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Per Nordin

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Site preparation, planting, and digital tools

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Regeneration measures in time and space: Site preparation, planting, and digital tools
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Abstract

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Regeneration success depends on decisions made based on factors on a regional, site, and microenvironmental level. Therefore, understanding and mapping of such factors between and within sites can guide decisions for better seedling establishment. Thus, the aim of this thesis was to find combinations of regeneration measures that result in low seedling mortality and high growth. Additionally, to explore the potential of digital tools in regeneration planning. Aims were handled using field experiments and a survey, by integrating digital tools in the analysis and experimental set-up.

Increased precipitation and decreased air temperatures between April and October during the planting year lowered seedling mortality. Planting in mineral soil also lowered the mortality rate, which emphasized the importance of planting and site preparation quality (Paper I). Selection of site preparation method was found to be of minor importance. The site preparation's ability to create suitable planting spots was most important for seedling survival and growth. Selection of site preparation affected soil disturbance, and natural regeneration was promoted with all methods used in the experiments (Paper II). Adapting planting position choice, following site preparation, to within-site variation was valuable to decrease mortality rates and promote growth (Paper II-III). In wet conditions, elevated planting positions were advantageous compared to lower ones, but more flexibility could be applied in drier conditions. Norway spruce, Scots pine, and silver birch reacted differently to planting position choice (Paper III). Paper I-III indicated that digital tools could be used in regeneration planning. A depth-to-water-raster successfully explained seedling mortality and growth in the extreme ends of the soil moisture spectrum. Using remote sensing derived variables can be valuable for further mapping and understanding of between and within-site variation in future regeneration planning. There were no long-term negative effects on stand productivity after 30 years following site preparation. The standing volume was largest after ploughing but disc trenching and mounding also had higher standing volume than the unscarified control (Paper IV). I conclude that regeneration

decisions made today, regarding species selection and regeneration method, should strive for increased precision for the benefit of the forests of tomorrow.

Keywords: *Betula pendula*, microsite, *Picea abies*, *Pinus contorta, Pinus sylvestris,* planting, regeneration, site preparation, remote sensing

Sammanfattning

För att lyckas med föryngringsåtgärder krävs beslut baserade på faktorer på regional, bestånds och mikromiljönivå. Därför kan förståelse och kartläggning av dessa faktorer mellan och inom bestånd vägleda beslut för att säkerställa god plantetablering. Syftet med denna avhandling var således att hitta kombinationer av föryngringsmetoder som resulterar i låg plantmortalitet och hög tillväxt. Därutöver, utforska potentialen för användning av digitala verktyg i föryngringsplanering. Syftena behandlades genom en användning av fältexperiment och en fältundersökning, genom att integrera digitala verktyg i analyser och försöksutlägg.

En ökning i nederbörd och lägre lufttemperatur mellan april och oktober under planteringsåret sänkte plantmortaliteten. Plantering i mineraljord ledde också till lägre mortalitet, vilket visar på betydelsen av planteringens och markberedningens kvalitet. Valet av markberedningsmetod hade mindre betydelse. Det viktigaste för överlevnad och tillväxt var markberedningens förmåga att skapa bra planteringspunkter. Markstörningen påverkades av valet av markberedningsmetod och naturlig föryngring gynnades av alla använda metoder i försöken. Att anpassa valet av planteringsposition, efter utförd markberedning, till ståndortsförhållanden var värdefullt för att minska mortaliteten och gynna tillväxten. Upphöjda positioner var fördelaktiga när förhållandena var blöta men valet kunde vara mer fritt när det blev torrare. Gran, tall, och björk reagerade olika på valet av planteringsposition. Artikel I-III indikerade att digitala verktyg skulle kunna användas i föryngringsplanering. Ett depth-to-water-raster förklarade plantmortaliteten och tillväxten i de extrema delarna av markfuktighetsskalan. Användningen av fjärranalysvariabler kan bli värdefullt för fortsatt kartläggning och förståelse av ståndortsvariation mellan och inom bestånd i framtida föryngringsplanering. Markberedning ledde inte till några negativa effekter på produktionsförmågan. Volymen var störst efter hyggesplöjning men harvning och högläggning visade också högre stående volym än den omarkberedda kontrollen. Min slutsats är att föryngringsbeslut idag, angående trädslagsval och föryngringsmetoder, bör sträva mot ökad precision för att gynna morgondagens skogar.

Nyckelord: *Betula pendula,* mikromiljö, *Picea abies, Pinus contorta, Pinus sylvestris,* föryngring, plantering, markberedning, fjärranalys

Preface

This doctoral thesis is a summary of the entirety of my PhD studies at Skogforsk and the Department of Forestry and Wood Technology at the Faculty of Technology, Linnaeus university (LNU). This thesis was the sixth and last to be produced within the research project Future Silviculture in southern Sweden (FRAS), a collaboration between Skogforsk, Swedish University of Agriculture (SLU), and LNU. The supervisor group consisted of Karin Hjelm (SLU), Erika Olofsson (LNU), Gisela Björse (Sveaskog), and Matts Karlsson (Södra).

This thesis is written based on four manuscripts that, in their own way, try to capture the complexity of forest regeneration. Whether it be climatic, site, and microenvironmental factors affecting seedling establishment, or site preparation choice and their effect on the future stand, they all contribute to the broadened understanding of forest regeneration. This thesis also stumbles into the digital age and incorporate digital tools, previously unused or underutilized, in forest regeneration planning. I try to, with this thesis, give examples of how digital tools can aid decision making but balancing my findings with both optimism and pessimism.

Per
2023

Dedication

To all of you who think outside of the box.

To all of you who ask questions.

To all the visionaries and pioneers.

"When Spring unfolds the beechen leaf, and sap is in the bough;
When light is on the wild-wood stream, and wind is on the brow;
When stride is long, and breath is deep, and keen the mountain-air,
Come back to me! Come back to me, and say my land is fair!

When Summer lies upon the world, and in a noon of gold
Beneath the roof of sleeping leaves the dreams of trees unfold;
When woodland halls are green and cool, and wind is in the West,
Come back to me! Come back to me, and say my land is best!"

J.R.R Tolkien, The Ent and the Entwife, *The Two Towers*.

"It is often said that a person's first thought is the most honest but that often isn't true. It's often the most stupid. Why else would we have afterthoughts"

Fredrik Backman, *Us against You*

"The best stories are never completely realistic and never entirely made-up"

Fredrik Backman, *Britt-Marie was here*.

Contents

List of appended papers

Paper I
Nordin, P., Olofsson, E., Wallertz, K., & Hjelm, K. Modelling seedling mortality: An exploratory study using field and digital data.
Manuscript

Paper II
Nordin P., Olofsson E., & Hjelm, K. 2022. Successful spruce regenerations – impact of site preparation and the use of variables from digital elevation models in decision-making. *Scandinavian Journal of Forest Research,* 37, 33-44.

Paper III
Nordin P., Olofsson E., & Hjelm, K. Within-site adaptation: Growth and mortality of Norway spruce, Scots pine and silver birch seedlings in different planting positions across a soil moisture gradient.
Submitted

Paper IV
Hjelm, K., Nilsson, U., Johansson, U., & Nordin, P. 2019. Effects of mechanical site preparation and slash removal on long-term productivity of conifer plantations in Sweden. *Canadian Journal of Forest Research*, 49, 1311-1319.

Author contributions

Paper I
Per Nordin: Conceptualization, Methodology, Formal analysis, Visualization, Writing -original draft, Writing -review & editing**. Erika Olofsson:** Supervision, Writing- Review and editing**. Kristina Wallertz:** Writing -review & editing, Data acquisition. **Karin Hjelm:** Conceptualization, Methodology, Writing -review and editing, Supervision, Data acquisition.

Paper II
Per Nordin: Conceptualization, Methodology, Formal analysis, Visualization, Writing -original draft, Writing -review & editing**. Erika Olofsson:** Supervision, Writing -review & editing, Conceptualization**. Karin Hjelm:** Conceptualization, Methodology, Writing -review & editing, Supervision.

Paper III
Per Nordin: Conceptualization, Methodology, Formal analysis, Visualization, Writing -original draft, Writing -review & editing**. Erika Olofsson:** Writing -review & editing, Supervision, Conceptualization**. Karin Hjelm:** Conceptualization, Methodology, Writing -review & editing, Supervision.

Paper IV
Karin Hjelm: Methodology, Formal analysis, Visualization, Writing -original draft, Writing -review & editing, Supervision. **Urban Nilsson:** Conceptualization, Methodology, Writing -review & editing. **Ulf Johansson:** Conceptualization, Methodology, Writing -review & editing. **Per Nordin:** Methodology, Writing -review & editing.

Notations

SFA	Swedish Forest Agency
MSP	Mechanical site preparation
ALS	Air-borne laser scanning
DEM	Digital elevation model
DTW	Depth-to-Water
eDTW	Depth-to-Water after log-transformation
DT	Disc trenching
LDT	Low intensity disc trenching
PW	Patch-wise treatment
DBH	Diameter at breast-height
NDVI	Normalized difference vegetation index
LST	Land surface temperature
UnSc	Unscarified
TH	Top height
BA	Basal area
C	Carbon
CO_2	Carbon dioxide

1 Introduction

Already in the earliest Swedish silvicultural handbook, *Om Skogars Skötsel* (Rosensten, 1737), the importance of regeneration through planting for future forests was emphasized. This has since been further cemented through legislation when the 1903 forestry act obliged forest owners to regenerate harvested forest areas within a reasonable time-period (Enander, 2007). Over the 20th century approaches to forest regeneration changed in light of trends in silviculture. In the early 1900s regeneration efforts were dominated by natural regeneration with retention of seed trees. The vast majority of planted areas occurred in afforestation efforts on heaths and other open areas in southern Sweden, and sporadically in regeneration areas in northern Sweden (Blennow & Hammarlund 1993; Kardell 2004). It was not until after World War II, and the large-scale shift towards clear-cut forestry, that planting gained more ground in Swedish silvicultural practice. At a similar time, further research explored how to rationalize forest planting (Enander, 2007), and verified practices which had been put forward earlier by Wahlgren (1922). The planted area thus began to increase over the coming decades, eventually reaching the levels observable today (SFA, 2022).

To improve success rates of planting, various site preparation methods were developed and evaluated between the 1950s and the 1990s. Mechanical site preparation (MSP) was also introduced and developed, to further rationalize forest planting (Enander, 2007; SFA, 2020). Most of the methods developed in this period are still applied in various forms and to different extents, but ploughing has since been banned because of its negative impact on forest ecosystems. However, planting has been maintained as manual labor, and still is to this day, although efforts are being made to mechanize it (Enander, 2007; Ersson, 2014; Ersson, 2022).

The large-scale introduction of the clear-cut system created new problems, such as increased competition from broadleaves and an abundance of large pine weevils (*Hylobius abietis L.*) feeding on the seedlings. The former was from the 1950s-1980s controlled using large-scale spraying of herbicides, which created massive protests and a subsequent attitude change towards the use of chemicals in Swedish forestry, causing an eventual prohibition of highly toxic herbicides like Hormoslyr (Östlund et al. 2022). The latter was dealt with using insecticides. Changing views about the use of chemicals in Swedish forestry, and the requirements of new certification schemes that emerged in the 1990s (Forest Stewardship Council, FSC, and The Programme for the Endorsement of Forest Certification, PEFC), meant that new ways to protect seedlings had to be developed. As early as the late 1980s pine weevil protection barriers made of nylon stockings were tested (Eidmann and von Sydow, 1989). These paved the way for the mechanical protection barriers that are widely used in Sweden today using e.g., glue and sand (Conniflex, Svenska skogsplantor) or wax (Ecowax, Norsk-Wax AS).

Currently, Swedish regeneration measures are heavily dominated by MSP followed by planting with improved nursery grown seedlings of either Norway spruce (*Picea abies* Karst.) or Scots pine (*Pinus sylvestris* L.). The dominance of planting is especially evident in southern Sweden where more than 90 % of the clear-felled area is planted, of which ~90 % is prepared with MSP (SFA, 2022). Due to browsing pressure and the relative profitability of Norway spruce, planting of Norway spruce has increased at the expense of Scots pine (Lodin et al., 2017). This has led to occurrence of poorly site adapted Norway spruce stands, grown at sites suitable for Scots pine or broadleaves (Felton et al., 2020). Although the success of regeneration has improved (Bergquist et al., 2017) poor site adaptation can lead to excessive mortality of planted seedlings, and a lost investment affecting future revenue. Questions arise as to whether future forests will consist of planted seedlings or naturally regenerated trees filling the gaps (Holmström et al., 2019; Gålnander et al., 2020). Either way, there is a need for better adaptation to local site conditions to ensure that future regeneration efforts are successful and achieve the forest owner's goals.

1.2 Background

Succeeding with any regeneration effort depends on several abiotic and biotic factors, at different spatial scales (Figure 1). Regionally, climate factors such as temperature and precipitation affect the species that can grow within the given ecological limitations. On a site level, the general topography, site productivity, soil conditions and other factors can challenge seedling establishment. Seedlings are also affected on a microlevel, how the nearby environment varies in e.g., soil moisture conditions, elevation, and mineral soil exposure. The interplay of all these factors has implications for the future forest stand.

1.2.1 Landscape level

In Sweden, there is a strong north-south gradient to climatic variability, with warmer temperatures and longer vegetation periods in the southern parts of the country. Within southern Sweden (Götaland) there are several biogeographic zones. The hemiboreal zone is dominant in the interior. Along the coastline and in the southernmost part the temperate vegetation zone dominates with a milder climate compared to the interior parts. In the southern Swedish highlands, the climate gets harsher and can be recognized as a southern boreal zone (Ahti et al., 1968). There is also a considerable difference in precipitation between the eastern and western parts of Götaland, with the east being characterized by less precipitation and drier conditions, and the west as a maritime humid climate with plenty of rain (SMHI, 2022). These diverse climatic conditions, in southern Sweden, allow for growth of both broadleaf species, associated with temperate forest, such as pedunculate oak (*Quercus robur* L.*)* and beech (*Fagus sylvatica* L.*)* and boreal coniferous species such as Scots pine and Norway spruce. In that sense, southern Sweden is different from the north, as a larger palette of different native tree species can thrive. However, the milder climate of the south also brings different challenges to those in the north, with faster response of competing vegetation to disturbance or higher abundance of pine weevil. Also, more ungulate species, with populations of moose (*Alces alces L.*), roe deer (*Capreolus capreoulus L.*), fallow deer (*Dama dama L.*) and red deer (*Cervus elaphus L.*), occur in southern Sweden resulting in a relatively high browsing pressure (Pfeffer et al., 2021).

Depending on regional differences in climate and site properties, precautions need to be taken when carrying out silvicultural activities (Subramanian et al., 2016). Adaptations can be made based on prevailing conditions and perceived current and future risks of damage e.g., from wind or drought (Blennow, 2012; Keskitalo et al., 2016). Mapping and understanding the region both in terms of site properties and weather patterns, such as precipitation and temperature, is vital for succeeding with establishment of a new stand (Lundmark, 1988). The weather cannot be controlled, but adaptations can be made based on historical data and predictions about the future climate (Spittlehouse and Childs, 1990). The challenge is to make decisions based on perceptions of how the climate will change (Keskitalo et al., 2016; Andersson and Keskitalo, 2018), and establish the level of risk that is acceptable (Uggla and Lidskog, 2016; Lodin et al., 2017). The future climate of southern Sweden is predicted to become warmer and wetter but with more frequent periods of drought in the summer months, and more frequent extreme weather events (Chen et al., 2015; Wilcke et al., 2020). Adaptations towards such a changing climate should therefore be considered in any establishment of new forest, both in terms of regeneration method and tree species selection (Kellomaki et al., 2008; Bolte et al., 2009; Schou et al., 2015).

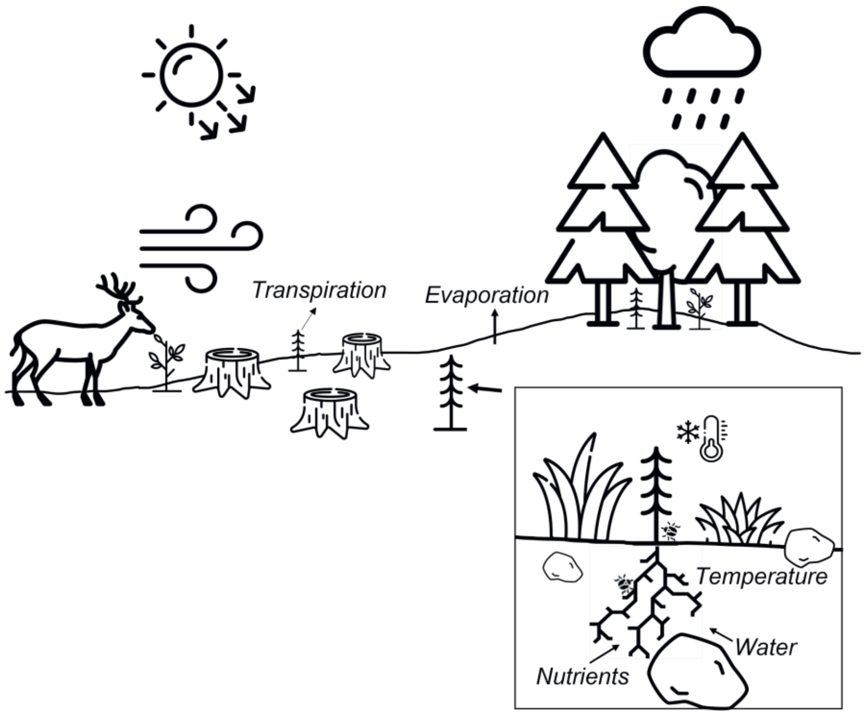

Figure 1. Examples of factors that affect the forest landscape and should be considered in regeneration decisions. From abiotic factors like sun radiation, precipitation, wind, and frost, to biotic risks such as browsing, insect feeding, and vegetation competition. Also, below-ground processes such as available nutrients, soil temperature and soil water. Created by Per Nordin using images from Flaticon.com

1.2.2 Site level

Following harvesting, seedlings planted on a reforestation area need to overcome immense stress before they have become established and coupled with the forest ecosystem (Margolis and Brand, 1990; Grossnickle, 2016). It is therefore important to create a suitable environment for seedlings, which can be achieved through different types of MSP. These can be categorized into continuous or intermittent methods (Löf et al., 2012; Sikström et al., 2020). Disc trenching is an example of continuous MSP that is widely used in Sweden. This method creates long continuous rows of furrows and berms, exposing large amount of mineral soil, creating many potential planting spots (Örlander et al., 1990; Sikström et al., 2020). It is widely used because it works well on most sites, except for moist and wet ones (Sikström et al., 2020). Intermittent MSP methods are characterized by the creation of planting spots which are scattered across the regeneration area. This can be done through e.g., patch scarification, mounding, or inversion. Patch scarification removes the upper organic layer, exposing a patch of mineral soil (Örlander et al., 1990). Mounding creates elevated planting spots covered with mineral soil and is especially suitable on mesic and moist sites where excessive water may limit seedling growth (Sutton, 1993). Inversion creates planting spots with an inverted soil profile at ground level (Örlander et al., 1998). As these methods create different planting environments, they should be selected on the basis of particular site conditions, species to be planted, seedling type, and the forest owner's goals.

The overarching goal of MSP is to ensure seedling survival and promote early growth. To achieve this, MSP removes and initially suppresses competing vegetation, giving the seedlings a head-start (Nilsson and Örlander, 1999; Thiffault and Jobidon, 2006; Wiensczyk et al., 2011) by increasing the availability of water and nutrients (Nilsson et al., 1996; Thiffault et al., 2003). Additionally, when removing vegetation and loosening the soil, soil temperature increases. Cold and dense soils can inhibit root growth (Örlander et al., 1998; Grossnickle, 2005). Not only does MSP alter site conditions, to favor seedling establishment, but it also reduces damage due to pine weevil feeding. The exposure of mineral soil around seedlings has been shown to be an efficient way of reducing the likelihood of pine weevil feeding on the seedling (von Sydow, 1997; Petersson et al., 2005; Nordlander et al., 2011).

