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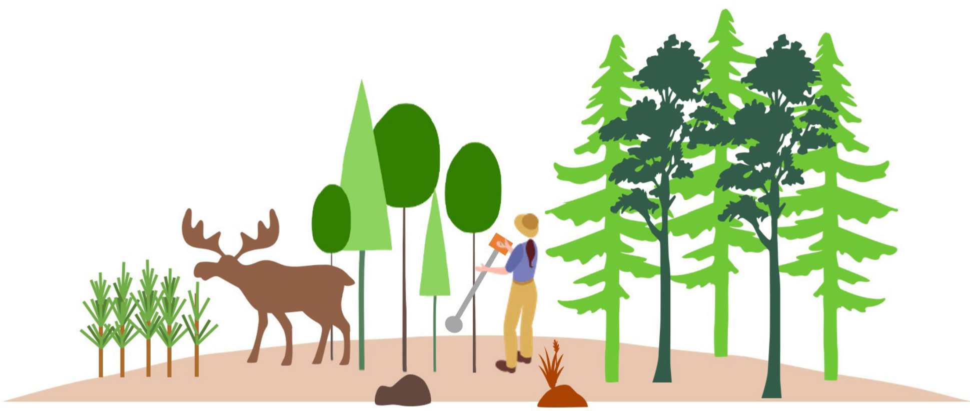
Establishment and early management of young forest in Sweden

Stand structure, spatial design and pre-commercial thinning

MOSTARIN ARA



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Cover: Ungulates interaction and silvicultural activities in the development of Swedish forest
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Abstract

Demands on forests have shifted from one (production) to multiple ecosystem services. New management strategies need to be developed to balance production and other services. In this thesis, I evaluate alternative forest management strategies to balance production, profit, and multiple ecosystem services. I also emphasize describing young Swedish forests. Field experiments and national inventory data from Sweden were analysed in this thesis.

No negative effect of rectangular planting design during forest establishment was found on the production of coniferous plantations. This provides an opportunity to select microsites for planting seedlings that can improve regeneration while facilitating existing forest operations or introducing new management practices. Although during establishment, either Norway spruce or Scots pine alone is used as a regeneration tree species, young forests mostly contain a mix of these species together with naturally regenerated broadleaves. Different pre-commercial thinning (PCT) strategies were experimentally applied in young unintended mixed forest (Norway spruce and birch in this case) which showed that some PCT techniques can provide forage for ungulates without losing volume production of Norway spruce. Moreover, such a mixture might also provide a wide range of ecosystem services with no or little economic loss in the long term. In addition, PCT can increase the full rotation profitability of Norway spruce stands compared to no-PCT stands. However, the timing of PCT appears to have little effect on the profitability of Norway spruce.

Overall, alternative forest management strategies tested in this thesis show potential to provide multiple ecosystem services and flexible forest management along with profitable production.

Keywords: browsing, establishment, mixed forest, pre-commercial thinning, planting design, production, young forest.

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Preface

The thesis represents the final work of my PhD studies at the Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Sweden. The thesis work was carried out between 2018-2022 and funded through a doctoral grant that I received within the FRAS (Future Silviculture in Southern Sweden) project.

The main objective of this thesis was to describe young stands and to evaluate alternative forest management strategies to combine forest production and other services. This thesis is based on four individual papers. Paper I involves regeneration failure and its consequences for the species composition and structure of young forests. Paper II examines the effect of planting design during forest establishment on the production and external wood quality of coniferous plantations. Papers I and II are published in scientific journals. Papers III and IV focus on different PCT strategies and how they can combine production and other ecosystem services. Paper III is under review by a scientific journal and paper IV is still a manuscript. This thesis summarizes and links the four papers together. The thesis starts with an introduction which is followed by materials and methods, results, discussion, and finally concluding remarks.

The thesis describes young forests in Sweden and discusses the potential of different alternative management strategies to combine production, profitability, and other ecosystem services with new possibilities for forest management. In the last part of this thesis, I point out some limitations of my research and give some ideas for future research possibilities. Finally, I try to translate the research findings for practical implementation.

Dedication

Begum Rokeya (1880-1932): Pioneer of women's education and employment in Bangladesh.

