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Forest development and financial outcomes under shelterwood and clearcut regimes in mixed stands

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Highlights

- Shelterwood and mixed species regeneration can be a viable strategy under suitable conditions.
- Active management and timely overstory removal in shelterwood systems are important for financial revenue and stand development.
- Clearcuts consistently yielded higher financial returns than shelterwood

Abstract

We assessed long-term outcomes of a regeneration experiment comparing clearcutting and shelterwood treatments, each with and without mechanical site preparation (MSP). The experiment was established in the early 1990s across Sweden and combined natural regeneration of Scots pine (*Pinus sylvestris* L.) with planting of Norway spruce (*Picea abies* (L.) H. Karst.; 2500 seedlings ha⁻¹). The first assessment showed Norway spruce dominance on southern sites and potential for mixed stands in central and northern regions. In 2022–2023, sites were re-measured to assess stand structure and productivity at mid-rotation, and the measured data were then used to parameterize Heureka decision support system (DSS) for simulations to final harvest. Southern sites developed into Norway spruce-dominated stands, with higher volume in clearcut than shelterwood treatments. Central and northern sites developed into mixed species stands, with higher volumes in shelterwood treatments in central Sweden. In northern Sweden, retained shelterwood negatively affected understory growth, highlighting the importance of active management while using shelterwood. Despite these regional differences, land expectation value (LEV) was consistently higher for clearcut treatments. Even in central Sweden, higher volumes in shelterwood treatments did not compensate for the additional costs associated with shelterwood cuttings. Our results show that establishing mixed species stands through shelterwood and planting can be viable depending on site conditions, but likely results in lower revenue than clearcutting.

Keywords *Picea abies*; *Pinus sylvestris*; combination method; Drettinge method; land expectation value

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1 Introduction

Mixed species forest, consisting of two or more tree species coexisting at any given time (Bravo-Oviedo et al. 2014), is thought to be more resilient (Jactel et al. 2009), maintain biodiversity (Felton et al. 2016; Huuskonen et al. 2021) and be less susceptible to damage (Agestam et al. 2006) than monocultures. Mixed species stands are furthermore suggested as an adaptation to climate change (Felton et al. 2010). Studies have shown that the most productive mixture of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.) produces volumes comparable to those of monocultures of the same species at intermediate site conditions (Agestam et al. 2006; Holmström et al. 2018; Huuskonen et al. 2021). Although interest in managing mixed forests is growing, practical experience and long-term data on the outcomes of different management practices are limited.

In the boreal region of Fennoscandia, the primary tree species used in forest regeneration are Scots pine and Norway spruce (Huuskonen et al. 2021). In Sweden, the distribution of these species varies regionally, with Norway spruce being predominant in the south and Scots pine more common in the north (SLU 2024). Scots pine is a more favorable fodder species, especially for moose (*Alces alces* L.), but also for roe deer (*Capreolus capreolus* L.; Felton et al. 2020; Ara et al. 2021). The selective browsing pressure and the profitability of Norway spruce stands have motivated planting only Norway spruce in the past (Månsson et al. 2007; Nilsson et al. 2010; Lodin et al. 2017). However, private forest owners are increasingly adopting mixed species forest management as a climate change adaptation (Blennow 2012). This shift is driven by risk awareness, a desire for aesthetic diversity and growing curiosity about other tree species (Lodin et al. 2017). Even when forest owners regenerate with a single species, stands turned into mixed species stands a few years after planting (Ara et al. 2021) and today approximately one third of Sweden's forest can be classified as conifer-mixed species stands (Lee et al. 2023).

Today, most stands in Sweden are regenerated through planting genetically improved seedlings after mechanical site preparation and clearcutting (MSP; Skogsstyrelsen 2024, 2025). This has been described as an efficient way to establish new stands, reducing seedling mortality (Heiskanen et al. 2013; Johansson et al. 2013; Sikström et al. 2020), shortening rotation length (Simonsen 2013; Serrano-León et al. 2021), increasing volume production (Holmström et al. 2018; Jonsson et al. 2022) and thus optimizing the financial outcome (Simonsen et al. 2010, 2013). In 2024, natural regeneration was used in less than 10% of the time (Skogsstyrelsen 2024). However, shelterwood reduces frost damage risk (Lundmark and Hällgren 1987; Langvall 2000), because the downwelling longwave radiation from the canopy increases the daily minimum air temperature (Man and Lieffers 1999; Langvall and Örlander 2001). Shelterwood stands has less competing ground vegetation (Béland et al. 2000) and pine weevil (*Hylobius abietis* L.) damage (von Sydow and Örlander 1994; Nordlander et al. 2003; Petersson and Örlander 2003; Wallertz et al. 2006; Wallertz 2009). Lower establishment costs and the value increase for the retained overstory, which later will be harvested, could potentially make shelterwood more profitable than clearcutting and planting (Glöde et al. 2003; Lula et al. 2021). However, the risk of wind damage to the retained shelterwood and thus loss of income needs to be considered (Örlander 1995; Nilsson et al. 2006). There is also a risk that seedlings might be damaged when the shelterwood is harvested (Niemistö et al. 2024). Furthermore, uneven seed distribution and variation in establishment success among years and sites make natural regeneration more uncertain (Miina and Saksa 2008; Jonsson et al. 2022; Lula et al. 2024), with the risk of reduced volume production (Lula et al. 2021) and prolonged rotation periods relative to planting (Strand et al. 2006; Simonsen et al. 2013; Tishler et al. 2020).

The combination method, also commonly called the “Drettinge method” in Sweden, combines natural regeneration with planting. In this approach, a retained Scots pine shelterwood

promotes natural regeneration of its seedlings while Norway spruce seedlings are actively planted (Karlsson and Örlander 2004). It intends to promote the development of a mixed species stand, combining planting and shelterwood systems' benefits while mitigating their risks. In Sweden, a nationwide regeneration experiment was initiated in the early 1990s to evaluate the combination method in comparison to conventional clearcutting followed by planting (Nilsson et al. 2006). The planted seedlings grew slower in the shelterwoods compared to the clearcuts and for naturally regenerated Scots pine, seedling density in the central region increased under both shelterwood and MSP. In the southern region, these treatments initially enhanced seedling density, but the effects were diminished after five years due to high mortality, possibly from browsing pressure or a fungal pathogen. Moreover, naturally regenerated Scots pine seedlings grew slowly across all regions, constraining future mixed species stands' establishment, particularly in southern Sweden.

We remeasured sites from the national regeneration experiment to assess long-term effects of clearcutting and shelterwood-cutting on species composition, basal area, volume and stand density. We used the measured stand variables to parameterize Heureka (a forest decision support system) to further simulate the stand development until final harvest. Using the simulation results, we quantified the effect of shelterwood-cutting and clearcutting on long-term volume production, cash flow (CF) and land expectation value (LEV) using different interest rates (IR).

2 Materials and methods

2.1 Study sites and experimental design

We remeasured twelve sites across Sweden, chosen from those established in the early 1990s (Nilsson et al. 2006). The sites were located between Skåne county in the south (56°21'N, 15°18'E) to Västerbotten county in the north (64°33'N, 18°24'E; Fig. 1). At the time of establishment, all twelve were classified as moderate-fertility sites, with either blueberry- or grass-dominated understory vegetation (Hägglund and Lundmark 1977). Site index (SIS), estimated from site properties, assessed as Scots pine or Norway spruce height after 100 years of growth, ranged from 20 to 29 m (Hägglund and Lundmark 1977; Table 1). All sites were located on mesic

Table 1. Description of study sites, using the same regional classification (south, central and north), and site numbers from the original design in Nilsson et al. (2006).

Region	Site	County	Latitude, Longitude	Altitude (m a.s.l.)	Temperature sum (degree-days)	Soil texture	SIS ¹ (m)
South	6	Jönköping	57°17'N, 15°17'E	185	1385	Sandy-silty	26–27 (SP)
South	7	Kronoberg	57°08'N, 14°49'E	230	1400	Sandy-silty	25–26 (SP)
South	11	Skåne	56°26'N, 14°20'E	150	1450	Sandy-silty	28 (NS)
South	15	Älvsborg	57°28'N, 13°08'E	175	1400	Sandy-silty	22 (NS)
South	16	Skaraborg	58°39'N, 13°47'E	70	1400	Sandy-silty	26 (SP)
Central	4	Södermanland	59°13'N, 16°49'E	60	1375	Sandy-silty	24–27 (SP)
Central	17	Värmland	59°25'N, 13°31'E	90	1380	Sandy-silty	26 (SP)
Central	18	Örebro	59°35'N, 15°27'E	85	1350	Sandy-silty	24–26 (SP)
Central	20	Dalarna	60°27'N, 15°45'E	157	1222	Sandy-silty	23 (NS)
North	23	Jämtland	63°44'N, 15°44'E	290	850	Sandy-silty	29–21 (SP)
North	24:1	Västerbotten	64°04'N, 20°17'E	145	1010	Sandy	23 (SP)
North	24:2	Västerbotten	64°33'N, 18°24'E	340	810	Sandy-silty	20–21 (SP)

¹ Site index, estimated from site properties, at experimental establishment, either based on dominant height at age 100 years for Scots pine (SP) or Norway spruce (NS)

