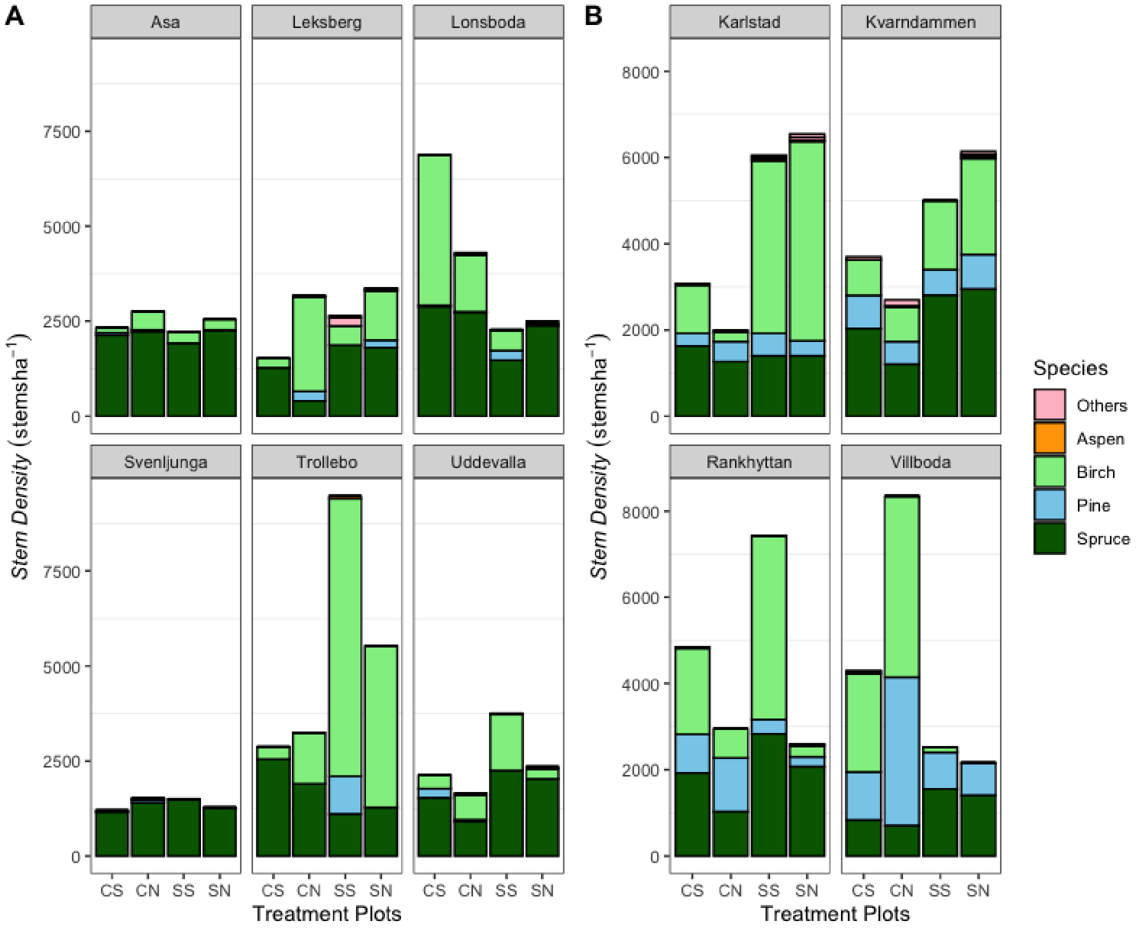

*Figure 3. The stem density (stemsha^{-1}) across the sites in southern Sweden **(A, left pane)** and central Sweden **(B, right pane)**. Key to abbreviations: CS (clearcut with soil scarification), CN (clearcut no soil scarification), SS (Shelterwood with soil scarification)*

Table 3: Average site values for stem density (stemsha^{-1}), basal area (m^{2}ha^{-1}) and volume (m^{3}ha^{-1}) in south and central Sweden

