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RESEARCH ARTICLE

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Will intensity of forest regeneration measures improve volume production and economy?

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ABSTRACT

The prevailing regeneration methods in Scandinavian countries are artificial regeneration methods including measures such as site preparation and planting. These measures are considered to be a part of a more intensive forest management and require an initial investment. The use of artificial regeneration measures can, however, increase the growth of a forest stand. In this study, the purpose was to investigate if such an investment is profitable by comparing three different intensity levels (low, medium and high) applied during the regeneration phase, with aspect on both economics (LEV, land expectation value) and growth (MAI, mean annual increment) after a full rotation. The forest stands used in this study were regenerated between 1984 and 1988 and the future growth of the stands was simulated using Heureka StandWise. It was clear that naturally regenerated (low intensity) stands resulted in better economics than stands actively regenerated (medium and high intensity). However, actively regenerated stands resulted in both higher volume production and growth, and the uncertainty of regeneration success was reduced using artificial regeneration measures. These factors are important when considering both the ongoing mitigation of carbon dioxide in the atmosphere and future access to raw material.

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Conifers; broadleaves; site preparation; planting; seedling; natural regeneration; plantation

Introduction

Regenerating forest stands following harvesting is complicated by many factors, such as competing vegetation, pine weevil damage, drought and frost (Örlander and Nilsson 1999; Grossnickle 2000). Some of these are directly related to the environmental conditions of the site, such as climate, topography, and water and nutrient availability. While these factors are not always predictable, many can be managed by active silvicultural measures. Appropriate site preparation can improve growing conditions, thereby increasing survival and growth of the planted seedlings (Nilsson and Örlander 1999; Johansson et al. 2013; Wallertz et al. 2018). The choice of seedling material may also improve the regeneration result. While still in the nursery, treatments affecting plant attributes can enhance a seedling's resilience to various growing conditions once it has been transplanted (Grossnickle 2000; Nilsson et al. 2010). One such plant attribute is the size of the seedling, larger seedlings have a better ability to handle competing vegetation and pine weevil damage than smaller seedlings (Thorsen et al. 2001; Jobidon et al. 2003; Wallertz et al. 2005; Thiffault and Roy 2011; Grossnickle and El-Kassaby 2016). Using nursery-grown seedlings are also an opportunity to enhance seedling growth through selective breeding (Westin and Sonesson 2005; Jansson 2007; Weng et al. 2008; Jansson et al. 2017; Liziniewicz et al. 2018). Furthermore, appropriate breeding can also help adapt forests to a changing climate (Fady et al. 2016).

Intensive forest regeneration methods are typical in the Nordic countries (Insley et al. 2002; Simonsen et al. 2010), including mechanical site preparation and planting (Sikström et al. 2020), and genetically improved seedlings (Jansson et al. 2017). Additional intensive methods include use of fertilizers, ditch maintenance and planting fast-growing tree species (Simonsen et al. 2010).

Previous studies have investigated the potential of intensified forest management for increasing timber volume production while maintaining forests' ecological functions and biodiversity (Carmean 2007; Park and Wilson 2007; McPherson et al. 2008). One approach, known as the "triad" (Seymour and Hunter 1992), is that forests are divided into three different zones (intensive, extensive and reserves), each managed for separate goals (Binkley 1997; Montigny and MacLean 2006; Messier et al. 2009). Zoning forest land in this way promotes higher volume production on intensively managed lands while increasing the area in forest reserves (Montigny and MacLean 2006), since less land is required to produce the targeted timber volume (Binkley 1997).

Intensive management measures can increase tree growth and timber production, thereby potentially also increasing

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carbon sequestration and storage in forests (Mason and Perks 2011; Poudel et al. 2012; Hynynen et al. 2015). However, clear-felling, the most common intensive forest management system, results in net carbon emissions from young forests before becoming a carbon sink again (Litvak et al. 2003; Fredeen et al. 2007; Ney et al. 2019). Less intensive management (e.g. close-to-nature forestry or combined objectives) or reserves, on the other hand can be of high importance for e.g. biodiversity and recreational values (Edwards et al. 2012; Sing et al. 2018).

Most regeneration measures are investments done with hope of ensuring the establishment, growth and persistence of forests. And intensive management during the regeneration phase clearly benefits volume production (Montigny and MacLean 2006; Simonsen et al. 2010; Hallsby et al. 2015; Serrano-León et al. 2021). But will these measures also pay off economically? The profitability of intensive forest management depends highly on establishment costs, timber prices at harvesting and the interest rate (Mäkinen et al. 2005; Simonsen et al. 2010; Serrano-León et al. 2021). These factors are in turn affected by soil fertility and site conditions (Ahtikoski et al. 2013; Hynynen et al. 2015). However, high establishment costs, high interest rates or low timber prices at felling will reduce profitability, even though the volume produced is high and the rotation length can be shortened (Serrano-León et al. 2021). However, some management measures can still have a positive effect on the profitability. Changing tree species and using genetically improved seedlings are the most profitable regeneration measures from both short- and long-term perspectives (Simonsen et al. 2010; Serrano-León et al. 2021).

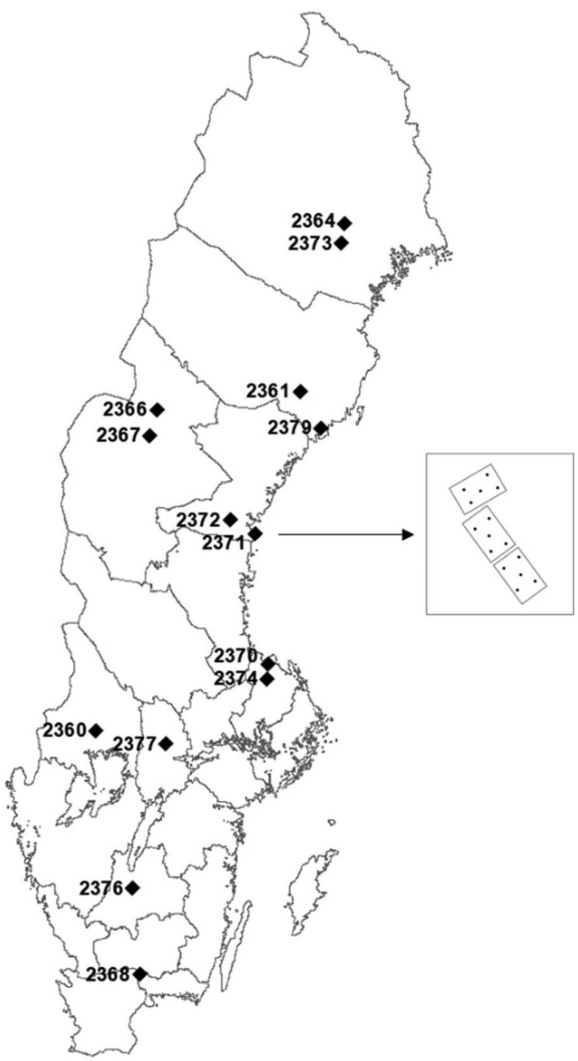

Figure 1. The geographical distribution of the sites included in the study. The diagram beside site 2371 shows the layout of the trial within sites, with three treatment areas and five sample plots within each treatment area.