Contents

List of publications

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

I. Ara, M., Barbeito, I., Kalen, C.,& Nilsson, U., (2021). Regeneration failure of Scots pine changes the species composition of young forests. Scandinavian Journal of Forest Research, 1-9.

II. Ara, M., Elfving, B., Johansson, U., Barbeito, I., & 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

III. Ara, M., Felton, M, A., Holmström, E., Petersson, L., Berglund, M., Johansson, U., & Nilsson, U. Pre-commercial thinning in Norway spruce-birch mixed stands can provide abundant forage for ungulates without losing volume production (Under review).

IV. Ara, M., Berglund, M., Fahlvik, N., Johansson, U., &Nilsson, U. Pre-commercial thinning increases the profitability of Norway spruce monoculture and supports the mixture of Norway spruce-birch in long term. (Manuscript).

Papers I-II are reproduced with the permission of the publishers.

The contribution of Mostarin Ara to the papers included in this thesis was as follows:

I. Developed the research idea, was responsible for data analysis and manuscript writing with the support of the co-authors.

II. Was responsible for data collection, led the work in data analysis and manuscript writing with the support of the co-authors.

III. Led the work in data analysis and manuscript writing with the support of the co-authors.

IV. Led the work in data analysis and manuscript writing with the support of the co-authors.

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Abbreviations and Terminologies

Browsing damage	Any damage caused by ungulates
Broadleaf dominated mixture (paper I)	More than 1500 trees ha^{-1} (TPH) but conifers were below 500 TPH.
Conifer dominated mixture (paper I)	Scots pine and Norway spruce together were between 1000-1500 TPH and additional broadleaves resulted in a total stem density exceeding 1500 TPH.
Group planting	A clustered tree planting scheme that consists of 20-30 seedlings planted with 0.25 or 1m initial spacing and approximately 200 or 100 such clusters ha^{-1}.
Ginni index	Index to measure the spatial heterogeneity of a forest stand.
LEV	Land Expectation Value: the value of land used for growing timber.
Microsite	A planting spot that has most of the resources seedlings need.
Mixed forest	The definition of mixed forest is not universal and differs between countries. In Sweden, the stand is called mixed if more than 30% of the basal area is

	covered by dominant tree species (Johansson, 2003).
MAI	Mean annual increment: MAI measures the productivity of a stand over a period of time.
Norway spruce monoculture, Scots pine monoculture, and coniferous mixed forest (paper I)	Scots pine, Norway spruce, or both in combination have more than 1500 trees ha^{-1} (TPH), respectively.
PAI	Periodic annual increment: Mean annual increment over a period of time.
Seed birch	Birch naturally regenerated from seed tree.
Soil scarification	Soil scarification is an operation performed to improve the site condition for the survival and early establishment of seedlings.
Stump sprout	A shoot that grows from the cut stem of a tree.
Timing of PCT	Height of the tree when PCT is carried out.
Thinning intensity	Thinning intensity is given as a percentage of the stand basal area removed during thinning.

1. Introduction

A silviculture system is a planned program of silvicultural treatments designed to achieve specific stand characteristics to meet one or several objectives during the whole life of a stand. It integrates regeneration, stand tending, and specific harvesting methods to achieve predictable stand structure and yield. In this system, regeneration, establishment, and early tending methods including early cleaning (EC, prior to pre-commercial thinning) and pre-commercial thinning (PCT) occupy a brief period compared to the whole rotation. Despite being brief, these treatments are the basis for sustainable production and other ecosystem services (Bataineh et al., 2013; Pitt et al., 2013). The application and success of these early silvicultural strategies secure sustainable end use of round wood in the future (Duchesne et al., 2013; Pitt et al., 2013b). However, silvicultural treatments come at a cost. Therefore, it is important to have a clear and sound knowledge of the status and early management of young forest and how it affects the development of a stand. Moreover, the demand on forests has been changing from one service (production) to multiple services which forest owners and society want. It is also important to design forest management in a way that can facilitate mechanised forest operations and also maintain forest production. Considering the multiple demands from forest and forest operations, it is necessary to evaluate new forest management strategies. Hence, it is valuable to understand the status of young forests and also test alternative forest-management strategies to meet different contemporary forestry demands, for example timber production, profit, ecological, and other ecosystem services.

