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Long-term effects of forest regeneration success on volume production, economics and stand structure

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Abstract

Forest regeneration is complicated by many factors, so active regeneration treatments such as site preparation and planting are often applied in Sweden. These have proven to increase seedling survival and growth during establishment. But, since forestry in Sweden is related to long rotations the long-term effect of these treatments needs to be studied. This thesis aimed to evaluate the long-term effects of forest regeneration success on volume production, economics and stand structure. Both experimental data from field trials and data from the Swedish National Forest Inventory were used. Simulations using the Heureka software were made to facilitate long-term analyses. Active regeneration treatments were found to increase survival of planted Norway spruce seedlings, as well as long-term volume growth. A high initial survival of planted and improved seedlings adapted to the site resulted in the highest long-term volume growth, although the investment in regeneration treatments was not always found to be economically viable when compared to natural regeneration. Increased growth could however be of importance for future biomass production and carbon sequestration. On the other hand, intensively managed forests might have negative effects on other ecosystem services. Therefore, different objectives need to be balanced to create and maintain a diversity of forests.

Keywords: planting, natural regeneration, site preparation, slash removal, multiple damage, simulation, Norway spruce, Scots pine, broadleaves

Långsiktiga effekter av lyckade skogsföryngringar på volymproduktion, ekonomi och beståndsstruktur

Sammanfattning

Föryngring av skog kan försvåras av många faktorer. Aktiva föryngringsåtgärder så som markberedning och plantering används därför ofta för att etablera ny skog i Sverige. Dessa åtgärder har visat sig öka både överlevnad och tillväxt av plantor. Eftersom skogsbruk i Sverige är förknippat med långa omloppstider behöver även de långsiktiga effekterna av dessa åtgärder studeras. Målet med denna avhandling var därför att utvärdera de långsiktiga effekterna av lyckade skogsföryngringar på volymproduktion, ekonomi och beståndsstruktur. Både data från försök och nationell skogsdata har använts. Simuleringar i analyssystemet Heureka gjordes för att möjliggöra långsiktiga analyser. Aktiva föryngringsåtgärder visade sig öka överlevnaden av planterade granplantor men även den långsiktiga volymtillväxten. En hög överlevnad av planterade och förädlade plantor anpassade för ståndorten resulterade i den högsta volymtillväxten, men investeringen i föryngringsåtgärder var inte alltid ekonomiskt lönsam om man jämförde med naturlig föryngring. Dock kan en högre tillväxt vara viktig med tanke på kolinbindning och framtida råvarutillgång. Men mer intensivt brukade skogar kan ha negativa effekter på andra ekosystemtjänster. Det finns därför ett behov av att balansera olika skötselmål för att skapa och bevara en mångfald av skogar.

Nyckelord: plantering, naturlig föryngring, markberedning, risrensning, multiskadad skog, simulering, gran, tall, lövträd

Contents

List of publications

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

I. Nilsson, U., Jonsson, A., Lämås, T., Petersson, M. Modelling mortality by pine weevils for planted Norway spruce in southern Sweden. (Manuscript)

II. Jonsson, A., Elving, B., Hjelm, K., Nilsson, U. (2022). Will intensity of forest regeneration measures improve volume production and economy? Scandinavian Journal of Forest Research, 37 (3), 200-212.

III. Jonsson, A., Subramanian, N., Trubins, R., Wikberg, P-E., Hjelm, K., Lämås, T., Nilsson U. The effects of young forest density and tree-species composition on long-term volume production and stand structure in northern Sweden. (Manuscript)

IV. Jonsson, A., Hjelm, K., Lämås, T., Örlander, G., Nilsson, U. Effects of delayed regeneration and slash removal 30 years after establishment of Norway spruce. (Manuscript)

Paper II is reproduced with the permission of the publishers.

The contribution of Axelina Jonsson to the papers included in this thesis was as follows:

I. Analysed data and wrote manuscript in collaboration with co-authors.

II. Responsible for data collection, analysed data and wrote the manuscript in collaboration with co-authors.

III. Led the data analysis and manuscript writing in collaboration with co-authors.

IV. Led the data analysis and manuscript writing in collaboration with co-authors.

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Abbreviations

DSS	Decision support system
LEV	Land expectation value
MAI	Mean annual increment
NFI	National forest inventory
SKA15	Swedish forest impact analysis 2015
SKA22	Swedish forest impact analysis 2022
Äbin	Moose browsing inventory (Swedish abbreviation)

1. Introduction

The conditions for forestry vary greatly within Sweden due to the north-south variation in climatic conditions and fertility. In southernmost Sweden, the growing season is up to 230 days while in the extreme north it can be as short as 120 days (SMHI 2024). In addition, the north often has lower growing season temperatures than the south. Three vegetation zones are found in Sweden; boreal, hemiboreal and temperate. These factors, together with local differences in soil fertility, topography and water availability affect both the possibility for different tree species to grow and thereby also the treatments required to regenerate forest stands. Norway spruce *(Picea abies)* and Scots pine *(Pinus sylvestris)* are the most commonly regenerated tree species in Sweden (Swedish Forest Agency 2023). In 2022, Norway spruce and Scots pine constituted 96% of the seedlings delivered for planting. These two tree species are therefore the focus of the studies included in this thesis. Naturally regenerated birch (*Betula spp.*) and other native broadleaves and planted lodgepole pine *(Pinus contorta)* are also included, but to a limited extent.

The different growing conditions found in Sweden pose different challenges for forest regeneration, such as competing vegetation, frost and drought (Nilsson & Örlander 1999; Grossnickle 2000), so seedlings encounter many risks when planted on clearcuts. Damage by pine weevils (von Sydow 1997; Örlander & Nilsson 1999; Petersson & Örlander 2003), browsing by ungulates and different fungal infections (Björkman 1948; Martinsson 1985; Martinsson & Nilsson 1987; Gill 1992; Edenius *et al.* 1995; Bernhold 2008; Wallgren *et al.* 2014; Bergquist *et al.* 2019) are also among the potential problems which forest owners try to mitigate through active regeneration treatments.

Clearcuts in Sweden are commonly regenerated through active regeneration treatments, which often includes mechanical site preparation, planting of bare-rooted or containerised seedlings, mechanical pine weevil protection and use of improved seedling material. From 2021 to 2022, 87% of the clearfelled area was regenerated through planting and 92% of the planted area was mechanically site prepared before planting (Swedish Forest Agency 2023). A clear majority of the seedlings (86% for Norway spruce and 97% for Scots pine) used for regenerations were improved, meaning they were derived from orchard-grown seeds. A majority of Norway spruce seedlings and a large share of Scots pine seedlings were also mechanically protected against pine weevil damage (Swedish Forest Agency 2023). These treatments give forest owners an opportunity to influence growing conditions and seedling establishment, and optimise tree species choice for specific site conditions.

All treatments done in the regeneration phase intend to increase establishment and survival of the planted seedlings. However, they all come at a cost. In commercial forest management, investments made in regeneration should be repaid by increased future income. It is therefore useful to understand both the short- and long-term effects of different regeneration treatments.

1.1 Short-term effects of regeneration treatments

Site preparation alone greatly increases both survival and growth of seedlings (Sikström *et al.* 2020) since many of the above-mentioned challenges can be reduced by a more suitable planting environment. The possibility of using site preparation methods tailored to local conditions is an important reason for its success in increasing seedling survival and growth. Different site preparation methods generates different planting spots. By choosing a method for specific site conditions, it is possible to reduce frost damage on frost-prone sites (Örlander *et al.* 1990; Langvall *et al.* 2001; Heiskanen *et al.* 2013), flooding on wet sites (Nordin 2023) and competition from ground vegetation on fertile and dry sites (Nilsson & Örlander 1995; Nilsson *et al.* 2010). Site preparation is also crucial for reducing mortality and damage caused by pine weevils (Petersson & Örlander 2003; Nordlander *et al.* 2011; Wallertz & Petersson 2011; Wallertz *et al.* 2018). On sites where pine weevil damage can be expected, site preparation should aim to create planting spots with bare mineral soil. This has been shown to reduce damage by pine weevils (Petersson & Örlander 2003; Wallertz *et al.* 2018).

The choice of seedling material can further improve both survival and growth at planting. Nursery-grown seedlings have often been treated to tolerate different growing conditions when planted (Grossnickle 2000; Nilsson *et al.* 2010). The size of a seedling can play an important role depending on site conditions. For example, larger seedlings cope better with competition from ground vegetation and pine weevil damage (Örlander & Nilsson 1999; Nordlander *et al.* 2011). Smaller containerised seedlings can be beneficial on more drought-prone sites due to better balance between root and shoot biomass (Nilsson & Örlander 1995; Grossnickle & El-Kassaby 2016). Further, the use of genetically improved seedling material has been shown to accelerate early growth (Liziniewicz *et al.* 2018; Liziniewicz *et al.* 2019). However, breeding programs often aim to improve more than just volume growth. Other traits often considered are survival, vitality, stem quality and resistance to different types of pathogens (Stener *et al.* 2015). This gives genetically improved seedlings further advantages compared to unimproved seedlings.

One of the biggest problems for forest regeneration in Sweden is pine weevil damage. Due to the pine weevils' life cycle on a clear-cut, where a high abundance of weevils the first years after harvest declines by four years after the harvest, delayed planting is a potential solution to minimise mortality (von Sydow 1997; Örlander & Nilsson 1999). Experimental results show a significantly higher seedling survival when regeneration has been done on older clearcuts, compared to planting during the same year or soon after clearfelling (von Sydow 1997; Örlander & Nilsson 1999). However, postponing regeneration would mean a loss of growing seasons and better-established competing vegetation before seedlings are planted. This might result in planted seedlings being outcompeted by other vegetation, reducing their growth and survival (Nilsson & Örlander 1999). Most planting in southern Sweden is done on one- and two-year-old clearcuts whereas two- and three-year-old clearcuts are commonly planted in northern Sweden (Berglund *et al.* 2024). Other methods to reduce pine weevil damage are therefore required. To minimise damage from pine weevils and increase survival of planted seedlings, they are instead often mechanically protected (Swedish Forest Agency 2023). The improved survival when using mechanical protections (Nordlander *et al.* 2009; Nordlander *et al.* 2011; Domevscik *et al.* 2024), especially in combination with site preparation (Petersson & Örlander 2003), have made combining these regeneration treatments the prevalent way to minimise pine weevil damage.