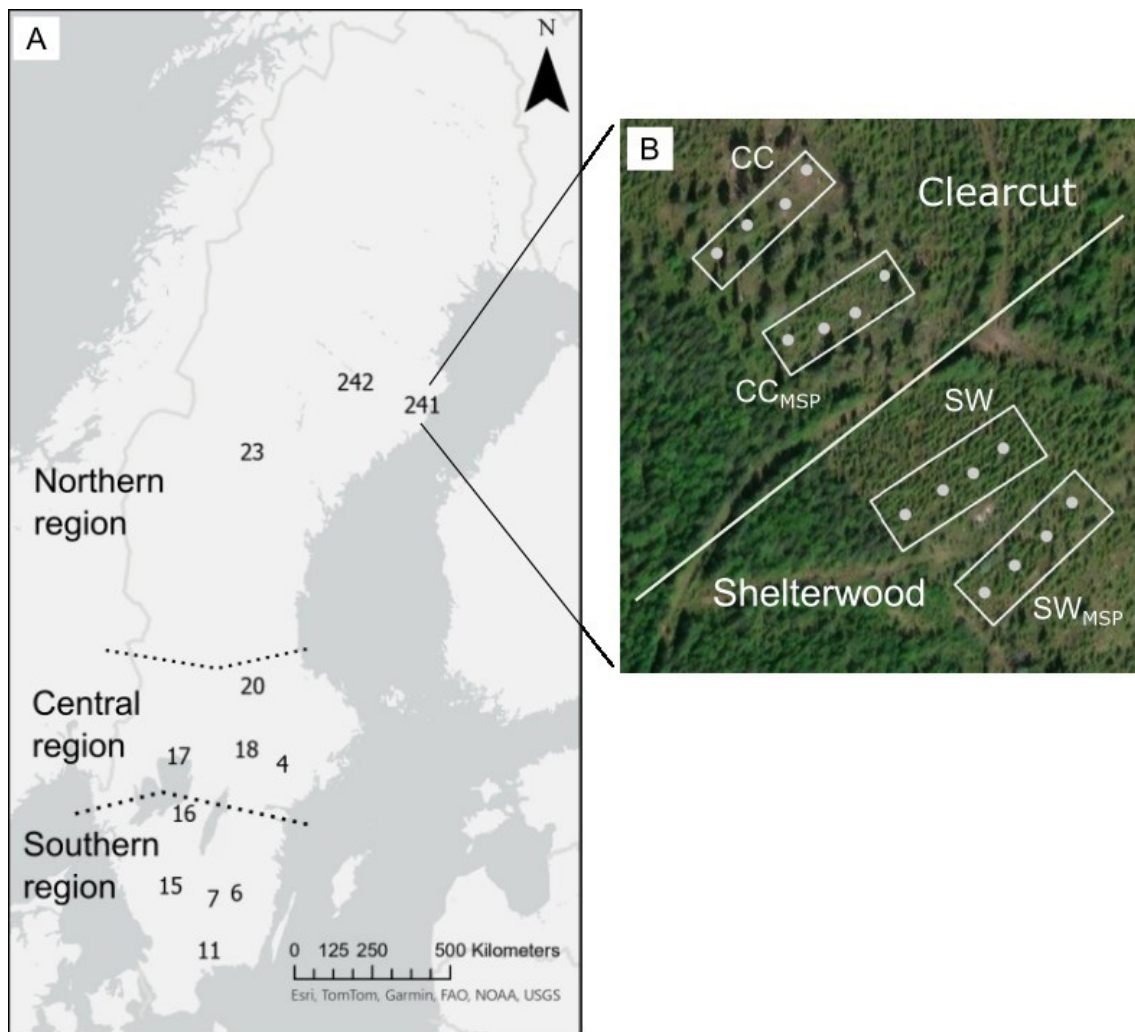


Fig. 1. Picture A shows a map over Sweden and the locations of the sites divided into the three regions, southern, central and northern Sweden. Picture B shows site 24:1 and the experimental design. The whole site equals one block divided into the two main treatments: clearcut (CC) and shelterwood (SW). The main treatments were then further divided into the two sub-treatments: mechanical site preparation (MSP) and no mechanical site preparation (no abbreviation). The four filled circles in the sub-treatments represent the sample plots established in 2022 or 2023.

soil, with annual temperature sums ranging from 810 degree-days (dd) in the north to 1450 dd in the south (Table 1; Nilsson et al. 2006). Soil texture was predominantly sandy-silty till, except for site 24:1, which was sandy.

In the 1990's, one block per site was established with a split-plot design. Each block was divided into two main treatments, either a clearcut or a shelterwood. The two main treatments were then further split into two sub-treatments, with or without MSP (Fig. 1). The specific MSP method varied by site, either disc trenching, patch scarification, or mounding (Table 2). These were, and still are, conventional MSP methods in forest regeneration in northern Europe (Sikström et al. 2020). In each block, both the main treatments and the sub-treatments were randomly assigned.

The original sub-treatment areas were 0.4 ha, resulting in a total block area of 1.6 ha (Table 2). Final felling for the clearcut treatments and the release cutting to establish the shelterwood occurred in 1994 and 1995 (Table 2). In total, between 114 and 156 trees ha⁻¹ were retained in the shelterwood treatments, corresponding to a volume range of 69 to 138 m³ ha⁻¹, with 78% to 100% of the

Table 2. Site-specific details of forest management operations during the establishment phase (Nilsson et al. 2006).

Site	Clearcut (month, year)	MSP ¹ (month, year)	MSP ¹ (type)	Planting (month, year)	Seedling type	Seedling age (years)
6	Oct-94	Apr-95	Patch	May-95	Bare-root	4
7	Mar-95	Nov-95	Disc trench.	May-96	Cont ²	1.5
11	Sep-95	Nov-95	Disc trench.	Jun-96	Bare-root	4
15	Feb-94	Sep-94	Disc trench.	Apr-95	Bare-root	4
16	Apr-94	Nov-94	Disc trench.	May-95	Cont ²	2
4	Apr-94	Oct-95	Disc trench.	May-96	Cont ²	1
17	Dec-94	Sep-95	Mound	May-96	Cont ²	1
18	Oct-95	Oct-96	Disc trench.	May-97	Cont ²	1
20	Dec-94	May-95	Disc trench.	Jun-95	Cont ²	1.5
23	Mar-95	Jun-96	Mound	Jun-96	Cont ²	1
24:1	Aug-94	Jul-96	Disc trench.	Sep-96	Cont ²	1
24:2	Jan-95	Sep-96	Disc trench.	Jun-97	Cont ²	1

¹Mechanical site preparation²Containerized seedlings

retained volume consisting of Scots pine (Nilsson et al. 2000, 2006). MSP was performed between 1994 and 1996. All sub-treatments were planted between 1995 and 1997 with a density of 2500 Norway spruce seedlings ha⁻¹, either with containerized or bare-root seedlings (Table 2; Nilsson et al. 2006). For additional details on the original experimental design, results, and measurements, see Karlsson and Nilsson (2005) and Nilsson et al. (2006).

2.2 Inventory design

At the time of the establishment in the 1990's, the location of each site and sub-treatments were documented on paper. Most of the sites were given coordinates for the general location of the experiment and had hand-drawn maps of the sub-treatment locations. In 2022, the sites were first relocated in ArcMap (version ArcGIS Pro 3.5.0) once the coordinates were converted from the old RT 38 reference system to SWEREF 99 TM. The outer bounds of the sub-treatments were then preliminarily located in ArcMap and more exactly positioned during the field visits. After this process, twelve of the original sites' locations and borders could be re-established. The twelve sites were measured between fall 2022 and spring 2023 (Supplementary file S1: Table S1, available at <https://doi.org/10.14214/sf.26005>).

In each of the original sub-treatments, four sample plots with a radius of 5.64 meters were established, (sixteen in total per block). The sample plots were laid out along a transect in the center of the sub-treatments at 15–23 m spacing with an exception for seven sub-treatments (six of which had three sample plots and one which had two sample plots due to uncertainties of the exact location of the sub-treatment). Within each sample plot, all trees above 1.3 meters were noted for species and diameter at breast height (DBH, measured twice with calipers at right angles and averaged). On selected sample trees, the height was also measured with a Vertex 5 (Haglöf Sweden n.d.). The sample trees were selected by size and location relative to the sample plot center. For each tree species present in the sample plot, the height of the two largest trees was measured, as well as the three trees closest to the center. If one of the largest trees also was one of the three closest to the center, the fourth-closest tree was then measured and so forth. The center of each sample plot was marked in the field, and the latitude and longitude were noted.

2.3 Data processing and analysis

Heights for the measured Norway spruce, Scots pine and birch trees (*Betula pendula* Roth and *Betula pubescens* Ehrh.) were estimated using diameter-height functions parameterized with data from sample trees for which both DBH and height were measured. For the six species with more limited occurrence, height estimates were derived from the Norway spruce data (hybrid larch, *Larix × marschlinsii* Coaz.) or the birch spp. data (gray alder – *Alnus incana* (L.) Moench, aspen – *Populus tremula* L., oak – *Quercus robur* L., rowan – *Sorbus aucuparia* L., and willow – *Salix caprea* L.). This grouping was also applied in the tree volume estimations.