MSP can also promote natural regeneration by mixing the soil and exposing favorable environments for germination (Karlsson et al., 2002; Floistad et al., 2018). Hence, MSP can be an efficient way to increase variation in forest stands planted with conifers by potentially creating mixed forests (Nilsson et al., 2006). Mixed forests spread risks and can increase the forest's resilience and biodiversity (Felton et al., 2016; Coll et al., 2018). From a biodiversity perspective, an admixture of broadleaves within conifer stands can have a positive impact on species richness and diversify the understory vegetation (Felton et al., 2010). From a resilience perspective, mixed stands of spruce and birch have shown to be more storm resilient than spruce monocultures (Hahn et al., 2021), and the mixing of species can also have a positive effect in terms of increasing resilience towards pests and pathogens (Felton et al., 2016; Coll et al., 2018). Mixed stands of conifers and broadleaves can be kept and managed without necessarily suffering economically compared to monocultures (Dahlgren Lidman et al., 2021; Ara et al., 2022b). This admixture could also be a good way of maintaining a good amount of forage for ungulates, reducing browsing pressure on crop trees (Ara et al., 2022c). However, the MSP method must be chosen according to the desired amount of natural regeneration that should compose the future forest, and the levels of effort and cost that will be reasonable for future management (Ahtikoski et al., 2010; Uotila et al., 2010).

Silvicultural measures are not consequence-free, and MSP is no exception as it disturbs the forest floor. The extent of this disturbance depends on the method used (Strömgren et al., 2017; Cardoso et al., 2020; Sikström et al., 2020). Of the methods mentioned above, disc trenching disturbs the largest area. More intense methods, such as ploughing, would lead to even greater amount of disturbance, both in terms of coverage and depth of disturbance (Cardoso et al., 2020; Sikström et al., 2020). In comparison, intermittent methods minimize the disturbed area, creating spot-wise disruption, but can still disturb at great depth. MSP can also cause damage to cultural remains. In fact, MSP is one of the major causes of damage to cultural remains in the forest landscape in Sweden (SFA, 2022). Being more aware of the whereabouts of such remains and trying to minimize the impact of MSP could therefore be necessary if the forestry sector wants to reduce the amount of damage inflicted. Further, the visual effect of MSP is known to be disliked by the general public. This affects the recreational value of the forest, which can be a significant issue close to urban settings (Gundersen and Frivold, 2008). Moreover, induced disturbance can influence the vegetation composition of the forest site, both in the short term but also affect the recovery of the forest vegetation over time (Haeussler et al., 2017).

1.2.3 Micro-level

How seedlings will endure and prosper in their new environment after planting largely depends on microsite conditions and the ability these provide for further growth above and below ground (Margolis and Brand, 1990). Much of the initial stress on seedlings relates to a lack of nutrients and water in the very proximity of the seedling, since the root system has not grown to a size where it can acquire the necessary resources (Grossnickle, 2005; Grossnickle, 2012). Soil temperature also plays an important role, because it promotes root growth if water conditions are favorable. The soil texture's ability to retain soil moisture, even in periods without precipitation, also affects the potential for water uptake by seedlings, although it can also hinder growth when water is superfluous (Margolis and Brand, 1990). Altering light conditions through shelterwood, retention trees, or edge effects from nearby forest stands can affect the microenvironment by stabilizing the air temperature and reducing the risk of frost damage (Langvall and Örlander, 2001; Langvall and Löfvenius, 2002). All these factors interact and influence each other, and they can vary considerably within the same site. Hence, silvicultural methods that promote seedling establishment should alter microsite conditions to favor the desired tree species and address any limiting factors.

Various types of microsite conditions that can offer favorable planting spots are created following MSP. The characteristics of the microsite, in terms of both elevation and mixing of organic material, strongly influences attributes such as soil moisture conditions, soil temperature, potential nutrient availability, and resilience in the face of biotic and abiotic risks. Elevated planting spots, like mounds or berms, alter hydrological conditions by lowering soil moisture, which can be needed on wet and moist sites (Sutton, 1993). However, due to their porous structure, these planting spots run the risk of drying out in instances of low precipitation, meaning that seedlings may experience increased water stress (Örlander et al., 1990; Luoranen et al., 2018; Häggstrom et al., 2021).

This is particularly an issue when the roots cannot reach the available capillary ground water (Burdett, 1990; Grossnickle, 2005). In planting spots that are at ground level or below ground level, like patches or furrows, water may be more easily accessible, even in dry conditions (Örlander, 1986; Hansson et al., 2018). However, in such spots the soil can become saturated, leading to oxygen deficiency in the root zone. This can reduce vitality and thus hinder growth or even lead to mortality (Pearson et al., 2011; Henneb et al., 2019). Soil temperature in prepared spots is higher than the undisturbed surrounding area, due to removal of insulating vegetation and loosening of the soil (Sutton, 1993). This procedure creates a microenvironment around the seedling with an increased availability of nutrients, partly due to increased mineralization in the underlying humus in berms and mounds (Smolander and Heiskanen, 2007), which will promote root growth (Grossnickle, 2005). Microsite characteristics also influence seedlings' susceptibility to frost. When vegetation is removed, air temperature around the seedling increases in spring and summer, lowering the risk of spring and summer frost damage, but on some occasions increases risk of fall frost (Langvall et al., 2001; Marquis et al., 2021).

Today, much forest management planning is done at stand level, at which decisions about forest regeneration are made for the entire stand, with little adaptation to within-site variation. Making decisions about regeneration, where the microsite conditions are so important, can therefore be difficult. Mapping the variation and identifying different microsites within a stand is very time consuming, and it is therefore difficult to initiate different management options within the same site. However, with knowledge of such within-site variation, more efficient forest regeneration may be adopted with higher precision (Castro et al., 2021). This could lead to a higher success rate for forest regeneration and ensure that the future forest is well-adapted to the given site conditions.

1.2.4 The digital age

Advancement in remote sensing has made high-resolution maps available, which can be used to understand environmental variation on a finer scale, using for example, optical images from satellites (Holmgren and Thuresson, 1998; Boyd and Danson, 2005; Drusch et al., 2012), or point clouds from air-borne laser scanning (ALS) (Wulder et al., 2004; White et al., 2016). The two nation-wide laser scanning projects in Sweden (Lantmäteriet 2022; Lantmäteriet 2023), have led to multiple products that can be used in forestry planning. Firstly, the point cloud from ALS was used to create a high-resolution digital elevation model (DEM) showing changes in elevation and offering a detailed description of the topography of the landscape. Further processing has generated maps that display an estimation of soil moisture on a 2×2 m scale. First as a nation-wide depth-to-water (DTW)-raster, displaying the perceived depth to the ground water based on local topography, distance to nearby water sources and how the water accumulates in the landscape (Ågren et al., 2014).

Later as a machine-learning product, which combines several data sources and shows the probability of whether a pixel in the raster being classified as wet (Ågren et al., 2021). These maps have mainly been implemented in practical forestry to plan logging operations or identifying streams where increased caution is needed (Ågren et al., 2015; Mohtashami et al., 2017). However, an increased use of these data sources could be implemented in the regeneration phase, to inform about both site adaptation and site preparation machinery usage (Holmström et al., 2019; Ring et al., 2020).

Knowledge of within-site variation opens the possibility of more detailed forest management, applying management to smaller units than the traditional stand level (O'hara and Nagel, 2013). Precision forestry is one of the concepts that utilizes more detailed information to support site specific management. This sets out to optimize management to make the most out of site resources and be as efficient as possible (Bare & Dryck, 2001). Demonstrations of how this could be implemented in forest regeneration have been offered by Saksa et.al. (2021), utilizing information from harvesters to delineate a site into smaller compartments based on which tree species should be regenerated. Similar approaches have been used by Friberg et al. (2019), who also added the use of a DTW to guide species choice in different parts of the site. Identifying the variation and then applying appropriate management could reduce soil disturbance and reduce costs. For example, MSP could be directed to where it is needed, and areas not suitable for planting could be left for natural regeneration. Hence, with higher precision and careful selection of planting environments the chances of seedlings survival become greater (Castro et al., 2021).

1.2.5 Long-term effects

Forest regeneration largely involves adopting the best management approach given the perceived future goals for that forest. Selecting tree species then relies on considerations such as perceived future risks, growth potential, and tradition (Lodin et al., 2017). Fitting together early management and site conditions strongly influence the potential growth of the future forest (Lundmark, 1988). As an example, the positive initial effect of MSP on tree growth has been confirmed (Sikström et al., 2020), but whether this effect is long term remains uncertain. Further, concerns about the depletion of nutrients through intensive site preparation have been raised (Lundmark-Thelin and Johansson, 1997). However, the findings of research in long-term experiments seems to show a lasting positive effect of site preparation on tree growth, at least over the initial decades (Johansson et al., 2013a; Thiffault et al., 2017).

Although there are positive effects on growth, the economic gain from early intensive management can be debated because of the large investment (Uotila et al., 2010; Jonsson et al., 2022). Regeneration methods that rely on natural regeneration and no subsequent management are not associated with initial investments. The economic results of such a strategy differ depending on the interest rates one accounts for and the risk of failed regeneration. Nevertheless, it is important to take the entirety of the rotation period into account to get a clear picture of the pros and cons of a given management option (Ahtikoski et al., 2010; Uotila et al., 2010; Dahlgren Lidman et al., 2021), especially if considering that the establishment cost is not realized in the harvested crop trees due to damage or other circumstances. Ara et al. (2021) showed that regeneration of Scots pine in Sweden often result in a mixture of the desired crop species and natural regeneration, deeming this as a failure given that the end goal was Scots pine dominated stands. Loss of invested seedlings in the future stand has also been shown in other studies (Holmström et al, 2019; Gålnander et al. 2020), further emphasizing the issue of wasted investment in planted seedlings. Finding ways to improve the precision and quality of planting, and regeneration in general, would therefore be of great value for meeting long-term economic goals.

Forestry works with long time horizons, meaning that the management practiced today will heavily influence the forest of tomorrow and future management flexibility. One consequence of this is that questions asked in the present time cannot be properly evaluated until several decades into the future. Furthermore, the main interests within the forest research landscape shift over time. The research questions being posed in Sweden today are not the same as those being asked in the 1950s and 1960s (Enander, 2007). At that time concerns revolved around restoring the forest landscape and creating forests with high yields that could sustainably supply raw material to the industry. The long-term effects evaluated today therefore answers concerns of yesterday. With time the forestry landscape has become more complex. Ecological and social needs are weighed against economic goals, meaning that they must also be considered in the regeneration phase. Therefore, long-term experiments established today could focus more on the consequences of management options and how these can be used to create multifunctional resilient forests.

1.3 Thesis aim and objectives

The overall aim of this thesis was to find combinations of regeneration measures, such as site preparation, selection of planting spot, and tree species choice, that result in low seedling mortality and high growth. It further aimed to evaluate the possibility of using digital tools to support decision making in regeneration planning based on local site conditions (Figure 2).

In the first part (Paper I), I focus on exploring potential variables that could explain seedling mortality and be useful in future modelling of seedling mortality on a landscape and site-level scale.

In the second part (Paper II), I evaluate the effect of different site preparation methods and intensities on the establishment of seedlings, and their consequences for soil disturbance and vegetation development.

In the third part (Paper II-III), my focus was on within-site variation and how this affects the choice of planting spot. Paper II evaluates within-site variation in soil moisture and topography at a plot level, but in Paper III the analysis is taken to the seedling level, considering the effects of soil moisture in different planting positions for different tree species. Soil moisture and topography were derived from high resolution maps.

In the fourth part (Paper IV), the long-term effects of different site preparation methods on growth are evaluated, based on field experiments established in northern and southern Sweden in the 1980s.

The following objectives were pursued:

- Explore the variables, both digitally available and field inventoried, that can be of value for explaining seedling mortality (Paper I).
- Evaluate how the choice of site preparation method and intensity affect seedling establishment and soil disturbance (Paper II).
- Test how the choice of planting spot affects seedling establishment of different tree species (Paper III).
- Determine how digital tools, such as soil moisture maps, can be used in forest regeneration planning (Paper I-III).
- Assess the long-term effect of site preparation of varying intensities on stand productivity (Paper IV).

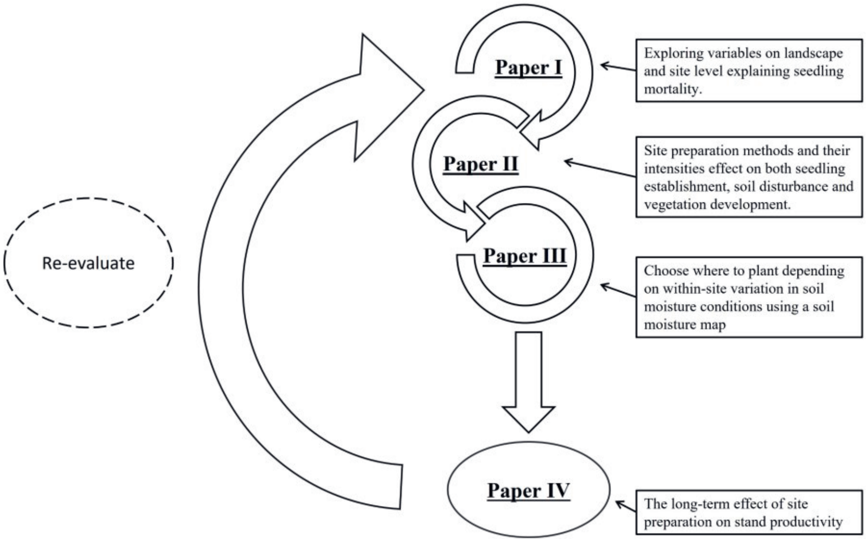

Figure 2. Illustration of the how Paper I-IV are structured and their relation to regeneration measures on both a spatial and temporal scale.

2 Material and Methods

2.1 Study areas and experimental designs

To meet the objectives of this thesis a mix of field experiments, both short term (Paper II-III) and long term (Paper IV), and surveys (Paper I) were used. Species studied in the thesis were Norway spruce (Paper I-IV), Scots pine (Paper III-IV), silver birch (*Betula pendula* Roth.) (Paper III), and lodgepole Pine (*Pinus contorta* Dougl.) (Paper IV). In this section a summary of the sites and experiments is given, for further details see each appended Paper I-IV.

2.1.1 Paper I

The 25 sites used in this study were limited to privately owned forest land in southern Sweden. They spanned an area from Scania in the south, Västergötland in the north, Halland in the west to Kalmar county in the east (Figure 3). The sites were clear-felled, site prepared, and subsequently planted in either 2018, 2019, or 2020, with containerized Norway spruce seedlings or a hybrid stock type of Norway spruce seedlings. Seedlings that were planted had one of either mechanical protective barriers against pine weevil, commonly used in Swedish forestry; Conniflex (Svenska Skogsplantor), Cambiguard (Södra), or Ekovax (Norsk-Wax AS).

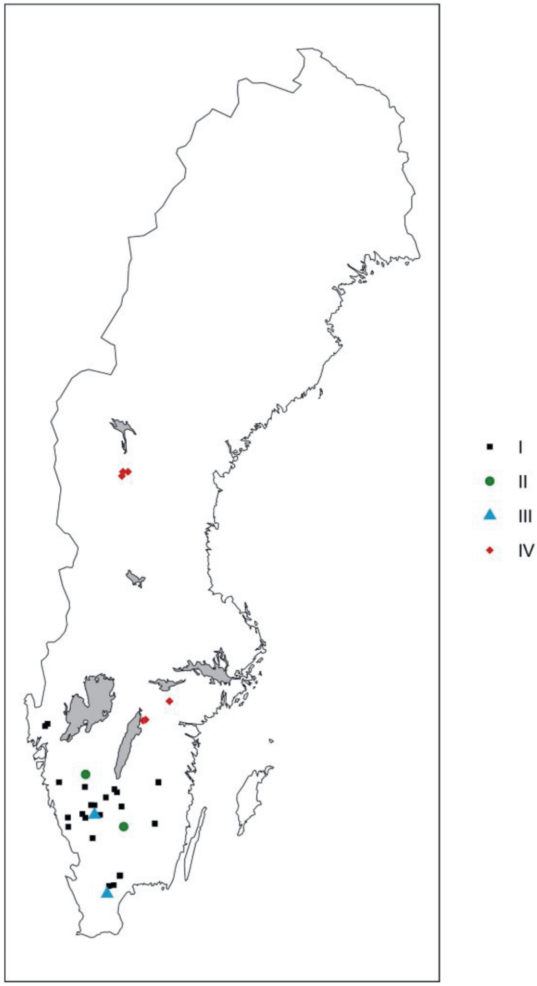

Figure 3. Map of Sweden showing the geographical location of the sites used in the papers. Black squares show the location of sites used in Paper I, green circles the location of sites in Paper II, blue triangles the location of sites in Paper III, and red diamonds the location of sites used in Paper IV.

At each site 20 circular plots (radius 2.82 m) were placed systematically in a line, at a fixed spacing based on the size of the clear-cut. The center of each plot was positioned using a GNSS, with an accuracy of at least 2 m. Within these plots all planted seedlings were marked with plastic sticks of different colors, to be able to revisit and measure them in the subsequent years.

2.1.2 Paper II

Two sites in southern Sweden, Fänneslunda (Västergötland county) and Tagel (Kronoberg county), where a site preparation and spacing experiment was established in 2017 and 2018 (Figure 3) were used. The two sites differed in precipitation, air temperature, and site characteristics such as stoniness and soil moisture. Due to stoniness, site preparation was more or less difficult to execute. Also, due to different planting years, the two sites experienced the heatwave of 2018 differently. Tagel was planted in the middle of this exceptional dry spell, while in Fänneslunda seedlings had a year to become established before the dry spell occurred. The 2018 heatwave was historically exceptional in a Swedish context, entailing a long period of high temperatures and limited precipitation (Wilcke et al., 2020).

At both sites five different treatments (Figure 4) were applied that combined two different site preparation methods, disc trenching and patch-wise inversion, with different intensities and spacings. A variety of planting spots were created by these treatments and their characteristics were registered when measuring the seedlings. The following treatments were applied on plots of 32×32 m and repeated over three blocks per site; (1) conventional disc trenching with 2 m between the double rows and a planting spacing of 2 m within rows (2 500 seedlings ha^{-1}) (DT2500), (2) low-intensity disc trenching with 6 m between the double rows and planting spacing of 2 m within rows (1 250 seedlings ha^{-1}) (LDT1250), (3) low-intensity disc trenching with 6 m between double rows and planting spacing of 1 m within rows (2 500 seedlings ha^{-1}) (LDT2500), (4) low intensity patch-wise site preparation resulting in 1 250 planting spots ha^{-1} with a spacing of approximately 3 m between patches (PW1250), (5) patch-wise site preparation resulting in 2 500 planting spots ha^{-1} with a spacing of approximately 2 m between patches (PW2500). Furthermore, 6 circular plots (radius 1.78 m) were placed on a diagonal transect with a fixed spacing within each plot to measure soil disturbance, stoniness, natural regeneration, and field vegetation cover.

When the experiment was established one aim was to investigate the long-term effects of the different combinations of site preparation and planting design, to see if highly productive forest could be established using less intensive methods. Hence, the seedling material used was genetically improved containerized cuttings of Norway spruce, to facilitate the best possible seedling material for enhanced forest productivity.