Region	Fellsys	Siteprep.	Stem Density	Basal Area	Volume
South	Clearcut	Yes	2821^a	21^c	133^c
	Clearcut	No	2775^a	17^b	97^b
	Shelterwood	Yes	3646^b	15^a	83^a
	Shelterwood	No	2929^a	15^a	83^a
Central	Clearcut	Yes	3981^a	21^{ab}	124^{bc}
	Clearcut	No	4000^a	23^b	134^c
	Shelterwood	Yes	5252^b	19^a	100^a
	Shelterwood	No	4369^a	18^a	102^a

** Values represented are average of the sites in both regions. Values with the same letter are not significantly different ($p < 0.05$).*

3.2.1 Stem Density

The silvicultural system and site preparation, as well as their interaction, had an effect on stem density with a significant ($p < 0.05$) higher stem density (5252 stemsha^{-1}) in shelterwood scarified treatment in the central region (Table 3). There were no differences in the clearcuts, as clearcut non-scarified treatment produced the lowest stem density (2775 stemsha^{-1}) in the south. Even though the shelterwood non-scarified was slightly higher than the clearcuts in both regions, it was not significantly different ($p > 0.05$) from the clearcuts (Supplementary Table 1, Fig. 4).

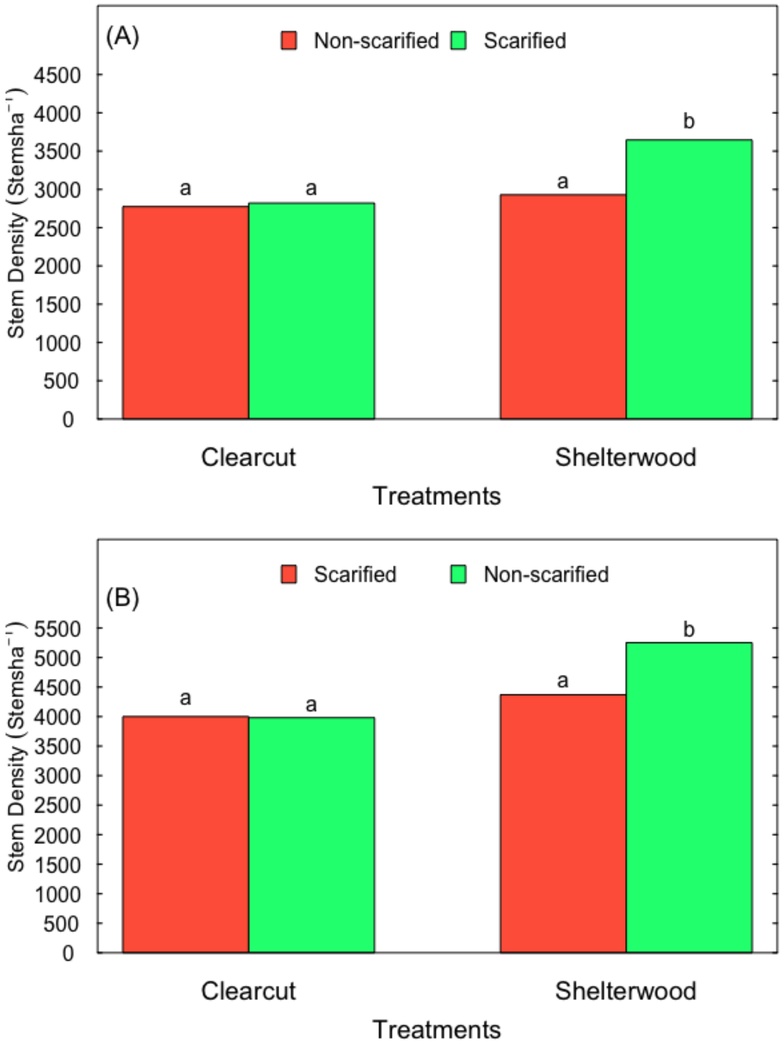

Figure 4. The average stem density (stemsha^{-1}) in southern Sweden ***(A, upper pane)*** *and central Sweden* ***(B, lower pane)****. * Values are the average of sites in both regions*

3.2.2 Basal Area

The shelterwood treatments had a significantly ($p < 0.05$) lower basal area compared to the clearcut treatments in both regions (Table 3, Fig. 5). The clearcut scarified treatment gave the highest basal area ($21m^2$) followed by the clearcut non-scarified ($17m^2$) in the south. The reverse is the case in the central region, with the clearcut non-scarified treatment having the highest basal area ($23m^2$). In the central region, site prep has no significant effect (p-value=0.56) on the basal area (Supplementary Table. 1)