1.1 Swedish forest

Sweden is the fifth-largest country in Europe with the second largest forested area. The majority of the Swedish mainland is occupied by forest (around 70%) which consists of 23 million ha of productive forest (SFA, 2015; Mattson, 2016). Most of the country is covered by boreal forest which is dominated by coniferous tree species. Approximately half of the forest land in Sweden is owned by private owners and the rest belongs to forest companies and public owners (SFA, 2015). Forest management is focused on timber and pulp production. The climate and soil conditions vary considerably along the latitudinal extension of the country (from 55°N to 69°N). The climatic and soil conditions in southern Sweden make it more favourable for tree growth compared to northern Sweden.

The conifer species Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) are the most dominant tree species in Sweden. Norway spruce dominates in southern Sweden and Scots pine in the north. Together, they contribute nearly 80% of the total standing volume of Swedish forests (Norway spruce: 39.7% and Scots pine: 39.3%; SLU, 2021). Besides these native conifers, lodgepole pine (*Pinus contorta*) from North America was introduced in Sweden on a large scale in the mid-1960s and currently corresponds to about 1% of the total volume (Swedish Forest Survey, 2010). The most important broadleaf species in Sweden are birch (*Betula pendula* L. and *B. pubescens* L.) (Hynynen et al., 2010), which make up 12% of the total standing volume of Swedish forest (SFA, 2015). Birch is distributed all over Sweden and is mostly naturally regenerated (Götmark et al., 2007; Holmström et al., 2016; Karlsson et al., 2002; Nilsson et al., 2002).

The Swedish forests have a very dense population of large ungulates (Hörnberg et al., 2001; Liberg et al., 2010). The number of ungulates started to increase in Sweden at the beginning of the 20th century (Hörnberg et al., 2001). Ungulates usually cause damage on trees by browsing on the apical shoot, lateral twigs or breaking main stems, or stripping stem bark (Bergqvist et al., 2001) resulting in reduced growth, timber quality, and sometimes mortality of seedlings and saplings (Edenius et al., 2002; Wallgren et al., 2014). This leads to a loss of production and profit (Nilsson et al., 2015). Due to their damaging effect on trees, ungulates are one of the major concerns in Swedish forest management (Bergqvist et al., 2003; Cederlund, 1989; Mysterud, 2000).

1.2 Establishment and management of young forest

The most commonly-used silvicultural cycle in Sweden starts with clear-cutting followed by soil preparation for regeneration and continues with other silvicultural practices until final felling, and the cycle continues (Figure 1). Soil preparation/scarification is done before regeneration to improve germination of seeds and seedling survival. Planting seedlings is the most common method of forest establishment during regeneration. More than 80% of harvested clear-cuts are regenerated by planting, followed by natural regeneration of Scots pine (10%) and shelter wood (4%) (SFA, 2019). The rest of the area is either naturally regenerated, direct seeded, not regenerated, or has no record of regeneration. Forest owners use Norway spruce and Scots pine in most of the forest area during regeneration; Norway spruce is dominant in the south and Scots pine in the north of Sweden. Moreover, as a substitute for Scots pine, lodgepole pine is planted in northern Sweden to some extent (Engelmark et al., 2001; SFA, 2015).

Figure 1. The forest management cycle used in Swedish forestry. The cycle starts with the final felling and continues with several activities: soil preparation, regeneration, pre-commercial thinning, commercial thinning, and the cycle begins again with final felling (Image-Skogforsk).

Traditionally, a square spacing distance of about 2.2 x 2.2 meters between seedlings is used in Swedish forestry during planting. This is done as it is assumed to maximise volume production compared to other planting designs, for example, rectangular grids. However, there is no scientific evidence for this assumption. One of the problems associated with square grids is finding the best microsite for planting seedlings. The microsite following a fixed distance might be rocky or otherwise unsuitable for planting seedlings. This could lead to poor establishment and mortality of seedlings as microsite is important for seedling survival (Jonsson, 1999). Moreover, Sweden uses highly-mechanised forest operations. Square planting grids reduce accessibility for machinery, leading to considerable stem damage (Lageson, 1997; Nikooy et al., 2020; Visiliauskas, 2001). This damage may lead to further biotic damage and could devalue the harvested logs (Visiliauskas, 2001).