This study aims to analyze and clarify differences among regeneration-phase management intensities, with respect to both economics and volume production after a full rotation. The analysis is based on measurements of stands after the regeneration phase representing the diversity of tree species, site conditions and climate found in Sweden. To facilitate the study, the Heureka forest decision support system (DSS; Wikström et al. (2011)) was used to simulate the further development of the stands.

We hypothesize that intensively managed forest regenerations will have a higher volume production, higher growth, and thereby a shorter economical optimal rotation length compared to a low intensity management in the regeneration phase. Secondly, intensively managed forest regenerations will result in higher land expectation values (LEV) than forest regenerations with a low intensity management, because of the faster growth and the shorter rotation length. LEV is the net present value with an infinite time frame. When it is expected that rotation ages will be different, LEV is suitable to use for economical comparison. In this study, it was expected that different management intensities in the regeneration phase will result in different rotation ages. Therefore, LEV was used for the economical comparison in this study.

Material and methods

Experimental design

This study was based on a regeneration trial established to study how different regeneration measures and their intensities affect forest growth (Sjögren and Näslund 1996). Fourteen sites spanned Sweden's different growing conditions from Scania county in the south to Norrbotten county in the north (Figure 1). Variation in fertility between sites was considerable. Site index according to site factors (SIS; Hägglund and Lundmark (1977)) varied from 18.5 m (H100) on poor sites in the north to 32.6 m for rich sites in the south (Table 1).

The trial was established between 1984 and 1988. All sites had been clearfelled in the year before establishment. Before clearfelling, the sites were divided into three treatment areas with sizes between 0.7 and 1 ha, the shape of the treatment areas varied and information about the total size of the clear-cut and surrounding stands was not registered. Each area was randomly assigned a different regeneration intensity level (high, medium or low intensity) and within each treatment area five fixed circular plots with a radius of 10 m were placed, resulting in a total of 210 sample plots (14 sites,

Table 1. The fourteen sites included in the trial with the most prevalent field vegetation, the average site index (SIS) and tree species regenerated at the sites, where P.a. = Picea abies, P.s. = Pinus sylvestris, P.c. = Pinus contorta.

Site	Lat (° N)	Long (° E)	Alt (m)	SIS (m H100)	Field vegetation	Tree species (high intensity)	Tree species (medium intensity)
2364 Edefors	66.14	20.57	170	18.9	*Vaccinium vitis-idaea*	P.s.	P.s.
2373 Harads	65.59	20.47	260	19.1	*V. myrtillus*	P.c.	P.s.
2361 Bjurholm	64.45	19.86	250	19.1	*V. myrtillus*	P.s., P.c.	P.c.
2379 Håknäsbacken	63.34	19.41	23	21.3	*V. vitis-idaea*	P.s.	P.s.
2366 Hökvattnet	63.54	14.48	440	18.5	Thin-leaved grass	P.s.	P.a.
2367 Gravbränna	63.33	14.36	430	20.4	Thin-leaved grass	P.c.	P.c.
2372 Huljen	62.25	16.54	270	23.5	Broad-leaved grass	P.a.	P.s., P.a.
2371 Björkön	62.13	17.36	10	22.2	*V. vitis-idaea*	P.c.	P.s.
2370 Skärplinge	60.29	17.48	25	27.3	No field vegetation	P.a.	P.a.
2374 Ulvsbo	60.18	17.46	40	26.7	Broad-leaved grass	P.a.	P.a., P.s.
2360 Ramsåsen	59.38	13.14	170	27.3	No field vegetation	P.a.	P.a.
2377 Nora	59.28	15.41	145	25.0	*V. myrtillus*	P.s.	P.s.
2376 Västermon	57.33	14.14	200	24.5	*V. myrtillus*	P.s.	P.s.
2368 Lönsboda	56.25	14.25	135	32.6	No field vegetation	P.a.	P.a.

three treatment areas per site and five sample plots per treatment area).

High-intensity regeneration involved immediate site preparation and planting after clearfelling, use of large containerized or bare-rooted seedlings (2-3 years old), supplementary planting and pre-commercial thinning if needed (Appendix 1), unfortunately the occurrence of pre-commercial thinning in the high intensity stands was not registered. The medium intensity treatment was at the time the most common way of regenerating forests. The main differences between the intensive and medium treatments were the timing of site preparation and planting and the size of the seedlings. For the medium treatment, site preparation and planting were done later after the harvest of the previous stand (Appendix 1) and smaller seedlings were used, often 1-year-old containerized seedlings. Two medium-intensity areas used natural regeneration of Scots pine in place of site preparation and planting. At three sites, different tree species was used in the intensive and medium treatments. For the medium intensity, the locally most-used tree species given the site conditions was selected whereas for the high-intensity treatment the tree species with the assumed highest production, given site properties and location, was chosen. The low-intensity treatment was left to naturally regenerate; no measures were taken after clearfelling of the previous stand.

Data collection

All experimental plots were measured in 2011 and 2019. Data from 2011 was only used to calculate the periodic annual increment (PAI) between the two inventories. All measurements were conducted in five fixed circular plots with 10 m radius within each treatment area. All trees in the sample plots with a diameter at breast height (DBH; 1.3 m above the ground) larger than 4 cm were measured by cross calipering to the nearest mm and tree species were registered. Visible damage was also recorded for all trees. Additionally, 20 sample trees were selected for each tree species within each treatment area, the five largest trees and 15 additional trees that reflected the diameter distribution, for a total of 2003 sample trees. In addition to DBH, tree height and height to first living branch were measured for these sample trees. Field vegetation type, soil type, moisture class, and topography were also classified for each circular sample plot according to the Swedish system of site-index estimation (Hägglund and Lundmark 1977).

Height and DBH of the sample trees in a treatment area were used to estimate height and volume for all trees within the same treatment area. The stem volume was calculated individually for the sample trees using either Brandel's (Brandel 1990) or Eriksson's (Eriksson 1973) volume functions depending on the tree species. Thereafter, regression volume functions were developed for each tree species (Scots pine, Norway spruce, lodgepole pine, birch and other broadleaves):

$$V = a \times DBH^{b}$$

where V is tree volume (m^3), DBH is diameter at breast height (cm) and a and b are coefficients to be estimated. Volume functions were thereafter used to estimate volume of each calipered tree and summed to total volume for each sample plot. The total volume was then used to calculate volume per hectare for each sample plot, which was used for calculating a mean volume per hectare for each treatment area. This was done for both the measurements in 2011 and 2019.

To assign a height to all trees within a treatment area, the equation for "Näslund's height-curve" (Näslund 1936) was used:

$$H = \frac{DBH^{x}}{(a + b \times DBH)^{x}} + 1.3$$

where H is the height of the tree (in m), DBH is the diameter (cm), a and b are coefficients estimated from our data for each treatment area and tree species (Scots pine, Norway spruce, lodgepole pine, birch and broadleaves) and x is 3 for spruce and 2 for all other tree species (Pettersson 1955). Data on tree height, DBH, field vegetation, moisture class, soil type, altitude and latitude were later used for simulations in the Heureka DSS.

The volume per hectare and the average canopy height for each treatment area were used to evaluate if the standing volume in 2019 fulfilled the minimum requirements for standing volume given by the Swedish forestry act (5 §) (Skogsstyrelsen 2020). According to the Swedish forestry act (5 §), when a stand reaches a height of 10 m, it should have produced a certain height-specific minimum volume. If the requirements are not met, the forest owner is obliged to establish a new stand. The volume per hectare and basal area weighted average height for each treatment area were also used to evaluate if the minimum required standing volume after thinning (10 §) (Skogsstyrelsen 2020) was met. The post-thinning standing volume requirement depends on the average stand height. If the thinning aims to promote the development of the stand and where the full growth potential of the site is to be used, the volume should not be lower than the minimum required standing volume.