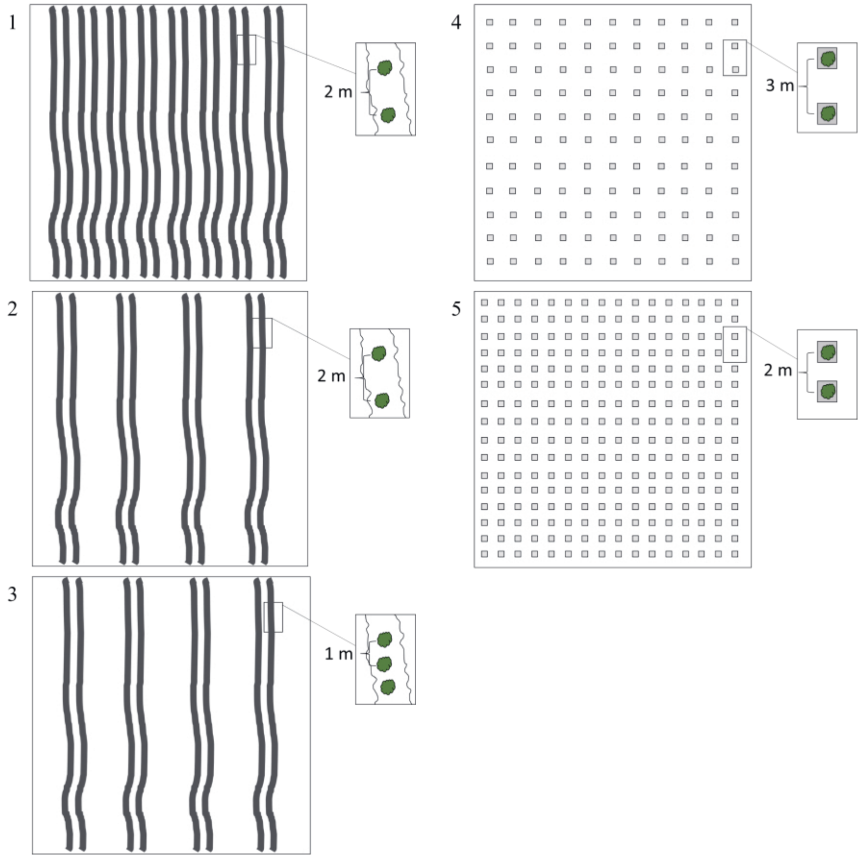

Figure 4. The design of site preparation treatments used in the experiment in Paper II. (1) DT2500, Conventional disc trenching, (2) LDT1250, Low-intensity disc trenching with sparse planting, (3) LDT2500, Low-intensity disc trenching with dense planting, (4) PW1250, Low-intensity patch-wise site preparation, (5) PW2500, Patch-wise site preparation.

2.1.3 Paper III

For Paper III, the experimental design required sites with a within-site variation in soil moisture conditions. Two sites, one in Jönköping county (Isberga) and one in Scania (Holkaberga) (Figure 3), were selected following evaluation of soil moisture conditions using a DTW-raster and onsite assessment. The two sites differed in terms of time between clear-felling and planting: on the Isberga site this was approximately five years, while on the Holkaberga site it was approximately 2 years. The sites were prepared using an excavator, which created mounds prior to planting. This created multiple planting positions within each planting spot (Figure 5).

25 blocks per site, consisting of 12 planting spots per block, were established. These blocks were distributed across the different soil moisture conditions within each site using the DTW-raster. Blocks were planted with containerized seedlings of Norway spruce, Scots pine and silver birch. Within each planting spot four seedlings of the same species were planted in the following positions; (1) Depression, (2) Hinge, (3) Mound, and (4) Unscarified (Figure 5). Seedlings were planted at a conventional depth with the peat plug buried a couple of centimeters below ground. In total 1 200 seedlings were planted per site, with 400 seedlings per tree species. Efforts to protect the seedlings against browsing were made by applying Trico (Organox), an emulsion fatty acid, to the leading shoot in the autumn of the first and second growing season. The coniferous seedlings were also provided with a mechanical protective barrier, Conniflex (Svenska Skogsplantor), for protection against pine weevil.

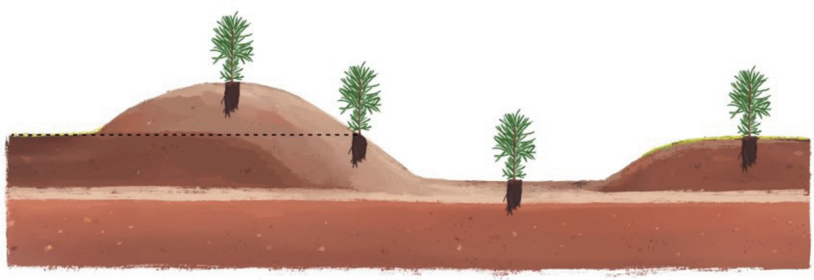

Figure 5. Illustration of the different planting positions within a planting spot in the experiment in Paper III. From the left; Mound, Hinge, Depression, and Unscarified. Illustration by Janie Jagborn.

2.1.4 Paper IV

In Paper IV an experiment established in the 1980s was used to evaluate the long-term effects of different site preparation methods and slash removal. Seven sites in southern and northern Sweden, were used in the final analysis (Figure 3). This was a subset of the original 13 sites, of which six were excluded due to limitations in experimental design and experiment management. Depending on site conditions, 2-year-old containerized seedlings of either Scots pine or Norway spruce were planted at the southern sites, and 1-year-old containerized seedlings of lodgepole pine were planted at the northern sites.

Treatments applied on the different sites were; (1) Untreated control, (2) Disc trenching (3) Mounding, and (4) Ploughing. These treatments were executed on 30×30 m plots which were replicated two or three times depending on the site. The southern sites were planted with a density of 2 500 seedlings ha^{-1} while the sites in northern Sweden varied in initial seedling density. On the northern sites higher densities were used in the control compared to the other treatment plots. In addition, supplementary planting to replace dying and dead seedlings was conducted on the northern sites on three occasions.

2.2 Field measurements and calculations

2.2.1 Paper I-III

Assessment of seedling vitality and damage types was carried out in a similar fashion for Papers I-III. Vitality assessment and damage registration was conducted in the autumn after planting, and repeated either once (Paper I) or twice (Paper II-III). A seven-level scale was used to classify the damage level of each seedling, 0 = No damage, 1 = Negligible damage, 2 = Slightly damaged (reduced growth but not smaller than the previous year), 3 = Severe damage (smaller than previous year), 4 = Lethal damage (expected to die the following year), 5 = Dead, and 6 = Missing. The major cause of damage was also registered, the dominant cause being drought, water logging, pine weevil feeding or browsing.

In Papers II-III seedling height above ground level was measured in the autumn after planting and repeated twice. Additionally, in Paper II, top shoot length was measured on the same occasions. In Paper III diameter at ground level was measured on three occasions after each growing season.

Planting spot characteristics were assessed using the same approach in Paper I-II. Characteristics were classified based on the environment in a 10 cm radius around the seedling, on a four-level scale; (0) No site preparation, (1) Disturbed humus, (2) Mineral soil mixed with humus, and (3) Bare mineral soil. In Paper II the type of planting spot was also registered based on the following classes; (0) No site preparation, (1) Furrow/hole/patch, and (2) Mound/berm/inverted planting spot.

Paper II included additional measurements of field vegetation cover and amount of natural regeneration of deciduous and coniferous seedlings in a 30 cm radius around the seedlings. Similar measurement was done in circular plots (described in 2.1.2) where the percentage of field vegetation cover was visually assessed, and the amount of natural regeneration of both deciduous and coniferous seedlings was counted. In those circular plots soil disturbance caused by site preparation was visually assessed by determining the percentage area of five disturbance classes; (0) Undisturbed ground, (1) Disturbed humus, (2) Mineral soil mixed with humus, (3) Mineral soil on top of humus, and (4) Bare mineral soil.

To measure volumetric soil moisture content in Paper III, consecutive measurements were made between May and October during two years, in one randomly chosen planting spot per block in all planting positions (described in

2.1.3). This was done with a Time-domain reflectometer (TDR, FieldScout TDR 350 Soil Moisture Meter) at a depth of 0.2 m.

2.2.2 Paper IV

27-32 years after the establishment of these experiments, the sites were inventoried by measuring the diameter at breast height (DBH) of all the planted trees. For the five largest trees and 15 sample trees, additional measurements required for volume calculations were made (height for all species, height to first living branch for Scots pine and Norway spruce, and bark thickness for Scots pine). The number of naturally regenerated trees above 1.3 m was also recorded, in DBH classes of 1 cm. Functions developed by Brandel (1990) were used to calculate stem volume for the sample trees. Furthermore, stem volume for the remaining trees was estimated in 2 cm diameter classes using the DBH^2-weighted volume of sample trees in each diameter class (Nilsson et al. 2010). For calculations of top height, the height curve developed by Näslund (1936) was used:

$$H = \frac{DBH^x}{(a + b \times DBH)^x} + 1.3 \tag{1}$$

Where H is tree height (m), DBH is diameter at breast height (cm), a and b are coefficients, and x = 2 for Scots pine and x = 3 for Norway spruce and lodgepole pine. Top height was further estimated as the mean height of the 100 trees with the greatest DBH per hectare. Dominant trees were defined as the 10 largest trees by DBH in each treatment plot.

2.3 Data sources and processing

Several data sources were used for the papers in this thesis. In this section a short description of each source is given, grouped by the paper in which they were used. Extraction of values from digital maps was foremost done using Arc GIS Pro (Esri, West Redlands, CA), with further processing in R (R Core Team, 2022). For more information about the sources see appended Papers I-IV and references for the given data source.

2.3.1 Paper I

This study utilized several digitally available data sources that described climate, topography, hydrology, and the surrounding environment such as distance to clear-cut edge and vegetation health. These spanned across digital maps, satellite imagery and open-source weather data from the Swedish Meteorological and Hydrological Institute (SMHI).

Weather data describing the precipitation sum and mean air temperature between April-October in the planting year was acquired from SMHI weather stations in the vicinity of the sites. SMHI has weather stations spread across Sweden, which measures a selected number of weather variables that are available for downloading and further processing. The time-period of April-October was chosen to ensure that the whole period from planting to the end of the growing season was captured. The planting season in southern Sweden normally starts around late March to mid-April.

From the national laser scanning, a digital elevation model (DEM) with a 2×2 m resolution was used. By calculating the elevation difference between pixels in the DEM, a slope raster was created. This was used to calculate the mean slope angle of each circular plot. The same approach was used in Paper II for extraction of mean slope angle per treatment plot (see section 2.1.2).

The database of executed harvests from the Swedish Forest Agency (SFA) was utilized to calculate the distance to clear-cut edge from the center of the circular plots in Paper I. This map layer visualizes the outline of a harvested stand. However, some stands were missing from the database, and an aerial photo was used as a template to draw the outline of those stands.

A soil moisture map developed by SLU, that displays the likelihood (0-100) of a pixel in a 2×2 m raster being classified as wet (Ågren et al., 2021), was used to determine local soil moisture conditions around the seedlings. The mean value for each circular plot was calculated. Prior to further analysis the mean values were transformed using a logit transformation to ensure a non-bound dispersion.

Soil depth values were extracted from a soil depth map created by the Geological survey of Sweden (SGU). This 10×10 m resolution product is a result of interpolation of soil depth measurements from different databases in combination with information about soil texture (Daniels and Thunholm, 2014).

Two different satellite systems were used to gather information about vegetation health (NDVI, Normalized Difference Vegetation Index), site productivity (maximum NDVI), and land surface temperature (LST). The mean NDVI values during the planting year between April-October, and maximum NDVI prior to clear-felling were retrieved and calculated from time series of images (10×10 m) from the Sentinel-2 system (Drusch et al., 2012) for the corresponding year. The same was done for LST using the Terra MODIS-system (Phan and Kappas, 2018), which takes images on a higher temporal scale but at a lower spatial resolution (1 000×1 000 m).

2.3.2 Paper II-III

A DTW-raster was used for estimation of soil moisture in both Paper II and Paper III, though with different approaches due to the differences in experimental set up. A DTW-map roughly displays the depth to ground water at a 2×2 m resolution, which gives an indication of the soil moisture conditions. The map is constructed by calculating where water accumulates in the landscape, based on nearby water sources and how the water moves in the landscape with the varying topography (Murphy et al., 2008; Murphy et al., 2011; Ågren et al., 2014). The values displayed in the raster can range between 0 m to more than 1000 m where the smaller the value, the wetter it is. For the statistical analysis those values were log-transformed (eDTW) in Paper II.

In Paper III DTW was used both to identify the layout of plots in the experiment, ensuring representation of a wide soil moisture gradient, and in the statistical analysis. Due to issues with linearity, a classification of the DTW-values was needed before conducting statistical analysis. Since there is a larger difference in soil moisture for values between 0-1 than values from 1 and upward the following classification was done; class 1 = 0-0.5 m, class 2 = 0.51-1 m, class 3 = 1.01-2 m, class 4 = 2.01-∞ m. Roughly, class 1 represented wet conditions, class 2 moist conditions, class 3 mesic conditions and class 4 dry conditions.

2.4 Statistical analysis

Most of the statistical analysis in this thesis was done in R (R Core Team, 2022), except for the analysis in Paper IV for which SAS (SAS Institute, Cary, N.C., USA) was used. To analyze the effect of different treatments on seedling growth (leading shoot growth, Paper II, or height and diameter growth, Paper III), standing forest variables (volume, top height, DBH, basal area, or stem number, Paper IV), mortality (Paper I-III), soil disturbance (paper II), field vegetation cover (Paper II) or natural regeneration (Paper II), different types of mixed effects models were used. Due to the experimental design the random factor was usually block (Paper II, III, and IV) or site (Paper I) and a nested variable of plot within block (Paper II and III) or site (Paper I). Both linear and logistic mixed effects models were used, utilizing different packages in R. Whenever a categorical variable was deemed significant a pairwise Tukey post-hoc test was conducted to check differences between treatments.

In Paper I, a backwards stepwise selection approach was used, using the R function *drop1* to exclude variables one-by-one until the best model was fitted. A variety of variables were included in the full model (Table 1). Elimination of variables was done based on Akaike Information Criterion (AIC). Additionally, a separation of the data set was carried out based on the planting spot to control the effects of different variables in those specific conditions.

Table 1. Potential variables and their ranges or categories used in the full model before backwards selection.

Variable	**Range or levels**
Planting spot	Unscarified, Disturbed humus, Mineral soil mixed with humus, Bare mineral soil
Precipitation (mm)[a]	283-782
Air temperature(°C)[b]	11.3-14.5
Soil moisture (%)	0-92.5
Slope angle (°)	0.7-38.6
Soil depth (m)	0-16
LST (°C)[c]	14.9-20.4
Distance clear cut edge (m)	2.6-96.6
NDVI[d]	0.3-0.8
Maximum NDVI[e]	0.5-0.8

[a] Precipitation sum April – October in the establishment year.
[b] Mean air temperature April – October in the establishment year.
[c] Mean Land Surface Temperature April – October in the establishment year.
[d] Mean NDVI April – October in the establishment year. The values are an index between -1 and 1.
[e] Maximum NDVI April – October prior to clear-felling. The values are an index between -1 and 1.

3 Results and discussion

3.1 Exploring variables explaining seedling mortality

It was clear that the main variables explaining seedling mortality were planting spot, air temperature, precipitation sum, and LST. An increase in precipitation sum clearly lowered the probability of mortality (Figure 6 and Paper I), ensuring seedlings escaped water stress after planting. Elevation in air temperature led to higher probability of mortality (Figure 7), with more seedlings dying when temperatures rose. This showed that weather conditions during the planting year significantly influenced seedling mortality. Yearly variation was pronounced where more seedlings died if planted in the dry year of 2018 (48 %) compared to 2019 (21 %) and 2020 (15 %). The most reoccurring cause of damage was pine weevil feeding, where around 13 % of the seedlings had been severely damaged (within damage class 3-5). However, pine weevil feeding activity was present on almost all seedlings, which emphasizes that pine weevil was still one of the most important agents of damage even in dry years.

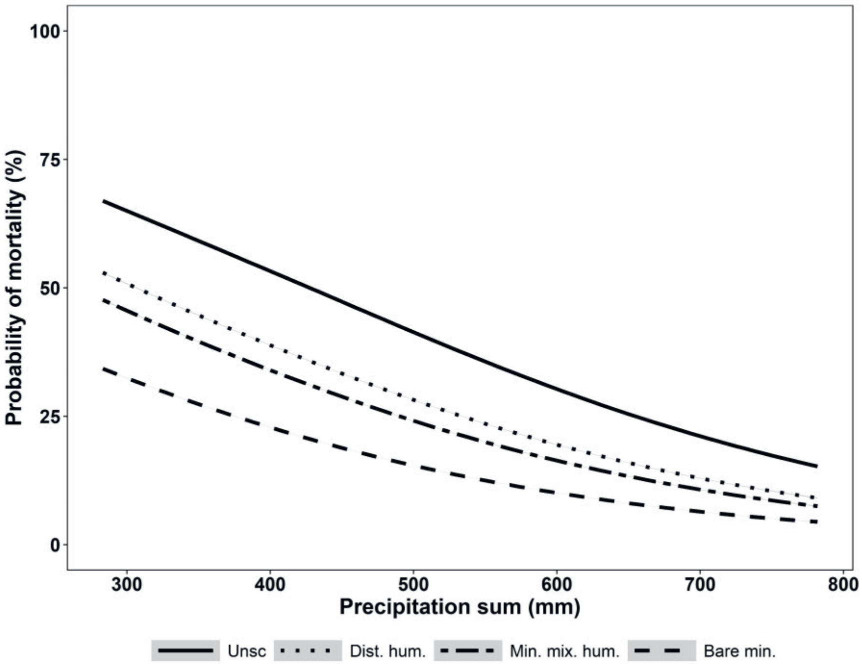

Figure 6. Probability of mortality in relation to the precipitation sum between April-October in the planting year grouped by different planting spot types. Unsc = Unscarified (solid line), Dist. hum. = Disturbed humus (dotted line), Min. mix. hum = Mineral soil mixed with humus (two-dash line), Bare min. = Bare mineral soil (dashed line).

Under Scandinavian conditions, higher temperatures at planting are generally seen as a positive thing, as it increases the time-period when soil temperature is high enough for root growth. In fact, many site preparation treatments, through the exposure of mineral soil, aim to increase the soil temperature in order to promote root growth (Örlander et al., 1990). However, when an increase in temperature is combined with water shortage due to lack of precipitation, growth will be inhibited because of water stress (Figure 7 and Paper I). This combination can lead to increased evaporation and less easily available water for the planted seedlings. Seedlings are especially vulnerable the initial time after planting when the distribution and functioning of the root system is limited, which reduces the water acquisition ability (Grossnickle, 2012). Not only does water stress lead to possible damage or lethal outcome directly caused by drought, but also lowers the vitality of the seedlings and thus their resilience to other damage. Also, increased temperature has shown to increase the abundance of severe pine weevil damage, at least in colder regions (Nordlander et al., 2017). This combination could potentially create a "perfect storm" where seedlings are water stressed due to high temperatures and low precipitation, and at the same time a large abundance of pine weevil feeding that kills the already weak seedlings.

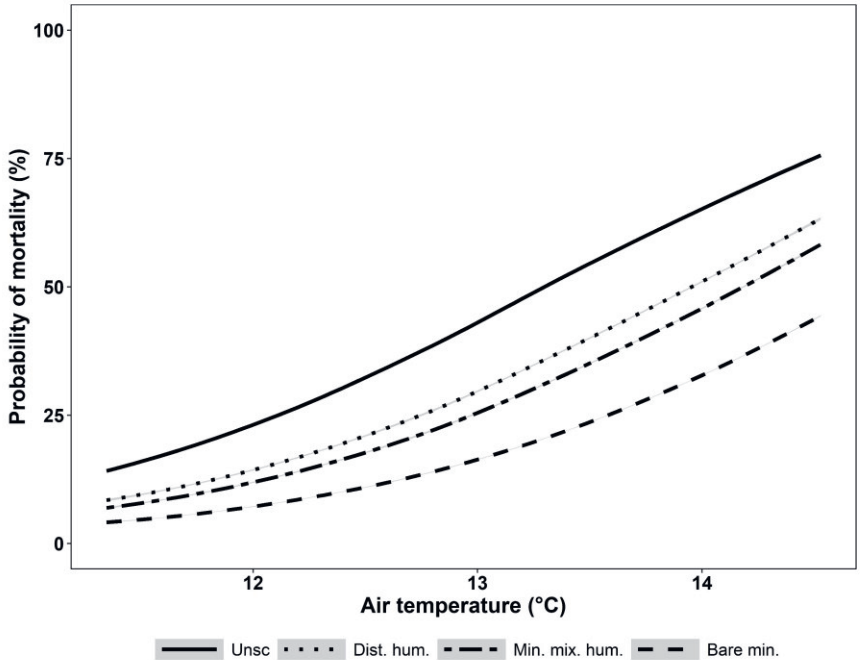

Figure 7. Probability of mortality in relation to the mean air temperature between April-October in the planting year grouped by different planting spot types. Unsc = Unscarified (solid line), Dist. hum. = Disturbed humus (dotted line), Min. mix. hum = Mineral soil mixed with humus (two-dash line), Bare min. = Bare mineral soil (dashed line).