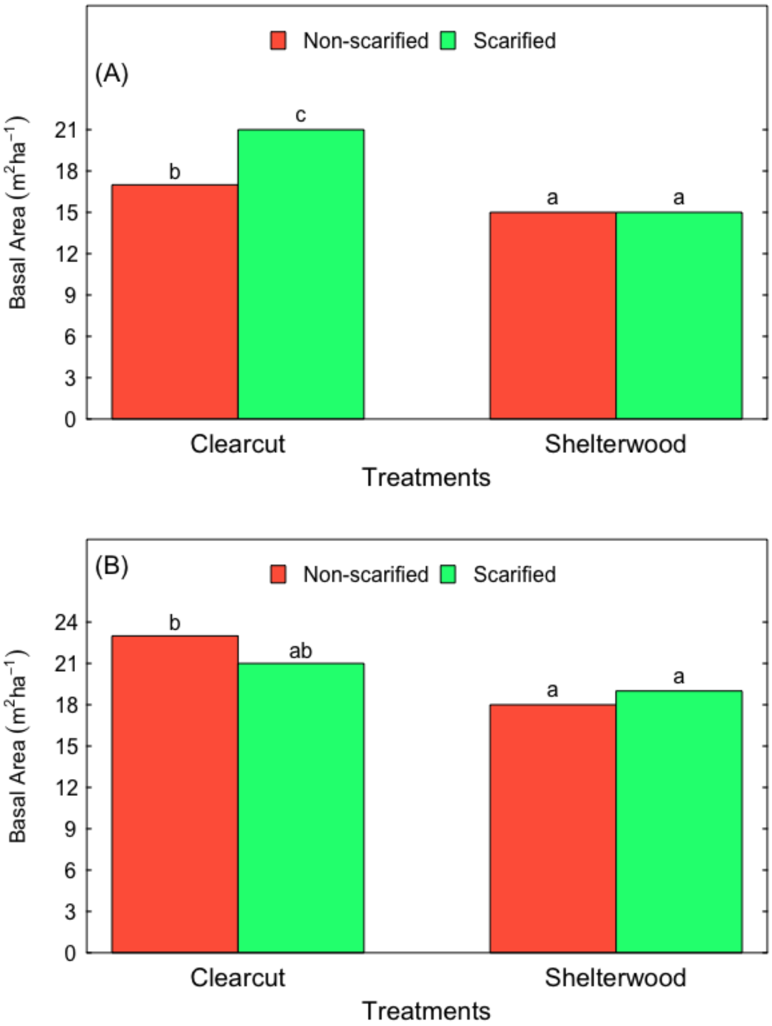

Figure 5. The average site basal area (m^2ha^{-1}) in southern Sweden ***(A, upper pane)*** *and central Sweden* ***(B, lower pane)****. * Values are the average of sites in both regions*

3.2.3 Volume Production

Volume production was significantly higher ($p < 0.05$) in the clearcut treatments in both regions (Fig. 6). In southern Sweden of this study, clearcut scarified had the highest volume produced (133m^{3}ha^{-1}), but in the central region of the study area, clearcut non-scarified had the highest volume production (134m^{3}ha^{-1}). The shelterwood treatment in both regions had a significantly ($p < 0.05$) lower volume production compared to the clearcut treatments (Fig. 6). There was no significant effect (p-value=0.36) of site preparation on volume production in the central region (Supplementary Table. 1).