Some problems related to square planting designs can be solved with rectangular planting design. The idea of rectangular planting is that the number of trees per unit area remains the same, but the spatial layout of seedlings changes (Sharma et al., 2002; Figure 2). Flexibility in microsite selection and machinery operations can be increased using a rectangular planting design. However, the question of resource distribution arises in rectangular planting as the distance between trees is not uniform which could affect long-term forest production. Moreover, the different distances between trees in a rectangular design may result in oval stems, increased branch thickness, and issues related to crown shape. However, this outcome has not been seen in experiments in other parts of the world (Gerrand & Neilson, 1998; Johnstone, 2008; Malinauskas, 2003; Salminen & Varmola, 1993; Sharma et al., 2002). Despite this evidence, the traditional square planting design is dominant in Swedish forest establishment even though a rectangular planting design could offer much more flexibility. In this context, comparing the stand characteristics between different planting designs in Swedish forests would be valuable to inspire Swedish forest owners to consider other planting design options.

Figure 2. Concept of rectangular planting design. (A) shows a uniform or square distribution of trees. (B) shows the same number of trees per unit area, but the distance between trees changes, and a strip road was created between tree rows.

After planting seedlings, probably the most crucial issue in the Swedish forestry is seedling survival. At the end of the regeneration phase, between 1800-2500 trees ha^{-1} is typically the target stem density (Nilsson et al., 2010), but this target is often not reached (Nilsson et al., 2010). Loss of seedlings is the most prevalent reason for this and is mostly attributed to the morphology of seedlings (Grossnickle, 2012), environmental stresses (Burdett, 1990; Nilsson et al., 2010), ungulate browsing (Bergqvist et al., 2003; Bergquist & Örlander,1998; Bergström & Bergqvist,1997; Bergquist & Örlander 1996; Miller et al.,1998; Palmer & Truscott, 2003), and diseases or damage by insects, especially by pine weevil (Day et al., 2007; Day & Leather, 1999; Eidmann et al., 1996; Hagner & Jonsson, 1995; Långström & Day, 2007; Lindtröm et al., 1986; Norlander et al., 2003; Pettersson et al., 2005; von Sydow, 1997; Wallertz et al., 2007; Wallertz et al., 2014; Örlander & Nilsson, 1999).

Broadleaves, especially naturally-regenerated birch, are abundant in planted stands because of soil preparation during regeneration (Holmström et al., 2016; Karlsson et al.,1998; Karlsson et al., 2002; Nilsson et al., 2002; Perala & Alm 1990; Prevost, 1997) and abundant production of widely-dispersed seeds (Karlsson, 2001). Because of their fast growth, broadleaves could overtop recently-planted conifers, resulting in reduced growth and mortality of crop trees. Although the regeneration goal is usually a Norway spruce or Scots pine forest, the combination of mortality of coniferous seedlings and natural regeneration of broadleaves often results in tree-species mixtures in the young forest (Drössler, 2010; SFA, 2015). Moreover, ungulate browsing irreversibly changes the tree structure, biomass production, and can even cause death of the tree (Bergqvist et al., 2003; Persson et al., 2000). This could change the species composition of the young forest (Gill, 1992) and result in a large economic loss (Glöde et al., 2004; Nilsson et al., 2015).

The unintended changes of species composition in young forests lead to new possible future stand development compared to what was planned at the time of regeneration. In this case, a new plan for forest management is needed to select future crop trees and other management schemes. An accurate description of stand structure and species composition is required to facilitate planning. In this context, an extensive large-scale study can provide a robust analysis of species composition and could be used for large-scale planning of future forest management. In addition, it is also important to implement the plan in early management operations to shape the future forest.