How climate variation affects the results of regeneration became clear when analyzing the experiment and sites established in 2018 (Paper I-II). Long dry periods in spring and summer, like the one experienced throughout Sweden in 2018 (Wilcke et al., 2020), could become more common in the future. In southern Sweden temperatures and yearly precipitation are expected to increase, with the expectation that spring and summer drought can become more frequent (Chen et al., 2015; Wilcke et al., 2020). Even if drought can become a future issue for large parts of southern Sweden, it is already a present issue in the southeast where dry periods and water shortage is common. Precautionary measures, which can help to reduce the risk of drought, or other expected damage caused by extreme weather, should therefore be taken to adapt the forest to a future climate. Tree species selection should be more carefully considered in the context of a changing climate, in which Norway spruce may not be as viable of an option in southern Sweden in the future where spring and summer climate is drier (Bergh et al., 1999; Schlyter et al., 2006; Goude et al., 2022).

Recommendations about how and where to plant could be further adapted to the region's climatic conditions, in which certain planting spots are more suitable when water is limited (Örlander, 1986, Örlander et al., 1991; Hansson et al., 2018). Mitigation against water stress can be achieved by good planting execution, ensuring that seedlings are planted in an environment where they can grow their roots quickly and take up more water from the surroundings. This increases seedling health and their ability to withstand other risk factors (Luoranen et al., 2018). Furthermore, seedlings need to be handled with care when transported from nurseries to the regeneration site. Making sure that they are well watered before planting is crucial if seedlings are to endure water stress once planted (Luoranen et al., 2023). In Paper I the quality of planting was emphasized through the lower mortality of Norway spruce seedlings planted in mineral soil. These seedlings were provided with a good planting environment and were most likely easier to plant. Site preparation was probably easier to execute in those areas because of less challenging site conditions (e.g., stoniness or woody debris), hence better planting execution (Wallertz et al., 2018).

3.2 Effect of site preparation

No differences were found between different site preparation methods, or their respective intensities on seedling mortality, on either of the experimental sites in Paper II. Previous studies have had similar results, finding minor differences between site preparation methods (Bedford and Sutton, 2000; Wallertz and Malmqvist, 2013), while others have had contradictory results where different site preparation methods were superior depending on the study (Örlander et al., 1998; Heiskanen et al., 2013). However, there was a tendency towards higher mortality rates in the patch-wise treatments compared to the disc trenching treatments. This was especially true for PW1250 in Tagel where mortality was exceptionally high on some of the plots, on average 77 % (Figure 8). This was partly explained by the extreme dry conditions of 2018, which dried out the elevated planting spots. For leading shoot growth no significant difference between disc trenching treatment and patch-wise treatment was found after the first three years. Nevertheless, at the Fänneslunda site, significant differences could be seen between the PW1250 treatment and the DT2500 and LDT1250 treatments (Figure 8). This suggests that the success of an MSP method in terms of promoting seedling growth depends substantially on the creation of suitable planting spots. Choosing an appropriate planting spot becomes difficult if there are limited spots available due to insufficient site preparation. Thus, it seems that the PW1250 treatment failed to create enough suitable planting spots for the given number of planted seedlings. On the contrary, Hallsby and Örlander (2004) and Johansson et al. (2013a) found no effect on mortality or height growth with different site preparation intensity when creating 2 500 planting spots ha^{-1} compared to 3 500 spots ha^{-1} when 2 500 seedlings ha^{-1} were to be planted. Hence, suggesting that if seedlings can be planted in a good planting environment, the MSP intensity does not matter.

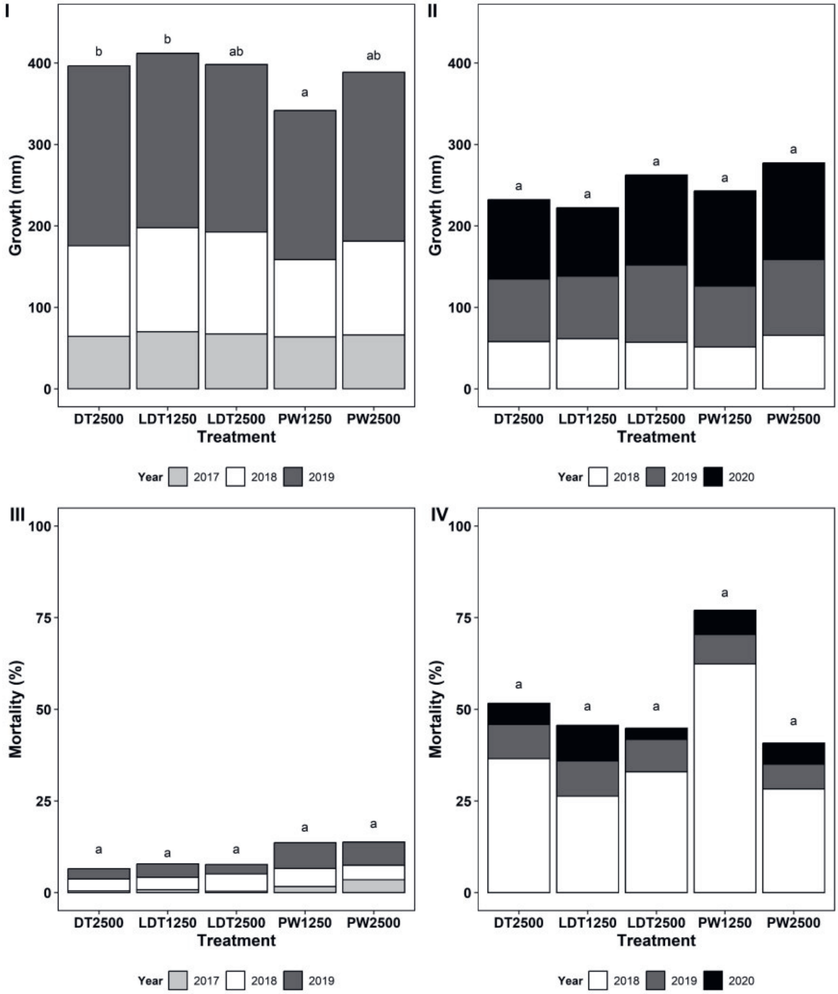

Figure 8. Growth, displayed as the total leading shoot growth, across different soil preparation treatments and study sites split by year. The mortality rates of the seedlings after three growing seasons across the different soil preparation treatments and study sites split by year are illustrated below. I = Growth in Fänneslunda, II = Growth in Tagel, III = Mortality in Fänneslunda, IV = Mortality in Tagel. Letters indicate significant difference between site preparation treatments. DT2500, Conventional disc trenching; LDT1250, Low-intensity disc trenching with sparse planting; LDT2500, Low intensity disc trenching with dense planting; PW1250, Low-intensity patch-wise site preparation; PW2500, Patch-wise site preparation.

It has been well established, both in Sweden and internationally, that site preparation is better than no site preparation in terms of seedling establishment (Örlander et al., 1990; Sutton, 1993; Wiensczyk et al., 2011; Sikström et al., 2020). This holds true if site-specific conditions are disregarded and site preparation is assumed to have been executed satisfactorily. There are some examples in the literature where no effect of site preparation was found (Wallertz and Malmqvist, 2013; Mallik and Kravchenko, 2016). These results were explained by site-specific reasons, such as the site fertility, and favorable weather conditions that promoted seedling vitality (Wallertz and Malmqvist, 2013), or instances where removal of vegetation by MSP led to increased damage from frost heaving and browsing (Mallik and Kravchenko, 2016). The between-site differences found in Paper II somewhat reflect those challenges where different results were obtained depending on site conditions and chosen planting spot. Foremost, the purpose of site preparation is to create suitable planting spots that meet the relevant goals for the given site. Stoniness or wet conditions can make this difficult, putting more emphasis on adapting the choice of method to the conditions and executing site preparation in areas that are more suitable (Wallertz et al., 2018). Allowing more flexibility in planting design and seedling spacing could support better adaptability to local site conditions and has been shown to not affect conifer tree growth (Ara et al., 2021).

3.2.1 Site preparation disturbance

The conventional disc trencher created a larger area of disturbance than any other site preparation treatment in Paper II (Figure 9). This was in line with previous findings and synthesis where the continuous rows disturb around 50 % of the regeneration area (Stromgren et al., 2017; Cardoso et al., 2020; Sikström et al., 2020). Surprisingly, there was no difference in disturbed area between the two patch-wise treatments, mostly due to similar amount of disturbed humus (Figure 9). Probably, this was caused by the excavator driving in a similar pattern independent of treatment. Also, the stoniness of Tagel most likely explains the larger area of soil disturbance compared to Fänneslunda. The area of soil disturbance caused by site preparation is one reason for why site preparation is considered ecologically and aesthetically problematic (Cardoso et al., 2020; Sikström et al., 2020). Intermittent methods, like those used in Paper II, could be used to limit the level of soil disturbance. Intermittent methods allow for more flexibility in terms of avoiding destruction of cultural remains, at least in comparison to continuous methods, which can cause accidental damage, especially in areas where the location of cultural remains is poorly documented. Paper II investigated the area of soil disturbance on the surface. However, MSP also disturbs the soil vertically (Collet et al., 2021). For example, mounding may not disturb as much on the surface but can disturb to depths of more than 30 cm (Sutton, 1993). Hence, the site preparation method should be chosen with consideration to whether that method can meet the stated goals on the site in question. If not, other options for ensuring good seedling establishment should be considered, such as size and stock type of planted seedlings or the regeneration method itself.

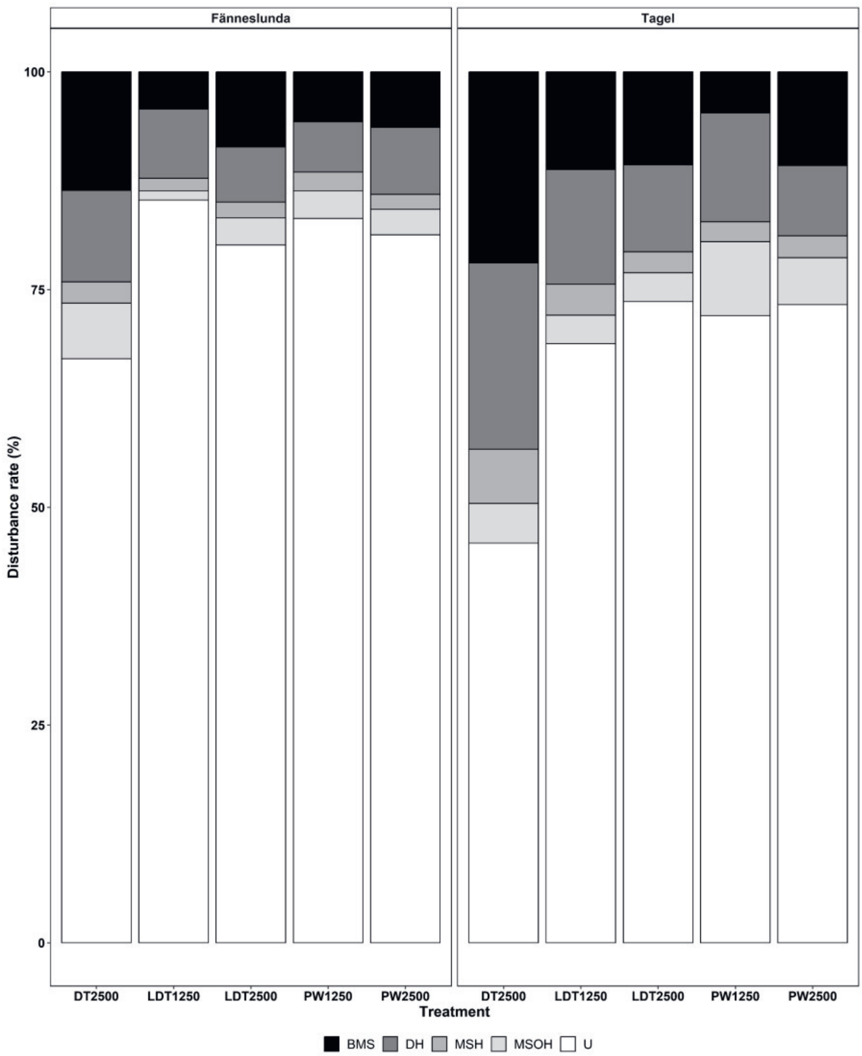

Figure 9. Soil disturbance rate across the different site preparation methods in Fänneslunda and Tagel. DT2500, Conventional disc trenching; LDT1250, Low-intensity disc trenching with sparse planting; LDT2500, Low-intensity disc trenching with dense planting; PW1250, Low-intensity patch-wise site preparation; PW2500, Patch-wise site preparation. BMS: Bare mineral soil; DH: Disturbed humus; MSH: Mineral soil mixed with humus; MSOH: Mineral soil on top of humus; U: Undisturbed.

3.2.2 Vegetation

One of the main reasons for using site preparation is vegetation suppression, ensuring that seedlings get a head start with limited competition for water and other resources (Löf et al., 2012; Reicis et al., 2022). Independent of site preparation intensity, field vegetation cover was similar across treatments after three years. This illustrates the speed with which field vegetation recovers from disturbances in southern Sweden (Paper II). There was slower recovery in Tagel, most likely due to the dry conditions of 2018, but it was still independent of site preparation treatment. Rapid recovery of field vegetation has been noted in previous studies as well (Nilsson and Örlander, 1999). The competition-free period is nonetheless important for seedlings to get an advantage over competing field vegetation. Recovery in Paper II was merely defined as the field vegetation cover, not species richness or vegetation type. This is important to have in mind, since site preparation can alter the vegetation type which recolonizes an area following such a large disturbance (Archibold et al., 2000; Pykälä, 2004; Haeussler et al., 2017; Cardoso et al., 2020).

3.2.3 Natural regeneration

No distinct difference between treatments in the amount of natural regeneration was found in Paper II. There was a large amount of natural regeneration in all treatments at both sites, which emphasizes that natural regeneration needs to be considered in the planning. Usually, site preparation and the level of disturbance promotes natural regeneration (Karlsson and Nilsson, 2005). This could be seen either as source of greater cost in future precommercial-thinning (Uotila et al., 2010) or as a free asset that can be used to meet the forest owner's goals (Nilsson et al., 2006; Dahlgren Lidman et al., 2021). Firstly, most of the natural regeneration consisted of deciduous trees, predominantly birch, which can be utilized to meet certification requirements and create mixed forest (Nilsson et al., 2006). Secondly, managing for mixtures of Norway spruce and birch can be advantageous in terms of flexibility (Dahlgren Lidman et al., 2021), forage production (Ara et al., 2022c), and creation of a larger variety of microhabitats in the future stand which can enhance biodiversity (Felton et al., 2010). Site preparation should therefore be chosen to meet multiple goals while also being well-suited to the site properties.

3.3 Planting spot and tree species

Following MSP, the choice of planting position, with consideration to within-site variation, proved to be important in avoiding seedling mortality for the three major tree species in Sweden (Norway spruce, Scots pine, and silver birch) (Paper III). Planting in lower planting positions (hinge and depression) in wet conditions resulted in higher mortality rates than planting in elevated positions (mound). As soil moisture conditions changed the differences between planting positions diminished, becoming similar for depression, hinge, and mound (Figure 10). This can be explained by elevated planting positions, like mounds, are better drained and therefore provide a better environment for seedling establishment in wet conditions (Sutton, 1993; Pearson et al., 2011). Seedlings planted in depressions suffered from oxygen deficiency due to water logging, causing poor development or mortality (Örlander et al., 1990). However, when conditions become drier planting in lower positions may become a suitable alternative to planting in the mound, especially in cases when the mound run the risk of drying out (Bassman, 1989; Örlander et al., 1991; Hansson et al., 2018; Häggstrom et al., 2021).

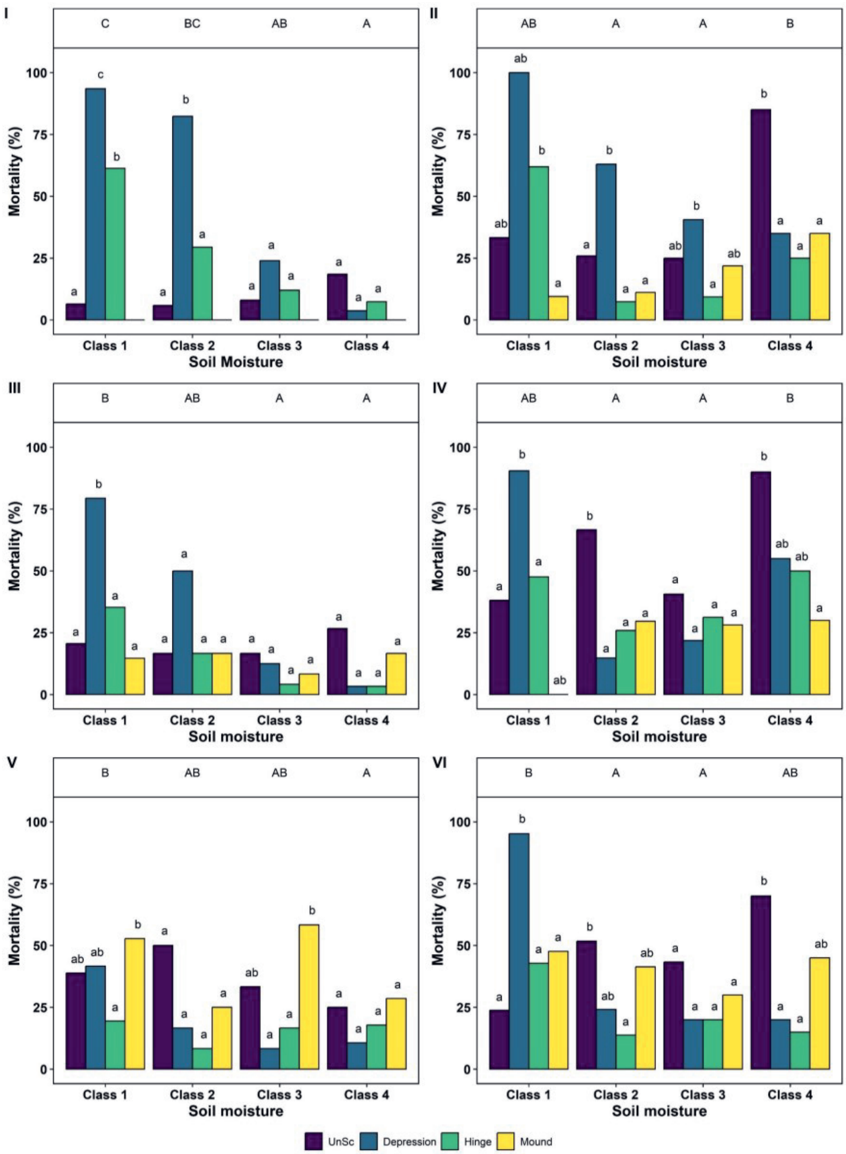

Figure 10. The mortality rate for each planting position within depth-to-water (DTW)-class split by site and tree species. Lower case letters indicate significant difference (p-value < 0.05) between planting positions within DTW-class. Upper-case letters indicate significant difference (p-value < 0.05) between DTW-classes. I, Norway spruce in Isberga; II, Norway spruce in Holkaberga; III, Scots pine in Isberga; IV, Scots pine in Holkaberga; V, silver birch in Isberga; VI, silver birch in Holkaberg. Class 1, DTW is 0-0.5 m; Class 2, DTW is 0.51-1 m; Class 3, DTW is 1.01 – 2 m; Class 4 is 2.01m – ∞. UnSc (dark blue), Unscarified; Depression (light blue); Hinge (green); Mound (yellow).