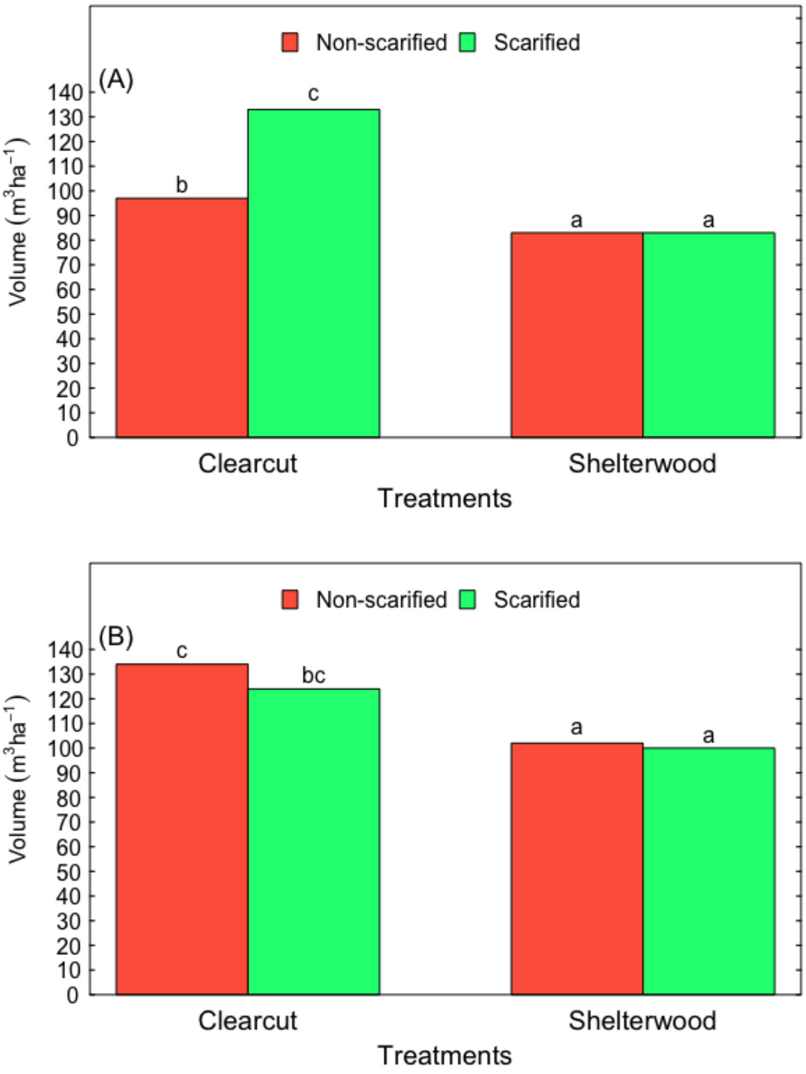

Figure 6. Average site volume (m^{3}ha^{-1}) in southern Sweden ***(A, upper pane)*** *and central Sweden* ***(B, lower pane)****. * Values are the average of sites in both regions*

3.3 Norway Spruce Volume Production

At a 5% significance level, there was no significant effect of felling systems, site preparation, and their interaction on spruce volume production in both south and central Sweden. In both regions, the volume of spruce in the shelterwood treatments is between (70 – 80m^{3}ha^{-1}) (Fig .7). Spruce volume was higher (120 m^{3}ha^{-1}) in the clearcut sacrificed in southern Sweden than in the central region. Still, there was no significant difference ($p > 0.05$) between the clearcut and shelterwood treatments in both regions (Fig. 7).