Tree height was estimated using Näslund's height function (1947; Eq. 1), implemented in R, version 2023.9.1.494 (R Core Team 2023) using the package *forestmangr* (Rabelo Braga et al. 2023). One α and one β coefficient (Eq. 1) were estimated for each combination of species, site, and sub-treatment based on the sample tree data. The fitted model was visually validated against the measured sample tree heights. Upon successful validation, the derived parameters were applied together with the measured DBH to predict individual tree height:

$$h = \frac{dbh^a}{(\alpha + \beta \times dbh)^a} + 1.3, \quad (1)$$

where h is the measured or estimated height (m), dbh is the measured DBH (cm) and a is a species-specific parameter. For Norway spruce and larch, a is 3; for all other species a is 2. α and β are the estimated site-, treatment- and species-specific parameters, and the +1.3 corrects for the height at which DBH was measured.

Volume was calculated for each tree using its measured DBH and estimated height. For trees with $DBH < 4$ cm, Andersson's volume functions (1954) were applied, while for trees with $DBH > 5$ cm, Brandel's volume function (1990) was used (Suppl. file S1). For trees with a DBH ranging from 4.0 to 5.0 cm, a smoothing function was applied to reduce possible divergence between functions (Holmström et al. 2016; Suppl. file S1). Quadratic mean diameter (QMD; Eq. 2) and Lorey's mean height (H_L ; Eq. 3) was also calculated for Scots pine, Norway spruce and birch spp. for each region and sub-treatment:

$$QMD = \sqrt{\frac{(\sum dbh_i^2)}{n}}, \quad (2)$$

where dbh_i is the measured DBH (cm) of tree i and n is the total number of trees (Curtis and Marshall 2000).

$$H_L = \left(\sum_{i=1}^n BA_i \times h_i \right) / BA_{tot}, \quad (3)$$

where BA_i is the basal area (m^2) of tree i and h_i is the height of tree i and BA_{tot} is the total basal area for all calipered trees in the sample plot (Kershaw et al. 2016).

2.4 Statistical analysis

To assess potential differences in stand density (stems ha^{-1}), volume, basal area, quadratic mean diameter (QMD) and Lorey's mean height (H_L), values were first calculated at sample plot level and then averaged for each sub-treatment. The averaged values were tested with linear mixed-effects

models which were fitted using the package *lme4* (Bates et al. 2015) in R version 2023.9.1.494 (R Core Team 2023). For stand density, the response variable was log transformed before the model fitting, to ensure normal distribution residuals. The fixed effects included main treatment (clearcutting and shelterwood) and sub-treatment (MSP and no MSP), while each site was one block and included as a random effect. Main treatment was nested within site to account for the split-plot experimental design. The general model structure was:

$$Y_{ijk} = \mu + a_i + \beta_j + (a\beta)_{ij} + \gamma_k + (\beta\gamma)_{jk} + \varepsilon_{ijk}, \quad (4)$$

where μ is an overall mean, a_i the random effect of the i -th block, β_j the fixed effect of main treatment, γ_k the fixed effect of sub-treatment, $(\beta\gamma)_{jk}$ the fixed interaction effect between main treatment and sub-treatment and $(a\beta)_{ij}$ and ε_{ijk} were the main treatment and sub-treatment error terms respectively. Random effects are assumed to be normally distributed with constant variances within the levels of the random factor and with independence between levels of the random factor.

Separate models were fitted for each region (south, central, and north), as well as for the combined dataset of the southern and central sites. The northern sites were excluded from the combined dataset due to the retention of the shelterwood trees on those sites. To adjust for small sample sizes, the Kenward–Roger approximation was used to estimate denominator degrees of freedom and a significance level of $p=0.05$ was used (Suppl. file S1: Tables S2–S6). Due to a deviation in management objectives at site 11 (sub-treatment CC), where the forest owner actively promoted birch spp. got it excluded from statistical analyses.

2.5 Simulations and calculations

Simulations were conducted using StandWise application in Heureka DSS to further analyze the effects of the four treatments on volume growth over a full rotation and their expected revenue. Heureka DSS is an open software tool used to simulate stand development based on growth and yield models in 5-year time steps (Lämås et al. 2023). Two different simulations were conducted, one for the overstory and one for the understory. Swedish SEK was used for the calculations and converted to EUR, using the conversion factor of 11.468 (April 2024).

2.5.1 Overstory simulations

For each stand, two management scenarios were simulated: one representing regeneration under a shelterwood system, and the other representing a clearcut system. For the shelterwood system, overstory development was simulated to cover the period from the initial release cutting until the assumed removal of the remaining shelter trees, set to occur ten years after release cutting. Input data for the simulations were based on stand measurements collected prior to the release cutting. The intensity of the simulated release cuttings closely reflected the actual basal area proportions of Norway spruce and Scots pine retained in the stands following intervention, while birch spp. was removed entirely during the release cuttings. In the shelterwood scenario, wind damage was included based on empirical data from southern Sweden, where an average of 9% of overstory basal area was lost to windthrow during the first seven years after release cutting (Nilsson et al. 2006). Therefore, during the simulation, an assumption was made that 9% of the basal area was lost due to windthrows.

2.5.2 Understory simulations

Data collected from the inventory served as the starting values for the simulations. Prior to the simulations, stems with a diameter at breast height (DBH) smaller than 5 cm were removed, provided that the remaining stem density exceeded 1000 stems ha⁻¹. All stands were subjected to a pre-commercial thinning following this protocol, except for two stands. For site 6 treatment SW_{MSP}, 12 stems of Scots pine trees with a dbh smaller than 5 cm were retained to maintain an equivalent number of 1000 stems ha⁻¹. Whereas for site 20 treatment SW, the trees were smaller than 1 cm in DBH, and where therefore still removed, leading to a total stem number below 1000 stems ha⁻¹ (Table 5).

During the simulations, the stands were managed in accordance with the thinning guidelines of Södra, the regional forest owners' association. For the thinnings to follow the guidelines, basal area had to reach a minimum of 31 m² before the stands reached a top height of 20 m. Otherwise, the following alternative predefined criteria were applied:

1. If the stem density exceeded 1500 stems ha⁻¹ with a top height of 16 m, the stand was thinned
2. If the stem density exceeded 1000 stems ha⁻¹ with a top height of 20 m, the stand was thinned

Following this, all stands, except three, had one or two simulated thinnings from below with 25% of basal area removal each time (Table 5).

2.5.3 Financial calculations

Three different IRs' were used for the financial calculations: 0%, 2.5% and 4% (Brukas et al. 2001). Depending on IR, when either the CF or the LEV reached its maximum value, the stands were harvested. For IR 0%, CF was calculated (Eq. 5):

$$CF = \frac{\sum_{t=1}^u (R_t - C_t)}{u}, \quad (5)$$

where R is revenue and C the cost at time t and u is the rotation length. For IRs 2.5% and 4%, LEV was instead calculated (Eq. 6):

$$LEV = \left(\sum_{t=1}^u \frac{R_t - C_t}{(1+r)^t} - I_0 \right) \times \frac{1}{(1 - (1+r)^{-u})}, \quad (6)$$

where R is the revenue and C is the cost, t (years) is the age of the stand, I_0 is the investment cost at year 0, r is the IR expressed as a decimal; for example, 2.5% was written as 0.025, and u is the rotation length (Faustmann 1849 as cited by Dosumu et al. 2024).

For the calculation of CF and LEV, the roadside timber price list specific to the Västergötland region (Suppl. file S1: Tables S10–S11) was used for both the overstory and understory. Operational harvester and forwarder costs for thinning and final felling were based on data provided by Södra for 2024. The thinning operation costs were 139.5 EUR hour⁻¹ for the harvester and 95.9 EUR hour⁻¹ for the forwarder, whereas final felling costs were 165.7 EUR hour⁻¹ for the harvester and 130.8 EUR hour⁻¹ for the forwarder. Furthermore, regeneration costs were included in accordance with Södra's 2024 financial data, including MSP (392.4 EUR ha⁻¹), seedling and planting labor (0.73 EUR seedling⁻¹), and pre-commercial thinning (436 EUR ha⁻¹). Only the

southern and central sites were used in the simulation since the shelterwood was still retained on the northern sites.

2.5.4 Financial outcomes of overstory retention

To evaluate the effect of selecting shelterwood retention instead of clearcutting on profitability, the financial outcomes of the shelterwood and clearcut treatments were compared. The resulting difference was then incorporated into the understory calculations as either an income or a cost at year 0 for the shelterwood treatments. It was calculated as the sum of discounted revenues from the shelterwood cuttings subtracted by the revenue from the clearcutting. If negative, it was treated as a cost, and if positive, as an income. For this analysis, the timber value of wind-felled shelter trees was assumed to be equal to the costs of their removal and were therefore excluded from the financial calculations.

2.6 Mixed species assessment

For this study, we adopted a baseline definition in which the dominant tree species comprised of no more than 75% of the stand basal area, based on treatment average. This threshold is slightly lower than that used by the Swedish NFI but is consistent with definitions applied in previous scientific studies (Agestam et al. 2006; Felton et al. 2016; SLU 2023).