Simulations

The Heureka DSS contains a number of applications for simulating forest dynamics and analyzing management procedures (Wikström et al. 2011). The system consists of a large number of models for tree growth and mortality, stem bucking, timber prices etc., as well as models for calculating costs for harvests and silviculture operations, which together enables a long-term multi-objective analysis at regional, forest or stand level (Elfving 2010; Wikström et al. 2011). In this study, the Heureka StandWise application (Wikström et al. 2011) was used as a tool for interactive simulation to analyze the development of individual stands, i.e. the treatment areas. A simulation in StandWise can begin in the stand establishment phase and simulate forest management throughout the rotation or it can cover the development and growth of an already-established stand (Wikström et al. 2011).

Data collected from the sites in 2019 were used as starting points for the simulations in StandWise. To manage the stands the same way regardless of their initial state, guidelines were set for thinning and final felling. No thinnings had been done before data collection in field, all eventual thinnings were simulated. The first thinning happened when the basal area was between 25 and 35 m^2ha^{-1}, and before top-height (average height of the 100 trees ha^{-1} with largest diameter) reached 15 m. However, the basal area was prioritized, meaning that top-height could be taller than 15 m at the first thinning. The second thinning was done before top-height reached 20 m and when the basal area had reached between 25 and 35 m^2ha^{-1}. For both thinning occasions, 25–30% of the basal area was removed, resulting in a stand with a basal area above 17 m^2ha^{-1}. Not all treatment areas met these requirements and were therefore not thinned during the simulations. The final felling of the simulated stands was conducted when the land expectation value (LEV) peaked.

Calculations and statistical analysis

For the calculation of LEV, the regeneration costs (site preparation, planting, and pre-commercial thinning) were added up (Appendix 2). These regeneration costs were based on statistics from the Swedish Forest Agency (Skogsstyrelsen 2021) and cost of seedlings was retrieved from the Södra forest owners' association (Södra 2019). Due to regional differences the simulations were simplified and the same costs were used for the two different ages (1- and 2-year-old) of containerized seedlings. The timber prices (sawn timber and pulp wood) in Heureka were updated to reflect autumn 2020 levels based on price lists from Södra (2020a, 2020b, 2020c) (Appendix 3, 4). The real interest rates used for the calculations were 2.5% and 1% and LEV was calculated according as

$$\mathrm{LEV} = \sum_{t=1}^{u} a_t \times e^{-rt} \times \frac{1}{1-e^{-ru}}$$

where a is net cost or income at time t, r is the discount rate, and u is rotation length (Faustman 1849).

Differences in volume production, PAI, mean annual increment (MAI) and LEV among intensity levels were statistically analyzed using ANOVA, and the following model was used:

$$y_{ij} = \mu + \alpha_i + \beta_j + e_{ij}$$

where α is the fixed effect of treatment area and β is the random effect of site.

The package TukeyC was used to identify which intensity levels that significantly differed from each other and a significance level of $p = 0.05$ was used. Calculations were done in R version 3.6.1 (R Core Team 2019).

Results

Volume production

For the stands where active measures had been taken during the regeneration phase, the dominant tree species was the planted species of conifer. In 2019 high-intensity plots had a higher proportion of stems of the planted species compared to the medium-intensity plots ($p = 0.005$; Table 2;). On average, the stem density of the planted species in 2019 was 69% of the number of seedlings in the high-intensity treatment, but only 46% in the medium-intensity stands. However, the planted tree species inventoried in 2019 in the high- and medium-intensity treatment area were likely a mixture of both planted and naturally regenerated seedlings.

For the sites where no measures had been taken during the regeneration phase, broadleaves were more commonly found and were the dominant tree species in 6 out of 14 sites.

Table 2. The planting density (seedlings ha^{-1}) at each site and the number of stems of the planted tree species found at the inventory in 2019 (stems ha^{-1}).

	High intensity			Medium intensity		
Site	Tree species	Planting density	Number of stems	Tree species	Planting density	Number of stems
2364	*P.s.*	2400	1191	*P.s.*	2375	662
2373	*P.c.*	2350	1229	*P.s.*	2600	1427
2361	*P.s./P.c.**	2500	1019	*P.c.*	2600	1350
2379	*P.s.*	2800	1927	*P.s.*	3175	2086
2366	*P.s.*	2700	2102	*P.a.*	2010	885
2367	*P.c.*	2750	1529	*P.c.*	2550	1070
2372	*P.a.*	2300	1796	*P.a.*	1283	968
2371	*P.c.*	2000	2178	*P.s.*	2300	936
2370	*P.a.*	2900	1108	*P.a.*	2600	904
2374	*P.a.*	2575	1503	*P.a./P.s.**	2550	815
2360	*P.a.*	2500	2185	*P.a.*	3050	1115
2377	*P.s.*	2600	2210	*P.s.*	2875	885
2376	*P.s.*	3000	2217	*P.s.*	Seed tree	1599
2368	*P.a.*	2150	1868	*P.a./P.a.**	3050	1891

Note: The tree species are *P.a.* = Picea abies, *P.s.* = Pinus sylvestris, *P.c.* = Pinus contorta. * These treatment areas received supplementary planting