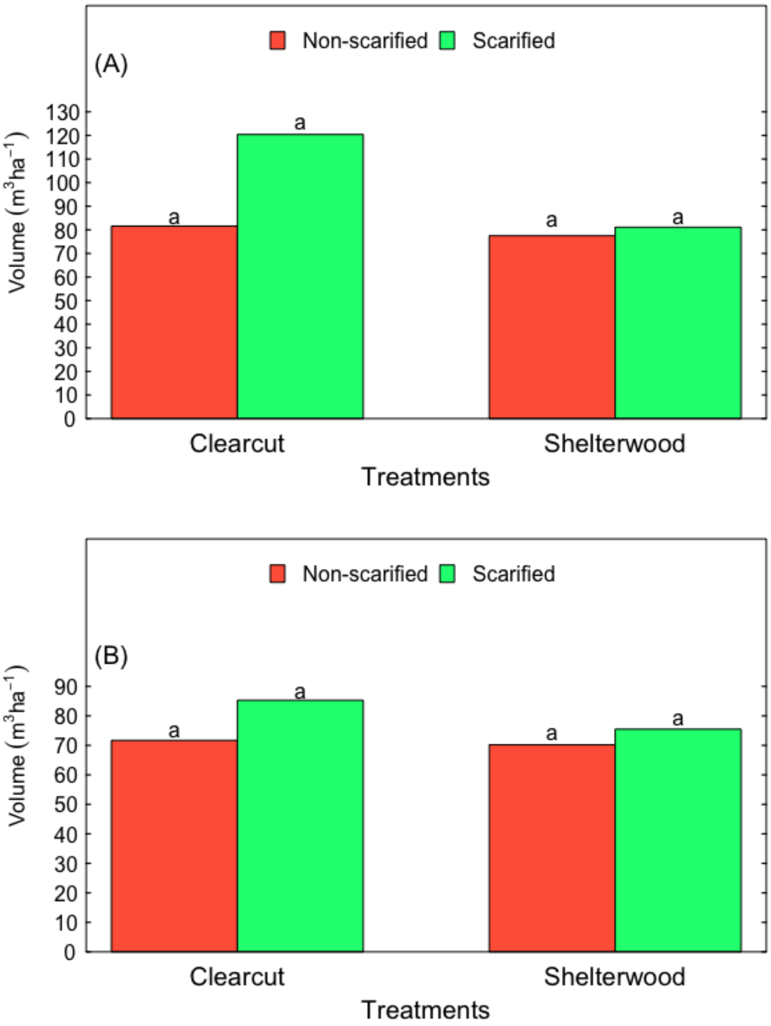

Figure 7. The average site volume production (m^{3}ha^{-1}) of spruce in southern Sweden (**A**, **upper pane**) and central Sweden (**B**, **lower pane**). * Values are the average of sites in both regions

4. DISCUSSION

4.1 Monoculture or mixed forest

Based on the average of the sites in both regions, the basal area of spruce as a dominant species was consistently higher than 75% in southern Sweden of this study area (Supplementary Fig. 2), exceeding the FAO 2020 standards. In central Sweden, the spruce basal area was less than 75% (Supplementary Fig. 2), and the second-ranking species, pine or birch, accounted for more than 10% of the total basal area (Fig. 2), which falls within the purview of FAO standards. Unsurprisingly, six years after its establishment, the study by Nilsson *et al.* (2006) revealed that the height difference between the planted spruce and naturally regenerated pine in the south was too wide; thus, it would be difficult for pine to be a part of the future stand. One can conclude that the combination method did not achieve the objective of creating a mixed forest in the south, but the objective was achieved in the central region. Hence, the hypothesis that both silvicultural systems would result in a new generation of Norway spruce-Scots pine mixed forest stands in southern and central Sweden will be rejected.

The presence of naturally regenerated birch, regardless of the treatment, reiterates the natural propensity of this species to colonise and persist in diverse ecological settings, particularly in southern Sweden, where there is abundant natural regeneration of birch. The inclusion of birch as a broadleaved species within the stands could be a way of significantly increasing tree diversity (Holmström *et al.* 2021). This is reported to be beneficial from a recreational and biodiversity viewpoint (Svedrup *et al.* 2002), but from an economic viewpoint, keeping birch in the mixture would require active management in terms of thinning (Holmstrom, 2015; Holmstrom et al. 2015). In addition, it could also positively affect the overall production and quality of spruce trees, particularly in regions where survival is challenging (Lindén 2003; Agestam 1985; Mielikäinen 1985).