In terms of seedling growth, similar patterns to those of mortality were observed in Paper III, particularly for the coniferous species used in the study. Mounds were the superior option when conditions were wetter, but as soil moisture decreased the differences became less prevalent (Paper III). The effect of planting position was clearer when comparing the diameter growth, with Norway spruce and Scots pine seedlings generally growing better in the mounds (Figure 12). Favorable conditions for root growth, both in terms of temperature and soil moisture, largely explains why the seedlings grew better in the mounds (Sutton, 1993; Heiskanen and Rikala, 2006). Interestingly the differences in growth between planting positions also diminished as conditions became drier, which could be an indication of similarity in water conditions between positions (Bassman, 1989; Örlander et al., 1991). Seedlings were no longer hindered by an excess of water in the lower positions, removing some advantages of planting in the mound.

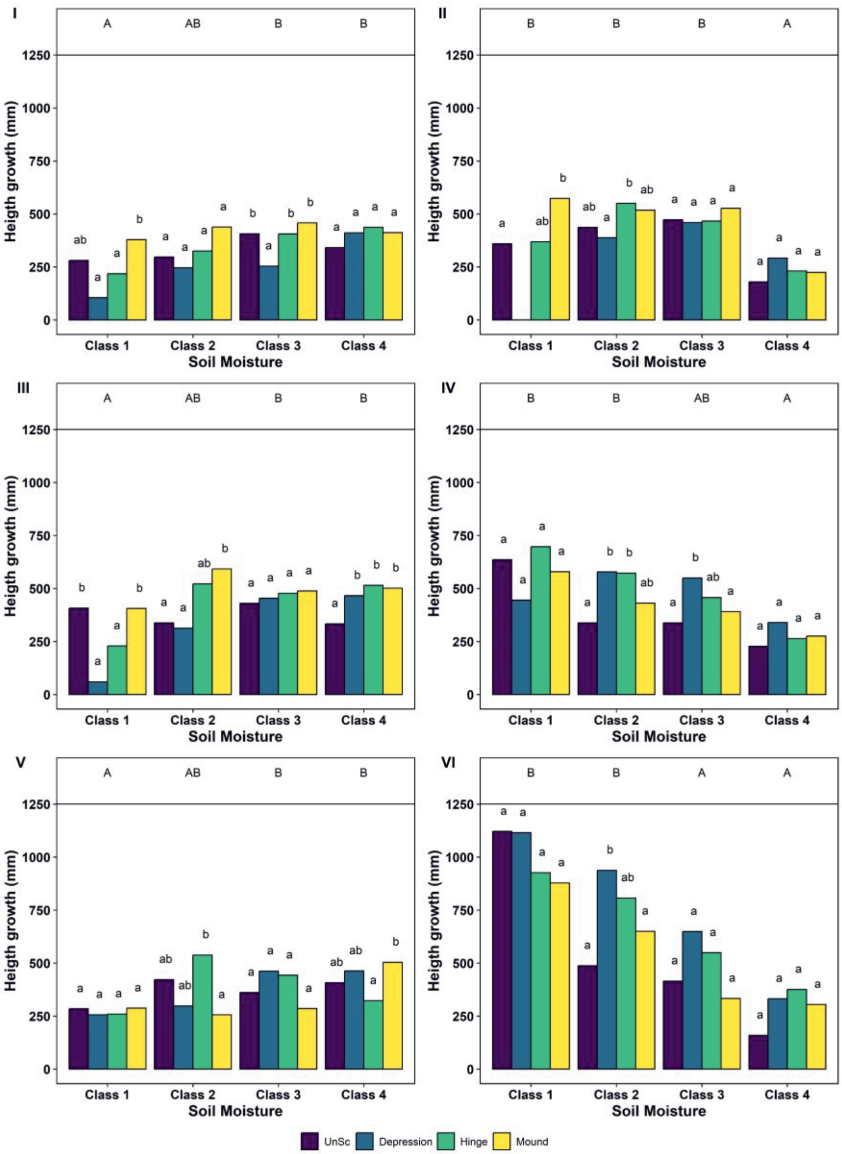

Figure 11. Mean height growth after three growing seasons for each planting position within depth-to-water (DTW)-class split by site and tree species. Lower case letters indicate significant difference (p-value < 0.05) between planting positions within DTW-class. Upper-case letters indicate significant difference (p-value < 0.05) between DTW-classes. I, Norway spruce in Isberga; II, Norway spruce in Holkaberga; III, Scots pine in Isberga; IV, Scots pine in Holkaberga; V, silver birch in Isberga; VI, silver birch in Holkaberg. Class 1, DTW is 0-0.5 m; Class 2, DTW is 0.51-1 m; Class 3, DTW is 1.01 – 2 m; Class 4 is 2 – ∞. UnSc (dark blue), Unscarified; Depression (light blue); Hinge (green); Mound (yellow).

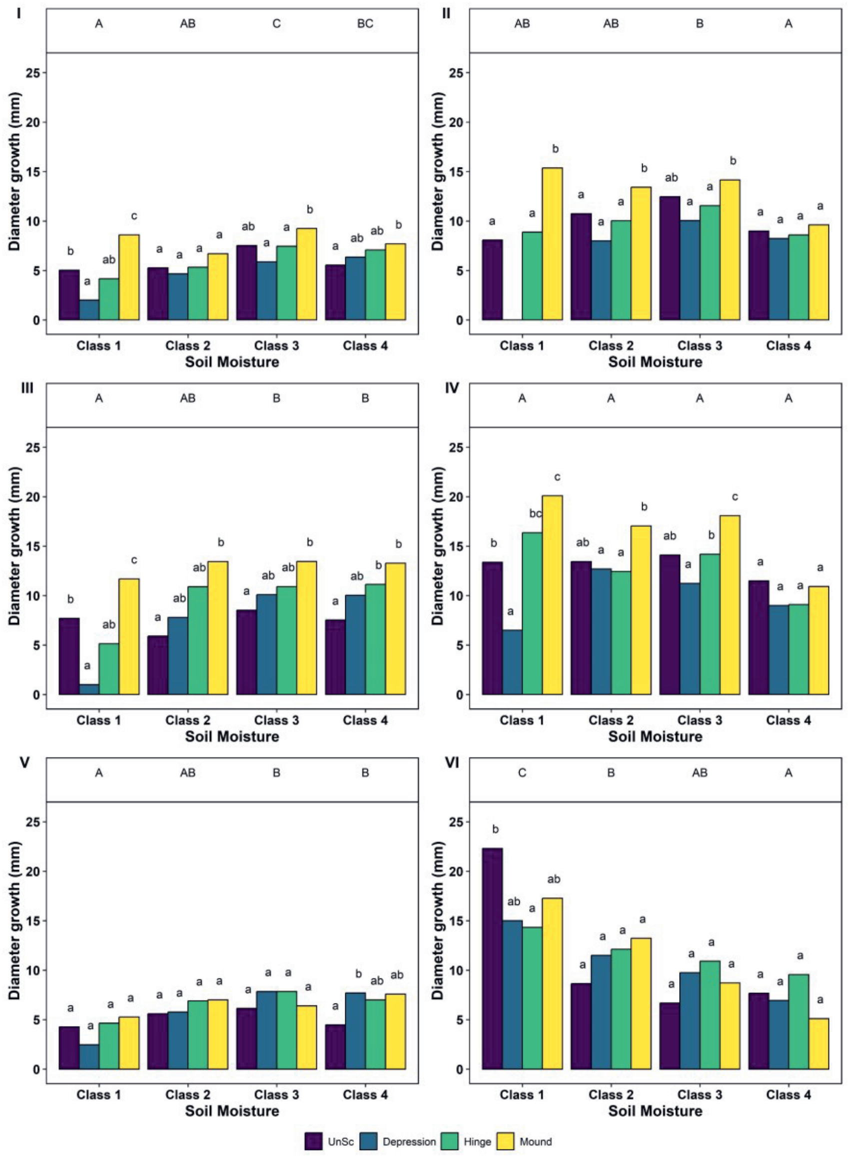

Figure 12. Mean diameter growth at ground level after three growing seasons for each planting position within Depth-to-water (DTW)-class split by site and tree species. Lower case letters indicate significant difference (p-value < 0.05) between planting positions within DTW-class. Upper-case letters indicate significant difference (p-value < 0.05) between DTW-classes. I, Norway spruce in Isberga; II, Norway spruce in Holkaberga; III, Scots pine in Isberga; IV, Scots pine in Holkaberga; V, silver birch in Isberga; VI, silver birch in Holkaberg. Class 1, DTW is 0-0.5 m; Class 2, DTW is 0.51-1 m; Class 3, DTW is 1.01 – 2 m; Class 4 is 2 – ∞. UnSc, Unscarified (dark blue); Depression (light blue); Hinge (green); Mound (yellow).

The effects of different planting positions across the soil moisture gradient differed somewhat depending on the tree species (Paper III). The conifers both responded with improved growth and a lower mortality rate in the mound position, but silver birch did not show such clear benefits from mounding (Figure 10, Figure 11, Figure 12). It could be that silver birch was sensitive to decreasing water availability, a condition reflected on one of the sites in Paper III (Figure 12), since silver birch generally rely on a continuous water supply (Hynynen et al., 2010). Thus, planting in mounds could be a greater risk for silver birch under conditions where there is a possibility of the mound drying out. Most research into planting of silver birch has focused on planting on former agricultural land (Karlsson, 2002; Daugaviete et al., 2003; Hytonen and Jylha, 2005). Hence, to my knowledge, limited research has been done into the effect of site preparation on silver birch planted on forest land, with only limited studies looking at those effects (Luoranen et al., 2003; Dumins and Lazdina, 2018; Pikkarainen et al., 2021), especially in Sweden. For other broadleaves, such as different Populus spp., planting in mounds has shown to be favorable for establishment (McCarthy et al., 2017; Thiffault et al., 2020).

Even when planting to avoid risks, biotic damage agents heavily impact the results of planting. Pine weevil feeding, browsing, and fungi infection were among the most common causes of damage in Paper III. Although the birches and pines survived browsing, their height growth was affected. Other types of ungulate damage, such as bark peeling or seedlings being dug up, were also common in Holkaberga (the southern-most site in Paper III). The risk of browsing is sometimes the determining factor in deciding not to plant certain species, one consequence of why more Norway spruce is being planted in non-optimal conditions (Lodin et al., 2017). Putting greater effort into planting to meet local site conditions could diversify the species composition in the landscape and thus alleviate some of the browsing pressure on birch and pine regenerations (Bergqvist et al., 2014; Bergqvist et al., 2018; Pfeffer et al., 2021).

The results of Papers II and III demonstrate the consequences of choice of planting position, showing differences both by yearly climatic variation and by within-site variation in soil moisture conditions. They also highlight a level of risk and reward to such choices. Growth was promoted in elevated spots but the risk of seedlings being heavily affected by water stress in dry years was increased (Paper II and Figure 13). In Swedish planting instructions, it is generally recommended to plant in these elevated positions, and to plant the seedling deeply (Skogskunskap, 2021). However, when seedlings cannot be planted deeply enough, or in areas that are dry, it would be valid to suggest that lower planting positions would be preferable (Hansson et al., 2018; Häggstrom et al., 2021). For Norway spruce this would possibly result in lower growth, because the distance to the humus layer would be increased and nutrients would not be as accessible, but the seedlings at least survive. Even so, Norway spruce seedlings have shown a good ability to grow their roots towards the nutrients when planted on the hinge (Celma et al., 2019). Scots pine growth may not be as negatively affected since it is less sensitive to removal of the humus layer (Nilsson et al., 2019). Results from Paper III suggest that, likewise, silver birch may not be negatively affected by a lower planting position when site conditions are drier. Planting without site preparation could also be an option with silver birch, which according to Hynynen et al. (2010) has been common practice in Finland before.

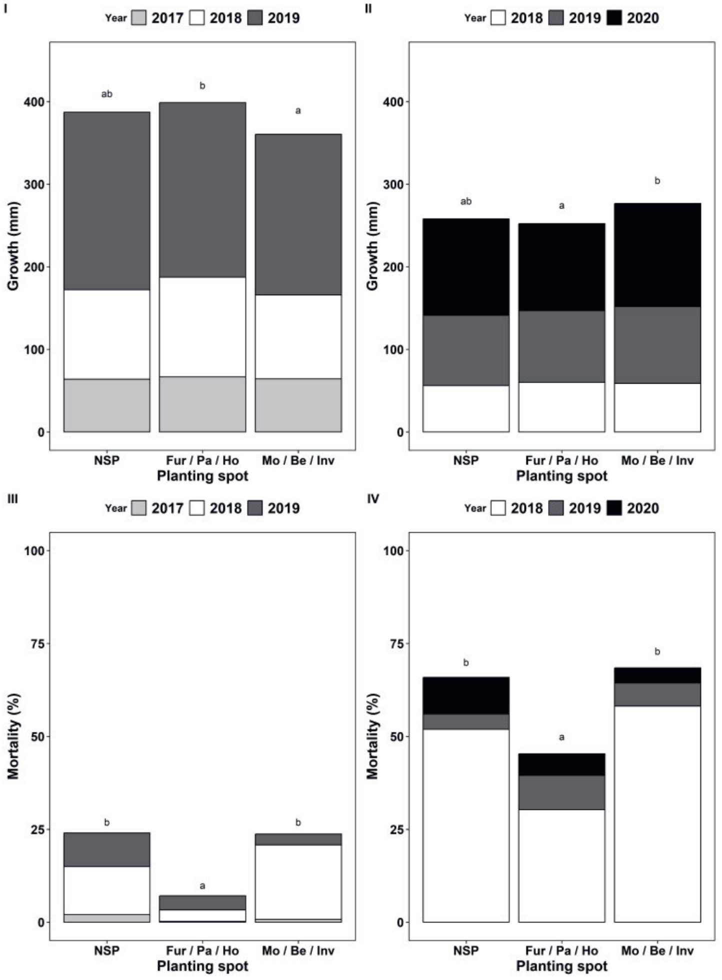

Figure 13. Growth, displayed as the total leading shoot growth, across different planting spot types split by year. Mortality rates of the seedlings after three growing seasons across the different planting spot types split by year. I = Growth in Fänneslunda, II = Growth in Tagel, III = Mortality in Fänneslunda, IV = Mortality in Tagel. Letters indicates significant difference between planting spot types. NSP = no site preparation, Fur/Pa/Ho = Furrow/Patch/Hole, Mo/Be/Inv = Mound/Berm/Inverted planting spot.

3.4 Digital tools and forest regeneration

The two soil moisture maps used (SLU soil moisture map for Paper I, and DTW-raster for Papers II and III) each showed different results. In Paper I, only seedlings planted in unscarified spots showed any significant response, which constituted an increase in mortality with drier conditions according to the map. In Paper II, DTW was found to have a negative relationship with growth, meaning that growth was reduced with drier conditions (Figure 14), although this result had limited significance and was only true for one site, Fänneslunda. Paper III showed how well the DTW-raster could explain the extremes of the soil moisture spectrum (see section 3.3). Using soil moisture maps could hence be used for delimiting stands into smaller compartments in which different management approaches might be recommended to minimize seedling mortality (Holmström et al., 2019; Ring et al., 2020). However, the papers revealed some limitations of using these maps. Their explanatory power becomes weaker as conditions get drier, meaning that it is harder to capture variation where conditions are somewhere between wet and dry (Ågren et al., 2014; Ågren et al., 2021). In terms of tree species selection, it may be the distinction between those middle classes that is of most importance as, in a traditional Swedish context, this can determine whether to plant Norway spruce or Scots pine. Further, the maps used were nationally developed maps and were not specially modified to the given sites. For DTW, this means that the catchment threshold value may have been non-optimal for those conditions (Larson et al., 2022). The maps are also a static image of what is perceived to be the "normal condition" of a pixel, which does not fully capture the dynamic and complex nature of soil moisture. For further accuracy, adaptations of these maps that fluctuate with the seasons could be useful to fully understand soil moisture conditions.

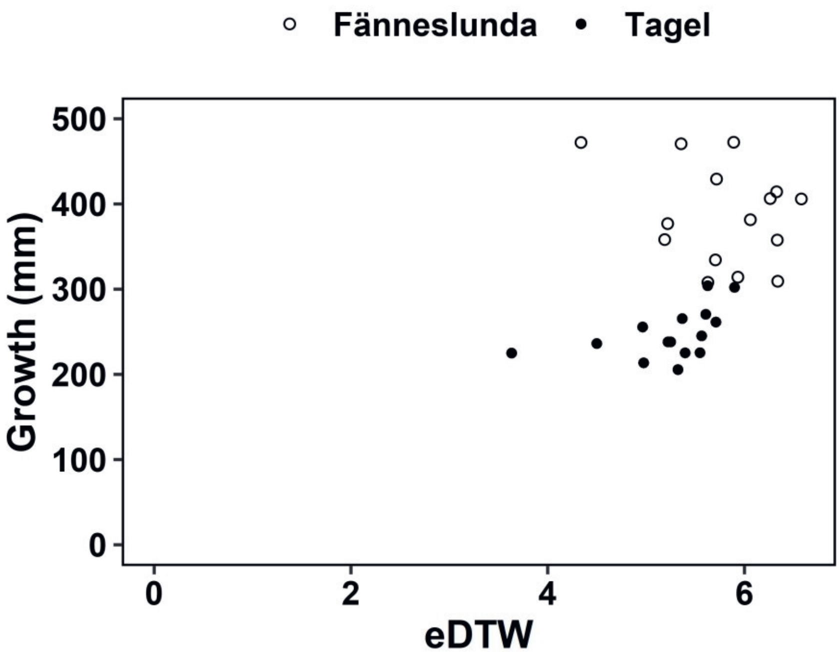

Figure 14. Effect of eDTW on total leading shoot growth after three growing seasons in Fänneslunda (open circle), and Tagel (filled circle).

The possibility to further implement digital tools in forest regeneration, with techniques which describes the microenvironment, exists (Castro et al., 2021). However, in Paper I, few of the remote-sensed variables that were explored showed any significant impact on the mortality of Norway spruce seedlings. LST derived from the TERRA MODIS satellite system did however exert significance in the full model. NDVI and maximum NDVI also exerted significance, but only in one of the sub-models.

An increase in LST, i.e., higher temperature, led to less mortality in Paper I. The low spatial scale could have influenced these results as LST values are influenced by the surrounding forest and structures (Phan and Kappas, 2018). Further, LST showed different results than the measured air temperature (positive effect on mortality) in Paper I. High LST did not necessarily coincide with dry weather, meaning that some high LST values were found on sites planted in years with favorable precipitation, which partly explains this difference.

Higher NDVI led to lower mortality for seedlings planted in mixed mineral soil with humus. As NDVI measures vegetation activity, the lower mortality observed may have indicated the general health of the vegetation at the clear-cut in the given year. NDVI has previously been used to measure drought effects

(Pettorelli et al.; 2005; Berner and Goetz, 2022), and possibly the lower NDVI at some sites in Paper I indicated that the vegetation and the seedlings were experiencing increased water stress. Maximum NDVI can be an indication of vegetation productivity, which could imply faster colonization of competing vegetation (Nijland et al., 2015), thereby, partly explaining why the probability of mortality increased with higher maximum NDVI. Nevertheless, it could also be a result of imbalance in the dataset used, since NDVI-variables only exerted significance in one of the sub-models. For example, if the prior stand consisted of more broadleaves, this would result in higher maximum NDVI as leaves and needles have different reflectance properties affecting NDVI (Pettorelli et al., 2005). Thus, we could not conclude that seedling mortality was directly connected to maximum NDVI or NDVI.

It would be worthwhile carrying out a deeper exploration of the digital variables used in Paper I to better understand their applicability to regeneration planning. There are already examples of how topographic maps can be used to optimize the routes that site preparation machines take and the creation of planting spots (Friberg et al., 2017). Also, by understanding how digital data can be used, machines can be trained to automate forest planting. For a machine to correctly plant seedlings, they need reliable information about the site, which digital data sources could provide (Skogforsk, 2022). Other variables not brought up in Paper I should also be further investigated, for example using harvester data for tree species selection (Saksa et al., 2021; Aza et al., 2022). Applying high resolution data to species distribution models could also provide possible support in tree species selection (Gastón et al., 2014). Overall, there is great value to the future development of such tools and decision-making supports in enabling more precise approaches to forest regeneration (Castro et al., 2021).