Slash removal facilitates site preparation, and can be used to produce bioenergy. However, this measure's effects on seedling establishment are not as consistent as for other regeneration measures. The early effects of slash removal seem to depend on regenerated tree species, site conditions, and the amount of slash removed (Thiffault *et al.* 2011; Egnell 2017). These factors might explain the different results for seedling survival and growth. Most studies find early growth to be either reduced or unaffected by slash removal (Thiffault *et al.* 2011; Hanssen *et al.* 2018), while seedling survival either increases (Thiffault *et al.* 2011; Egnell 2017) or remains similar to when slash is retained (Nilsson & Örlander 1995; Egnell 2017; Hanssen *et al.* 2018). The positive effect of slash removal on seedling survival could potentially be an indirect effect of site preparation being easier (Saarinen 2006) which in turn can have a large impact on seedling survival.

1.2 Long-term effects of regeneration treatments

Ensuring survival of planted seedlings is a key factor for long-term volume production. High seedling mortality leads to lower stem densities or stands dominated by naturally regenerated seedlings, both of which affect forest stands' future growth. Regeneration treatments often aim to improve seedling survival, and thus also have a long-term effect on volume production. One treatment is site preparation which has been found to positively affect height growth (Johansson *et al.* 2013; Prévost & Dumais 2018; Sikström *et al.* 2020) and long-term volume production (Mattsson & Bergsten 2003; Hjelm *et al.* 2019). The long-term effect of site preparation has been suggested to be due to maintained short-term effects (Johansson *et al.* 2013), the head start from improved growth conditions, reduced competition from vegetation and reduced pine weevil damage lasts, but does not increase over time.

From a short-term perspective, slash removal can potentially facilitate site preparation and planting and could thereby increase establishment and survival of planted seedlings. However, slash removal could potentially have the opposite long-term effect on growth and volume production. Several studies conducted 10 to 30 years after stand establishment have reported reduced volume production and growth when slash has been removed (Egnell & Leijon 1999; Egnell 2011; Helmisaari *et al.* 2011; Jacobson *et al.* 2017). This reduction is often explained by the loss of nutrients from the removed slash (Egnell & Leijon 1999; Egnell 2011; Helmisaari *et al.* 2011; Jacobson *et al.* 2017). But other studies have found no long-term negative effect of slash removal on growth and standing volume (Tamminen & Saarsalmi 2013; Egnell 2016; Egnell 2017; Hjelm *et al.* 2019). It has therefore been suggested that the long-term effect of slash removal on growth might be both site and tree species specific (Thiffault *et al.* 2011; Egnell 2016). Egnell (2017) found a tendency of Norway spruce to be more sensitive to slash removal than Scots pine. Norway spruce was also found to be more sensitive to slash removal on less fertile sites.

The seedling material used when regenerating a forest stand has a big impact on long-term growth and volume production (Jansson 2007; Liziniewicz *et al.* 2018; Liziniewicz *et al.* 2019), especially when comparing genetically improved to unimproved seedling material (Liziniewicz *et al.* 2018; Liziniewicz *et al.* 2019). The increased survival and growth of improved seedlings at the beginning of the rotation set the pace for the continued development of the stand. Large long-term gains in height growth and volume production have been found when genetically improved seedlings are used. For the improved Norway spruce and Scots pine seedlings commonly used in Swedish forestry the long-term estimated increase in volume production is between 10 and 25% compared with unimproved seedling material (Jansson *et al.* 2017).

Using genetically improved seedlings has a large effect on the economics of more intensively managed forests (Simonsen *et al.* 2010; Jansson *et al.* 2017). Tree species choice has similar impacts (Simonsen *et al.* 2010; Chamberland *et al.* 2020; Serrano-León *et al.* 2021), mainly due to the potential to increase volume production at a relatively low cost. To improve profitability, active regeneration is basically required to have this effect. A higher volume production can partially compensate for the early investment, both by directly increasing volume, and also by potentially shortening the rotation age. These are two key variables in the economics of forest management (Jansson *et al.* 2017). Studies evaluating the economics of intensive forest management have concluded that the initial costs together with the interest rate and timber prices at harvest are the factors most influencing the economic outcome (Faustmann 1849; Mäkinen *et al.* 2005; Hyytiäinen *et al.* 2006; Simonsen *et al.* 2010; Serrano-León *et al.* 2021).

1.3 Regeneration treatments and climate change

With the changing climate, Sweden is generally expected to experience increased temperatures and longer growing seasons (Sjökvist *et al.* 2015; Eriksson *et al.* 2016). These new growing conditions are expected to accelerate forest growth. However, certain negative consequences are also likely. The wetter and warmer conditions are expected to favour both existing and new pests and pathogens. The number of days with heavy rainfall is also predicted to increase (Sjökvist *et al.* 2015; Eriksson *et al.* 2016), potentially causing flooding. The increase is likely to be during winter and spring, so increased water deficit and drought risk during the growing season is also a possible outcome. A longer growing season is not solely positive either, as it can increase frost damage risk.

The regeneration treatments mentioned above can have important roles in the context of expected growing conditions in Sweden. The choice of regeneration method will continue to be of great importance, perhaps even of greater importance in a future climate.

1.4 Simulated long-term effects of regeneration treatments

Forestry in the boreal region is characterized by long time frames. In Sweden, rotation ages vary depending on fertility and tree species, but the average stand age at clearfelling is currently about 100 years (Swedish Forest Agency 2023). These long timeframes makes it difficult to evaluate the full-rotation-period effects of regeneration measures taken. Simulations of forest development offer insights much faster than experiments can.

Full-rotation forest growth and development simulations require many models covering growth in different stages, mortality and harvesting treatments. The models need to be based on extensive data to give a reliable results. In Sweden, the commonly used simulator is the Heureka Decision Support System (DSS; Lämås *et al.* (2023)). It both simulates forest growth and development and optimises forest management at different geographical scales. Simulations allow exploration of different management scenarios and can be a useful tool in both research and practical forestry to get insight into potential long-term effects of different forest management treatments. Simulation studies have, for example, been used to evaluate long-term effects of different regeneration methods (planting, sowing or natural regeneration) on growth and economics (Hyytiäinen *et al.* 2006; Lula *et al.* 2021). They have also been used to evaluate the long-term effects of using genetically improved seedling material, alternative tree species, pine weevil protection, fertilisation, etc. (Simonsen *et al.* 2010; Serrano-León *et al.* 2021).

2. Thesis aim

In Sweden large efforts are taken in the forest regeneration phase to ensure high survival and continued growth of new stands. Many of the regeneration treatments have proven highly successful to reach short-term goals. However, most regeneration studies have a short-term perspective and are evaluated after the establishment phase. But understanding the long-term effects of applied regeneration treatments is needed to decide whether regeneration phase investments are justified.

There is therefore a need to explore the long-term effects of early survival and growth. This thesis therefore aims to evaluate the long-term effects of forest regeneration success on volume production, economics and stand structure.

To study the effects of different regeneration treatments on mortality caused by pine weevils, a mortality model was constructed in Paper I. The remaining papers in this thesis analyse long-term effects of forest regeneration success on volume production, economics and stand structure. Paper II evaluates three different regeneration phase intensities after a simulated full rotation on a wide range of sites covering Sweden's differences in growing conditions. Paper III analyses three different damage levels, including both browsing and fungal damage, and their effects on the development of young Scots pine stands over a simulated 100-year period. Finally, Paper IV evaluates slash removal after clearfelling and different clearcut ages at planting after 30 years of growth in Norway spruce plantations.

3. Material and methods

3.1 Paper I

The mortality model in Paper I was based on data from 44 regeneration experiments established between 1988 and 2003 in southern Sweden, all followed for at least three years. The experiments all recorded initial root-collar diameter and mortality due to pine weevil after three growing seasons. In four experiments, planting was done in clearcuts of different ages, from fresh clearcuts to four-year-old clearcuts. For the remaining experiments, planting was done on fresh or one-year-old clearcuts.

Seedlings were planted in pure mineral soil, in a mixture of humus and mineral soil (humus mix) or in undisturbed soil. The pine weevil protection used where either an insecticide, permethrin, which was allowed when the experiments were established but is now banned in Sweden, or some kind of mechanical protection. Many of the included studies aimed to evaluate different mechanical pine weevil protections so the mechanical protection variable in the model consists of several mechanical protections. However, only protections significantly reducing mortality compared to unprotected seedlings were included.

Since the four experiments focusing on different-aged clearcuts did not include any pine weevil protection, two models were constructed. One for the four experiments (model 2), and one for the remaining experiments plus the data from planted unprotected seedlings on fresh and one-year-old clearcuts from the four other experiments (model 1). Model 1 aimed to estimate mortality given soil disturbance, pine weevil protection and root-collar diameter. Model 2 aimed to estimate mortality given root-collar diameter and clearcut age. In the four clearcut age experiments, site preparation was done before planting.

Seedling mortality is a binomial-process – seedlings are either alive or dead. Therefore, when modelling the probability of mortality, a generalised form of the logistic equations for mortality was used:

$$p = \frac{1}{(1 + e^{-(a+b'X)})}$$

where p is the probability of mortality, a is the intercept and $b'X$ a linear combination of the explanatory variables. The model was estimated using a mixed effect framework.

3.2 Paper II

In Paper II data from 14 sites covering Sweden's large variation in soil fertility and climatic conditions was used. At each site, three clearcuts between 0.7 and 1 ha, were regenerated using high-, medium- and low-intensity methods (Figure 1). Both high- and medium-intensity methods used active regeneration treatments and often involved both site preparation and planting. The two intensities differed in time of regeneration and size of seedlings. High-intensity stands were regenerated the same year as the clearfelling, while medium-intensity stands were regenerated between one to three years after clearfelling. The seedlings in most high-intensity regeneration sites were two-year-old seedlings while at the medium-intensity the seedlings were smaller one-year-old seedlings. For low-intensity, the stands depended entirely on natural regeneration, no active regeneration treatments were done. For the evaluation, stand data was collected about 30 years after stand establishment. Since the study aimed to evaluate the long-term effect after a full rotation the Heureka DSS simulation software was used to simulate growth and management of the stands during a full rotation. The starting values for the simulations were single-tree measurements (height, diameter at breast height and age) and site characteristics for each individual stand. Data generated from the simulations were used to calculate mean annual increment (MAI) and land expectation value (LEV). Maximum LEV was used to determine the rotation length of each individual stand.