4.2 Density, basal area and volume production

The lack of a significant effect of scarification on clearcut density in both southern and central regions (Supplementary Table 1) could be attributed to several factors. A nationally recognised cause of damage in pine and spruce plantations in both southern and central Sweden is pine weevil (Wallertz & Petersson 2011). To reduce the impact of this damaging insect, the planted seedlings were treated with (Permethrin) insecticide. Despite these measures, studies have shown that treated seedlings do not offer absolute protection against pine weevil damage (Petersson *et* *al.* 2004). This could be a potential explanation for the observed lower stem density observed in the clearcuts. A study by Petersson and Örlander (2003) has shown that scarification can help reduce damage by pine weevils. One could suggest that the absence of standing trees and the resulting exposure of the forest floor outweighs the positive effects of scarification on the density. It could also be that unavailable seed sources, competition from herbaceous vegetation and other site-specific conditions may also contribute to the observed lack of statistical significance (Nyland 2016). Although early summer frost is recognised as a damaging factor for planted spruce which typically reduces growth rate and hence subjects them to other damages like browsing, competition from vegetation e.t.c (Nyland 2016; Langvall *et al.* 2001). The shelterwood system has been extensively reported to be effective in mitigating frost damage (Langvall & Örlander 2001; Lundmark & Hällgren 1987; Örlander 1993). It is plausible that the observed positive effect on the density of the shelterwood treatments were at least partially attributed to the reduction in frost damage. Spruce consistently exhibited higher density in both regions, except for the clearcut non-scarified (CN) treatment in central Sweden, where pine density was higher (Fig. 3). This exception could be attributed to the treatment creating favourable conditions for pine, such as increased light availability and reduced competition from spruce.

The basal area and volume production in the shelterwoods was significantly lower ($p < 0.05$) than the clearcuts in both regions (Table 2). This finding validates Nilsson *et al.* (2006) findings that the shelterwood treatments had reduced heights after 5 growing seasons in all regions. A possible reason for this could be that the pine sheltertrees retained could have had a negative shading effect which reduced the amount of available light reaching the forest floor and hence limited the growth and development of the trees. One practical approach is to remove the shelter trees earlier after planting, but the density of planted spruce seedlings should be reduced. However, careful consideration must be given to ensure that the seedlings are sufficiently large and robust to withstand potential damage from pine weevils, which may be attracted to the freshly cut stumps of the shelter trees, as found by Wallertz *et al.* (2005). By striking a balance between the timing of shelter tree removal and the size and resilience of the seedlings, it is possible to minimise the risk of pine weevil infestation while still benefiting from the positive effects of early shelter tree removal.

In line with the third hypothesis, that stand variables were positively affected by soil scarification will be rejected. Precisely because only the density of shelterwood treatment was positively affected (Fig. 4), while clearcut was not positively affected by the soil scarification in both regions (Fig. 4). Also, soil scarification only influenced basal area and volume in the south, whereas in the central region, it was not positively affected (Table 2). Scarification significantly increased the basal area and volume of clearcut in the south, while in the central, non-scarified clearcut had higher values than the scarified clearcut. Although it was not significantly higher (Fig. 5 & 6). This finding contradicts the expectation that scarification would promote higher basal area and volume by creating favourable conditions for regeneration. For the central region, the soil disturbance caused during the removal of the old trees during clearcutting could be a form of site preparation which could have positively influenced the basal area and volume production in the non-scarified treatment. This could explain why there is no significant difference between the clearcut scarified (CS) treatment and the clearcut non-scarified (CN) treatment. The statistically significant effect of scarification on shelterwood density suggests its importance in promoting regeneration in this type of regeneration method.

In conclusion, while thinning practices in Sweden often prioritise commercially valuable species, it can be argued that the conducted PCT had limited impact on the overall species composition. Other factors, such as browsing, likely influenced the outcome of the experiment, as evident from significant signs of browsing observed across the sites.

5. CONCLUSION

The findings of this study demonstrate that the silvicultural systems compared in this study had different outcomes on the density, basal area and volume production. The clearcut had higher basal area and volume production with lower stem density in both regions. Although, not all the analysed variables were affected by scarification. Overall, the retained shelterwood did not result in creating a mixed forest which is the main focus of this method, particularly in the south. However, the lack of information regarding the shelter trees and the timing of removal could be a limiting factor to this method of regenerating mixed-conifer forests. The various factors discussed could potentially influence the results of the stands' development after 30 years. These limitations highlight the need for further research and data collection to comprehensively assess the effects of these factors on the stand development in both regions. Hence, the combination method needs to be further developed, particularly in the south, so that the limiting factor can be considered to ensure a successful outcome.