3 Results

3.1 Stand development

3.1.1 Stand density

Stand density ranged from 2956 to 7008 stems ha⁻¹ (Fig. 2). There were no statistically significant differences overall or for the separate regions (south, central and north; Suppl. file S1: Tables S2–S3) in stand density between the clearcut and shelterwood treatments. MSP had also no significant effect on stand density.

3.1.2 Stand volume

Standing volume ranged from 14.2 to 132.2 m³ ha⁻¹ (Fig. 3). Between the clearcut and shelterwood treatments, there were no significant differences overall in volume (Suppl. file S1: Tables S4–S5). However, when analyzed by region, the southern and northern region showed significantly higher volumes in the clearcut treatments than in the shelterwood treatments, and MSP also increased volume in the north. In the central region, neither harvesting method nor MSP had a statistically significant impact on volume.

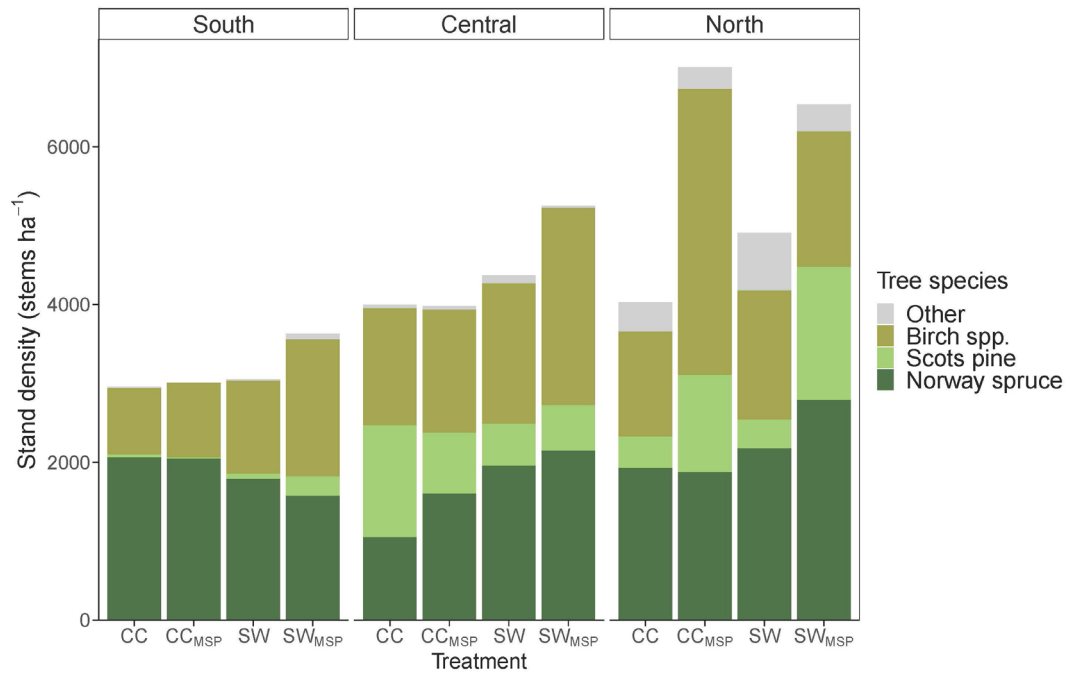


Fig. 2. Stand density (stems ha⁻¹) for the different regions (south, central and north), treatments (CC, CC_{MSP}, SW and SW_{MSP}), and species (Norway spruce, Scots pine, birch spp. and other). The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

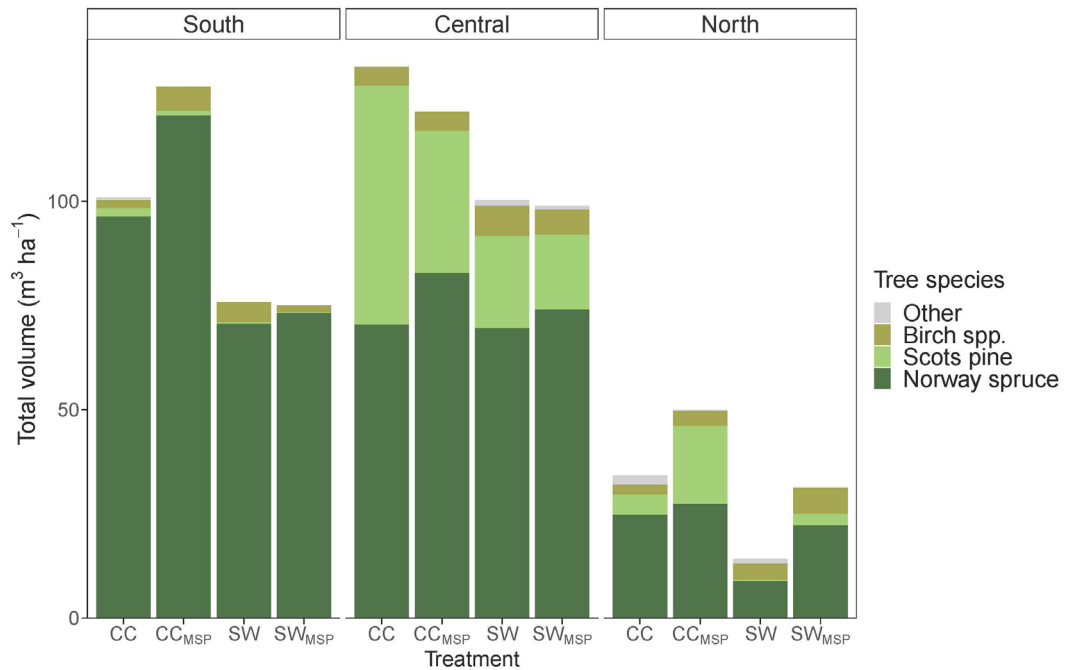


Fig. 3. Total standing volume in m³ ha⁻¹ for the different regions (south, central and north), treatments (CC, CC_{MSP}, SW and SW_{MSP}), and species (Norway spruce, Scots pine, birch spp. and other). The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Table 3. Quadratic mean diameter (QMD) $\pm$ SE and Lorey's mean height (H_L) $\pm$ SE by region and treatment. The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Region	Treatment	QMD (cm)			Lorey's height (m)		
		Spruce	Pine	Birch spp.	Spruce	Pine	Birch spp.
South	CC	10.3 $\pm$ 0.9	6.4 $\pm$ 3.7	2.0 $\pm$ 0.5	10.0 $\pm$ 0.9	7.4 $\pm$ 2.3	5.8 $\pm$ 1.6
South	CC _{MSP}	11.4 $\pm$ 1.5	5.7 $\pm$ 3.3	4.7 $\pm$ 2.2	12.1 $\pm$ 0.9	9.5 $\pm$ 4.0	6.8 $\pm$ 2.4
South	SW	9.9 $\pm$ 1.0	2.9 $\pm$ 1.0	1.8 $\pm$ 0.7	9.8 $\pm$ 0.9	4.5 $\pm$ 1.4	5.2 $\pm$ 1.4
South	SW _{MSP}	9.6 $\pm$ 1.1	0.6 $\pm$ 0.4	3.8 $\pm$ 1.2	9.7 $\pm$ 1.1	2.4 $\pm$ 0.2	6.2 $\pm$ 1.3
Central	CC	10.2 $\pm$ 2.3	11.0 $\pm$ 1.0	4.3 $\pm$ 1.6	10.9 $\pm$ 1.0	10.7 $\pm$ 0.8	7.3 $\pm$ 1.4
Central	CC _{MSP}	10.3 $\pm$ 0.5	9.7 $\pm$ 0.5	2.9 $\pm$ 0.5	11.0 $\pm$ 1.0	9.7 $\pm$ 1.4	6.7 $\pm$ 0.7
Central	SW	9.0 $\pm$ 1.1	8.4 $\pm$ 2.2	3.0 $\pm$ 1.4	10.1 $\pm$ 0.8	8.5 $\pm$ 1.9	8.9 $\pm$ 1.1
Central	SW _{MSP}	9.3 $\pm$ 1.0	7.4 $\pm$ 2.1	2.0 $\pm$ 0.5	10.0 $\pm$ 0.6	8.2 $\pm$ 2.0	5.1 $\pm$ 1.4
North	CC	6.4 $\pm$ 1.3	5.3 $\pm$ 1.7	2.3 $\pm$ 0.6	7.1 $\pm$ 1.1	4.8 $\pm$ 1.3	4.8 $\pm$ 1.0
North	CC _{MSP}	6.9 $\pm$ 0.5	7.1 $\pm$ 1.0	1.2 $\pm$ 0.3	7.0 $\pm$ 0.2	7.5 $\pm$ 0.1	3.9 $\pm$ 1.2
North	SW	4.2 $\pm$ 0.7	1.8 $\pm$ 0.1	3.4 $\pm$ 0.5	4.8 $\pm$ 0.5	2.6 $\pm$ 0.1	4.8 $\pm$ 0.4
North	SW _{MSP}	5.1 $\pm$ 0.5	2.5 $\pm$ 0.6	3.5 $\pm$ 0.5	6.2 $\pm$ 0.7	3.8 $\pm$ 0.5	5.9 $\pm$ 0.6

3.1.3 Diameter and height

The clearcut and shelterwood treatments did not have a statistically significant effect on quadratic mean diameter overall (QMD; Suppl. file S1: Table S6). In contrast, species differences were evident, with Norway spruce exhibiting significantly larger QMD values compared to Scots pine (Table 3). When analyzed separately by region (southern, central, and northern), the clearcut and shelterwood treatments again showed no significant effect on QMD. However, Norway spruce QMD was significantly larger than Scots pine QMD in the southern and northern regions.