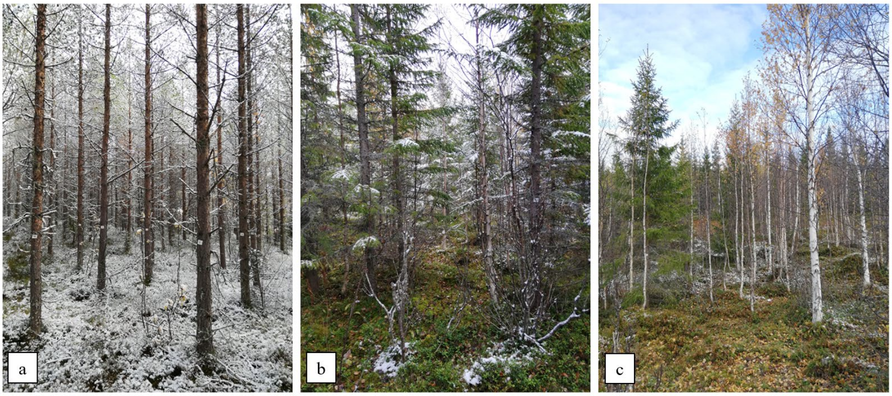

Figure 1. An example of the three intensity levels about 30 years after clearfelling at one of the sites included in Paper II (site 2366 Hökvattnet, Jämtland); (a) high intensity, (b) medium intensity and (c) low intensity.

3.3 Paper III

In Paper III, Swedish National Forest Inventory (NFI) data from 2015-2019 from the four northernmost regions (Norrbotten, Västerbotten, Jämtland and Västernorrland) in Sweden was used as a base for simulations. The NFI data used represented 11.5 million ha of productive forest land. Site indices according to site factors (SIS) for the included forests varied considerably, between T10 and T28 (height (m) of Scots pine at 100 years). A large proportion (64%), however, had a site index lower than T20. The data was the starting point for the simulations of the three scenarios included in the study: damage free (DF), damage according to a damage model (DM) and damage according to a specific moose browsing inventory called "Äbin" (DI). The three scenarios represented different damage levels in the regeneration phase, with DF representing the lowest level and DI the highest level. The Äbin inventory used in the DI scenario provided the number of stems per hectare and the tree species composition for the regenerations made in the four regions. The regenerations made in DM were based on the present day forestry scenario in the nationwide forest impact analysis SKA15 (Claesson *et al.* 2015), where the regenerations are made according to the Swedish Forest Agency's regeneration survey. The DF scenario aimed to represent forest owners' intentions when regenerating. The planted tree species were therefore the same as for the reported regenerated tree species in the Äbin inventory, but stem numbers after pre-commercial thinning were set to 2000 trees per hectare.

In the simulations, the three scenarios differed only in their regeneration and pre-commercial thinning settings. Subsequent management, such as commercial thinning and clearfelling, followed current management recommendations. The simulations were done over a 100-year period and the volume production outcomes and tree species compositions were evaluated and compared among the three scenarios for the last 20 years of the simulated period.

3.4 Paper IV

Data for Paper IV, was collected from an experiment established between 1989 and 1993. The experiment comprised four fertile sites, site indices according to height (SIH) between G30 and G34 (height (m) of Norway spruce trees at 100 years age), in southern Sweden (Figure 2). The effects of slash removal and clearcut age at planting were evaluated in the experiment. Therefore, a clearcut was made on each site every year between 1989 and 1993. The clearcuts were divided into halves. Slash was removed from one half while on the other half slash was retained. Each clearcut half was then divided into equally large plots and regenerated with Norway spruce the following years. This resulted in following planting schedule: the first year (1989) only fresh cleracuts were regenerated, the second year (1990) both fresh clearcuts and one-year-old clear cuts were regenerated, The third year (1991) fresh clearcuts, one-year-old and two-year-old clearcuts were regenerated, and so on until the last year (1993) when regenerations were made on clearcuts ranging in age from fresh to four-years-old.

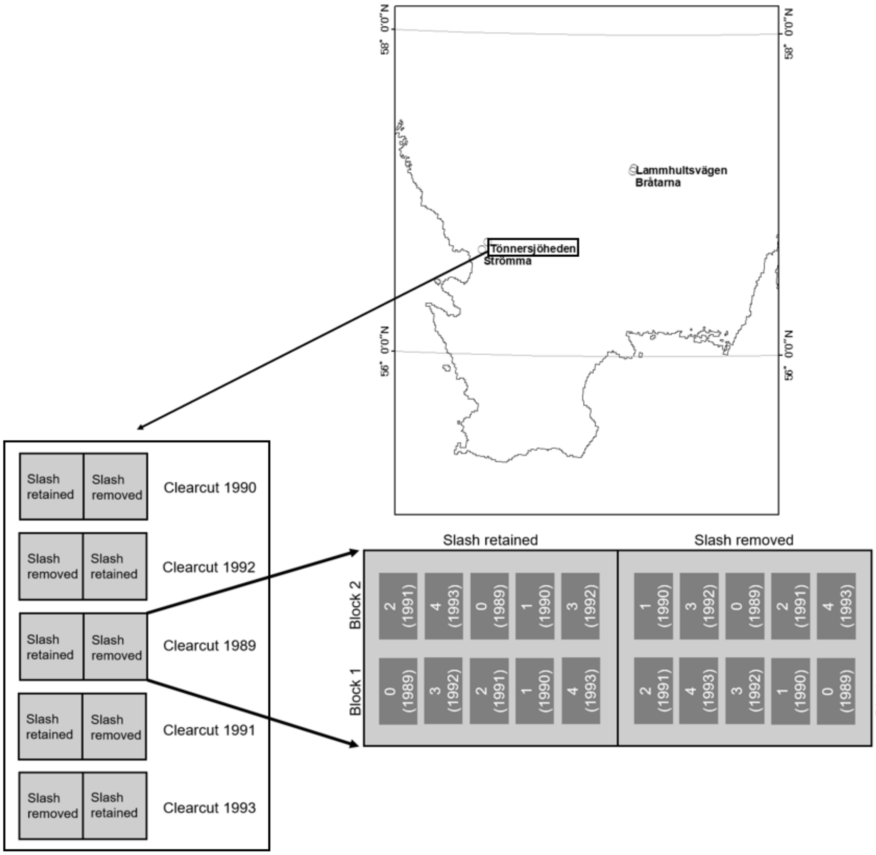

Figure 2. The location of the four sites (Strömma, Tönnersjöheden, Bråtarna and Lammhultsvägen) included in the study and the experimental design within them. Five clearcuts were made in each of five years (1989-1993) and parts of them regenerated in each of the five following years, resulting in five clearcut ages (0-4 years). Years in parentheses are the planting years.

In this study, data from measurements of 30-year-old trees was used to evaluate differences in volume production for the two slash treatments and the five clearcut ages at planting. The evaluations were based on the 1500 largest trees per hectare in each plot to capture the effect of the treatments on the future crop trees. In the results, the estimated mean is presented as the average value for the response variable, that is, the total volume for the 1500 largest trees per hectare.

4. Results and discussion

4.1 Short-term effects of regeneration treatments on seedling survival (Paper I)

The model results showed that the effect of clearcut age, seedling size, mechanical protection against pine weevil damage and planting spot on survival of planted Norway spruce seedlings were significant. Delaying regeneration treatments up to four years resulted in significantly lower mortality due to pine weevils compared to planting on fresh or one-year-old clearcuts (Figure 3). This agrees with previous results (von Sydow 1997; Örlander & Nilsson 1999). But as mentioned, delaying regeneration treatments is not an optimal method for reducing pine weevil damage in southern Sweden, as it creates an opportunity for competing vegetation to establish. This competition can in turn greatly reduce both growth and survival of planted seedlings (Nilsson & Örlander 1999). There are, however, treatments that both promote high seedling survival and are practically implementable such as mechanical protection against pine weevils and site preparation.

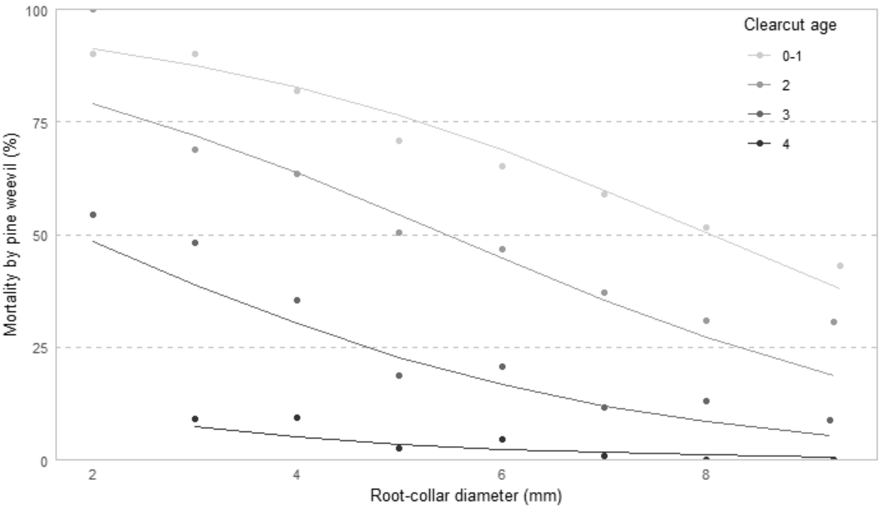

Figure 3. The effect of clearcut age at planting according to model 2 (solid lines) and measured data (dots) (effect of protected seedlings not considered in model 2). The effect of root-collar diameter at planting is shown on the x-axis.

Paper I showed that mechanical pine weevil protection decreases mortality on fresh and one-year-old clearcuts from more than 75% to about 25% (Figure 4). This result confirms many other studies using single experiments (Nordlander *et al.* 2009; Nordlander *et al.* 2011; Eriksson *et al.* 2018; Domevscik *et al.* 2024). However, today's mechanical protections might be more effective in reducing pine weevil damage than those used in the experiments used to construct model 1. Domevscik *et al.* (2024) and Eriksson *et al.* (2018) found that mechanical pine weevil protection increased seedling survival substantially and was as effective as insecticides. This means the effect of mechanical protection might be underestimated in model 1.