3.5 Long term effects

The short-term benefits of site preparation are clear, from a growth and survival perspective (Thiffault and Jobidon, 2006; Johansson et al., 2013b; Sikström et al., 2020), and these positive effects persist over at least the first 30 years (Paper IV). Standing volume was greater with an increase in site preparation intensity, with ploughing followed by mounding and disc trenching having the highest standing volumes, all greater than the unscarified control (Figure 15). Similar results were shown for the other variables, with taller and thicker trees (top height and DBH), and denser stands (basal area and stem numbers) following site preparation compared to the control (Table 2). Further, the diameter distribution was skewed towards more trees with a larger diameter in the site prepared treatments. Initial concerns about decreasing productivity with intensive site preparation could be disregarded on the basis of these results, at least in the timespan studied. Other studies have shown an increase in growth that is sustained over time following site preparation (Örlander et al., 1996; Boateng et al., 2009; Johansson et al., 2013a; Thiffault et al., 2017; Prévost and Dumais, 2018). This sustained growth is largely explained by lower mortality rates and an initial boost to growth (Johansson et al., 2013a). One implication of the finding that site preparation has a positive effect on growth is that rotation lengths could be shortened (Thiffault et al., 2010). However, it should be acknowledged that ploughing, which generated the greatest standing volume in Paper IV, is illegal in Sweden due to the large soil disturbance it causes, with negative impacts on both ecological and aesthetic values.

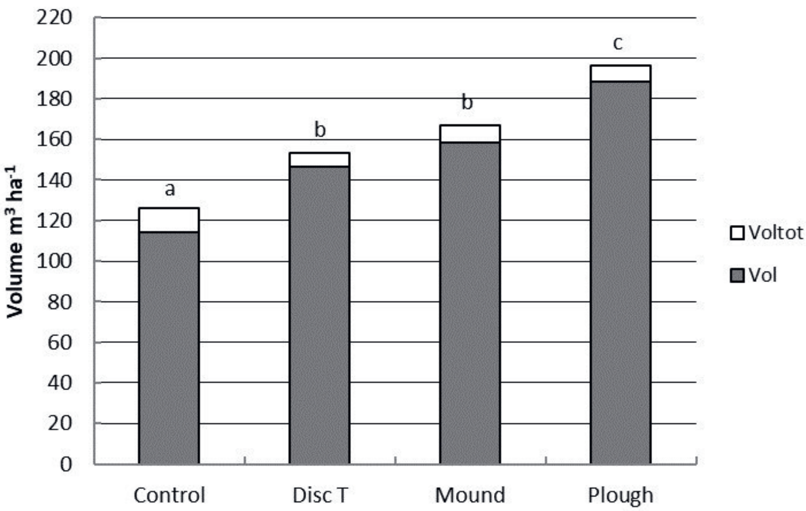

Figure 15. Mean values (least square means) of standing volume per hectare (m^3 ha^{-1}) in different soil preparation treatments on all sites about 30 years after planting. VOL = the volume of planted trees and VOL_{tot} = the volume of all trees, including naturally regenerated trees. Different letters show significant differences between the treatments.

Table 2. Mean values (least square means) of the measured variables per scarification treatment on a stand level (ha^{-1}). Values followed by different letters are significantly different column wise. DBH is the quadratic mean breast height diameter (cm), TH is the mean top height (m), BA is the basal area (m^2) and Stems the number of stems per hectare. A statistical summary of the effects of site, scarification and their interaction shown as p-values of least square means of different growth variables at stand level is presented below the mean values.

Treatment	**DBH**	**TH**	**BA**	**Stems**
Control	10.7 a	11.7 a	18.7 a	1830 a
Disc T	11.6 b	12.7 b	22.8 b	2016 b
Mound	11.6 b	12.8 b	24.0 b	2088 b
Plough	12.5 c	13.5 b	26.9 c	2054 b
Effect, p-values				
Site	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Scarification	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Site × Scarification	0.1626	0.9483	0.0969	**0.0001**

It should be noted that the approach taken in Paper IV did not enable comparison between tree species. That does not mean that the effect of site preparation can differ depending on tree species. Theoretically, Norway spruce react more positively to site preparation as it is more dependent on nutrient availability, especially at less fertile sites (Bergh et al., 2010). There are indications that the overall benefits of site preparation are dependent on the species and their ecological ability to utilize the resources available (Thiffault et al., 2010; Thiffault et al., 2017; Nilsson et al., 2019). Thus, further studies are needed to evaluate how species-dependent the long-term benefits of site preparation on Swedish forest trees are.

Paper IV was primarily concerned with the long-term effects of site preparation on stand productivity. However, it is also important to acknowledge the long-term effects of site preparation on other aspects and values than simply forest growth. Site preparation can increase initial CO_2 emissions and reduce the stock of carbon (C) in the soil (Piirainen et al., 2015) although it can increase C sequestration in the long-term through increased tree growth (Mjöfors et al., 2017). The major soil disturbance caused by site preparation can also alter the forest vegetation composition of the future (Haeussler et al., 2017). With the large disturbance early successional species are promoted which initially can increase species richness (Roberts and Zhu, 2002; Pykälä, 2004) but the recovery of other species groups, such as lichens (Eriksson and Raunistola, 1990) or bryophytes (Echiverri et al., 2022), may be hampered. Additionally, in combination with shorter rotation lengths such species may not recover by the time of the next felling, resulting in loss of biodiversity (Petersson et al., 2019; Lariviere, 2023). Furthermore, the disturbance rate can lead to an excessive amount of natural regeneration, resulting in increased tending costs (Uotila et al., 2010).

Paper IV highlights the importance of long-term experiments for evaluating the effect of different silvicultural treatments over time. Forest management takes place over many decades, and initial effects may not persist into the future. The long timespan becomes a challenge in decision making about forest regeneration, as decisions made today will affect the forests of tomorrow. For example, planting storm sensitive species in the present will lead to storm sensitive forests in the future (Schou et al., 2015). Further, if no consideration is given to ecological values at an early stage, there might be limited ecological values to manage in the future. Hence, plans for achieving ecological and social goals must be put in place before a forest area is harvested and regenerated. Future long-term experiments could therefore be designed to evaluate the possible consequences on ecological values of different silvicultural measures. Cognizance of the consequences of current management are therefore important for adaptation of management in a future climate (Bolte et al., 2009; Blennow, 2012; Keskitalo et al., 2016; Lodin et al., 2017; Venäläinen et al., 2020).

4 Conclusion and implications

Understanding differences in climate between regions and sites was shown to be valuable in explaining seedling mortality. In Paper I, precipitation and air temperature between April and October in the year of planting significantly explained seedling mortality, highlighting the influence of climate on planting success. It also showed that the selection of planting spots can mitigate against abiotic and biotic damage from e.g., pine weevil feeding or drought, giving seedlings the ability to develop into a resilient future forest. Also, emphasizing that high quality of site preparation and planting can lead to lower mortality rates and greater opportunity to meet the end goals of forest management. In a changing climate, with drier and warmer growing seasons expected in southern Sweden, choosing suitable tree species, planting material, and regeneration methods that are adapted to local site conditions will be crucial in creating resilient forests.

Selection of site preparation method had little effect on seedling growth and mortality in Paper II but showed significant long-term effects on growth in Paper IV. The intensity and ability to create suitable planting spots probably influences planting success more than the methods themselves, as this provides better ability to choose the right planting spot. Hence, selecting a site preparation method that can create suitable planting spots with minimum soil disturbance would be ideal. This combination of minimum soil disturbance and suitable planting spot would spare ecological and aesthetic values, while still promoting fast seedling establishment by evading potential abiotic and biotic risks. In southern Sweden field vegetation will recolonize an area independent of site preparation method used (Paper II), but preparation does provide seedlings with some initial relief from competition. Also, indifferent of site preparation method, plenty of natural regeneration was registered within three years in Paper II. The resulting emergence of mainly deciduous seedlings should always be accounted for, both in projecting future costs but also as a resource for promoting mixed forest in the future stand.

The importance of adapting planting position to within-site variation emerged clearly in Paper III. An elevated planting position, in mounds, was advantageous in decreasing the mortality rates under wet conditions. As soil moisture conditions became drier, more flexibility in the selection of planting position could be applied. Lower positions, in depressions and hinges, were equally good options for minimizing seedling mortality under drier conditions. Growth of coniferous species, especially diameter growth, was promoted when planted in mounds. However, for silver birch no real differences, in terms of growth between planting positions could be identified. Hence, planting should be adapted to within-site variation, but different tree species may react differently to different planting positions. Therefore, more research is needed into how to plant birch on forest land to clarify the recommended practice.

Papers I-III showed examples of how digital tools can be useful in forest regeneration planning, but also highlighted some of the current limitations. The SLU-soil moisture map only showed significance in explaining mortality for seedlings planted in unscarified soil, suggesting that site preparation reduces some within-site variation (Paper I). In Paper II a DTW-raster had a limited level of significance in explaining growth and mortality. However, when the entire spectrum of soil moisture from wet to dry was represented, the DTW successfully identified and explained growth and mortality levels at the extremes (Paper III). Due to the limitations in delineating soil moisture classes that lie in between wet and dry, it would be difficult to base tree species selection on these maps alone. Despite limitations, digital tools could be used to better understand within-site variation and provide decision-support when instructing selection of planting spots, areas to be left for natural regeneration, and what management approach should be applied to different parts of a regeneration area.

No negative long-term effects of site preparation on stand productivity over 30 years could be found. Rather the opposite was true, with ploughing resulting in the largest standing volume compared to the other treatments. While ploughing is banned, the other legally permitted site preparation methods also showed better volume production than the unscarified control, indicating that site preparation could be used to enhance growth over time. However, caution should still be applied as site preparation may have long-term impact on other values than stand productivity. Thus, long-term experiments are crucial for evaluating management options over a longer time span and seeing their effects across the entire rotation. Hence, newly established long-term experiments should aim to be able to explore the long-term consequences of different regeneration measures on ecological values.

5 Future of forest regeneration

Ever since Sweden's Forest Act was introduced in 1903 there has been pressure to find more efficient ways of carrying out forest regeneration. This has resulted in a homogeneous approach to regeneration management, in which clear-felled areas are almost always planted following MSP. Adaptations to variation, whether on a landscape level or site level, have been largely simplified to spruce sites and pine sites, which is reflected in the species used for regeneration (Bergquist et al., 2017; Ara et al., 2022a; SFA, 2022). Nature is rarely that simple, multiple species can be suitable for different microhabitats within the same site. Planting multiple species at the same site and creating a mixture within the stand would be a reasonable way forward instead of creating homogenous stands. This approach would not only produce better outcomes in terms of production goals, but also meet the need for ecological and social sustainability (Coll et al., 2018). Mixed stands have the potential to be beneficial for ecological values and an admixture of broadleaves are generally appreciated for recreational values (Gundersen and Frivold, 2008; Felton et al., 2010; Felton et al., 2016). Also, utilizing more species in the forest spreads the risks in a changing climate and creates more resilient forests against e.g., storms and pests. Hence, future research needs to focus on how to create mixed stands already in the regeneration phase and how to manage these when the stand ages. There is also a need to explore how to implement more precision management in mixed stands and move away from a stand-level management mindset.

Adapting management to the forest landscape, i.e., site adapted forest management, was already mentioned in the 1980s (Lundmark 1986). However, implementation of site adaptation is difficult, particularly when discussions usually end around species choice. Greater consideration must be given to management alternatives in the regeneration phase, and not forcing management methods onto areas where it is doomed to fail. An example might be areas that experience spring and summer drought, like those in southeastern Sweden, which may not be suitable for planting due to elevated water stress. In such areas seed trees or different shelterwood systems may be better suited to create a good regeneration environment. The same logic could be applied to frost prone sites or areas which would be heavily colonized by competing vegetation, where a shelterwood system would be beneficial. Mapping and understanding different site properties should be better implemented in forest regeneration to avoid unnecessary failures and hence extra costs. Detailed maps could also aid in minimizing the disturbance caused by site preparation in the future. Future regeneration efforts should aim to adapt management to the specific site characteristics and minimize the disturbance rate. More emphasis needs to be placed on the long-term effects on ecological values and the proper evaluation of the long-term consequences of different management options.

With interest arising in using broadleaves in Sweden there is an apparent knowledge gap that needs to be filled. Although there has been research into management systems which utilize natural regeneration of several broadleaf species (Agestam et al., 2003; Karlsson and Nilsson, 2005) limited research on planting of broadleaves has been made (Löf et al., 1998; Löf, 2000; Löf et al., 2006). In Paper III planting of birch was briefly evaluated, but studies that further explore how to plant birch are needed in the future. The same basically applies to most underutilized tree species in Sweden to improve understanding of how they react to different microenvironments. There are benefits of using a wider range of species in the future to diversify the landscape, which can have positive implications on biodiversity and productivity (Felton et al., 2010). Future research needs to focus on how to regenerate broadleaved species with as much risk evasion as possible. For example, alternative management options for browsing protection, which do not include large scale investments like fencing, need to be further explored.

Digital tools in forest management have evolved over the years and will most definitely continue to evolve in the future. As more and more forest owners live further away from their forest estates (SFA, 2022), such tools will become more important for decision-making. Currently, much of the so-called precision forestry research has focused on later stages in the silvicultural rotation, i.e., thinning and final felling. With high resolution data and mapping of the microenvironment precision forestry should be applied in the regeneration phase as well. As elaborated in Papers I-III of this thesis, there is already potential with the use of soil moisture maps in regeneration planning, but more detailed mapping is needed. Castro et al. (2021) discussed a future with precision forest restoration, in which a variety of digital sources could be used to select appropriate management and understanding site properties. More research is needed on how to implement the digital sources that are available, but also more development in mapping important factors. Such factors could include soil texture, distribution of stone blocks in the landscape, or fluctuation in water availability and surface temperature over time. If such factors were mapped with good accuracy and resolution, they could be further implemented for more detailed planning and perhaps be used to automate forest regeneration.

5.1 A personal outlook

Hindsight is the gift of time, the possibility of looking back at past generations and learning from their actions. However, we do inherit the mistakes of the past, especially in silviculture which operates over long timespans. I do not imagine that reforestation of meadows and heaths in the 1900s was perceived as problematic, rather as something positive which generated an increase in forest resources greatly needed at the time (Blennow and Hammarlund, 1993). Now those open landscapes are scarce and instead need protection in a more densely forested landscape. Neither was large scale herbicide treatment of broadleaves between the 1950s-1980s an evil, but an efficient way of cleaning and promoting the coniferous crop trees. It became an issue when herbicides became a threat to human health (Östlund et al., 2022). The effects of such treatments are reflected in today's need to increase the proportion of broadleaves in the forest. The past centuries (read 19th and 20th century) have generally looked at the forest resource for maximized production and profit, initially for direct profit, but later sustainable growth and flow of raw material to the industry. These aspects have been reflected in actions and legislation. In some respects, times have changed, and forest resources are now to be managed for more than just wood production. More of everything is an expression that have tried to describe the Swedish forestry model (Lindahl et al., 2017). I am not in a position to judge whether or not this is possible, though I doubt it since compromises need to be made, taking away value from one aspect to the benefit of another. Nevertheless, it does represent a change in perspective from the past since wood production is now to be made with consideration to nature instead of at the expense of it. To some extent I do believe we are living in a paradigm changing age, where we are being more cognizant of the impact silviculture has on the landscape. Only future generations will be able to judge whether this leads to meaningful change in silvicultural practice. My belief is that foresters, policy makers, and researchers need to be open minded and ready to re-evaluate former "truths" in order to adapt to an ever-changing world and meet the challenges the future holds.

References

Agestam, E., Ekö, P.-M., Nilsson, U. & Welander, N. 2003. The effects of shelterwood density and site preparation on natural regeneration of Fagus sylvatica in southern Sweden. *Forest Ecology and Management,* 176**,** 61-73. https://doi.org/10.1016/S0378-1127(02)00277-3

Ågren, A., Lidberg, W. & Ring, E. 2015. Mapping Temporal Dynamics in a Forest Stream Network—Implications for Riparian Forest Management. *Forests,* 6**,** 2982. https://doi.org/10.3390/f6092982

Ågren, A., Lidberg, W., Strömgren, M., Ogilvie, J. & Arp, P. 2014. Evaluating digital terrain indices for soil wetness mapping–a Swedish case study. *Hydrology and Earth System Sciences,* 18**,** 3623-3634. https://doi.org/10.5194/hess-18-3623-2014

Ågren, A. M., Larson, J., Paul, S. S., Laudon, H. & Lidberg, W. 2021. Use of multiple LIDAR-derived digital terrain indices and machine learning for high-resolution national-scale soil moisture mapping of the Swedish forest landscape. *Geoderma,* 404**,** 115280. https://doi.org/10.1016/j.geoderma.2021.115280

Ahti, T., Hämet-Ahti, L. & Jalas, J. 1968. Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici,* 5**,** 169-211. https://www.jstor.org/stable/23724233

Ahtikoski, A., Alenius, V. & Mäkitalo, K. 2010. Scots pine stand establishment with special emphasis on uncertainty and cost-effectiveness, the case of northern Finland. *New Forests,* 40**,** 69-84. https://doi.org/10.1007/s11056-009-9183-2

Andersson, E. & Keskitalo, E. C. H. 2018. Adaptation to climate change? Why business-as-usual remains the logical choice in Swedish forestry. *Global Environmental Change-Human and Policy Dimensions,* 48**,** 76-85. https://doi.org/10.1016/j.gloenvcha.2017.11.004

Ara, M., Barbeito, I., Elfving, B., Johansson, U. & Nilsson, U. 2021. Varying rectangular spacing yields no difference in forest growth and external wood quality in coniferous forest plantations. *Forest Ecology and Management,* 489**,** 119040. https://doi.org/10.1016/j.foreco.2021.119040

Ara, M., Barbeito, I., Kalen, C. & Nilsson, U. 2022a. Regeneration failure of Scots pine changes the species composition of young forests. *Scandinavian Journal of Forest Research,* 37**,** 14-22. https://doi.org/10.1080/02827581.2021.2005133

Ara, M., Berglund, M., Fahlvik, N., Johansson, U. & Nilsson, U. 2022b. Pre-Commercial Thinning Increases the Profitability of Norway Spruce Monoculture and Supports Norway Spruce-Birch Mixture over Full Rotations. *Forests,* 13, 1156 https://doi.org/10.3390/f13081156

Ara, M., Felton, A. M., Holmstrom, E., Petersson, L., Berglund, M., Johansson, U. & Nilsson, U. 2022c. Pre-commercial thinning in Norway spruce-birch mixed stands can provide abundant forage for ungulates without losing volume production. *Forest Ecology and Management,* 520, 120364. https://doi.org/10.1016/j.foreco.2022.120364

Archibold, O. W., Acton, C. & Ripley, E. A. 2000. Effect of site preparation on soil properties and vegetation cover, and the growth and survival of white spruce (*Picea glauca*) seedlings, in Saskatchewan. *Forest Ecology and Management,* 131**,** 127-141. https://doi.org/10.1016/S0378-1127(99)00205-4

Aza, A., Kallio, A. M. I., Pukkala, T., Hietala, A., Gobakken, T. & Astrup, R. 2022. Species selection in areas subjected to risk of root and butt rot: Applying Precision forestry in Norway. *Silva Fennica,* 56, 10732. https://doi.org/10.14214/sf.10732

Bassman, J. H. 1989. Influence of two site preparation treatments on ecophysiology of planted *Picea engelmannii* × *glauca* seedlings. *Canadian Journal of Forest Research,* 19**,** 1359-1370. https://doi.org/10.1139/x89-210

Bedford, L. & Sutton, R. F. 2000. Site preparation for establishing lodgepole pine in the sub-boreal spruce zone of interior British Columbia: the Bednesti trial, 10-year results. *Forest Ecology and Management,* 126**,** 227-238. https://doi.org/10.1016/S0378-1127(99)00090-0

Bare, B., & Dyck, B. (2001, June 17 - 20). Opening remarks - Precision Forestry. Preceedings of The First International Precision Forestry Cooperative Symposium Seattle, Washington.