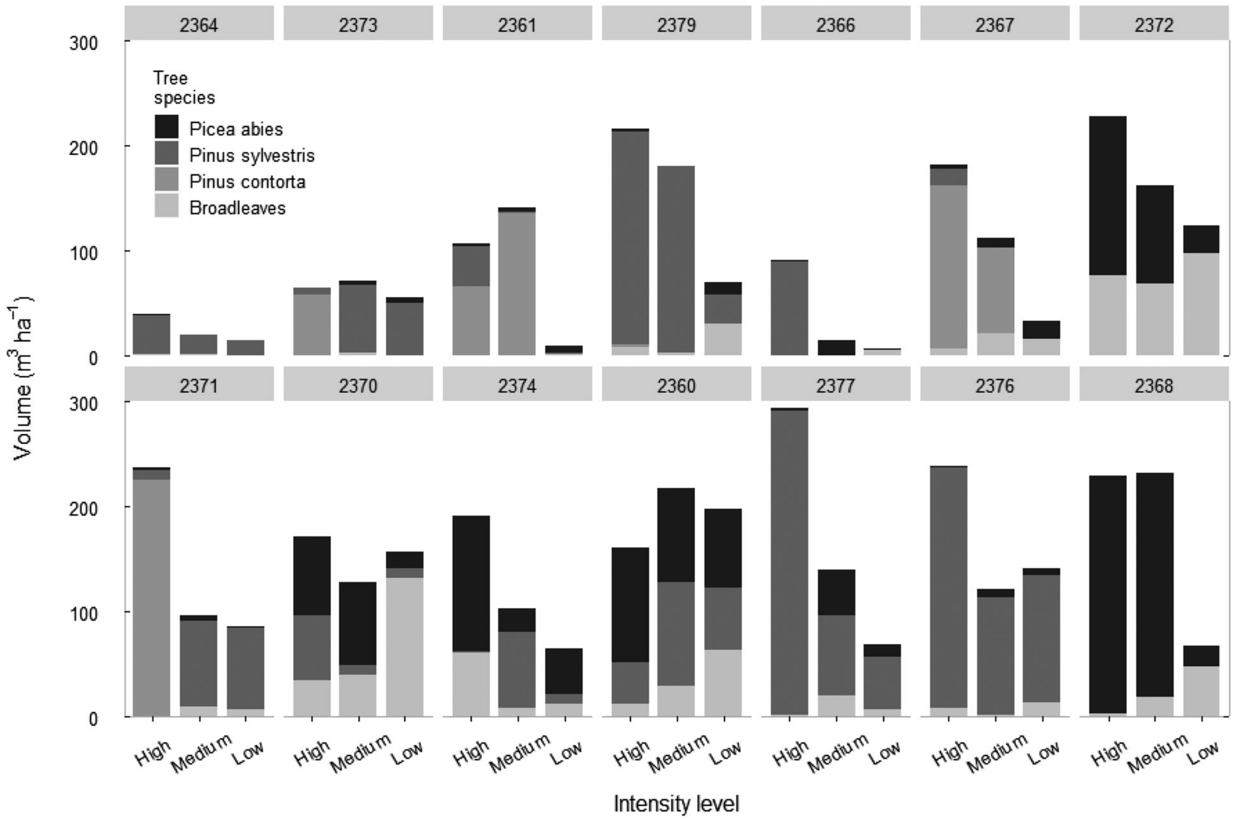

Figure 2. Standing volume (m^3 ha^{-1}) of different tree species in 2019 at the different sites (sorted from north to south) for the respective intensity levels (high, medium and low).

Coniferous monocultures, where 70% of the basal area was of a single tree species, were equally common in high- and medium-intensity stands (10 sites out of 14), and less common for low-intensity stands (7 out of 14).

Active measures in the regeneration phase resulted in a significantly higher standing volume (Figure 2). The average standing volume was significantly higher in the high compared to the medium intensity stands ($p = 0.018$; Table 3), with similar patterns between the high and low intensities ($p < 0.0001$; Table 3) and medium and low intensities ($p = 0.033$; Table 3). The average standing volume for high-intensity stands was 175.1 m^3 ha^{-1} in 2019, for the medium intensity 124.5 m^3 ha^{-1} and for the low-intensity stands 78.4 m^3 ha^{-1}. For the medium intensity, this corresponds to 71.1% of the high-intensity average volume and for the low intensity 44.7%.

The volume produced until 2019 in each stand fulfilled the minimum requirements of standing volume given by the Swedish forestry act (5 §) (Skogsstyrelsen 2020), in all cases where the stands were within the height interval stated in the act (10–20 m; Figure 3). However, three low-intensity stands did not reach the lowest required standing volume after a thinning (10 §) (Skogsstyrelsen 2020). Additionally, seven stands had not yet reached a height of 10 m and were not yet above the lowest required standing volume, so it was not possible to determine if they would reach the required post-thinning standing volume in the future. Three of these stands were at site 2364, where height growth and volume production has been affected by the high browsing pressure in the area.

The periodic annual increment (PAI) between the two inventories (2011 and 2019) was, in general, higher for high- and medium-intensity stands than for low-intensity stands (Figure 4). The average PAI was significantly different between high and medium intensity plots ($p = 0.029$; Table 3), high and low intensity ($p < 0.0001$; Table 3) and medium

Table 3. *P*-values for the differences among intensity levels when conducting ANOVA and Tukey test for the included variables, volume (m^3 ha^{-1}), periodic annual increment (PAI), mean annual increment (MAI) and land expectation value (LEV).

		p-value					
	df	Volume	PAI	MAI 2.5%	MAI 1%	LEV 2.5%	LEV 1%
Treatment	2	<0.0001	<0.0001	<0.0001	<0.0001	0.001	0.182
Site	13	0.0009	0.0001	0.0002	8.08e-05	0.0003	<0.0001
Tukey							
High-Medium		0.018	0.029	0.382	0.445	0.956	0.959
High-Low		<0.0001	<0.0001	<0.0001	<0.0001	0.004	0.198
Medium-Low		0.033	0.018	<0.0001	<0.0001	0.002	0.308

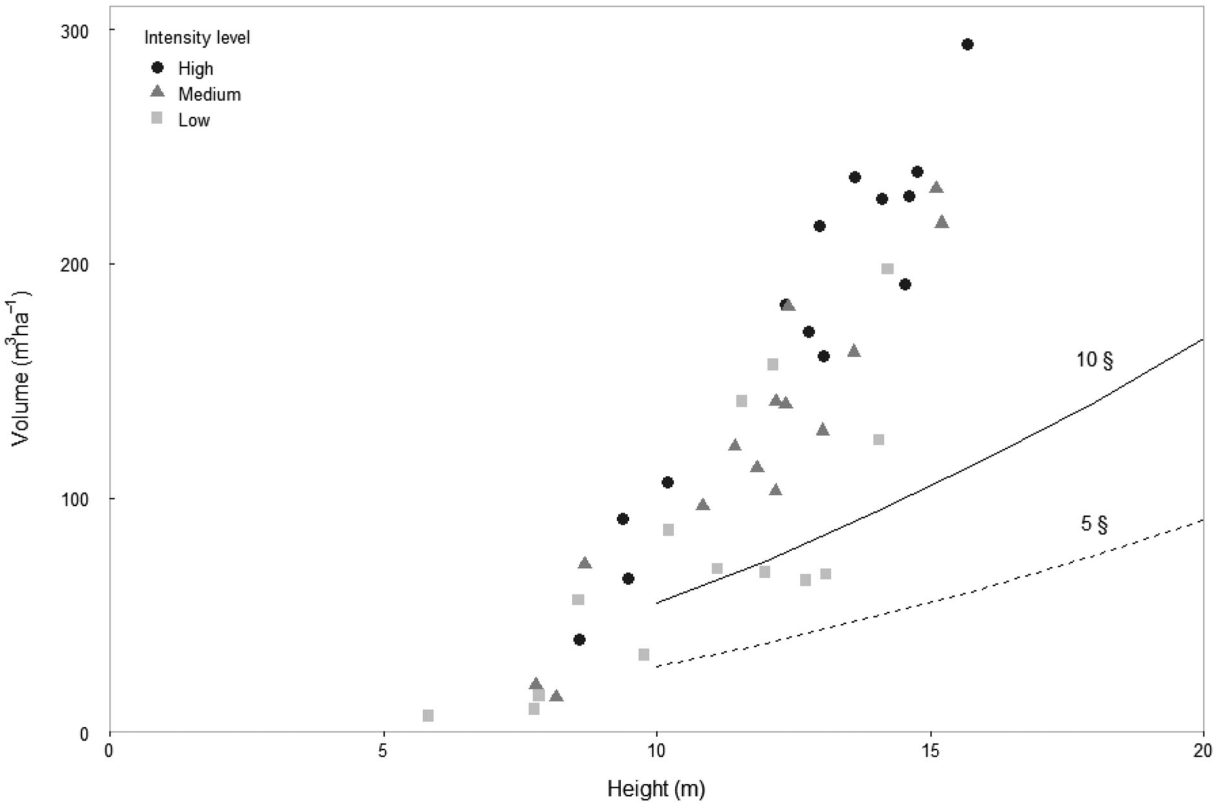

Figure 3. Standing volume (m^3 ha^{-1}) in 2019 for each treatment area, plotted in relation to the minimum requirements for standing volume at certain heights (5 §, dashed line) and in relation to the minimum allowable standing volume after thinning at a given height (10 §, solid line).

and low intensity ($p = 0.018$; Table 3). The average PAI was 10.11 m^3 ha^{-1} yr-1, 7.57 m^3 ha^{-1} yr^{-1} and 4.84 m^3 ha^{-1} yr^{-1} for the high, medium and low intensity, respectively. For the medium and low intensity stands this corresponded to 72.5% and 46.1% respectively of the average PAI of high intensity stands.