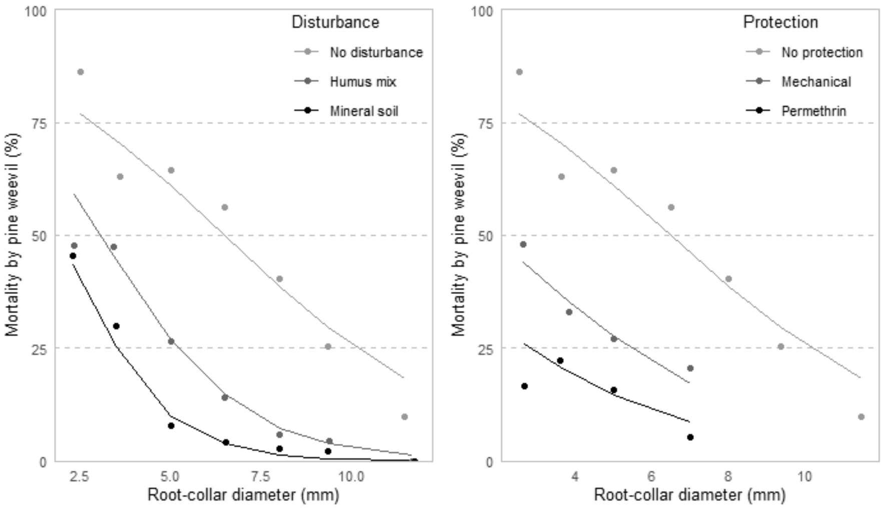

Figure 4. The effect of soil disturbance (left) and pine weevil protection (right) according to model 1 (solid lines) and measured data (dots). The effect of clearcut age was not considered in model 1. For both figures, the effect of root-collar diameter at planting is shown on the x-axis.

Model 1 also showed that site preparation, or more specifically, the degree of soil disturbance, had an important role for decreasing mortality by pine weevil (Figure 4). Planting seedlings in mineral soil or in mixed-mineral and humus soils resulted in significantly lower mortality than planting in undisturbed soil. Ensuring that seedlings are planted in mineral soil was shown to be crucial for seedling survival in several studies (Petersson & Örlander 2003; Wallertz & Petersson 2011; Wallertz *et al.* 2018). A newly established inventory reported that in southern Sweden about 60% of Norway spruce seedlings planted in 2023 were planted in mineral soil after site preparation (Berglund *et al.* 2024). Survival and vitality of planted Norway spruce seedlings could therefore potentially be increased if a higher proportion of seedlings were planted in mineral soil. This might be facilitated by abandoning the traditional quadratic spacing when planting, which potentially could increase the possibility of finding a suitable planting spot. Ara (2022) found that square vs. rectangular spacing had no effect on volume production and wood quality, and highlighted that density rather than spatial positioning is important for forest production. Planting seedlings in good substrates could be more important than regular spacing between seedlings when regenerating a forest stand.

Model 1 also allowed exploration of the effects of combining regeneration treatments. A combination known to increase survival is site preparation together with mechanical pine weevil protection (Petersson & Örlander 2003). The model result confirmed this previously established knowledge (Table 1). The combination of large seedlings and mineral soil was also found to decrease mortality (Figure 4). In general, larger seedling died less frequently than smaller ones (Figures 3 and 4). This also agrees with previous results (Örlander & Nilsson 1999; Nordlander *et al.* 2011). However, larger seedlings are more expensive to produce and plant. Smaller containerised seedlings are therefore more commonly used in practical forestry (Swedish Forest Agency 2023).

Table 1. Measured mortality due to pine weevil and estimated mortality according to model 1 (effect of clearcut age is not considered) for different degrees of disturbance and mechanical protection. Only seedlings with root collar diameters between 2-5 mm were included.

	Measured value (%)	**Estimated value (%)**
No treatment	65.5	69.2
Humus mix	44.0	43.3
Mechanical protection	33.7	34.9
Mechanical protection + Humus mix	29.9	25.1
Mineral soil	26.3	23.2
Mechanical protection + Mineral soil	24.8	14.6

The model results suggest that it is essential for regenerations using smaller containerised seedlings to be mechanically protected to reduce seedling mortality. Treatments could be combined to further minimise mortality, especially plant mechanically protected seedlings in mineral soil. If not possible, large seedlings and/or planting on old clearcuts might be options to minimise mortality due to pine weevil.

It should be mentioned that the data used for constructing the models was from experiments only. Seedlings in forest regeneration experiments are commonly planted very carefully. Mortality of seedlings due to pine weevil might be higher in practical forestry than in the experiments used for constructing the model, so mortality might be underestimated by the models.

The results from Paper I confirm what has been concluded by many earlier studies. However, individual results from previous studies have been restricted to the specific conditions given for each study. By combining data from several experiments, as was done in the models, the usability of the individual results has been increased. It is now possible to analyse the mortality due to pine weevil over a range of root-collar diameters for a given treatment, planting spot, pine weevil protection and clearcut age at planting. The models can therefore have an important role both in research and potentially also practical forestry when planning forest regenerations.

4.2 Long-term effects of different intensities of regeneration treatments (Paper II)

The three regeneration-phase management intensities differed clearly in standing volume after about 30 years of growth (Figure 5). The high regeneration intensity resulted in the highest standing volume, significantly higher than both medium and low intensities. The medium-intensity level generated on average the second-highest standing volume, significantly higher than the low-intensity. These differences remained after a simulated full rotation (Figure 6). High- and medium-intensity treatments resulted in significantly higher growth than low intensity, by between 50 and 70% over a full rotation period. This agrees with results from other studies evaluating the effects of different stand establishment intensities (Simonsen *et al.* 2010; Nilsson *et al.* 2011; Hallsby *et al.* 2015; Serrano-León *et al.* 2021). However, no significant difference was found between high and medium intensities. This indicates that active management at a high or medium intensity in the regeneration phase results in higher volume production after 30 years but also potentially after a full rotation period.

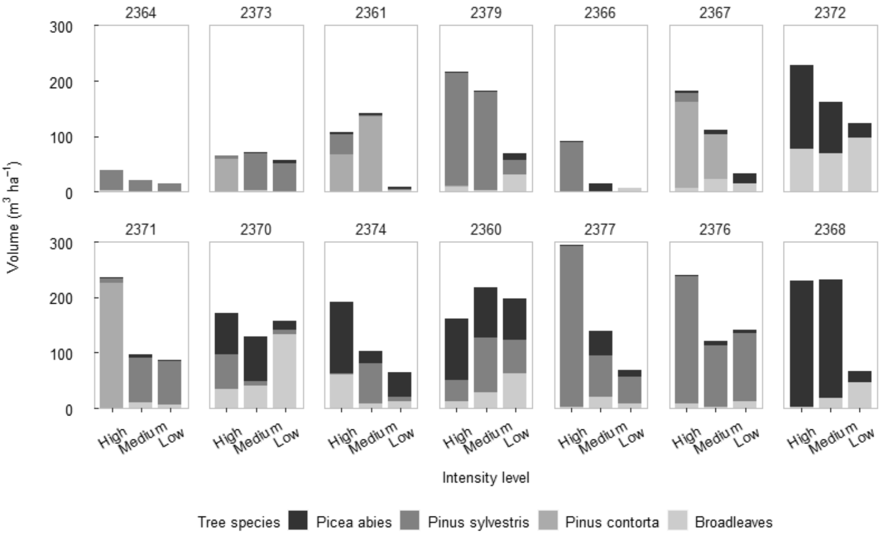

Figure 5. Standing volume of different tree species in 2019 at the included sites (sorted from north to south) at high, medium and low intensities.

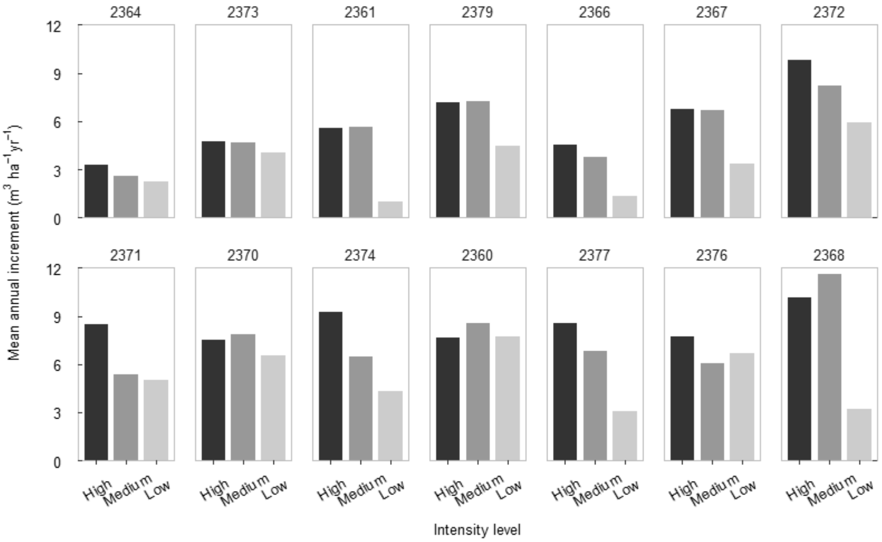

Figure 6. Estimated mean annual increment (MAI) for all sites (sorted from north to south) and intensity levels after a simulated full rotation.

The long-term effect on growth and volume production could be explained by the treatments applied in the regeneration phase and the forest structures resulting from the different intensity levels. Most stands regenerated under high or medium intensities were site prepared before seedling establishment. Site preparation alone has been found to substantially enhance seedling survival and growth (Sikström *et al.* 2020) and long-term volume production (Mattsson & Bergsten 2003; Hjelm *et al.* 2019). By reducing competing vegetation, increasing soil temperatures, increasing nutrients and water availability, and reducing pine weevil damage, site preparation can significantly increase seedling survival (Nilsson *et al.* 2010). Furthermore, active management in the regeneration phase can further improve survival and growth by the choice of seedling material (Nilsson & Örlander 1995; Örlander & Nilsson 1999; Grossnickle 2000; Nordlander *et al.* 2011; Grossnickle & El-Kassaby 2016; Nilsson *et al.* 2020). Paper II, used nursery-grown seedlings, allowing optimisation of both seedling type and tree species for site conditions, potentially enhancing growth.