When the regions were tested together, the clearcut and shelterwood treatments had no effect on Lorey's mean height (H_L ; Suppl. file S1: Table S7), while the Norway spruce was significantly taller than Scots pine (Table 3), this was true for the northern region as well. For the southern and central regions, the H_L were significantly higher in the clearcut treatments compared to the shelterwood; Norway spruce trees were also significantly taller than Scots pine trees.

3.1.4 Basal area

The mean basal area ranged from 4.1 to 22.4 m² ha⁻¹ (Fig. 4). The clearcut and shelterwood treatments had no significant effect on basal area overall or for the southern and central region when tested separately (Suppl. file S1: Tables S8–S9). In the north however, where the shelterwood was still retained, the clearcuts had significantly higher basal area than shelterwood treatments. MSP significantly increased basal area as well.

3.1.5 Mixed forest

All southern sites, irrespective of clearcut or shelterwood treatments, had a Norway spruce basal area proportion exceeding 75% (Fig. 5), corresponding to a single-species stand. In contrast, on central and northern sites, Norway spruce accounted for less than 75% of the total basal area across all clearcut and shelterwood treatments.

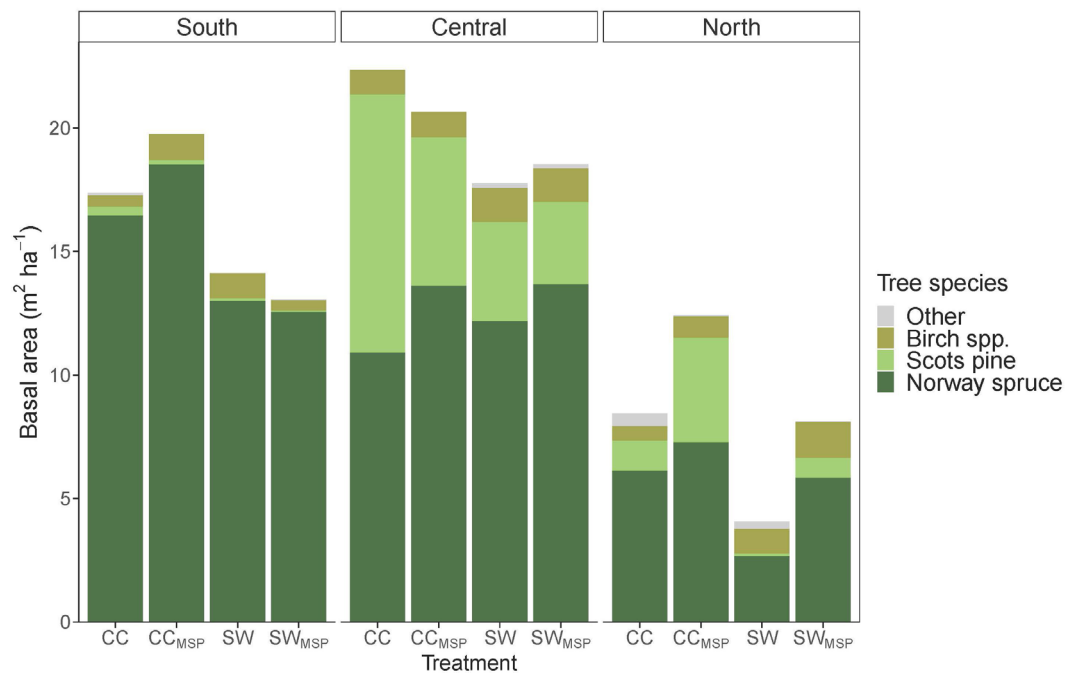


Fig. 4. Total basal area of the new regeneration for sites in southern, central and northern Sweden. The shelterwoods were still retained on the northern sites but were not included in the calculated basal area. The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

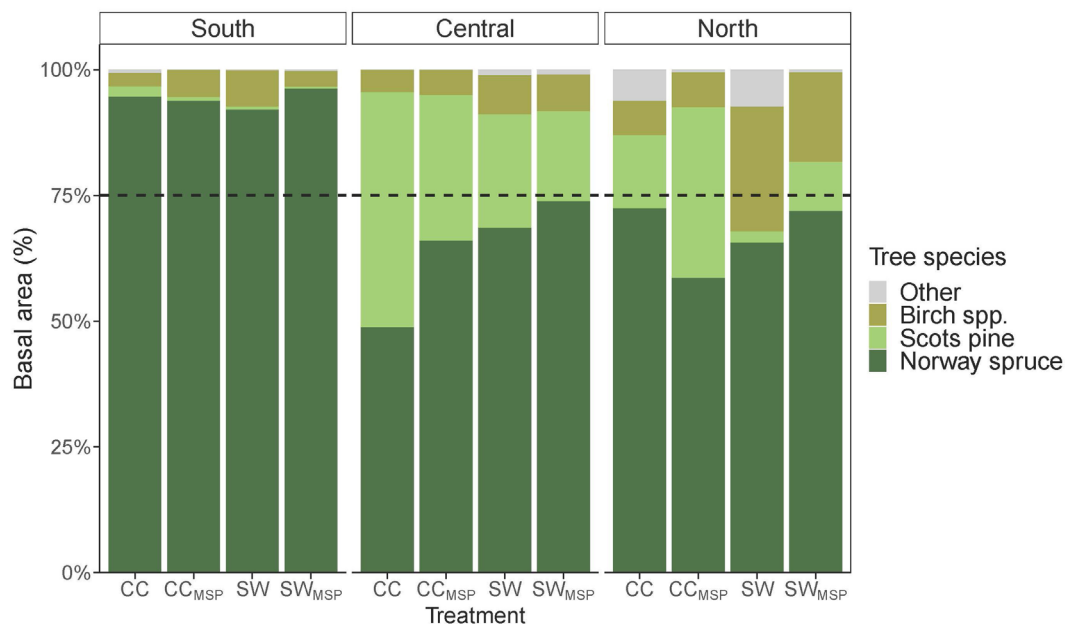


Fig. 5. Basal area divided by region and species in percent. The black dotted line shows the cut-off for mixed species stands (75%). The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Table 4. The quadratic mean diameter (QMD) for Scots pine and Norway spruce and the QMD ratio for Scots pine vs. Norway spruce for the four central sites. The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Site	Treatment	QMD (cm)		QMD ratio
		Scots pine	Norway spruce	
4	CC, CC _{MSP}	11.1	11.5	1.0
4	SW, SW _{MSP}	9.9	9.0	1.1
17	CC, CC _{MSP}	10.6	10.9	1.0
17	SW, SW _{MSP}	11.3	10.5	1.1
18	CC, CC _{MSP}	8.8	6.8	1.3
18	SW, SW _{MSP}	8.4	10.8	0.8
20	CC, CC _{MSP}	10.8	11.9	0.9
20	SW, SW _{MSP}	1.8	6.3	0.3

The ratio of QMD for Scots pine vs. Norway spruce was close to 1 in all the clearcut treatments but varied in the shelterwoods between 0.3 to 1.1 (Table 4; Fig. 6). In addition, the visualized diameter distributions of the four central sites demonstrated the same diameter range for the two species (Fig. 6).

3.2 Simulations

Using the defined criteria for the simulations, one or two thinnings were carried out in all sites and sub-treatments, except in three stands where thinnings were omitted due to low stem density (site 6, sub-treatment SWMSP; site 11, sub-treatment SW; and site 20, sub-treatment SW; Table 5). The first thinning was simulated when the stand age ranged from 29 to 66 years, with a corresponding basal area between 19 m² ha⁻¹ and 34 m² ha⁻¹. The wood volume removed during the first thinning ranged from 29.5 to 70.8 m³ ha⁻¹. A second thinning was simulated in applicable 34–54-year-old stands, with basal area varying between 21 m² ha⁻¹ and 31 m² ha⁻¹. The wood volume removed during the second thinning ranged from 43.9 to 64.3 m³ ha⁻¹. The optimal rotation age defined as the stand age at which the CF or LEV was maximized varied with the applied IR. At an IR of 0%, optimal rotation ages were the longest, ranging from 69 to 156 years, and with an IR of 4%, the optimal rotation ages were the shortest, ranging between 49 to 96 years.

3.2.1 The revenue or cost of shelterwood

Across the nine sites where simulations were conducted, the economic outcome of the shelterwood system relative to clearcutting varied depending on the IR applied (Table 6). At an IR of 0%, shelterwood treatments were more profitable than clearcutting across both the southern and central regions (except for site 16). In contrast, at IRs of 2.5% and 4%, shelterwood consistently resulted in a negative outcome relative to clearcutting, representing a relative loss regardless of region.