Bergh, J., Linder, S., Lundmark, T. & Elfving, B. 1999. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *Forest ecology and management,* 119**,** 51-62. https://doi.org/10.1016/S0378-1127(98)00509-X

Bergh, J., Nilsson, U., Kjartansson, B. & Karlsson, M. 2010. Impact of climate change on the productivity of silver birch, Norway spruce and Scots pine stands in Sweden and economic implications for timber production. *Ecological Bulletins***,** 53, 185-196. https://www.jstor.org/stable/41442030

Bergquist, J., Fries, C. & Svensson, L. 2017. *Skogsstyrelsens återväxtuppföljning Resultat från 1999–2016*. Rapport 2017/6. Skogsstyrelsen, Jönköping, Sweden. [In Swedish]

Bergqvist, G., Bergström, R. & Wallgren, M. 2014. Recent browsing damage by moose on Scots pine, birch and aspen in young commercial forests–effects of forage availability, moose population density and site productivity. *Silva Fennica,* 48, 1077. https://doi.org/10.14214/sf.1077

Bergqvist, G., Wallgren, M., Jernelid, H. & Bergström, R. 2018. Forage availability and moose winter browsing in forest landscapes. *Forest Ecology and Management,* 419**,** 170-178. https://doi.org/10.1016/j.foreco.2018.03.049

Berner, L. T. & Goetz, S. J. 2022. Satellite observations document trends consistent with a boreal forest biome shift. *Global Change Biology,* 28**,** 3275-3292. https://doi.org/10.1111/gcb.16121

Blennow, K. 2012. Adaptation of forest management to climate change among private individual forest owners in Sweden. *Forest Policy and Economics,* 24**,** 41-47. https://doi.org/10.1016/j.forpol.2011.04.005

Blennow, K., & Hammarlund, K. 1993. From Heath to Forest: Land-use Transformation in Halland, Sweden. *Ambio*, 22, 561-567. https://www.jstor.org/stable/4314148

Boateng, J. O., Heineman, J. L., Bedford, L., Harper, G. J. & Linnell Nemec, A. F. 2009. Long-term effects of site preparation and postplanting vegetation control on *Picea glauca* survival, growth and predicted yield in boreal British Columbia. *Scandinavian Journal of Forest Research,* 24**,** 111-129. https://doi.org/10.1080/02827580902759685

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.-J., Schall, P., Spathelf, P. & Rock, J. 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research,* 24**,** 473-482. https://doi.org/10.1080/02827580903418224

Boyd, D. S. & Danson, F. M. 2005. Satellite remote sensing of forest resources: three decades of research development. *Progress in Physical Geography,* 29**,** 1-26. https://doi.org/10.1191/0309133305pp432ra

Brandel, G. 1990. *Volume functions for individual trees; Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula & Betula pubescens)*. Report. 26. Department of Forest Yield Research, Swedish University of Agricultural Sciences, Garpenberg, Sweden. [in Swedish with English summary]

Burdett, A. N. 1990. Physiological processes in plantation establishment and the development of specifications for forest planting stock. *Canadian Journal of Forest Research,* 20**,** 415-427. https://doi.org/10.1139/x90-059

Cardoso, J. C., Burton, P. J. & Elkin, C. M. 2020. A Disturbance Ecology Perspective on Silvicultural Site Preparation. *Forests,* 11**,** 1278. https://doi.org/10.3390/f11121278

Castro, J., Morales-Rueda, F., Navarro, F. B., Lof, M., Vacchiano, G. & Alcaraz-Segura, D. 2021. Precision restoration: a necessary approach to foster forest recovery in the 21st century. *Restoration Ecology,* 29. https://doi.org/10.1111/rec.13421

Celma, S., Blate, K., Lazdiņa, D., Dumins, K., Neimane, S., Ŝtāls, T.A., & Ŝtikāne, K. 2019. Effect of soil preparation method on root development of *P.sylvestris* and *P.abies* saplings in commercial forest stands. *New Forests*, 50, 283-290. https://doi.org/10.1007/s11056-018-9654-4

Chen, D. L., Achberger, C., Ou, T. H., Postgard, U., Walther, A. & Liao, Y. M. 2015. Projecting future local precipitation and its extremes for sweden. *Geografiska Annaler Series a-Physical Geography,* 97**,** 25-39. https://doi.org/10.1111/geoa.12084

Coll, L., Ameztegui, A., Collet, C., Löf, M., Mason, B., Pach, M., Verheyen, K., Abrudan, I., Barbati, A., Barreiro, S., Bielak, K., Bravo-Oviedo, A., Ferrari, B., Govedar, Z., Kulhavy, J., Lazdina, D., Metslaid, M., Mohren, F., Pereira, M., Peric, S., Rasztovits, E., Short, I., Spathelf, P., Sterba, H., Stojanovic, D., Valsta, L., Zlatanov, T. & Ponette, Q. 2018. Knowledge gaps about mixed forests: What do European forest managers want to know and what answers can science provide? *Forest Ecology and Management,* 407**,** 106-115. https://doi.org/10.1016/j.foreco.2017.10.055

Collet, C., Vast, F., Richter, C. & Koller, R. 2021. Cultivation profile: a visual evaluation method of soil structure adapted to the analysis of the impacts of mechanical site preparation in forest plantations. *European Journal of Forest Research,* 140**,** 65-76. https://doi.org/10.1007/s10342-020-01315-2

Dahlgren Lidman, F., Holmström, E., Lundmark, T. & Fahlvik, N. 2021. Management of spontaneously regenerated mixed stands of birch and Norway spruce in Sweden. *Silva Fennica*, 55, 10485. https://doi.org/10.14214/sf.10485

Daniels J., & Thunholm B. 2014. *Rikstäckande jorddjupsmodell.* Rapport 2014:4. Swedish Geological Survey of Sweden. Uppsala, Sweden. [In Swedish]

Daugaviete, M., Krumina, M., Kaposts, V. & Lazdins, A. 2003. Farmland afforestation: the plantations of birch Betula pendula Roth. on different soils. *Baltic Forestry,* 9**,** 9-21.
Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F. & Bargellini, P. 2012. Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment,* 120**,** 25-36. https://doi.org/10.1016/j.rse.2011.11.026
Dumins, K., & Lazdina, D. 2018. Forest Regeneration quality – Factors affecting first year survival of planted trees. *Research for Rural Development,* 1. https://doi.org/10.22616/rrd.24.2018.008
Echiverri, L. F., Macdonald, S. E. & Nielsen, S. E. 2022. Mounding treatments set back bryophyte recovery on linear disturbances in treed peatlands. *Restoration Ecology***,** 31, e13813. https://doi.org/10.1111/rec.13813
Eidmann, H.H. & von Sydow, F. 1989. Stockings for protection of containerized conifer seedlings against pine weevil (*Hylobius abietis L.*) damage. *Scandinavian Journal of Forest Research*, 4, 537-547. https://doi.org/10.1080/02827588909382586
Enander, K-G. 2007. *Skogsbruk på samhällets vilkor: Skogsskötsel och skogspolitik under 150 år*. Report 1, Swedish University of Agriculture, Umeå, Sweden. [In Swedish]
Eriksson, O. & Raunistola, T. 1990. Impact of soil scarification on reindeer pastures. *Rangifer,* 10**,** 99-106. https://doi.org/10.7557/2.10.3.837
Ersson B-T. 2014. Concepts for Mechanized Tree Planting in Southern Sweden. Doctoral dissertation. *Acta Universitatis Agriculturae Sueciae,* 2014:76
Ersson, B-T. 2022. *Maskinell plantering-analys av planteringsmaskinen PlantmaX potential inom privatskogsbruket*. Skogsmästarskolans rapportserie 2022:01. Swedish University of Agricultur, Skinnskatteberg, Sweden. [In Swedish with English summary]
Felton, A., Lindbladh, M., Brunet, J. & Fritz, O. 2010. Replacing coniferous monocultures with mixed-species production stands: An assessment of the potential benefits for forest biodiversity in northern Europe. *Forest Ecology and Management,* 260**,** 939-947. https://doi.org/10.1016/j.foreco.2010.06.011
Felton, A., Nilsson, U., Sonesson, J., Felton, A. M., Roberge, J. M., Ranius, T., Ahlstrom, M., Bergh, J., Bjorkman, C., Boberg, J., Drossler, L., Fahlvik, N., Gong, P., Holmstrom, E., Keskitalo, E. C. H., Klapwijk, M. J., Laudon, H., Lundmark, T., Niklasson, M., Nordin, A., Pettersson, M., Stenlid, J., Stens, A. & Wallertz, K. 2016. Replacing monocultures with mixed-species stands: Ecosystem service implications of two production forest alternatives in Sweden. *Ambio,* 45**,** S124-S139. https://doi.org/10.1007/s13280-015-0749-2
Felton, A., Petersson, L., Nilsson, O., Witzell, J., Cleary, M., Felton, A. M., Björkman, C., Sang, Å. O., Jonsell, M. & Holmström, E. 2020. The tree species matters: Biodiversity and ecosystem service implications of replacing Scots pine production stands with Norway spruce. *Ambio,* 49**,** 1035-1049. https://doi.org/10.1007/s13280-019-01259-x
Floistad, I. S., Hylen, G., Hanssen, K. H. & Granhus, A. 2018. Germination and seedling establishment of Norway spruce (*Picea abies*) after clear-cutting is affected by timing of soil scarification. *New Forests,* 49**,** 231-247. https://doi.org/10.1007/s11056-017-9616-2
Friberg, G., Berlin, M., Johannesson, T. & Eliasson, L. 2017. *Lutningsindex – beslutsstöd vid markberedning*. Arbetsrapport 928-2017. Skogforsk, Uppsala, Sweden.

Friberg, G., Jacobsson, S., Möller, J., Bhuiyan, N., & Willén, E. 2019. *Föryngringsplanering med hjälp av skördarinformation och geodata*. Arbetsrapport 1002-2019. Skogforsk, Uppsala, Sweden. [In Swedish with English summary]

Gålnander, H., Berlin, M., & Sonesson, J. 2020. *Framtidens skogar – Består de av planterade plantor eller naturligt föryngrade träd?* Arbetsrapport 1052-2020. Skogforsk, Uppsala, Sweden. [In Swedish with English summary]

Gastón, A., García-Viñas, J. I., Bravo-Fernández, A. J., López-Leiva, C., Oliet, J. A., Roig, S. & Serrada, R. 2014. Species distribution models applied to plant species selection in forest restoration: are model predictions comparable to expert opinion? *New forests,* 45**,** 641-653. https://doi.org/10.1007/s11056-014-9427-7

Goude, M., Nilsson, U., Mason, E. & Vico, G. 2022. Using hybrid modelling to predict basal area and evaluate effects of climate change on growth of Norway spruce and Scots pine stands. *Scandinavian Journal of Forest Research,* 37**,** 59-73. https://doi.org/10.1080/02827581.2022.2039278

Grossnickle, S. 2016. Restoration silviculture: an ecophysiological perspective: "lessons learned across 40 years. *Reforesta* 1: 1-36. http://dx.doi.org/10.21750/REFOR.1.02.2

Grossnickle, S. C. 2005. Importance of root growth in overcoming planting stress. *New forests,* 30**,** 273-294. https://doi.org/10.1007/s11056-004-8303-2

Grossnickle, S. C. 2012. Why seedlings survive: influence of plant attributes. *New Forests,* 43**,** 711-738. https://doi.org/10.1007/s11056-012-9336-6

Gundersen, V. S. & Frivold, L. H. 2008. Public preferences for forest structures: A review of quantitative surveys from Finland, Norway and Sweden. *Urban Forestry & Urban Greening,* 7**,** 241-258. https://doi.org/10.1016/j.ufug.2008.05.001

Haeussler, S., Kaffanke, T., Boateng, J. O., Mcclarnon, J. & Bedford, L. 2017. Site preparation severity influences lodgepole pine plant community composition, diversity, and succession over 25 years. *Canadian Journal of Forest Research,* 47**,** 1659-1671. https://doi.org/10.1139/cjfr-2017-0142

Häggstrom, B., Domevscik, M., Ohlund, J. & Nordin, A. 2021. Survival and growth of Scots pine (*Pinus sylvestris*) seedlings in north Sweden: effects of planting position and arginine phosphate addition. *Scandinavian Journal of Forest Research,* 36**,** 423-433. https://doi.org/10.1080/02827581.2021.1957999

Hahn, T., Eggers, J., Subramanian, N., Caicoya, A. T., Uhl, E. & Snall, T. 2021. Specified resilience value of alternative forest management adaptations to storms. *Scandinavian Journal of Forest Research,* 36**,** 585-597. https://doi.org/10.1080/02827581.2021.1988140

Hallsby, G. & Örlander, G. 2004. A comparison of mounding and inverting to establish Norway spruce on podzolic soils in Sweden. *Forestry: An International Journal of Forest Research,* 77**,** 107-117. https://doi.org/10.1093/forestry/77.2.107

Hansson, L. J., Ring, E., Franko, M. A. & Gärdenäs, A. I. 2018. Soil temperature and water content dynamics after disc trenching a sub-xeric Scots pine clearcut in central Sweden. *Geoderma,* 327**,** 85-96. https://doi.org/10.1016/j.geoderma.2018.04.023

Heiskanen, J. & Rikala, R. 2006. Root growth and nutrient uptake of Norway spruce container seedlings planted in mounded boreal forest soil. *Forest Ecology and Management,* 222**,** 410-417. https://doi.org/10.1016/j.foreco.2005.10.047

Heiskanen, J., Saksa, T. & Luoranen, J. 2013. Soil preparation method affects outplanting success of Norway spruce container seedlings on till soils susceptible to frost heave. *Silva Fennica,* 47**,** 893. https://doi.org/10.14214/sf.893

Henneb, M., Valeria, O., Thiffault, N., Fenton, N. J. & Bergeron, Y. 2019. Effects of Mechanical Site Preparation on Microsite Availability and Growth of Planted Black Spruce in Canadian Paludified Forests. *Forests,* 10, 670. https://doi.org/10.3390/f10080670

Holmgren, P. & Thuresson, T. 1998. Satellite remote sensing for forestry planning—A review. *Scandinavian Journal of Forest Research,* 13**,** 90-110. https://doi.org/10.1080/02827589809382966

Holmström, E., Gålnander, H. & Petersson, M. 2019. Within-Site Variation in Seedling Survival in Norway Spruce Plantations. *Forests,* 10**,** 181. https://doi.org/10.3390/f10020181

Hynynen, J., Niemisto, P., Vihera-Aarnio, A., Brunner, A., Hein, S. & Velling, P. 2010. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. *Forestry,* 83**,** 103-119. https://doi.org/10.1093/forestry/cpp035

Hytonen, J. & Jylha, P. 2005. Effects of competing vegetation and post-planting weed control on the mortality, growth and vole damages to Betula pendula planted on former agricultural land. *Silva Fennica,* 39**,** 365-380.

Johansson, K., Nilsson, U. & Örlander, G. 2013a. A comparison of long-term effects of scarification methods on the establishment of Norway spruce. *Forestry: An International Journal of Forest Research,* 86**,** 91-98. https://doi.org/10.1093/forestry/cps062

Johansson, K., Ring, E. & Högbom, L. 2013b. Effects of pre-harvest fertilization and subsequent soil scarification on the growth of planted *Pinus sylvestris* seedlings and ground vegetation after clear-felling. *Silva Fennica,* 47**,** 1016. https://doi.org/10.14214/sf.1016

Jonsson, A., Elfving, B., Hjelm, K., Lämås, T. & Nilsson, U. 2022. Will intensity of forest regeneration measures improve volume production and economy? *Scandinavian Journal of Forest Research***,** 37, 200-212. https://doi.org/10.1080/02827581.2022.2085784

Kardell, L. 2004. *Svenskarna och skogen, Del 2: Från baggböleri till naturvård*. Skogsstyrelsen, Ödeshög, Sweden. [In Swedish]

Karlsson, A. 2002. Site preparation of abandoned fields and early establishment of planted small-sized seedlings of silver birch. *New Forests,* 23**,** 159-175. https://doi.org/10.1023/A:1015605216150

Karlsson, M. & Nilsson, U. 2005. The effects of scarification and shelterwood treatments on naturally regenerated seedlings in southern Sweden. *Forest Ecology and Management,* 205**,** 183-197. https://doi.org/10.1016/j.foreco.2004.10.046

Karlsson, M., Nilsson, U. & Örlander, G. 2002. Natural Regeneration in Clear-cuts: Effects of Scarification, Slash Removal and Clear-cut Age. *Scandinavian Journal of Forest Research,* 17**,** 131-138. https://doi.org/10.1080/028275802753626773

Kellomaki, S., Peltola, H., Nuutinen, T., Korhonen, K. T. & Strandman, H. 2008. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philosophical Transactions of the Royal Society B-Biological Sciences,* 363**,** 2341-2351. https://doi.org/10.1098/rstb.2007.2204

Keskitalo, E., Bergh, J., Felton, A., Björkman, C., Berlin, M., Axelsson, P., Ring, E., Ågren, A., Roberge, J.-M., Klapwijk, M. & Boberg, J. 2016. Adaptation to Climate Change in Swedish Forestry. *Forests,* 7**,** 28. https://doi.org/10.3390/f7020028

Lantmäteriet. 2022. *Product description Laser data Download, NH*. Lantmäteriet, Gävle, Sweden. https://www.lantmateriet.se/globalassets/geodata/geodataprodukter/hojddata/e_pb_laser data_nedladdning_nh.pdf
Lantmäteriet. 2023. *Product description Laser data Download, forest*. Lantmäteriet, Gävle, Sweden. https://www.lantmateriet.se/globalassets/geodata/geodataprodukter/hojddata/e_pb_laser data_nedladdning_skog.pdf
Langvall, O. & Löfvenius, M. O. 2002. Effect of shelterwood density on nocturnal near-ground temperature, frost injury risk and budburst date of Norway spruce. *Forest ecology and Management,* 168**,** 149-161. https://doi.org/10.1016/S0378-1127(01)00754-X
Langvall, O., Nilsson, U. & Örlander, G. 2001. Frost damage to planted Norway spruce seedlings — influence of site preparation and seedling type. *Forest Ecology and Management,* 141**,** 223-235. https://doi.org/10.1016/S0378-1127(00)00331-5
Langvall, O. & Örlander, G. 2001. Effects of pine shelterwoods on microclimate and frost damage to Norway spruce seedlings. *Canadian Journal of Forest Research,* 31**,** 155-164. https://doi.org/10.1139/x00-149
Lariviere, D. 2023. Old trees in young forests: Biodiversity management in planted conifer forests in southern Sweden. Doctoral dissertation. *Acta Universitatis Agriculturae Sueciae*.
Larson, J., Lidberg, W., Ågren, A. M. & Laudon, H. 2022. Predicting soil moisture conditions across a heterogeneous boreal catchment using terrain indices. *Hydrology and Earth System Sciences,* 26**,** 4837-4851. https://doi.org/10.5194/hess-26-4837-2022
Lindahl, K. B., Stens, A., Sandstrom, C., Johansson, J., Lidskog, R., Ranius, T. & Roberge, J. M. 2017. The Swedish forestry model: More of everything? *Forest Policy and Economics,* 77**,** 44-55. https://doi.org/10.1016/j.forpol.2015.10.012
Lodin, I., Brukas, V. & Wallin, I. 2017. Spruce or not? Contextual and attitudinal drivers behind the choice of tree species in southern Sweden. *Forest Policy and Economics,* 83**,** 191-198. https://doi.org/10.1016/j.forpol.2016.11.010
Lundmark, J-E. 1986. *Skogsmarkens ekologi – ståndortsanpassat skogsbruk del 1-Grunder.* Skogsstyrelsen, Jönköping, Sweden. [In Swedish]
Lundmark, J-E. 1988. *Skogsmarkens ekologi – ståndortsanpassat skogsbruk del 2 – Tillämpning*. Skogsstyrelsen, Jönköping, Sweden. [In Swedish]
Lundmark-Thelin, A. & Johansson, M.-B. 1997. Influence of mechanical site preparation on decomposition and nutrient dynamics of Norway spruce (*Picea abies* (L.) Karst.) needle litter and slash needles. *Forest Ecology and Management,* 96**,** 101-110. https://doi.org/10.1016/S0378-1127(97)00040-6
Luoranen, J., Riikonen, J. & Saksa, T. 2023. Damage caused by an exceptionally warm and dry early summer on newly planted Norway spruce container seedlings in Nordic boreal forests. *Forest Ecology and Management,* 528**,** 120649. https://doi.org/10.1016/j.foreco.2022.120649
Luoranen, J., Rikala, R. & Smolander, H. 2003. Root egress and field performance of actively growing Betula pendula container seedlings. *Scandinavian Journal of Forest Research,* 18**,** 133-144. https://doi.org/10.1080/02827580310003704a