Site preparation and seedling choice, including the choice of tree species, are probably the main factors why active regeneration leads to even-aged monocultures. After active regeneration treatments, regenerated tree species became the dominant species, more often leading to coniferous monocultures compared to when no regeneration treatments were applied. For the low-intensity level, no regeneration measures were taken; the stands relied on natural regeneration. The success of natural regeneration depends on several factors, such as seed production (which depends in turn on factors such as climate, site conditions and genetics), distance to seed sources, and seed fall (Beland *et al.* 2000; Karlsson 2001; Holmström 2015). Due to a large variation in regeneration success among those stands, a broader variety of tree ages and species compositions was found under low-intensity management. Forests dominated by naturally regenerated broadleaves were more commonly found after no treatment compared to after active regeneration. Even-aged stands and monocultures of suitable tree species for the site, as found for high and medium intensities, typically increase volume production (Tahvonen *et al.* 2010; Nilsson *et al.* 2011; Jansson *et al.* 2017) and could explain some of the differences found between intensity levels.

Pre-commercial thinning was supposed to be included in the management of the high-intensity stands. It was, however, not recorded whether if or how this treatment was conducted. Pre-commercial thinning plays a big role in forming the future stand, by early selection of tree species composition and trees with preferred properties. This treatment has also shown to improve both survival and diameter growth of retained trees (Pettersson 1993). Pre-commercial thinning could have affected the long-term volume growth in the high-intensity stands by shaping the stand structure and promoting the most suitable trees within the stands.

Active management in the regeneration phase comes at a cost. It was clear that the active treatments applied at the beginning of a rotation greatly impacted their long-term economics. From a solely economic perspective, passive management in the regeneration phase was found to be more profitable than active management. In 13 out of 14 sites, low intensity generated the highest land expectation value (LEV) after a full rotation period when a 2.5% interest rate was used. This shows the large impact initial regeneration costs have on the long-term profitability of forest management, which has been highlighted before (Hyytiäinen *et al.* 2006). Profitability has also been shown to be highly sensitive to the interest rate (Hyytiäinen *et al.* 2006; Simonsen *et al.* 2010; Serrano-León *et al.* 2021). This sensitivity was evident also in this study. When applying a lower interest rate (1%) there was no significant difference in LEV among the three intensity levels.

Seedlings of the best available genetic material at the time was used in this study. The improvement of seedling material has, however, come a long way and most seedlings used today are genetically improved (Swedish Forest Agency 2023), bred to grow faster and survive better (Stener et al. 2015; Liziniewicz et al. 2018; Liziniewicz et al. 2019). If today's improved seedling material were used, increased growth could be expected for actively regenerated stands. This could potentially shorten the rotation length for these stands, which affects the LEV. In Paper II, no differences in rotation lengths were found among the three intensity levels. In more recent studies using genetically improved seedling material, actively regenerated stands have proven more profitable (Simonsen *et al.* 2010; Chamberland *et al.* 2020; Serrano-León *et al.* 2021).

This study’s full rotation results are based on data derived from simulations. Simulations are useful for exploring and analysing potential future scenarios, especially in forestry with long rotations times, where they allow analysis of potential future effects of certain events or forest management choices. However, simulations have limitations. The models used for estimating forest development are based on how forests have grown historically. Simulations can therefore give insight into how forests might develop if historical conditions persist. A changing climate will, however, change growing conditions and affect future forest growth and development. A solution could be to turn to processed-based growth models or hybrid models combining empirical and process-based models (Felton *et al.* 2017).

The results in Paper II indicate the potential of active regeneration treatments when aiming for volume production. However, some sites were more suitable for natural regeneration than others and generated similar long-term volume growth to actively regenerated stands (Figures 5 and 6). It is, however, not always easy to judge beforehand which stands will benefit from active regeneration treatments or which will be more suitable for natural regeneration. Most stands in this study did benefit from active regeneration treatments. Knowledge about the stand and its growing conditions, however, might allow less intensive regeneration. This could be beneficial from both ecological and economic perspectives (Hyytiäinen *et al.* 2006; Sing *et al.* 2018).

4.3 Long-term effects of browsing and fungal damage in young Scots pine stands (Paper III)

The damage level found in the DI (damage according to a specific moose browsing inventory called Äbin) scenario significantly reduced volume growth (Figure 7). The DI scenario had lower volume growth than either the DF (damage free) or DM (damage according to a damage model) scenarios. This agrees with results from other studies investigating the effects of browsing (Heikkilä & Löyttyniemi 1992; Edenius *et al.* 1995; Pettersson *et al.* 2010; Wallgren *et al.* 2014; Nilsson *et al.* 2016). For the last 20 years of the 100-year simulation period, the DI scenario showed a volume growth reduction of 26% below DF and 17% below DM when improved seedling material was used (Figure 7). Using unimproved seedling material, the differences among the scenarios were smaller. The average volume growth in the DI scenario was approximately 17% below DF and 13% lower than DM for the last 20 years. The within-scenario volume growth differences between improved and unimproved seedling material varied among scenarios. The biggest difference was found in DF, followed by DM and DI (Figure 7).

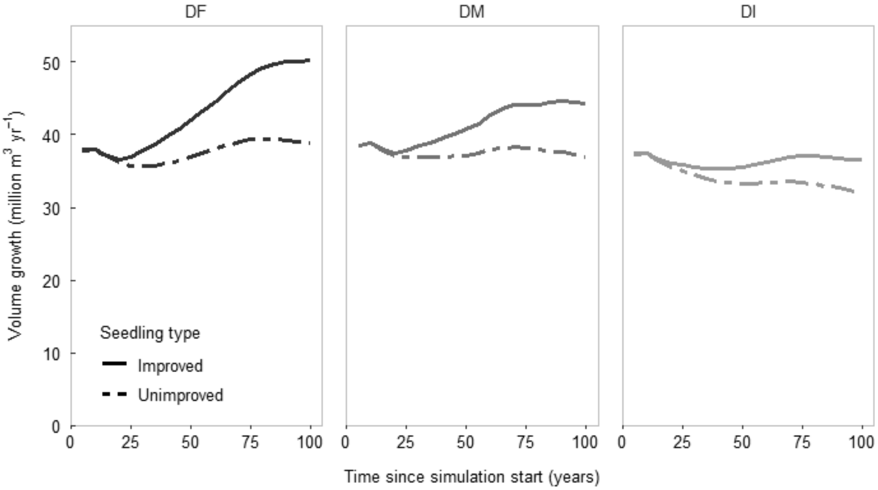

Figure 7. Total net annual volume growth for all regions (Norrbotten, Västerbotten, Jämtland and Västernorrland) over the simulation period for the three scenarios (damage free (DF), damage according to a damage model (DM) and damage according to a specific moose browsing inventory called Äbin (DI)).

The differences in volume growth could be partly explained by the lower basal area and stem density found in the DI scenario compared to scenarios DF and DM. The improved seedling material and the tree species per se were probably also an important part of the explanation. The DF and DM scenario stands consisted largely of improved seedlings of the regenerated tree species by the end of the simulation period (Figures 7 and 8). In the DI scenario, naturally regenerated seedlings had mostly replaced the planted seedlings. A large proportion of the stands included in the study had a site index lower than T20 (Scots pine reaching a height of 20 m after 100 years) and were commonly regenerated with Scots pine. This gives the scenarios where the regenerated tree species dominate the stand structure advantages in volume growth in two ways. First, improved seedlings grow faster compared to naturally regenerated seedlings (Jansson *et al.* 2017). Second, Scots pine have a higher growth on less fertile sites than Norway spruce or birch (Nilsson *et al.* 2012; Hallsby & Fries 2013; Rytter *et al.* 2014; Lula 2022). A lower proportion of Scots pine on these types of sites will negatively affect volume production.

In Paper III, the DI scenario was based on the stem numbers from the Äbin-inventory; no other considerations of how browsing affects tree growth were taken. Browsing could, however, affect volume growth in ways not considered in this scenario. Studies have, for example, shown that the browsing intensity can affect how large the negative effect on volume growth will be (Gill 1992; Heikkilä & Löyttyniemi 1992; Edenius *et al.* 1995; Wallgren *et al.* 2014). Repeated browsing is another factor. Previously-browsed trees have a higher risk of being browsed again (Bergqvist *et al.* 2001; Wallgren *et al.* 2013). This affects the time needed to grow beyond browsing height, which is also affected by soil fertility. Less-fertile sites can therefore prolong the time spent within browsing height. These factors, repeated browsing and time needed to grow beyond browsing height were not considered in this study, nor was the direct growth reduction which top and side shoots lead to since the study was only based on stem numbers reported in the Äbin inventory.

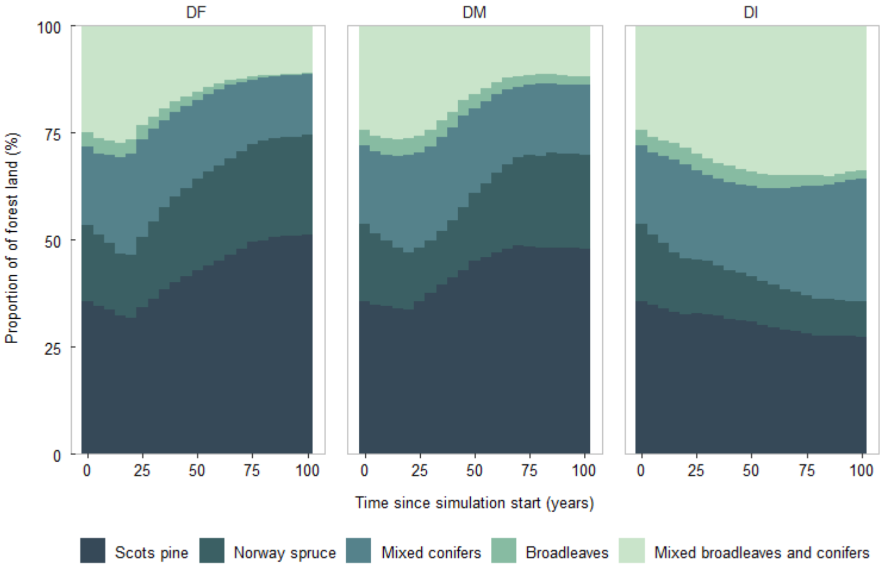

Figure 8. The stand structures for the three different scenarios (damage free (DF), damage according to a damage model (DM) and damage according to a specific moose browsing inventory called Äbin (DI)) as a proportion of the total productive forest land in the four northernmost regions in Sweden (Norrbotten, Västerbotten, Jämtland and Västernorrland).