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Popular science summary

Heading

The Drettinge Method: It's Potential in Creating a Mixed Conifer in Sweden

Forests are important sources of food, timber, fuelwood, bioenergy for electricity, wildlife habitat, etc. In the face of climate change, we need to sustainably manage our forests to reduce the adverse effect on forests. A practical way to reduce the effect of climate change on trees while ensuring their continuous supply is by growing them in mixtures. However, Sweden's boreal forest is dominated by cultivating single-species forests of Norway spruce or Scots pine. This has raised concerns about their vulnerability to climate-related disturbances. In recent years, alternative practices of continuous cover and shelterwood/seed trees regeneration have gained attention to address these concerns. A recommendable way of cultivating trees in mixtures in Sweden is the Drettinge method. This method combines the natural regeneration of Scots pine and planted Norway spruce. Yet only a little research has been done on this method.

This study presents the findings of a 30-year research that aimed to create a mixed forest in some sites in southern and central Sweden using naturally regenerated Scots pine and planted Norway spruce. At Each site, a plot was established by clearcutting a part, and the other part was left with sheltertrees. Thereafter, each plot was prepared by soil scarification or no soil scarification. We visited six sites in southern Sweden and four in central Sweden to gather information and assess the forests there. The goal was to assess whether this method is suitable and practical for our forests in Sweden.

The results showed that the treatments in the southern sites resulted in predominantly Norway spruce stands, with more than 75% of the basal area composed of Norway spruce. However, in the central region, the treatments resulted in a mixture of spruce-pine or pine-spruce. Interestingly, birch grew naturally in large numbers in both regions, making the forests even more diverse.

Regarding growth, the basal area and volume production of the treatments were similar in both regions. The shelterwood treatment, where some trees were retained, had less basal area and volume. But it had a higher stem density, increasing the trees per unit area. We found that soil scarification had a limited effect on the growth in both regions. The volume of the planted Norway spruce does not differ in the treatment (clearcut & shelterwood) in both regions. The clearcut treatments often outperformed shelterwood treatments, indicating that further improvements are needed to enhance the combination method and promote successful mixed forest establishment, particularly in the south. The timing of shelter tree removal is unknown across the sites due to different management personnel, which I believe affected the result of this experiment.

Although the combination method used in this experiment did not achieve the desired mixed forests, it provided valuable insights into the dynamics of tree species composition and forest regeneration. The results highlighted the importance of considering local conditions and refining the combination method to balance economic, ecological, and recreational objectives in sustainable forest management.

The long-term experiment has highlighted the challenges and opportunities of creating mixed forests in Sweden. By understanding the complexities of tree species interactions, researchers and forest managers can continue to work towards enhancing biodiversity and sustainable forest practices.

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“My heart is so filled with Joy 😊,
the joy that fills my body and soul,
so much joy that never goes low,
comes from my father above,
freedom to scream and shout for joy”, (Ife)