Luoranen, J., Saksa, T. & Lappi, J. 2018. Seedling, planting site and weather factors affecting the success of autumn plantings in Norway spruce and Scots pine seedlings. *Forest Ecology and Management,* 419-420**,** 79-90. https://doi.org/10.1016/j.foreco.2018.03.040
Löf, M. 2000. Influence of patch scarification and insect herbivory on growth and survival in *Fagus sylvatica* L., *Picea abies* L. Karst. and *Quercus robur* L. seedlings following a Norway spruce forest. *Forest Ecology and Management,* 134**,** 111-123. https://doi.org/10.1016/S0378-1127(99)00250-9
Löf, M., Dey, D. C., Navarro, R. M. & Jacobs, D. F. 2012. Mechanical site preparation for forest restoration. *New Forests,* 43**,** 825-848. https://doi.org/10.1007/s11056-012-9332-x
Löf, M., Gemmel, P., Nilsson, U. & Welander, N. T. 1998. The influence of site preparation on growth in *Quercus robur* L. seedlings in a southern Sweden clear-cut and shelterwood. *Forest Ecology and Management,* 109**,** 241-249. https://doi.org/10.1016/S0378-1127(98)00254-0
Löf, M., Rydberg, D. & Bolte, A. 2006. Mounding site preparation for forest restoration: Survival and short term growth response in *Quercus robur* L. seedlings. *Forest Ecology and Management,* 232**,** 19-25. https://doi.org/10.1016/j.foreco.2006.05.003
Mallik, A. & Kravchenko, D. 2016. Black spruce (*Picea mariana*) restoration in Kalmia heath by scarification and microsite mulching. *Forest Ecology and Management,* 362**,** 10-19. https://doi.org/10.1016/j.foreco.2015.10.020
Margolis, H. A. & Brand, D. G. 1990 An ecophysiological basis for understanding plantation establishment.. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 20**,** 375-390. https://doi.org/10.1139/x90-056
Marquis, B., Duval, P., Bergeron, Y., Simard, M., Thiffault, N. & Tremblay, F. 2021. Height growth stagnation of planted spruce in boreal mixedwoods: Importance of landscape, microsite, and growing-season frosts. *Forest Ecology and Management,* 479**,** 118533. https://doi.org/10.1016/j.foreco.2020.118533
McCarthy, R., Rytter, L. & Hjelm, K. 2017. Effects of soil preparation methods and plant types on the establishment of poplars on forest land. *Annals of Forest Science,* 74**,** 47. https://doi.org/10.1007/s13595-017-0647-9
Mjöfors, K., Strömgren, M., Nohrstedt, H.-Ö., Johansson, M.-B. & Gärdenäs, A. I. 2017. Indications that site preparation increases forest ecosystem carbon stocks in the long term. *Scandinavian Journal of Forest Research,* 32**,** 717-725. https://doi.org/10.1080/02827581.2017.1293152
Mohtashami, S., Eliasson, L., Jansson, G. & Sonesson, J. 2017. Influence of soil type, cartographic depth-to-water, road reinforcement and traffic intensity on rut formation in logging operations: a survey study in Sweden. *Silva Fennica,* 51, 2018. https://doi.org/10.14214/sf.2018
Murphy, N. C. P., Ogilvie, J., Meng, F.-R., White, B., Bhatti, S. J. & Arp, P. A. 2011. Modelling a mapping topographic variations in forest soils at high resolution. *Ecological modelling,* 222**,** 2314-2332. https://doi.org/10.1016/j.ecolmodel.2011.01.003
Murphy, P. N. C., Ogilvie, J., Castonguay, M., Zhang, C.-F., Meng, F.-R. & Arp, P. A. 2008. Improving forest operations planning through high-resolution flow-channel and wet-areas mapping. *The Forestry Chronicle,* 84**,** 568-574. https://doi.org/10.5558/tfc84568-4
Näslund, M. 1936. *Skogsförsöksanstaltens gallringsförsök i tallskog.* Meddelande från Statens Skogsförsöksanstalt 29. [In Swedish with English summary.]

Nijland, W., Coops, N. C., Macdonald, S. E., Nielsen, S. E., Bater, C. W., White, B., Ogilvie, J. & Stadt, J. 2015. Remote sensing proxies of productivity and moisture predict forest stand type and recovery rate following experimental harvest. *Forest Ecology and Management,* 357**,** 239-247. https://doi.org/10.1016/j.foreco.2015.08.027

Nilsson, O., Hjelm, K. & Nilsson, U. 2019. Early growth of planted Norway spruce and Scots pine after site preparation in Sweden. *Scandinavian Journal of Forest Research,* 34**,** 678-688. https://doi.org/10.1080/02827581.2019.1659398

Nilsson, U., Gemmel, P. & Hällgren, J. 1996. Competing vegetation effects on initial growth of planted *Picea abies*. *New Zealand Journal of Forestry Science,* 26**,** 84-98.

Nilsson, U. & Örlander, G. 1999. Vegetation management on grass-dominated clearcuts planted with Norway spruce in southern Sweden. *Canadian Journal of Forest Research,* 29**,** 1015-1026. https://doi.org/10.1139/x99-071

Nilsson, U., Örlander, G. & Karlsson, M. 2006. Establishing mixed forests in Sweden by combining planting and natural regeneration—effects of shelterwoods and scarification. *Forest ecology and management,* 237**,** 301-311. https://doi.org/10.1016/j.foreco.2006.09.053

Nilsson, U., Agestam, E., Ekö, P.-M., Elfving, B., Fahlvik, N., Johansson, U., Karlsson, K., Lundmark, T., Wallentin C. 2010. Thinning of Scots pine and Norway spruce monocultures in Sweden: effects of different thinning programmes on stand-level gross and net stem volume production. *Studia Forestalia Suecica*. 219: 1–46.

Nordlander, G., Hellqvist, C., Johansson, K. & Nordenhem, H. 2011. Regeneration of European boreal forests: Effectiveness of measures against seedling mortality caused by the pine weevil *Hylobius abietis*. *Forest Ecology and Management,* 262**,** 2354-2363. https://doi.org/10.1016/j.foreco.2011.08.033

Nordlander, G., Mason, E. G., Hjelm, K., Nordenhem, H. & Hellqvist, C. 2017. Influence of climate and forest management on damage risk by the pine weevil *Hylobius abietis* in northern Sweden. *Silva Fennica*, 51, 7751.https://doi.org/10.14214/sf.7751

O'hara, K. L. & Nagel, L. M. 2013. The stand: revisiting a central concept in forestry. *Journal of Forestry,* 111**,** 335-340. https://doi.org/10.5849/jof.12-114

Örlander, G. 1986. Effect of planting and scarification on the water relations in planted seedlings of Scots pine, *Studia Forestalia Suecica,* 173, 3-17

Örlander, G., Egnell, G. & Albrektson, A. 1996. Long-term effects of site preparation on growth in Scots pine. *Forest Ecology and Management,* 86**,** 27-37. https://doi.org/10.1016/S0378-1127(96)03797-8

Örlander, G., Gemmel, P. & Hunt, J. 1990. *Site preparation: A Swedish overview*. Ministry of Forests, Brittish Columbia.

Örlander, G., Gemmel, P. & Wilhelmsson, C. 1991. *Markberedningsmetodens, planteringsdjupets och planteringpunktens betydelse för plantors etablering i ett område med låg humiditet i södra Sverige*. Swedish University of Agriculture, Umeå, Sweden. [In Swedish with English summary]

Örlander, G., Hallsby, G., Gemmel, P. & Wilhelmsson, C. 1998. Inverting improves establishment of *Pinus contorta* and *Picea abies*— 10-year results from a site preparation trial in Northern Sweden. *Scandinavian Journal of Forest Research,* 13**,** 160-168. https://doi.org/10.1080/02827589809382972

Östlund, L., Laestander, S., Aurell, G., & Hörnberg, G. 2022. The war on deciduous forest: Large-scale herbicide treatment in Swedish boreal forest 1948-1984. *Ambio*, 51, 1352-1366. https://doi.org/10.1007/s13280-021-01660-5

Pearson, M., Saarinen, M., Minkkinen, K., Silvan, N. & Laine, J. 2011. Mounding and scalping prior to reforestation of hydrologically sensitive deep-peated sites: factors behind Scots pine regeneration success. *Silva Fennica*, 45, 647-667.

Petersson, L., Holmström, E., Lindbladh, M. & Felton, A. 2019. Tree species impact on understory vegetation: Vascular plant communities of Scots pine and Norway spruce managed stands in northern Europe. *Forest Ecology and Management,* 448**,** 330-345. https://doi.org/10.1016/j.foreco.2019.06.011

Petersson, M., Örlander, G. & Nordlander, G. 2005. Soil features affecting damage to conifer seedlings by the pine weevil *Hylobius abietis*. *Forestry,* 78**,** 83-92. https://doi.org/10.1093/forestry/cpi008

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J. & Stenseth, N. C. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in ecology & evolution,* 20**,** 503-510. https://doi.org/10.1016/j.tree.2005.05.011

Pfeffer, S. E., Singh, N. J., Cromsigt, J. P. G. M., Kalén, C. & Widemo, F. 2021. Predictors of browsing damage on commercial forests – A study linking nationwide management data. *Forest Ecology and Management,* 479**,** 118597. https://doi.org/10.1016/j.foreco.2020.118597

Phan, T. N. & Kappas, M. 2018. Application of MODIS land surface temperature data: a systematic literature review and analysis. *Journal of Applied Remote Sensing,* 12**,** 041501. https://doi.org/10.1117/1.JRS.12.041501

Piirainen, S., Finér, L. & Starr, M. 2015. Changes in forest floor and mineral soil carbon and nitrogen stocks in a boreal forest after clear-cutting and mechanical site preparation. *European Journal of Soil Science,* 66**,** 735-743. https://doi.org/10.1111/ejss.12264

Pikkarainen, L., Luoranen, J. & Peltola, H. 2021. Early Field Performance of Small-Sized Silver Birch and Scots Pine Container Seedlings at Different Planting Depths. *Forests,* 12**,** 519. https://doi.org/10.3390/f12050519

Prévost, M. & Dumais, D. 2018. Long-term growth response of black spruce advance regeneration (layers), natural seedlings and planted seedlings to scarification: 25th year update. *Scandinavian Journal of Forest Research,* 33**,** 583-593. https://doi.org/10.1080/02827581.2018.1430250

Pykälä, J. 2004. Immediate increase in plant species richness after clear-cutting of boreal herb-rich forests. *Applied Vegetation Science,* 7**,** 29-34. https://doi.org/10.1111/j.1654-109X.2004.tb00592.x

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reicis, K., Bradley, R. L., Joanisse, G., Thiffault, N., Scott, D. & Parsons, W. F. J. 2023. Mechanical scarification can reduce competitive traits of boreal ericaceous shrubs and improve nutritional site quality. *Forestry: An International Journal of Forest Research,* 96, 293-303. https://doi.org/10.1093/forestry/cpac047

Ring, E., Ågren, A., Bergkvist, I., Finér, L., Johansson, F. & Högbom, L. 2020. *A guide to using wet area maps in forestry*. Arbetsrapport 1051-2020. Skogforsk, Uppsala, Sweden.

Roberts, M. R. & Zhu, L. 2002. Early response of the herbaceous layer to harvesting in a mixed coniferous–deciduous forest in New Brunswick, Canada. *Forest Ecology and Management,* 155**,** 17-31. https://doi.org/10.1016/S0378-1127(01)00544-8

Rosensten, A. (1737). *Tanckar, om skogars skiötzel eller Underrättelse om alla willa träns natur och egenskaper, som finnes uti Sweriges rike, huru de kunna och böra, antingen genom såning eller ock plantering updragas, at däraf ofelbart, med god och hastig fortgång winna skog på behörige orter af slättbygderne, som deraf nu lida stor brist på bränne, byggningz timber samt alla andra til huushåldning nödige och omistelige träwaror. Hwarjämte följer ett bihang om allehanda fruchtbärande : träns skiötzel,som höra til trägårdar. Wälment utgifne af Anders Rosensten. Stads Major*. Lund: Ludvig Decreaux, directeur öfwer kongl. academiens priviligerade tryckerij i Lund. [In Swedish]
Saksa, T., Uusitalo, J., Lindeman, H., Häyrynen, E., Kulju, S. & Huuskonen, S. 2021. Decision Support Tool for Tree Species Selection in Forest Regeneration Based on Harvester Data. *Forests,* 12**,** 1329. https://doi.org/10.3390/f12101329
Schlyter, P., Stjernquist, I., Bärring, L., Jönsson, A. M. & Nilsson, C. 2006. Assessment of the impacts of climate change and weather extremes on boreal forests in northern Europe, focusing on Norway spruce. *Climate Research,* 31**,** 75-84.
Schou, E., Thorsen, B. J. & Jacobsen, J. B. 2015. Regeneration decisions in forestry under climate change related uncertainties and risks: Effects of three different aspects of uncertainty. *Forest Policy and Economics,* 50**,** 11-19. https://doi.org/10.1016/j.forpol.2014.09.006
SFA. 2020. *Forest management in Sweden: Current practice and historical background*. Skogsstyrelsen, Jönköping, Sweden.
SFA. 2022. Swedish Forest Agency, statistics database. https://www.skogsstyrelsen.se/en/statistics/statistical-database/
Skogforsk. 2022. Presentation av Autoplant på Världsutställningen. https://www.skogforsk.se/kunskap/kunskapsbanken/2022/presentation-av-autoplant-pa-varldsutstallningen/ [Video presentation of the project Autoplant by Linnea Hansson]
Skogskunskap. 2021. *Rätt planteringspunkt*. https://www.skogskunskap.se/skota-barrskog/foryngra/plantering/ratt-planeringspunkt/ [In Swedish]
Sikström, U., Hjelm, K., Hanssen, K. H., Saksa, T. & Wallertz, K. 2020. Influence of mechanical site preparation on regeneration success of planted conifers in clearcuts in Fennoscandia–a review. *Silva Fennica*, 54, 10172. https://doi.org/10.14214/sf.10172
SMHI. 2022. *Sveriges klimat*. Swedish Meteorological and Hydrological Institute, Norrköping, Sweden. https://www.smhi.se/kunskapsbanken/klimat/sveriges-klimat/sveriges-klimat-1.6867 [In Swedish]
SMHI. Swedish Meteorological and Hydrological Institute, Norrköping, Sweden. http://opendata-download-metobs.smhi.se/explore/
Smolander, A. & Heiskanen, J. 2007. Soil N and C transformations in two forest clear-cuts during three years after mounding and inverting. *Canadian Journal of Soil Science,* 87**,** 251-258. https://doi.org/10.4141/S06-028
Spittlehouse, D. & Childs, S. 1990. Evaluating the seedling moisture environment after site preparation. Sustained productivity of forest soils. In *Proceedings of the 7th North American Forest Soils Conference,* 80-94. University of British Columbia, Vancouver, Canada
Strömgren, M., Mjöfors, K. & Olsson, B. A. 2017. Soil-surface CO2 flux during the first 2 years after stump harvesting and site preparation in 14 Swedish forests. *Scandinavian Journal of Forest Research,* 32**,** 213-221. https://doi.org/10.1080/02827581.2016.1221993

Subramanian, N., Bergh, J., Johansson, U., Nilsson, U. & Sallnäs, O. 2016. Adaptation of Forest Management Regimes in Southern Sweden to Increased Risks Associated with Climate Change. *Forests,* 7**,** 8. https://doi.org/10.3390/f7010008
Sutton, R. 1993. Mounding site preparation: a review of European and North American experience. *New forests,* 7**,** 151-192. https://doi.org/10.1007/BF00034198
Thiffault, N., Elferjani, R., Hébert, F., Paré, D. & Gagné, P. 2020. Intensive mechanical site preparation to establish short rotation hybrid poplar plantations—A case-study in Québec, Canada. *Forests,* 11**,** 785. https://doi.org/10.3390/f11070785
Thiffault, N. & Jobidon, R. 2006. How to shift unproductive *Kalmia angustifolia – Rhododendron groenlandicum* heath to productive conifer plantation. *Canadian Journal of Forest Research,* 36**,** 2364-2376. https://doi.org/10.1139/x06-090
Thiffault, N., Jobidon, R. & Munson, A. D. 2003. Performance and physiology of large containerized and blare-root spruce seedlings in relation to scarification and competition in Quebec (Canada). *Annals of Forest Science,* 60**,** 645-655. https://doi.org/ 10.1051/forest:2003057
Thiffault, N., Titus, B. D. & English, B. 2017. Twenty-five years post-treatment conifer responses to silviculture on a Kalmia-dominated site in eastern Canada. *Forestry Chronicle,* 93**,** 161-170. https://doi.org/10.5558/tfc2017-022
Thiffault, N., Titus, B. D. & Moroni, M. T. 2010. Silviculture and planted species interact to influence reforestation success on a Kalmia-dominated site–a 15-year study. *The Forestry Chronicle,* 86**,** 234-242. https://doi.org/10.5558/tfc86234-2
Uggla, Y. & Lidskog, R. 2016. Climate risks and forest practices: forest owners' acceptance of advice concerning climate change. *Scandinavian Journal of Forest Research,* 31**,** 618-625. https://doi.org/10.1080/02827581.2015.1134648
Uotila, K., Rantala, J., Saksa, T. & Harstela, P. 2010. Effect of soil preparation method on economic result of Norway spruce regeneration chain. *Silva Fennica* 44**,** 511-524.
Venäläinen, A., Lehtonen, I., Laapas, M., Ruosteenoja, K., Tikkanen, O.-P., Viiri, H., Ikonen, V.-P. & Peltola, H. 2020. Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. *Global Change Biology,* 26**,** 4178-4196. https://doi.org/10.1111/gcb.15183
von Sydow, F. 1997. Abundance of pine weevils (*Hylobius abietis*) and damage to conifer seedlings in relation to silvicultural practices. *Scandinavian Journal of Forest Research,* 12**,** 157-167. https://doi.org/10.1080/02827589709355397
Wahlgren, A. 1922. *Skogsskötsel: Handledning vid uppdragande, vård och föryngring*. P.A Norstedt & Söners förlag, Stockholm, Sweden. [In Swedish]
Wallertz, K., Björklund, N., Hjelm, K., Petersson, M. & Sundblad, L.-G. 2018. Comparison of different site preparation techniques: quality of planting spots, seedling growth and pine weevil damage. *New Forests***,** 705-722. https://doi.org/10.1007/s11056-018-9634-8
Wallertz, K. & Malmqvist, C. 2013. The effect of mechanical site preparation methods on the establishment of Norway spruce (*Picea abies* (L.) Karst.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) in southern Sweden. *Forestry,* 86**,** 71-78. https://doi.org/10.1093/forestry/cps065
White, J. C., Coops, N. C., Wulder, M. A., Vastaranta, M., Hilker, T. & Tompalski, P. 2016. Remote Sensing Technologies for Enhancing Forest Inventories: A Review. *Canadian Journal of Remote Sensing,* 42**,** 619-641. https://doi.org/10.1080/07038992.2016.1207484

Wiensczyk, A., Swift, K., Morneault, A., Thiffault, N., Szuba, K. & Bell, F. W. 2011. An overview of the efficacy of vegetation management alternatives for conifer regeneration in boreal forests. *Forestry Chronicle,* 87**,** 175-200. https://doi.org/10.5558/tfc2011-007

Wilcke, R. a. I., Kjellström, E., Lin, C., Matei, D., Moberg, A. & Tyrlis, E. 2020. The extremely warm summer of 2018 in Sweden – set in a historical context. *Earth System. Dynamics.,* 11**,** 1107-1121. https://doi.org/10.5194/esd-11-1107-2020

Wulder, M. A., Hall, R. J., Coops, N. C. & Franklin, S. E. 2004. High Spatial Resolution Remotely Sensed Data for Ecosystem Characterization. *BioScience,* 54**,** 511-521. https://doi.org/10.1641/0006-3568(2004)054[0511:HSRRSD]2.0.CO;2

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