The intended stand structure, a monoculture of Scots pine or Norway spruce, was not well realised under the DI scenario (Figure 8). Only 32% of the productive forest land in this scenario was Scots pine or Norway spruce dominated at the end of the simulation period. Instead, mixed forests were dominant. Conifers were still predominant, but the proportion of monocultures was considerably lower than what was found for the DF and DM scenarios. The tree species composition is largely affected by the browsing pressure, as moose prefer certain species as fodder more than others. Most preferred are rowan, aspen and willows but Scots pine is also heavily browsed (Månsson *et al.* 2007). This leads to declining abundance of these tree species where browsing occurs. Studies comparing inside and outside of fenced areas have confirmed that Scots pine abundance is reduced outside the fence (Bergquist *et al.* 1999; Speed *et al.* 2013). The stand structure found in the DI scenario is therefore a likely outcome if browsing pressure remains at today's levels.

A new forest impact analysis (SKA22) has been made since this study was done (Bergqvist *et al.* 2022). In SKA22, updated browsing damage levels are higher than in the former SKA15. A new study based on the present-day scenario in SKA22 would probably result in more similar results in growth and tree species composition for the DM and DI scenarios.

The reduction of Scots pine-dominated stands might not only be a result of browsing. The Äbin inventory only examines stands with heights of 1 to 4 meters. Scots pine seedlings are exposed to many risks, both abiotic and biotic, before reaching a height of 1 meter, all which can limit survival and continued growth. Drought, frost and competing vegetation are problems to consider when regenerating a stand (Nilsson & Örlander 1999; Grossnickle 2000). But there are other more specific problems related to young Scots pine stands' survival and growth, namely fungal infections such as resin-top disease (*Cronartium flaccidum*, *Peridermium pini*), snow blight (*Phacidium infestans*), scleroderris canker (*Gremmeniella abietina*) and pine twist rust (*Melampsora pinitorqua*) (Björkman 1948; Martinsson 1985; Martinsson & Nilsson 1987). These factors can have severe consequences for Scots pine seedling survival and growth before stands reaches the lower height limit of the Äbin inventory.

The reduced growth and abundance of Scots pine in northern Sweden affect forest economic outcome. A reduction in volume production, lower-quality timber and longer rotations are factors clearly reducing profitability (Nilsson *et al.* 2016; Bergquist *et al.* 2019). Factors which further affect forest economics are costs of supplementary planting or replanting of a stand, which can be required in cases of severe damage. Beyond these potential economic losses, there are also potential ecological losses. Scots pine provides a forest type which offers more light to understory vegetation (Felton *et al.* 2020). Lichens and dwarf shrubs benefit from these light conditions (Felton *et al.* 2020), including *Vaccinium* species that are important moose food (Spitzer 2019). With less *Vaccinium sp.* available browsing of pine is likely to continue.

The mixed forest types found in the DI scenario also offer important structures for both biodiversity and forest resilience to pests, pathogens and storms (Jactel *et al.* 2017; Huuskonen *et al.* 2021). Mixed forests better accommodate a wider variety of species and thereby also a wider biodiversity (Felton *et al.* 2016; Huuskonen *et al.* 2021). This reason alone highlights the need to also manage forests towards a mixed structure, and it does not necessarily imply a loss in volume production or profitability (Felton *et al.* 2016; Huuskonen *et al.* 2021; Ara 2022; Dosumu *et al.* 2024).

4.4 Long-term effects of clearcut age when planting and slash removal after clearfelling (Paper IV)

Time since clearcutting and slash treatment both had significant impact on volume production 20 and 30 years after establishment for the 1500 largest trees per hectare. By 30 years after planting, a significant difference was found between the youngest clearcut ages, 0 and 1 year old, and the oldest (4 year; Figure 9). The youngest clearcut ages had higher total volume than the oldest. Retaining slash resulted in a higher total volume than removing slash after 30 years of growth (Figure 10).

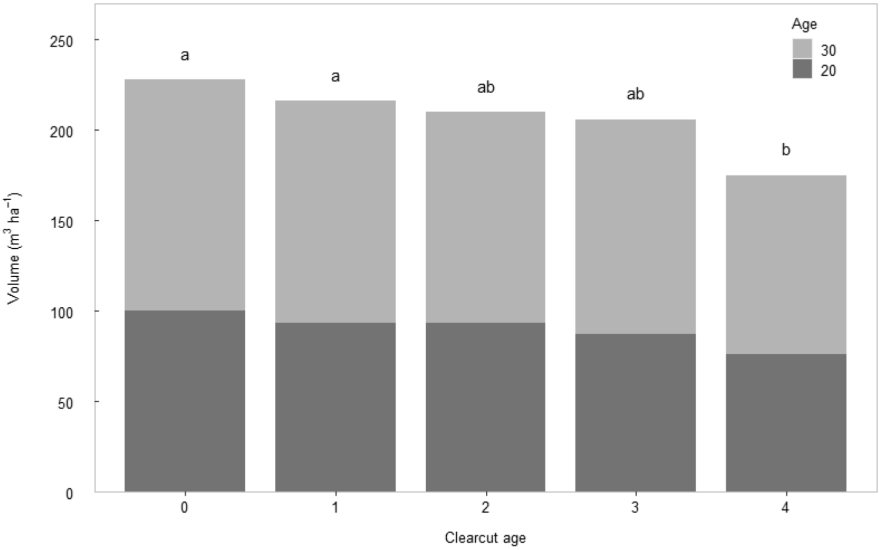

Figure 9. Total volume 20 and 30 years after planting for each clearcut age for the 1500 largest trees per hectare. Significant differences ($p<0.05$) among clearcut ages after 30 years are indicated with different letters.

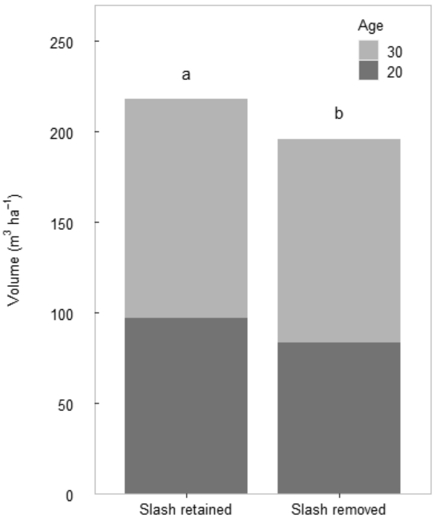

Figure 10. Total volume 20 and 30 years after planting under the two slash treatments for the 1500 largest trees per hectare. Significant differences ($p<0.05$) between slash treatments after 30 years are indicated with different letters.

4.4.1 Clearcut age

The volume production differences between clearcut ages might be explained by the early growing conditions which differed between younger and older clearcuts. Older clearcuts had more competing vegetation than younger ones (Nilsson & Örlander 1999). This had a clear effect, significantly reducing survival and growth of planted seedlings on older clearcuts.

Early differences in survival and growth due to reduced competition can persist long after the establishment phase. This has been confirmed by studies evaluating long-term effects of site preparation (Nilsson & Allen 2003; Johansson *et al.* 2013). The studies found that the early advantages of reduced competition from other vegetation for seedling survival and growth of seedlings remained 18 years after establishment. This led to higher volume production in site prepared or more intensively prepared stands compared to stands with no site preparation or less intensively prepared. Therefore, the lower establishment phase competition in younger clearcuts of this experiment could potentially explain their higher total volume 30 years after establishment.

The design of this experiment is unbalanced since there are more observations for younger clearcut ages than for older ones. This makes the results more certain for younger clearcuts. The mixed models used in the statistical analyses accounted for this problem.

In this study, the different clearcut ages were compared when all stands had grown for 30 years. However, this comparison ignores the additional years of growth the younger clearcut ages had gained while the oldest reached 30 years. The youngest clearcut age reached 30 years of growth 30 years after clearfelling, while the oldest reached 30 years of growth 34 years after clearfelling. This costs the oldest clearcuts four growing seasons compared to the youngest clearcut age. The real differences in total volume and growth would be greater than what is shown in this study if the clearcut ages were all inventoried the same year after clearfelling instead of at a fixed post-planting age.

4.4.2 Slash treatment

When slash is removed from a clearcut, nutrients are removed with it. Nutrient loss has therefore been suggested as the main explanation for lower volume production where slash has been removed compared to stands with retained slash (Egnell & Leijon 1999; Egnell 2011; Helmisaari *et al.* 2011; Jacobson *et al.* 2017). Helmisaari *et al.* (2011) compensated for slash removal by adding NPK fertiliser. They found no difference in growth between unfertilised stands with slash and fertilised stands without slash, indicating a relationship between slash removal and nutrient loss. The differences found in Paper IV between the two slash treatments are likely explained by the nutrients loss via slash removal.

However, other studies show no differences in volume production between retaining and removing slash after clearfelling (Tamminen & Saarsalmi 2013; Egnell 2016; Egnell 2017; Hjelm *et al.* 2019). It has been suggested that the effect of slash depends on both site and tree species characteristics (Thiffault *et al.* 2011; Egnell 2016). Norway spruce is suggested to be more sensitive to slash removal than Scots pine. The reduced volume production due to slash removal in Norway spruce stands is more pronounced on less fertile sites (Egnell 2017). This is likely due to Norway spruce's soil fertility requirements for optimal growth. This study only included four fertile sites in southern Sweden, so such a comparison was not possible.

Slash removal could, however, positively affect the regeneration phase by facilitating regeneration treatments such as site preparation (Saarinen 2006). This in turn could increase seedling survival and growth. There could, therefore, be a need to balance the loss in total volume when slash is removed against regeneration success.