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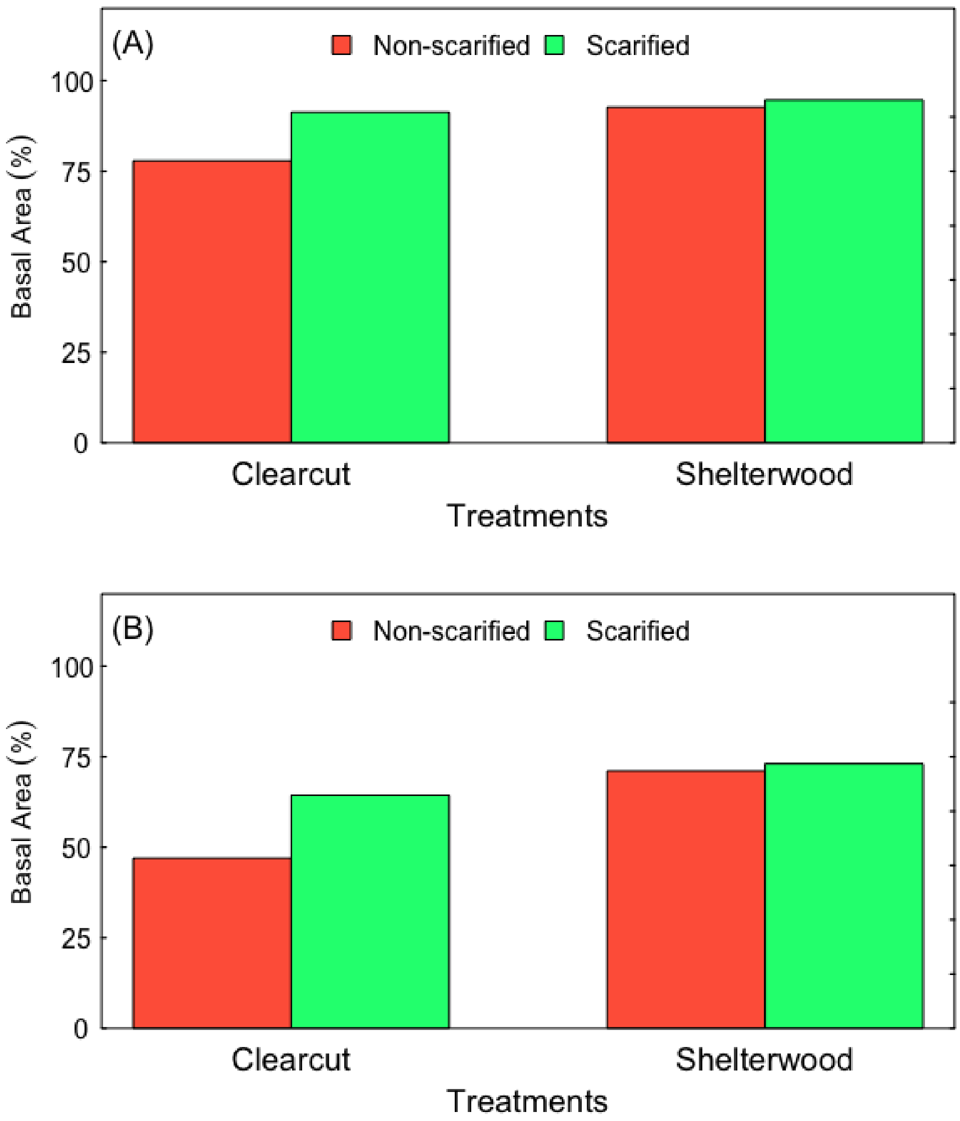
Appendix 1

Supplementary Table 1. Analysis of variance of the effects of the treatments on stem density (stemsha^{-1}), basal area (m^{2}ha^{-1}) and volume (m^{3}ha^{-1}). At a 5% level of significance

Stand Variables	**Fixed Effects**	**chisq**	**df**	***Pr(>Chisq)***
All region				
Stem Density	silvsys	13.5	1	0.00024***
	siteprep	5.6	1	0.01764*
	silvsys:siteprep	5.1	1	0.02414*
Basal Area	silvsys	71.3	1	< 2e-16***
	siteprep	3.4	1	0.06419
	silvsys:siteprep	5.8	1	0.01613*
Volume	silvsys	82.1	1	< 2.2e-16***
	siteprep	6.4	1	0.011392*
	silvsys:siteprep	7.8	1	0.005332**
South				
Stem Density	silvsys	6.9	1	0.00844 **
	siteprep	4.2	1	0.04025 *
	silvsys:siteprep	3.3	1	0.07115
Basal Area	silvsys	71.6	1	< 2.2e-16 ***
	siteprep	12.5	1	0.0004146 ***
	silvsys:siteprep	29.4	1	5.908e-08 ***
Volume	silvsys	81.4	1	< 2.2e-16 ***
	siteprep	25.1	1	5.407e-07 ***
	silvsys:siteprep	25.6	1	4.198e-07 ***
Central				
Stem Density	silvsys	6.7	1	0.009684 **
	siteprep	1.9	1	0.172528
	silvsys:siteprep	2.0	1	0.154652
Basal Area	silvsys	17.0	1	3.642e-05 ***
	siteprep	0.3	1	0.5645
	silvsys:siteprep	2.2	1	0.1375
Volume	silvsys	20.3	1	6.664e-06 ***
	siteprep	0.8	1	0.3652
	silvsys:siteprep	0.3	1	0.5491

** Values analysed are the average of the sites.*



Supplementary Figure 1. The percentage basal area of spruce in southern Sweden (**A**, **upper pane**) and central Sweden (**B**, **lower pane**). * *Values are average of sites in both regions*

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