Simulations

Mean annual increment

The mean annual increment (MAI) after a simulated full rotation (ending at peak LEV) was similar regardless of the applied interest rate (1% or 2.5%; $p = 0.907$). Treatment intensity affected full-rotation MAI; the low-intensity treatment differed significantly from both the high- ($p < 0.0001$; Table 3) and medium-intensity ($p < 0.0001$; Table 3) treatments, but the high and medium intensity MAIs were not distinguishable ($p = 0.382$; Table 3). High intensity resulted in, at most sites, the highest MAI, and low intensity gave, in general, the lowest MAI (Figure 5). The average MAI for all sites, using a 2.5% interest rate, was 7.2 m^3 ha^{-1} yr^{-1}, 6.5 m^3 ha^{-1} yr^{-1} and 4.2 m^3 ha^{-1} yr^{-1}, for high-, medium- and low-intensity stands, respectively. The average rotation age was not significantly different among any of the treatment intensities at either interest rate ($p \geq 0.094$ in all cases; Table 3). The average rotation age for high-, medium- and low-intensity stands was 78.6, 78.7 and 78.9 years, respectively, at an interest rate of 2.5%. At 1% interest, the rotation age increased to 90.4, 93 and 97.5 years, for high-, medium- and low-intensity stands, respectively.

Land expectation value

After a simulated full rotation including management measures (site preparation, planting, pre-commercial thinnings, thinnings and final felling) LEV was significantly higher for the low-intensity stands at a 2.5% interest rate, compared to high ($p = 0.004$; Table 3) and medium ($p = 0.002$; Table 3) intensities (Figure 6). There was no significant difference in LEV between high and medium intensity ($p = 0.956$; Table 3). The average LEV across sites, at 2.5% interest, was 626 EUR ha^{-1}, 543 EUR ha^{-1} and 1 643 EUR ha^{-1} for high- medium- and low-intensity stands, respectively. A 1% interest rate reduced the relative LEV differences among the three intensity levels (Figure 7), and there were no significant differences between high and medium intensity ($p = 0.959$; Table 3), high and low intensity ($p = 0.198$; Table 3) and medium and low intensity ($p = 0.308$; Table 3). The average LEV, with 1% interest, was 10 382 EUR ha^{-1}, 10 080 EUR ha^{-1} and 8 438 EUR ha^{-1} for high-, medium- and low-intensity stands, respectively.

Discussion

This study aimed to contribute knowledge about the effects of different forest regeneration intensity levels on both economics and volume production. One of the hypotheses was that intensively managed forest regenerations would result in a higher volume production, and by 2019 the high intensity stands had, on average, produced the highest volume. The intensive artificial-regeneration measures in the high intensity stands resulted in even-aged stands and often monocultures. These factors are all keys to increased volume

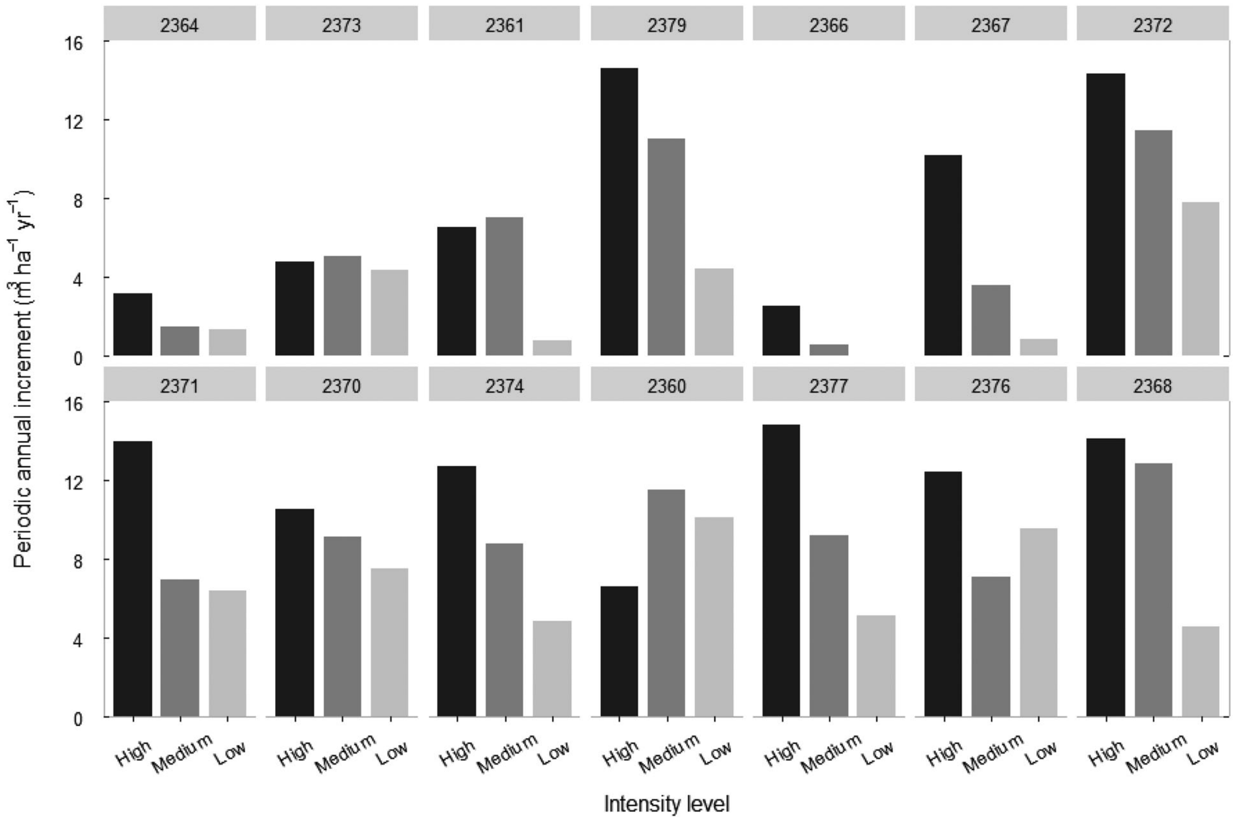

Figure 4. Periodic annual increment (PAI) (m^3 ha^{-1} yr^{-1}) between 2011-2019, for the three intensity levels at all sites (ordered from north to south) included in the study.