It should be mentioned that the differences between the two slash treatments could be different in practical forestry due to the possibility of creating suitable planting spots. When the stands in Paper IV were regenerated, great care was taken in both site preparation and planting, ensuring near-optimal planting spots regardless of slash treatment. The site preparation in the experiment was done with an excavator which can help create more suitable planting spots when slash is retained. In practical forestry, where a continuous site preparation method is more common, retaining slash could hinder creating suitable planting spots (Saksa *et al.* 2018), potentially reducing seedling survival, in turn affecting long-term volume production.

There is, however, still a need to explore the longest-term effects of slash removal. These studies examine at most 30 years of growth. So far, to my knowledge, there is no full rotation study nor any study of the effects of repeated slash removal on soil fertility and forest growth.

5. Conclusions

This thesis shows the potential of active regeneration treatments to shape future forests. High planted seedling survival was found to be a key factor for long-term volume production. During stand establishment, problems such as pine weevil damage, competition from vegetation, or damage caused by browsing or fungal infections are likely to occur. Regeneration treatments aim to improve growing conditions for seedlings, thereby reducing competition and damage. These early regeneration treatments were found to increase early survival of seedlings but also had long-term effects on volume growth. Survival of planted seedlings ensured that the established stands had a high proportion of improved seedlings and the most suitable tree species for the site. This resulted in high long-term volume growth.

However, high regeneration phase survival comes at a cost. Early investment in regeneration treatments was less profitable than relying on natural regeneration. These treatment's increased growth could, however, be important when considering carbon sequestration or providing raw material for wood-based products. But intensified forest management can have negative effects on other ecosystem services and biodiversity. There is therefore a need to balance different objectives when maintaining and creating a diversity of forests.

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Popular science summary

Seedling survival is key for long-term volume production

Most forests in Sweden are actively regenerated using treatments like site preparation and planting. This ensures good growing conditions for the planted seedlings and protects them from lurking dangers like competition, drought, frost, fungi and insects, hopefully increasing seedling survival. But do the efforts pay off?

Actively preparing sites and protecting against pine weevils substantially increased survival of planted Norway spruce seedlings. These regeneration treatments show great potential in fulfilling their short-term purpose, but what about longer-term objectives?

If high wood production is the goal, active regeneration seems to be the way to go. Actively regenerated forests with high survival of planted seedlings had notably more long-term wood production compared to forests without any active regeneration measures or where survival was low. In short, forests allowed to develop as intended met their long-term goal of high wood production.

The main explanation of abundant wood production was the trees that formed the stands. It was best when sites were planted with tree species and genetically improved seedlings suited to the local growing conditions. Furthermore, active regeneration improved seedling survival. This increased the number of well-suited, genetically improved trees that were still growing 30 years or more after establishment. This was a key factor for long-term wood production.

But is the effort worth it? From a strict economic perspective, the regeneration phase investments were less profitable than leaving the forest to regenerate naturally. But active regeneration has other benefits. Their higher growth supplies more raw material for future industrial use and can help reduce climate change. But intensive forestry can reduce biodiversity and recreational possibilities. We must ensure that diverse forests are created and maintained to meet future needs. This thesis has shown that active regeneration is a powerful tool to shape future forests, and with great powers comes great responsibility.

Populärvetenskaplig sammanfattning

Plantöverlevnad är nyckeln till långsiktig volymproduktion

I Sverige föryngras skog vanligtvis genom aktiva föryngringsåtgärder för att försäkra sig om att ge så goda förutsättningar som möjligt till den planterade plantan och på så sätt skydda den från skador orsakade av torka, frost och snytbaggar. Men ger dessa aktiva åtgärder lön för mödan?

Att vara aktiv i föryngringsfasen och använda sig av föryngringsåtgärder så som markberedning och snytbaggeskydd visade sig öka överlevnaden av planterade granplantor väsentligt. Föryngringsåtgärderna verkar därmed ha stora möjligheter att uppnå den kortsiktiga anledningen till att använda dem. Men hur ser det ut för långsiktiga mål?

Om målet är volymproduktion, verkar aktiva föryngringsåtgärder vara nyckeln till framgång. När skogar var aktivt föryngrande och överlevnaden av planterade plantor var hög blev den långsiktiga volymproduktionen markant högre än om skogarna var naturligt föryngrade eller hade låg överlevnad av planterade plantor.

Huvudförklaringen till detta berodde på vilka träd som utgjorde de framtida bestånden. När man aktivt föryngrar en skog finns det möjligheter att optimera trädslagsvalet utifrån förutsättningarna som finns på plats, och välja det trädslag som lämpar sig bäst utifrån givna förutsättningar. Det finns även möjlighet att använda sig av förädlat plantmaterial. Dessutom ökar plantöverlevnaden när man använder aktiva föryngringsåtgärder. Sammanlagt ledde detta till att aktiva föryngringsåtgärder resulterade i en hög överlevnad av förädlade plantor och det mest optimala trädslaget för platsen. Detta var alltså nyckeln till en hög långsiktig volymproduktion, att ha en stor andel av förädlade plantor av det bäst lämpade trädslaget, kvar i ett bestånd 30 år eller mer efter etablering.

Men är det värt det? Rent ekonomiskt så var investeringen som gjordes i föryngringsfasen inte lika lönsam som att låta naturlig föryngring skapa den nya skogen. Men det finns andra fördelar med aktiva föryngringsåtgärder. Den högre tillväxten som dessa åtgärder leder till kan bli viktig som råvara för framtida användning och kan hjälpa till att minska klimatförändringar. Men mer intensivt brukade skogar och monokulturer kan ha negativa effekter på biodiversitet, rekreation och ekologiska värden. Det finns därför ett behov av att skapa och bevara en mångfald av skogstyper för att möta framtida behov. Den här avhandlingen visar att aktiva föryngringsåtgärder har stora möjligheter att forma framtidens skogar, men med detta följer även ett stort ansvar.

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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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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, clearfelling, 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).

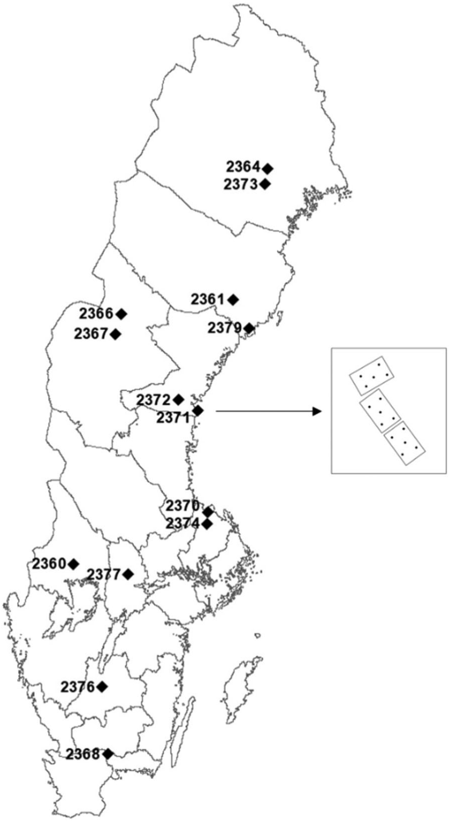

Figure 1. The geographical distribution of the sites included in the study. The diagram beside site 2371 shows the layout of the trial within sites, with three treatment areas and five sample plots within each treatment area.

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 clearcut 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

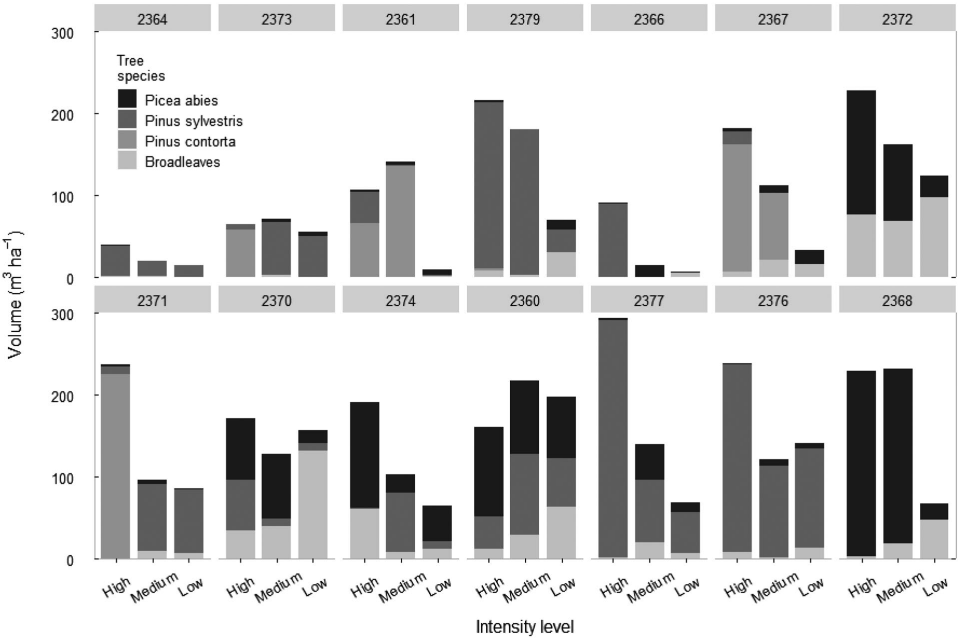

Figure 2. Standing volume (m^3 ha^{-1}) of different tree species in 2019 at the different sites (sorted from north to south) for the respective intensity levels (high, medium and low).