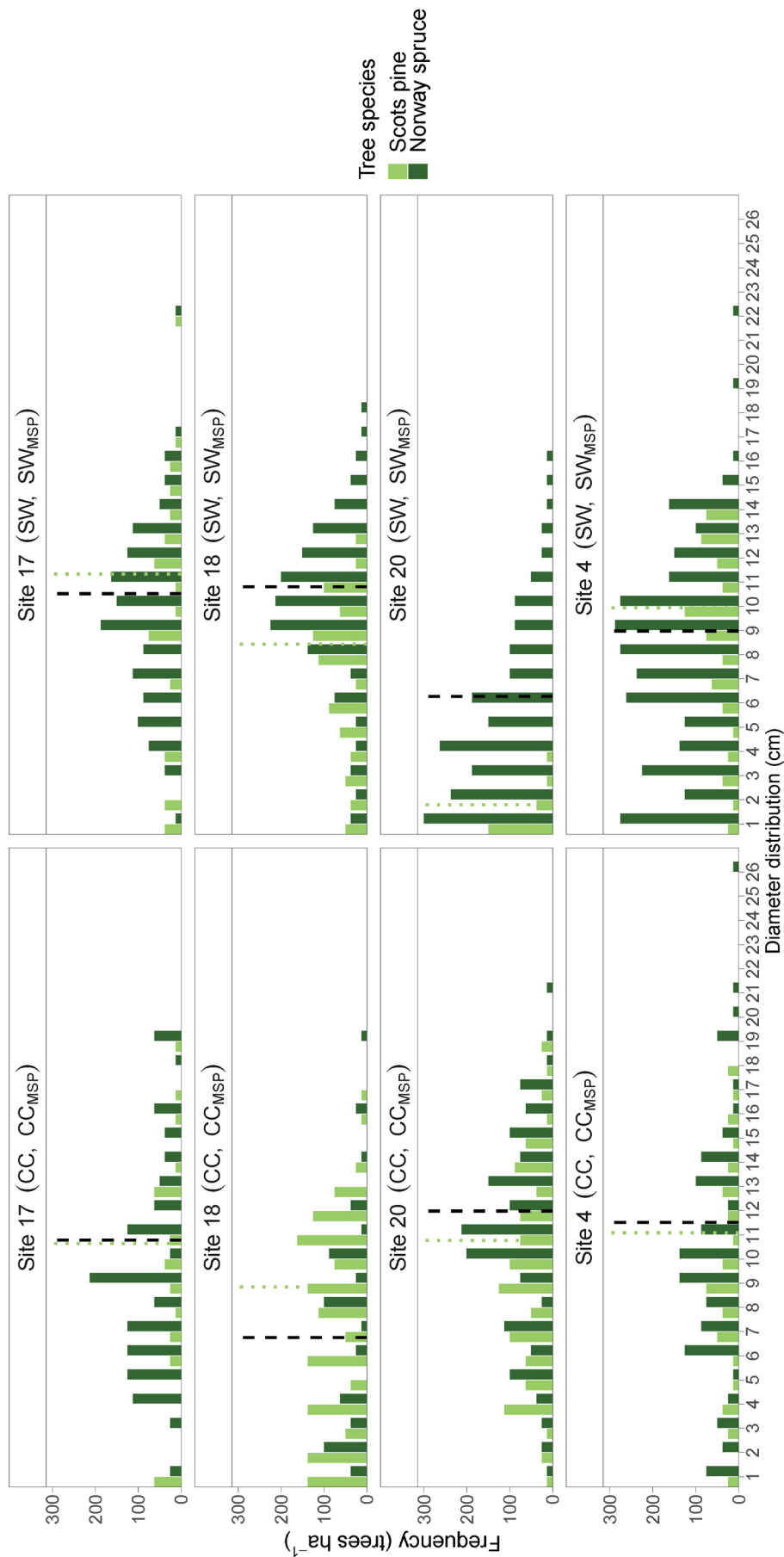


Fig. 6. The diameter distribution of Scots pine and Norway spruce for the clearcut treatments (with and without mechanical site preparation together) and shelterwood treatments (with and without mechanical site preparation together) for the four different sites in central Sweden. The vertical dashed lines represent the mean QMD for Scots pine (dotted, light green) and Norway spruce (dashed, black) for each site. The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Table 5. Starting values for the different stands and treatments, as well as the simulated thinnings and ages at final harvest for the three different interest rates (IR). The values are shown per hectare. The treatments are abbreviated CC = clearcut without mechanical site preparation, CC_{MSP} = clearcut with mechanical site preparation, SW = shelterwood without mechanical site preparation, and SW_{MSP} = shelterwood with mechanical site preparation.

Site	Treatment	Starting values ¹			1st thinning			2nd thinning			Final harvest (IR = 0%)			Final harvest (IR = 2.5%)			Final harvest (IR = 4%)		
		Stems	BA (m ²)	Age	Height ⁴ (m)	BA ³ (m ²)	Vol. ⁵ (m ³)	Age	Height ⁵ (m)	BA ³ (m ²)	Vol. ⁶ (m ³)	Age	Vol. ⁶ (m ³)	Age	Vol. ⁶ (m ³)	Age	Vol. ⁶ (m ³)		
6	CC	1950	17	37	15.5	22 (16)	151.9 (36.3)	47	19.6	25 (19)	221.1 (53.3)	107	641.2 (730.8)	77	466.0 (555.6)	62	388.2 (477.8)		
6	CC _{MSP}	2225	15	37	15.2	19 (14)	129.4 (31.0)	47	19.1	23 (17)	196.4 (47.3)	112	643.4 (721.7)	77	438.3 (516.6)	67	348.0 (426.3)		
6	SW	1300	14	42	19.3	21 (15)	162.6 (37.7)	-	-	-	-	107	559.4 (597.1)	67	330.5 (368.2)	62	290.2 (327.9)		
6	SW _{MSP}	700	9	-	-	-	-	-	-	-	-	122	546.0 (546.0)	77	313.1 (313.1)	72	280.6 (280.6)		
7	CC	2150	18	34	15.5	22 (16)	149.7 (35.4)	44	19.9	26 (19)	230.2 (54.9)	104	676.0 (766.3)	69	452.2 (542.5)	59	347.7 (438.0)		
7	CC _{MSP}	2300	20	29	14.5	20 (15)	128.0 (31.3)	39	19.6	25 (19)	224.6 (55.0)	94	686.4 (772.7)	64	478.1 (564.4)	64	478.1 (564.4)		
7	SW	1875	12	39	14.6	19 (15)	128.0 (30.3)	54	20	26 (20)	237.0 (56.7)	114	603.5 (660.2)	74	422.2 (509.2)	69	380.5 (467.5)		
7	SW _{MSP}	1750	16	34	14.7	20 (15)	134.6 (32.6)	44	19	24 (18)	207.6 (50.6)	99	613.5 (696.7)	74	460.7 (543.9)	69	417.7 (500.9)		
11	CC	2225	15	41	15.8	22 (17)	158.8 (37.7)	51	19.5	25 (19)	220.0 (52.7)	116	654.2 (744.6)	76	407.0 (497.4)	66	313.7 (404.1)		
11	CC _{MSP}	2200	15	36	14.3	19 (14)	120.7 (29.5)	51	19.9	27 (20)	241.9 (59.4)	111	647.6 (736.5)	76	428.5 (517.4)	66	333.2 (422.1)		
11	SW	2000	9	66	19.8	32 (24)	282.8 (67.4)	-	-	-	-	136	644.2 (711.6)	86	441.5 (508.9)	76	364.3 (431.7)		
11	SW _{MSP}	1000	3	-	-	-	-	-	-	-	-	156	582.4 (582.4)	101	352.0 (352.0)	96	323.4 (323.4)		
15	CC	1450	18	41	18.5	27 (20)	222.8 (54.1)	-	-	-	-	101	670.0 (724.1)	66	448.3 (502.4)	56	342.3 (396.4)		
15	CC _{MSP}	1175	17	41	19.3	25 (19)	220.7 (54.2)	-	-	-	-	96	649.6 (703.8)	66	446.7 (500.9)	61	395.1 (449.3)		
15	SW	1250	17	46	20	29 (21)	258.8 (63.3)	-	-	-	-	96	616.5 (679.8)	71	458.0 (521.3)	61	359.3 (422.6)		
15	SW _{MSP}	1500	17	46	20	29 (21)	258.1 (62.9)	-	-	-	-	101	653.8 (716.7)	71	465.7 (528.6)	66	417.0 (479.9)		
16 ²	CC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
16	CC _{MSP}	1500	30	34	19.6	34 (25)	288.3 (70.8)	-	-	-	-	69	580.8 (651.6)	49	409.7 (480.5)	49	409.7 (480.5)		
16	SW	1825	16	34	14.3	20 (15)	125 (30.2)	49	20	28 (21)	247.8 (60.3)	99	617.5 (708.0)	69	439.9 (530.4)	64	398.6 (489.1)		
16	SW _{MSP}	1775	20	29	13.5	20 (15)	125.5 (30.5)	39	18.5	26 (19)	213.5 (52.1)	89	606.3 (688.9)	64	442.4 (525.0)	59	395.0 (477.6)		
4	CC	1433	23	37	19.3	31 (23)	260.0 (63.6)	-	-	-	-	77	579.5 (643.1)	57	425.8 (489.4)	52	375.1 (438.7)		
4	CC _{MSP}	2567	22	37	18.2	31 (23)	249.9 (60.6)	-	-	-	-	102	756.4 (817.0)	62	489.2 (549.8)	57	437.9 (498.5)		
4	SW	3025	26	27	13.3	26 (20)	157.9 (38.5)	37	18.5	31 (24)	254.5 (62.1)	92	693.1 (793.7)	62	488.4 (589.0)	57	439.6 (540.2)		
4	SW _{MSP}	2525	21	42	20	33 (25)	289.0 (70.0)	-	-	-	-	102	732.0 (802.0)	67	505.5 (575.5)	62	457.4 (527.4)		
17	CC	1325	16	37	18.7	25 (19)	205.3 (49.8)	-	-	-	-	87	595.8 (645.6)	62	424.8 (474.6)	57	377.7 (427.5)		
17	CC _{MSP}	1850	14	37	16	22 (17)	156.0 (36.9)	47	19.9	25 (19)	219.3 (52.3)	97	555.9 (645.1)	72	399.5 (488.7)	67	356.9 (446.1)		
17	SW	2500	26	37	19.6	34 (26)	289.0 (69.2)	-	-	-	-	87	660.0 (729.2)	57	456.8 (526.0)	57	456.8 (526.0)		
17	SW _{MSP}	1850	18	42	18.8	31 (23)	252.4 (61.2)	-	-	-	-	102	670.0 (731.2)	67	453.2 (514.4)	62	408.4 (469.6)		
18	CC	2200	18	36	14.6	26 (20)	170.6 (41.9)	51	19.8	31 (23)	260.5 (64.3)	101	508.2 (614.4)	66	365.9 (472.1)	61	334.4 (440.6)		
18	CC _{MSP}	1700	15	31	15.5	20 (15)	128.8 (31.4)	41	19	23 (17)	194.0 (47.4)	111	650.5 (729.3)	61	330.2 (409.0)	56	284.8 (363.6)		
18	SW	1975	17	31	13.8	21 (16)	133.1 (32.5)	41	18.3	26 (19)	213.2 (52.2)	106	677.3 (762.0)	71	467.6 (552.3)	66	425.8 (510.5)		
18	SW _{MSP}	1975	19	31	15.6	24 (18)	168.6 (41.2)	36	18.1	23 (18)	190.6 (46.7)	91	651.9 (739.8)	66	480.2 (568.1)	61	435.5 (523.4)		
20	CC	2000	24	29	15.2	24 (18)	165.3 (40.3)	39	20.2	28 (21)	252.7 (62.0)	99	713.2 (815.5)	59	417.5 (519.8)	54	363.4 (465.7)		
20	CC _{MSP}	2625	29	29	15.8	29 (22)	203.9 (49.8)	34	18.6	27 (20)	227.0 (55.6)	89	716.8 (822.2)	59	491.2 (596.6)	54	437.4 (542.8)		
20	SW	867	6	-	-	-	-	-	-	-	-	124	540.4 (540.4)	79	326.8 (326.8)	69	261.9 (261.9)		
20	SW _{MSP}	2200	11	39	15.5	18 (14)	124.1 (29.8)	49	19	21 (16)	181.9 (43.9)	104	581.9 (655.6)	79	444.5 (518.2)	74	407.7 (481.4)		