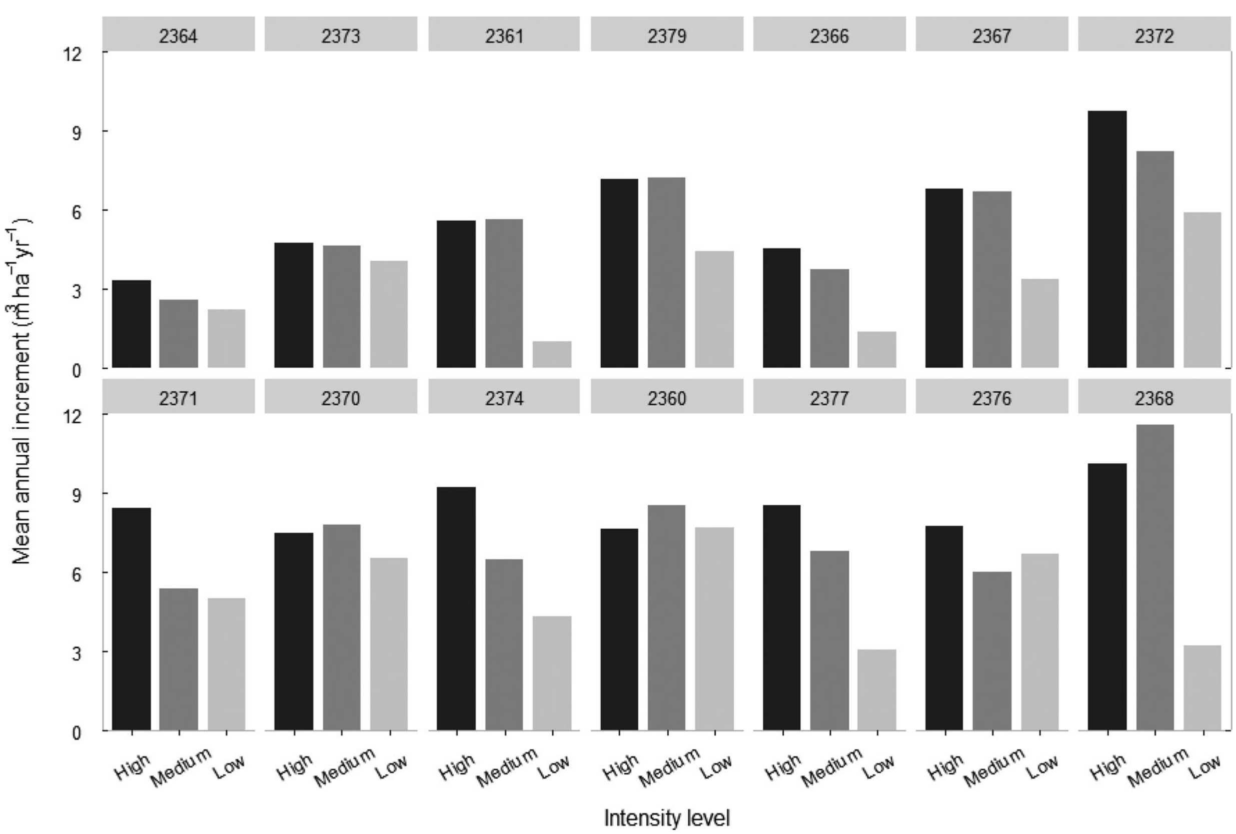

Figure 5. Estimated mean annual increment (MAI) (m^3 ha^{-1} yr^{-1}) for all sites (sorted from north to south) and intensity levels at 2.5% interest.

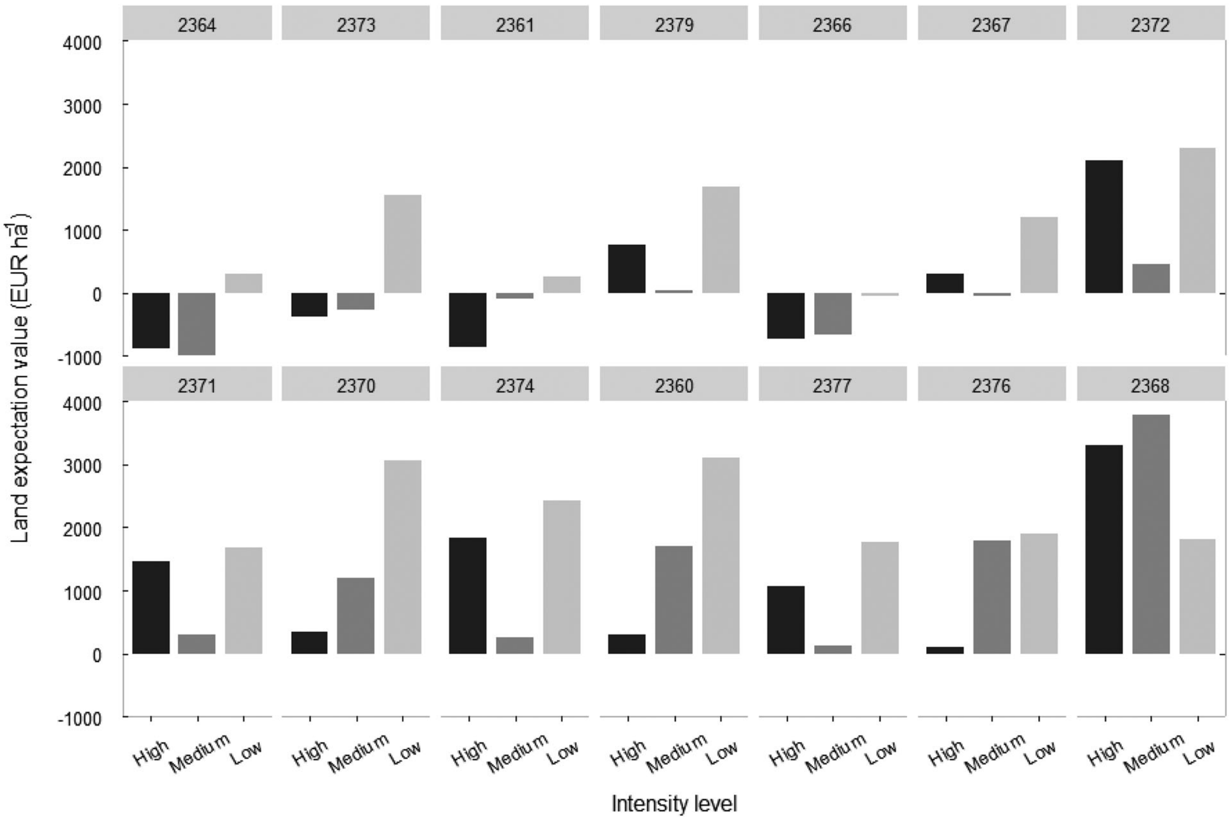

Figure 6. Estimated land expectation value (LEV; EUR ha^{-1}) for all sites (ordered from north to south) and intensity levels with a 2.5% interest rate.

production (Tahvonen et al. 2010; Nilsson et al. 2011; Jansson et al. 2017). It was not registered if and how pre-commercial thinning was conducted in the high intensity stands. This is a shortcoming with the study since pre-commercial thinning was one of the measures included in the high-intensity management and can affect the mentioned factors (even-aged stands and monocultures). Pre-commercial thinning provides an opportunity to form a stand, by selecting the tree species composition and trees with desired properties. Previous studies have found that pre-commercial thinning lead to higher survival and larger diameter of retained trees (Pettersson 1993). Moreover, pre-commercial thinning can increase the sawlog removals in thinnings and at final felling (Huuskonen et al. 2020).