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

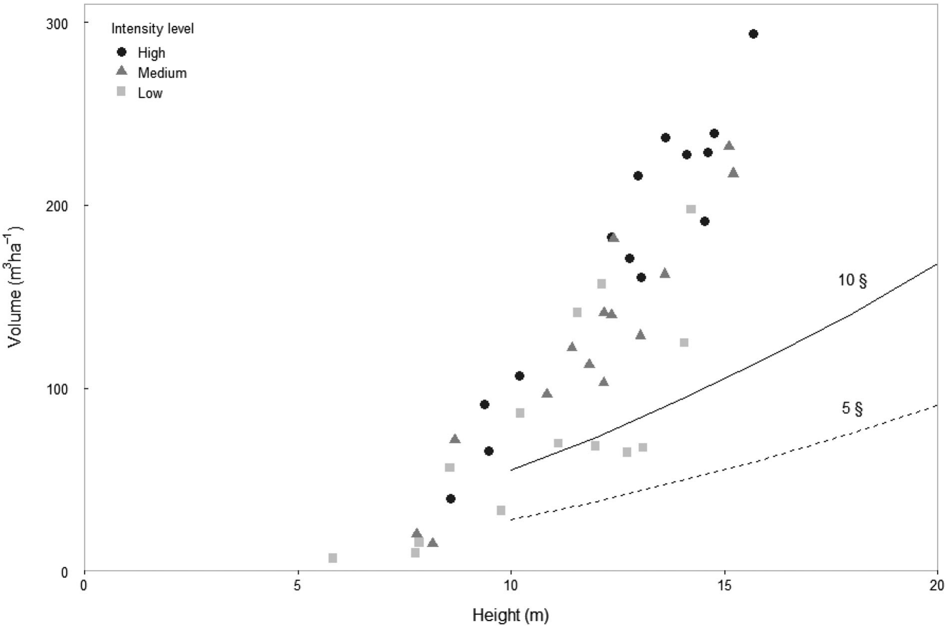

Figure 3. Standing volume (m^3 ha^{-1}) in 2019 for each treatment area, plotted in relation to the minimum requirements for standing volume at certain heights (5 §, dashed line) and in relation to the minimum allowable standing volume after thinning at a given height (10 §, solid line).

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

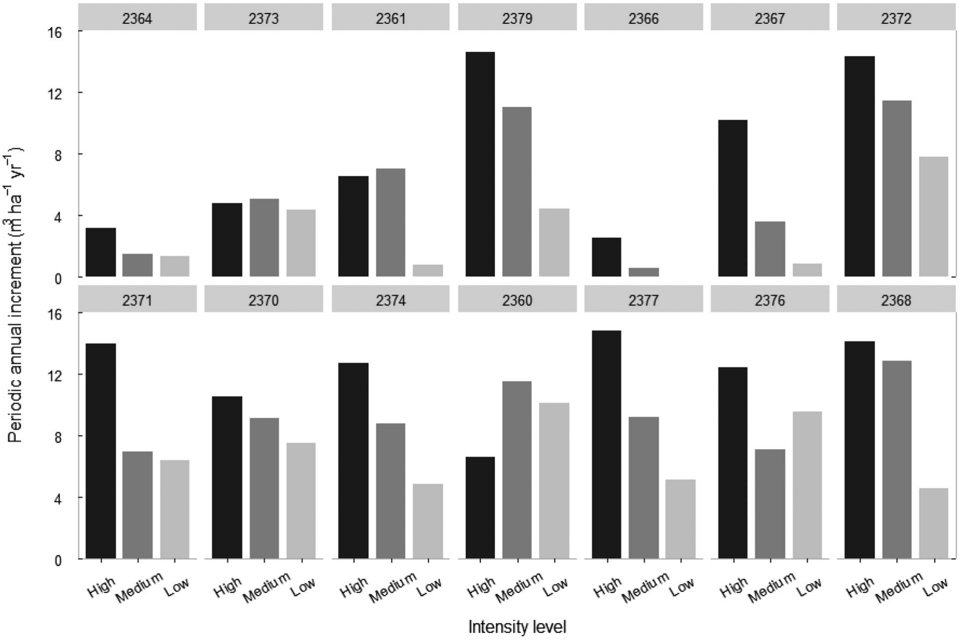

Figure 4. Periodic annual increment (PAI) (m^3 ha^{-1} yr^{-1}) between 2011-2019, for the three intensity levels at all sites (ordered from north to south) included in the study.

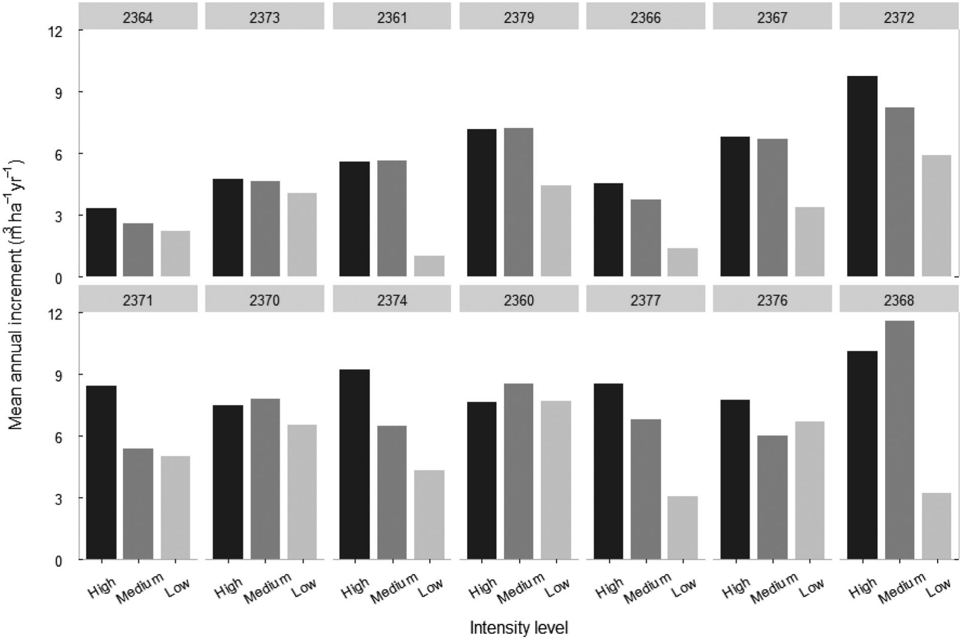

Figure 5. Estimated mean annual increment (MAI) (m^3 ha^{-1} yr^{-1}) for all sites (sorted from north to south) and intensity levels at 2.5% interest.

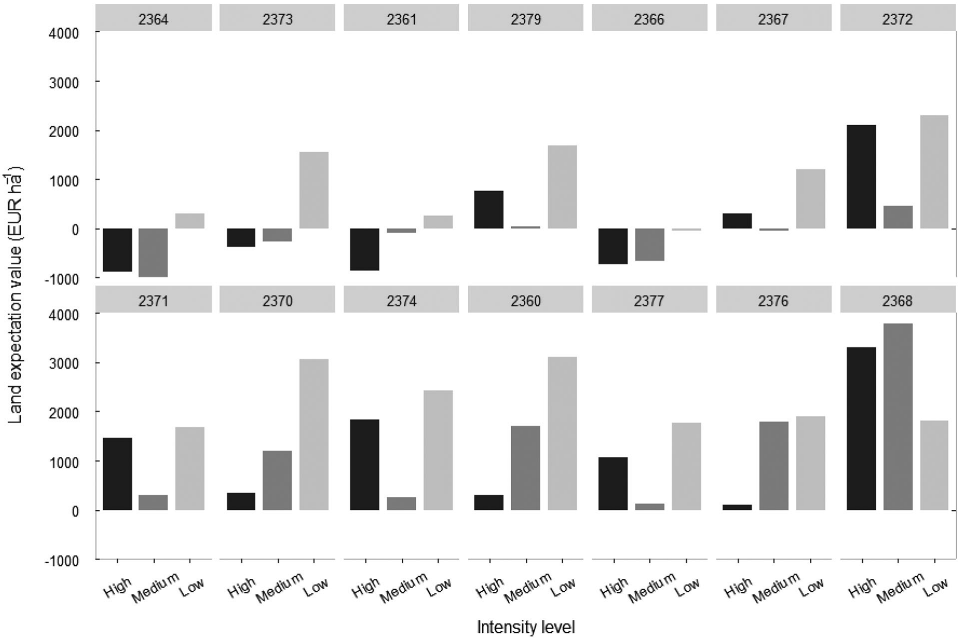

Figure 6. Estimated land expectation value (LEV; EUR ha^{-1}) for all sites (ordered from north to south) and intensity levels with a 2.5% interest rate.

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;

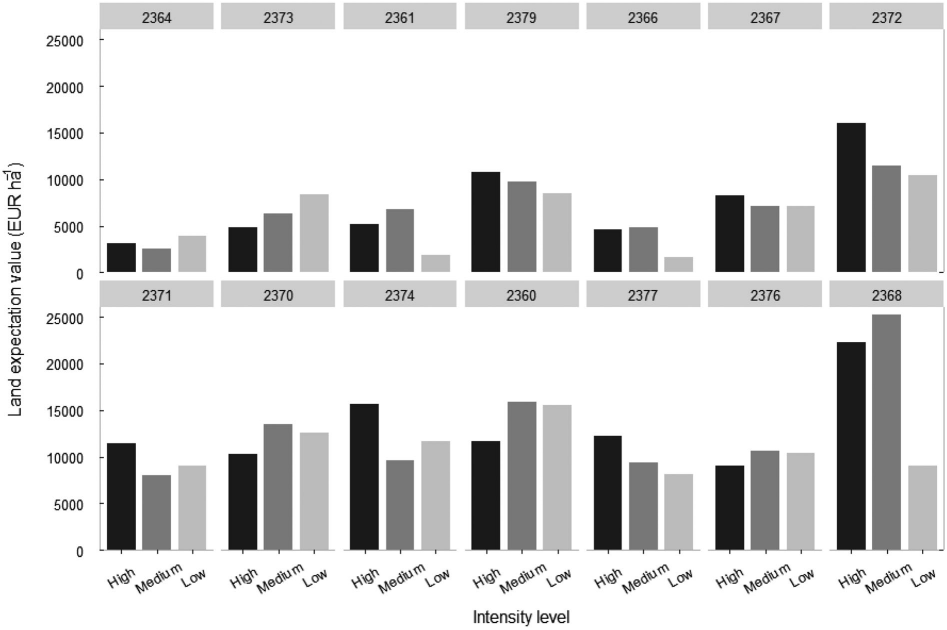

Figure 7. Estimated land expectation value (LEV; EUR ha^{-1}) for all sites (ordered north to south) and intensity levels at 1% interest.

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.

	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
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

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This thesis shows the power of active regeneration treatments to shape future forests. Although the investment active regeneration required was not as profitable as relying on natural regeneration, it led to higher long-term growth, which could improve future biomass production and carbon sequestration. But with great power comes great responsibility. More intensively managed forests can negatively affect other ecosystem services. There is therefore a need to maintain and create a diversity of forests to meet future needs.

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