¹Values after the simulated PCT; ²Stand was removed from the simulation due to the forest owner favoring birch spp. during thinning; ³Basal area before thinning and basal area after thinning in parentheses; ⁴Dominant height before thinning; ⁵Standing volume before thinning and volume removed in parentheses; ⁶Final volume at the time of the LEV reaching its maximum value; the total harvested volume in parentheses

Table 6. The financial outcome of the shelterwood by region (south and central) compared to the financial outcome of clearcutting in EUR ha⁻¹ together with the mean and standard errors for the region. A positive number meant shelterwood was more profitable than clearcutting, whereas a negative number indicates that clearcutting was more profitable.

IR	South			Mean			SE
	6	7	Site 11	15	16		
CF 0%	1042	474.5	731.3	831.4	-162.5	583.4	207.6
LEV 2.5%	-873.0	-1424.9	-1776.4	-654.7	-2659.0	-1478.4	355.7
LEV 4%	-1797.5	-2341.8	-2987.0	-1372.1	-3864.4	-2472.5	440.8
IR	Central			Mean			SE
	4	17	Site 18	20			
CF 0%	484.0	1318.8	305.4	752.1		715.0	221.2
LEV 2.5%	-1429.3	-1041.1	-2113.0	-1328.2		-1477.9	227.1
LEV 4%	-2352.9	-2180.5	-3280.5	-2332.5		-2536.6	251.0

3.2.2 Cash flow and land expectation value

On the southern sites, CF and LEV were consistently higher for the clearcut treatments compared to the shelterwood treatments, irrespective of the IR applied (0%, 2.5%, and 4%; Table 7). CF and LEV remained positive across all treatments and IRs, except for the shelterwood treatments (SW and SW_{MSP}) at a 4% IR, where LEV was negative. The inclusion of MSP resulted in an increase in CF and LEV for the clearcut treatments across all IRs. In contrast, for the shelterwood treatments, MSP led to a decrease in CF and LEV relative to the corresponding treatments without MSP. On the central sites, a similar pattern was observed: CF and LEV were consistently higher for the clearcut treatments compared to the shelterwood treatments, regardless of the IR. CF and LEV remained positive across all treatments and IRs, except for the shelterwood treatments (SW and SW_{MSP}) at the 4% IR, where LEV was negative. However, unlike the southern sites, MSP consistently decreased CF and LEV on the central sites across all treatments, with one exception (IR 0% and the two shelterwood treatments).

Table 7. Financial results of the simulated full rotation in EUR ha⁻¹ with moderate wind damage. For IR 0%, cash flow (CF) is shown, whereas land expectation value (LEV) is shown for IR 2.5% and 4%.

IR	South				Central			
	CC	C _{MSP}	SW	SW _{MSP}	CC	C _{MSP}	SW	SW _{MSP}
CF 0%	470	508	415	413	493	487	461	472
LEV 2.5%	4142	5120	1727	1084	5896	4820	2809	2339
LEV 4%	118	430	-2767	-3250	1055	333	-2313	-2801

4 Discussion

4.1 Stand development

The combined method of naturally regenerated Scots pine and planted Norway spruce did not automatically result in mixed species stands (Fig. 5). On the southern sites, stands remained dominated by Norway spruce irrespective of initial regeneration treatment. In contrast, on the central and northern sites, stands developed into Norway-spruce-dominated mixed species stands regardless of treatment, with no single species exceeding 75% of the basal area (Fig. 5). This indicates the presence of nearby seed sources, as the clearcut treatments also developed into mixed species stands. Seeds may have originated from either the shelterwood or from adjacent stands. In central Sweden, the Scots pine trees are currently significantly shorter than the Norway spruce trees (Table 3). However, the QMD ratio between the two species is close to 1.0, with one exception (the shelterwood treatments on Site 20; Table 4). A comparable QMD between the two species gives better option for retaining a mixture after thinning, in systems where thinnings are usually done from below (Holmström et al. 2021; Persson 2022). In northern Sweden, however, a large proportion of the basal area consisted of broadleaved species, particularly in the shelterwood treatments. The shelterwood trees were still retained during our mid-rotation inventory and has thus continued to compete with the understory since planting.

To improve seedling establishment under shelterwood, delaying MSP to perform it just prior to a good seed year has been recommended (Karlsson and Örlander 2000; Lula et al. 2024). On fertile sites, this is rarely implemented in practice though due to potential production losses (Johansson et al. 2007) and the risk of increased competition from vegetation (Karlsson et al. 2002). During the first inventory, measurements showed that shelterwood and MSP had a positive effect on Scots pine seedling density three years after planting in the southern and central regions, but not in the north (Karlsson and Nilsson 2005; Nilsson et al. 2006). However, during the second measurement, five years after planting, most Scots pine seedlings in the southern region had disappeared and the positive effect was no longer observed. The authors speculated that this could be due to several factors, including ungulate browsing, pine weevil damage, or fungal diseases (Nilsson et al. 2006). Since these factors were not directly tested, the exact cause remains uncertain. The remaining Scots pine seedlings were smaller than the Norway spruce seedlings, and Nilsson et al. (2006) then speculated that the pine trees would most likely not be a substantial part of the future stand. We have now confirmed this with the mid-rotation inventory, where Scots pine represented only a small proportion of the stands in southern Sweden (Fig. 5). As a pioneer species, Scots pine is sensitive to competition (Malcolm et al. 2001), so in admixtures with larger seedlings of Norway spruce, interspecific competition increases and Scots pine is likely to be outcompeted.