For the low intensity stands, where no measures had been taken during the regeneration phase, the regeneration success varied more than in other cases and there were also a broader variety in age and tree species composition. The variation in success for the low-intensity stands could probably be explained by several factors, such as seed production (which depends on factors such as climate, site conditions and genetics), distance to seed sources and seed fall (Beland et al. 2000), which all play a role in whether a natural regeneration will be successful.

Some sites had large differences in standing volume among intensity levels. One possible explanation for the large differences can be the size of the treatment areas (0.7–1 ha). The large treatment areas used can make it difficult to get equal site conditions for all treatments. Another explanation can be the change in tree species. Lodgepole pine has faster growth and volume production than Scots pine (Elfving et al. 2001) and a similar effect has been found in a previous study, where the profitability of management measures to increase growth was examined (Simonsen et al. 2010).

For all stands, the minimum required standing volume (5 §) (Skogsstyrelsen 2020) was met in 2019 (Figure 3). There were, however, three low intensity stands that had not yet reached the minimum post-thinning standing volume (10 §) (Skogsstyrelsen 2020). This means that these stands cannot be legally thinned. The forest owner will be limited to the existing properties of the stand without the possibility of forming the stand through thinning. Thus, the full growth potential of the stand might not be used. For this study, one of the focuses was to evaluate differences in volume production, hence, not using the full growth potential and not being able to manage a stand could be considered a disadvantage. However, volume production might not be the management goal. The low intensity stands were mostly dominated by broadleaved tree species, and with a management goal of increasing resilience and adaptation to climate change a mixture of tree species is probably advantageous (Felton et al. 2016). Stands composing a mixture of broadleaves and conifers are more resistant to disturbances, such as fires, windstorms and pest outbreaks than monocultures, due to a larger variation in functional traits (Jactel et al. 2017; Huuskonen et al. 2021). Furthermore, mixed forests and less intensively managed stands have positive effects on ecosystem services such as biodiversity, recreational values and water quality (Felton et al. 2016; Sing et al. 2018;

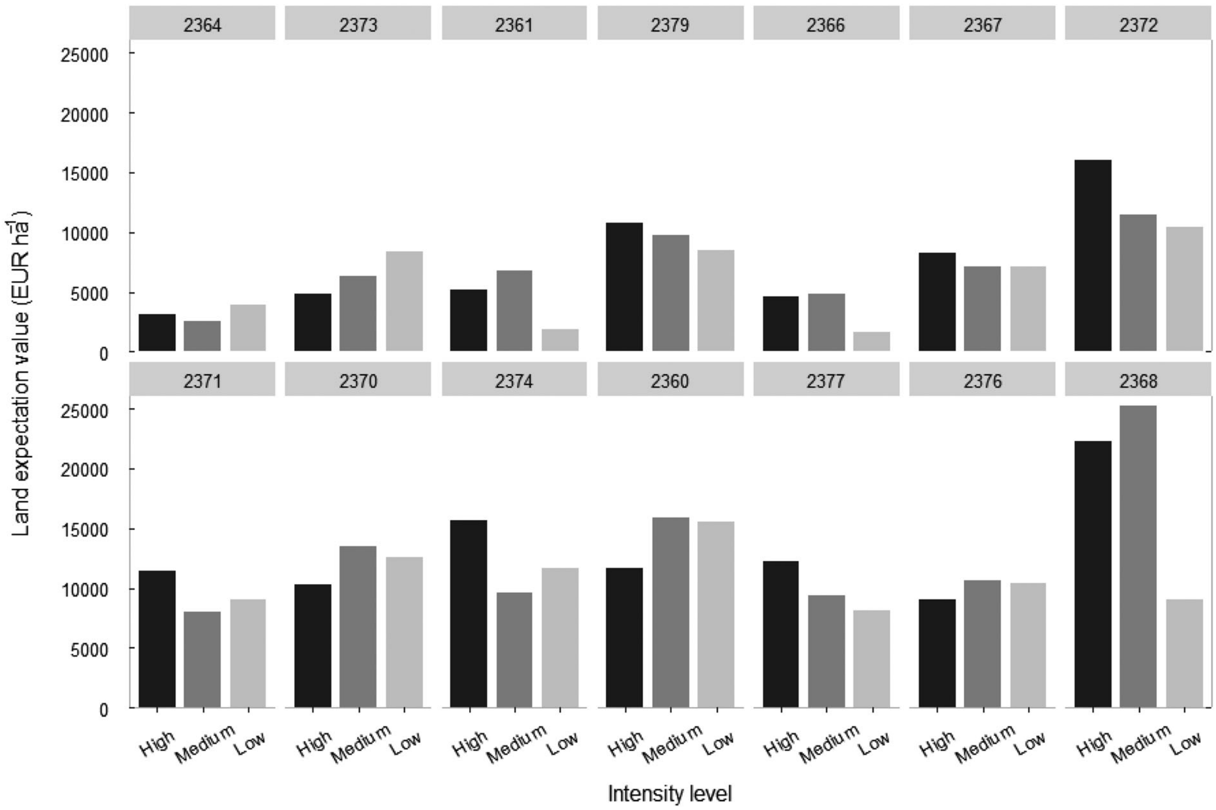

Figure 7. Estimated land expectation value (LEV; EUR ha^{-1}) for all sites (ordered north to south) and intensity levels at 1% interest.

Huuskonen et al. 2021). The use of more intensive forest management measures has a potential negative effect on biodiversity. Among others, site preparation is disturbing the humus layer and has been shown to destroy and decrease the amount of coarse woody debris (Hunter and Hunter Jr 1999; Hautala et al. 2004), which is an important substrate for many bryophytes, fungi and lichens (Hunter and Hunter Jr 1999; Voller and Harrison 2011).

As hypothesized, the actively regenerated stands had according to the simulations a significantly higher growth over a full rotation period than those left to regenerate naturally. This has also been found in other studies investigating differences in stand-establishment intensities (Simonsen et al. 2010; Nilsson et al. 2011; Hallsby et al. 2015; Serrano-León et al. 2021). In this study, the higher growth is explained by the higher volume production in the actively regenerated stands and the insignificant difference in rotation length among intensity levels. Applying active regeneration measures could increase growth between 50 and 70% over a full rotation period compared to a low-intensity regeneration approach. This growth increase could be important when considering the future demand for wood products as a substitute for fossil fuels, or when considering the land required to produce the volumes demanded in the future. Faster growth means that less land is needed to produce equivalent amounts of wood (Binkley 1997). Finally, forests with higher growth have a higher carbon sequestration and carbon stock (Mason and Perks 2011; Poudel et al. 2012; Hynynen et al. 2015). Therefore, more intensively managed forests have a greater potential to reduce atmospheric carbon dioxide, which is important for climate change mitigation. However, reducing atmospheric carbon dioxide through increased growth and accumulation of biomass potentially have negative effects on other ecosystem services and biodiversity and consequently the balancing of different objectives is needed.