Our mid-rotation inventory showed no differences in stand density, basal area, or QMD between treatments in the southern and central regions (Fig. 2; Fig. 4; Table 3). However, height was negatively affected by the shelterwood in both regions (Table 3). In central Sweden, height differences were already observed five years after planting, with Norway spruce seedlings being shorter in shelterwood treatments (Nilsson et al. 2006). In southern Sweden, no height differences were initially observed, but they became evident by the mid-rotation inventory, with taller trees in the clearcut treatments. Although the timing of shelterwood removal is unknown, the shelterwood remained present at least five years after planting (Nilsson et al. 2006). Thus, they most likely started to compete with the seedlings for nutrients, light and water (Axelsson et al. 2014; Häggström et al. 2024) before they were removed. Previous studies indicate that shelterwood competition typically becomes significant already a few growing seasons after planting (Strand et al. 2006; Tishler et al. 2020; Huth et al. 2022). The effect of competition from the shelterwoods was further visual-

ized by the northern sites where retained, or forgotten, shelterwood resulted in significantly lower volumes and basal areas compared to clearcut treatments (Fig. 3; Fig. 4). All the sites in southern and central Sweden have most likely been pre-commercially thinned (Suppl. file S1: Table S1). Nonetheless, we found consistent results across all sites, despite the diversity in forest owners and unknown strategies in the tending of the young forest.

In southern and central Sweden, no long-term positive effects of MSP were observed for stand density, volume, or basal area (Figs. 2–4). This is somewhat unexpected, as MSP commonly improves seedling establishment through increased soil temperature sum (Nilsson and Örlander 1999; Nilsson et al. 2019), improved soil moisture availability (Nilsson and Örlander 1995; Löf et al. 2012), reduced vegetation competition (Löf et al. 1998; Johansson et al. 2013), and reduced pine weevil damage (Nordlander et al. 2005; Petersson et al. 2005; Nordlander et al. 2011; Wallertz et al. 2018). However, retained shelterwood can also reduce pine weevil damage (Petersson and Örlander 2003; Wallertz 2005) and limit ingrowth of competing vegetation (Béland et al. 2000; Lula et al. 2024). Additionally, all planted seedlings were treated with insecticide (forbidden in Sweden today), which likely improved survival rates across treatments. Another contributing factor may be seedling type. In southern Sweden, bare-rooted seedlings were used on half of the sites and containerized seedlings on the remaining sites (Nilsson et al. 2006). Bare-rooted seedlings were older (4–4.5 years) and thus most likely larger at planting than the containerized seedlings. Larger seedlings generally perform better under conditions of intense vegetation competition (Grossnickle and El-Kassaby 2015) and pine weevil pressure (Nordlander et al. 2011; Luoronen et al. 2017; Jonsson 2024), both of which are common when MSP is not applied in southern Sweden (Öhlund et al. 2025). The mid-rotation and early measurements highlight the importance of successful seedling establishment and early growth during the regeneration phase. Initial differences are generally retained throughout the rotation which has also been shown in other studies of long-term effects of establishment (Johansson et al. 2013; Hjelm et al. 2019; Jonsson et al. 2022).

4.2 Revenues and costs

4.2.1 Overstory

When no IR (IR 0%) was applied, the shelterwood cuttings were more profitable than the clearcutting, with one exception (Site 16; Table 6). In this case, the cost of splitting the harvest operation into two occurrences was balanced with the slight increased growth in the retained shelterwood trees. With an IR of 2.5% or 4%, which are more commonly used by forest companies in Sweden (Brukas et al. 2001), clearcutting was consistently more profitable than the shelterwood cuttings, with one exception (Site 17; Table 6). This indicates that although the retained shelterwood following the release cutting had more time and space to grow into higher-value timber, it was not sufficient to offset the increased harvesting costs associated with multiple entries in the forest. Lula et al. (2021) compared the LEV of seed-tree systems, shelterwood, and clearcutting under different levels of wind damage. Their results showed that when wind damage was assumed to be 9%, overstory retention was more profitable than clearcutting at an IR of 0%. At IR 2.5%, however, only the shelterwood produced higher LEV than clearcutting, seed-tree systems did not. Our results showed a similar pattern at IR 0%, whereas at IR 2.5%, the clearcut treatments consistently produced higher LEV than the shelterwood treatments. Which could potentially be explained by our shelterwood having lower densities than in Lula et al. (2021) study.

In the simulations of this study, the shelterwood was assumed to be removed 10 years after the release cutting, with 9% of the shelterwood basal area lost due to wind damage (Nilsson et al. 2006). Wind damage can vary between sites due to differences in stand characteristics and timing

of wind events after cutting (Örlander 1995; Valinger and Fridman 2011; Albrecht et al. 2012). With higher wind damage, the revenue from the shelterwood cuttings would decrease. Additional operational constraints, not considered in the calculations of this study, is the complexity of shelterwood removal. Performing felling and logging while avoiding damaging future crop trees, typically reduces operational efficiency and increases costs (Hånell et al. 2000; Niemistö et al. 2024).

4.2.2 Understory

When comparing understory development over a full rotation between treatments, the southern and central regions showed different patterns (Table 5). In the southern region, the clearcut treatments consistently produced higher volumes than the shelterwood treatments when stands were harvested at the same time. However, because stands were harvested when the CF or LEV culminated, shelterwood treatments were sometimes harvested later, resulting in higher standing volumes at the time of harvest compared to the clearcut treatments. This outcome is not surprising, as differences in height and volume between the clearcut and shelterwood treatments were already evident in southern Sweden during our mid-rotation inventories. In central Sweden, the same pattern was not observed. At three out of the four sites, the shelterwood treatments generated higher volumes than the clearcut treatments, with one exception (Site 4 at IR 0%). In addition, rotation lengths in the shelterwood treatments were sometimes shorter, the same, or longer compared to the clearcut treatments. However, these differences in volume did not translate into higher CF or LEV in either region. For both regions, the CF was roughly the same for both the clearcut and shelterwood treatments (IR 0%; Table 7). Whereas the LEV were consistently higher for the clearcut treatments compared to the shelterwood treatments (Table 7). Which means that even for the central sites when the shelterwood treatments had a higher volume than the clearcut treatments, it was not enough to carry the extra cost from the shelterwood removal. Other studies (Hyytiäinen et al. 2006; Jonsson et al. 2022), showed that with a low IR (<2.5%), artificial regeneration gave a better financial result than natural regeneration. With higher IR however, the opposite was true. During the establishment phase of this experiment, between 2000 to 2500 Norway spruce seedlings ha⁻¹ were planted, irrespective of clearcut or shelterwood treatment (Nilsson et al. 2006). Thus, the cost of between 2000 to 2500 Norway spruce seedlings was used during the calculation of CF and LEV. This explains why the clearcut treatments in this study produced higher financial returns than the shelterwood treatments. All sub-treatments had to carry the cost of planting, but the clearcut treatments avoided the additional harvesting costs from overstory retention. Today, in practical forestry, if the goal is to create a mixed species stand, between 1000 to 2000 seedlings ha⁻¹ would be planted (Karlsson and Örlander 2004). It would lead to higher CF and LEV for the shelterwood treatments if seedling establishment is successful following natural regeneration, since the procurement of seedlings would be lower (Jonsson 2024).

Although the shelterwood treatments generated less income compared to the clearcutting treatments, it still produced positive CFs and LEVs over a full rotation (with the IR of 0% and 2.5%; Table 7). Indicating that regenerating with the combination method (using shelterwood and planting) may remain a viable silvicultural option, if the forest owner is not driven by maximizing the financial outcome.

5 Conclusions and management implications

In southern Sweden, natural regeneration of Scots pine failed, leading to Norway spruce monocultures regardless of treatment. This resulted in lower volumes and revenue in the shelterwood treatments compared to the clearcut treatments. In central Sweden, however, spruce-dominated mixed forests developed regardless of treatment. This suggests that when seed sources are nearby and survival of naturally regenerated Scots pine is high, mixed species stands can establish on clearcuts even when only one species is planted. The results also indicate that the combination method can work, provided that the Scots pine seedlings survive the establishment phase. With successful regeneration under a shelterwood, the total volume over a rotation is comparable to that obtained from regeneration following clearcutting. However, regenerating following clearcutting remained more profitable, due to higher costs of harvesting the shelterwood (the release cutting and final harvest of the shelterwood). The results from northern Sweden instead highlight the importance of management planning, as failing to remove the shelterwood negatively affected the development of the new stand. Overall, this study shows that establishing a new stand using the combination method can be successful, but the forest owner will most likely notice a slight reduced revenue compared to clearcutting.

Supplementary files

S1.pdf,
Metadata of research data.pdf,
available at <https://doi.org/10.14214/sf.26005>.

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Data availability

The data that support the findings of this study are contained in the dataset Nyberg et al. (2026) and are openly accessible at: <https://doi.org/10.5878/rmrv-xh80>.

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Author's contribution

Research design (U.N and G.Ö), collection of data (T.S.N, H.A and E.H), data simulations (T.S.N, M.L., U.N, E.H) analyzing of data (T.S.N, E.H), all writers contributed to the writing process; all authors read and approved the submitted version.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI, ChatGPT [Large language model] checking for grammar and spelling. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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