From a solely economic perspective, the LEV calculations showed that active regeneration measures are less profitable than a passive management during the regeneration phase at a 2.5% real interest rate. This is the opposite of what was hypothesized. When lowering the interest rate from 2.5% to 1%, the management regimes' LEVs no longer differ significantly, indicating that the profitability of active regeneration depends on interest rates (Faustman 1849). A higher interest rate will support the choice of natural regeneration and no regeneration measures (low intensity), and a low interest rate allows for investments in the regeneration phase. This has been concluded by several previous studies (Mäkinen et al. 2005; Hyytiäinen et al. 2006; Simonsen et al. 2010; Serrano-León et al. 2021), some of which also highlighted the importance of regeneration costs. In this study, regeneration costs were the biggest driver of LEV. In 13 out of 14 sites, natural regeneration measures with no investment costs gave the highest LEV among the three regeneration treatments at 2.5% interest rate.

It can be concluded that the active regeneration measures used when establishing this trial were not economical over a full rotation. But these measures generated both faster growth and higher volume production. Both are important for the sequestration of atmospheric carbon dioxide and for future generations' access to raw materials. The seedlings used in this trial were selected from the best genetic material available in the mid-1980s. But as mentioned earlier, genetic improvement has come a long way and the use of improved seedlings is common. The growth of these seedlings is between 10 and 25% higher than local provenances (Jansson et al. 2017). Therefore, a similar study established today could result in better economics for the actively regenerated stands, as has been found in more recent trials using genetically improved seedlings (Simonsen et al. 2010; Chamberland et al. 2020; Serrano-León et al. 2021). Furthermore, it might not always be obvious which sites will profit from active regeneration measures, but the uncertainty of regeneration success is reduced by using artificial regeneration measures. Lastly, to secure future wood supply, reduce global deforestation and atmospheric carbon dioxide investments in the regeneration phase can be motivated even though it is not economically beneficial in terms of traditional business investments (Moriguchi et al. 2020).

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Appendices

Appendix 1

Regeneration measures done at the study sites. Tree species are *P.*a. = Picea abies, *P.*s. = Pinus sylvestris, *P.*c. = Pinus contorta. Seedling types are C = containerized, B = bare-rooted and Seed tree = uncut trees are left to promote natural regeneration. The planting density is given in seedlings ha^{-1}. * These treatment areas received supplementary planting.

	High intensity						Medium intensity					
Site	Site preparation	Tree species	Seedling type	Seedling age	Planting density	Planting year	Site preparation	Tree species	Seedling type	Seedling age	Planting density	Planting year
2364 Edefors	None	*P.*s.	C	2	2400	1984	None	*P.*s.			2375 ± 275	1986 ± 1
2373 Harads	None	*P.*c.	C	2	2350	1987	Disc trench	*P.*s.			2600 ± 250	1989 ± 1
2361 Bjurholm	Mound	*P.*s., *P.*c.*	C	2	2500	1984	Disc trench	*P.*c.	C	1	2600 ± 250	1985
2379 Håknäsbacken	Patch	*P.*s.	C	1	2800	1988	Disc trench	*P.*s.	C	1	3175 ± 250	1990, 1991
2366 Hökvattnet	Patch	*P.*s.	C	2	2700	1986	Patch	*P.*a.	C	1	2010	1989
2367 Gravbränna	Patch	*P.*c.	C	2	2750	1986	Patch	*P.*c.	C	1	2550 ± 250	1988
2372 Huljen	Patch	*P.*a.	C	1	2300	1987	Disc trench	*P.*s., *P.*a.	C	1	2379, 1283	1989 ± 1
2371 Björkön	None	*P.*c.	C	2	2000	1987	None	*P.*s.	C	1	2300	1989 ± 1
2370 Skärplinge	Mound	*P.*a.	C	2	2900	1987	Disc trench	*P.*a.			2600 ± 250	1988, 1989
2374 Ulvsbo	Disc trench	*P.*a.	C, B	2, 3	1575, 1000	1988	Disc trench	*P.*a., *P.*s.*			2550 ± 250	1990
2360 Ramsåsen	Mound	*P.*a.	B	3	2500	1984	Disc trench	*P.*a.			3050 ± 300	1986
2377 Nora	Disc trench	*P.*s.	C, B	2, 3	750, 1850	1988	Mound	*P.*s.	Seed tree, C	1	2875 ± 200	1988
2376 Västermon	Disc trench	*P.*s.	B	3	3000	1988	Disc trench	*P.*s.	Seed tree			
2368 Lönsboda	Mound	*P.*a.	B	3	2150	1987	Disc trench	*P.*a.*	C, B		3050 ± 300	1988, 1989

Appendix 2

Prices used to calculate regeneration costs for each treatment plot.

Type of measure	Cost (EUR ha^{-1})	Cost (EUR seedling^{-1})
Site preparation (patch and disc trench)	246	
Site preparation (mound)	296	
Containerized seedlings with pine weevil protection (*P. abies*)	1133	0.45
Bare-rooted seedlings with pine weevil protection (*P. abies*)	1232	0.49
Containerized seedlings (*P. abies*)	862	0.34
Bare-rooted seedlings (*P. abies*)	936	0.37
Containerized seedlings with pine weevil protection (*P. sylvestris*)	1109	0.44
Bare-rooted seedlings with pine weevil protection (*P. sylvestris*)	1232	0.49
Containerized seedlings (*P. sylvestris*)	838	0.34
Bare-rooted seedlings (*P. sylvestris*)	936	0.37
Planting containerized seedlings with site preparation	493	0.20
Planting bare-rooted seedlings with site preparation	665	0.27
Planting containerized seedlings without site preparation	567	0.23
Planting bare-rooted seedlings without site preparation	739	0.30
Supplementary planting	361	
Pre-commercial thinning	296	
Pre-commercial thinning (low intensity plots)	444	
Pre-commercial thing before thinning	296	

Appendix 3

Timber prices for Pinus sylvestris, Pinus contorta and Picea abies, depending on quality and diameter class.

	P. sylvestris and *P.* contorta (EUR m^{-3})				*P.* abies (EUR m^{-3})	
Diameter class (cm)	Quality 1	Quality 2	Quality 3	Quality 4	Quality 1	Quality 2
18	57.8	52.8	52.8	52.8	53.3	53.3
20	67.1	53.3	53.3	53.3	54.3	54.3
22	75.0	53.8	53.8	53.8	57.3	57.3
24	79.9	54.3	54.3	54.3	59.7	59.7
26	84.9	54.8	54.8	54.8	60.7	60.7
28	84.9	55.3	55.3	55.3	61.7	61.7
30	89.8	56.3	56.3	52.8	62.2	62.2
32	89.8	56.3	56.3	52.8	62.7	62.7
34	89.8	57.3	57.3	47.9	62.7	62.7

(*Continued*)

Continued.

Diameter class (cm)	*P.* sylvestris and *P.* contorta (EUR m^{-3}) Quality 1	Quality 2	Quality 3	Quality 4	*P.* abies (EUR m^{-3}) Quality 1	Quality 2
36	89.8	57.8	57.8	45.4	62.7	62.7
38	75.0	52.8	52.8	45.4	48.4	48.4
	Expected quality distribution of the timber					
	Quality 1	Quality 2	Quality 3	Quality 4	Quality 1	Quality 2
Butt	31%	0%	57%	12%	86%	14%
Middle	0%	31%	57%	12%	86%	14%
Top	0%	31%	57%	12%	86%	14%

Appendix 4

Pulp wood prices for the different tree species.

Tree species	(EUR m^{-3})
Conifers (*P. abies, P. sylvestris, P. contorta*)	29.6
Birch (*B. pendula, B. pubescens*)	31.5
Aspen (*P. tremula*)	31.5
Other broadleaves	27.1