Pre-commercial thinning (PCT) is the most often used silvicultural strategy in this situation to select future crop trees. PCT is usually used to release competition to favour the growth of individual trees (Braastad & Tveite, 2000; Jäghagen & Sandström, 1994; Pettersson, 1993; Ruha & Varmola, 1997; Simard et al., 2004; Varmola & Salminen, 2004; Weiskittel et al., 2009). Spacing of crop trees after PCT has been well studied so far. However, the timing of PCT (height during PCT) has been less studied and only for Scots pine (Ruha & Varmola, 1997; Varmola & Salminen, 2004) despite its importance for stand-level growth and profitability (Fahlvik et al., 2018). Long-term experimental studies are needed to provide a full picture of PCT timing on the growth and profitability of a forest stand. The lack of long-term experimental data makes it difficult to do such an analysis. However, while waiting for data from long-term experiments, simulations with a forest decision support system could give estimates of production and stand dynamics over the full rotation.

Moreover, during PCT, broadleaves are usually removed as they are considered competitors to the conifers. However, in recent times, environmental and social concerns have resulted in new demands on the forest, thus shifting the focus from production to a wider range of ecosystem services. Therefore, there is a growing interest in creating a mixed forest by supporting both Norway spruce and birch in PCT. Norway spruce-birch mixed forests provide a wide range of ecosystem services (Felton et al., 2016 and other references therein). However, although Norway spruce-birch mixtures may provide a higher yield compared to Norway spruce monocultures in early rotation (Fahlvik et al., 2005; Frivold & Frank, 2002; Johansson, 2003; Tham, 1994; Valkonen & Valsta, 2001), a high proportion of birch could result in reduced volume production later in the rotation (Fahlvik et al., 2011; Fahlvik et al., 2015) and reduced economic profitability (Fahlvik et al., 2018). Because of this, adjustment of species composition is often recommended in the latter part of the rotation. However, it is important to support both species over a full rotation for a sustainable mixed forest, yet very few studies do so (Fahlvik et al., 2005; Fahlvik et al., 2011; Holmström et al., 2016; Mielikäinen, 1985). More studies need to be conducted to enrich the knowledge of mixed forest management and to prescribe silvicultural operations in a mixed stand.

Moreover, young Norway spruce-birch mixed stands are a potential forage source for ungulates; leaves and twigs of birch are a medium-ranked forage for ungulates (Cederlund et al., 1980; Danell et al., 1985; Felton et al., 2020). This could increase the forage availability in forest landscapes and consequently lower the browsing pressure on crop trees (Månsson, 2007). In this regard, PCT can be used as a tool to adjust the species composition of birch and Norway spruce (Fahlvik et al., 2011; Fahlvik et al., 2014; Holmström et al., 2016) to release competition for Norway spruce and at the same time provide forage for ungulates. Therefore, evaluating the potential of different PCT strategies to adjust species composition in Norway spruce-birch mixtures would be valuable to combine forage and volume production.

2. Objectives

In this thesis, I aim to describe the young Swedish forest and to evaluate alternative strategies of establishment and management of young forest to maintain or promote production, including profit as well as multiple ecosystem services (Figure 3).

In the first part of this thesis, I focus on the regeneration, establishment, and stand structure of young forests. I investigated the stand structure and species composition of young forest (paper I). I also evaluated the effect of different planting designs (square vs. rectangular) on different stand characteristics of coniferous plantations (paper II). This was done to test the potential of rectangular planting designs to facilitate silviculture and forest operations without losing timber production.

In the second part of this thesis, I focus on different PCT strategies and their potential to supply both timber production and other ecosystem services. In paper III, different PCT strategies were tested in a young Norway spruce-birch mixture to reduce the trade-off between volume and forage production. Furthermore, stand development of Norway spruce-birch mixtures and Norway spruce monocultures was simulated in full rotation using different PCT strategies. This was done to evaluate the profitability of doing PCT in Norway spruce stands over a full rotation and to evaluate the potential of Norway-spruce birch mixtures to support production, profit, and other ecosystem services (paper IV).

To reach this aim, I address the following research questions:

Research question 1: Does species composition in young forest change from what was intended by forest owners during regeneration?

Research question 2: Can rectangular planting design be applied to facilitate forest regeneration success and young stand management without losing forest production?

Research question 3: Is it possible to use PCT strategies in a Norway spruce-birch mixture to combine forage for ungulates and volume production of Norway spruce?

Research question 4: How can different PCT strategies in mixtures with planted Norway spruce and naturally-regenerated birch be used to influence the long term outcome of timber production, profit, and other ecosystem services?

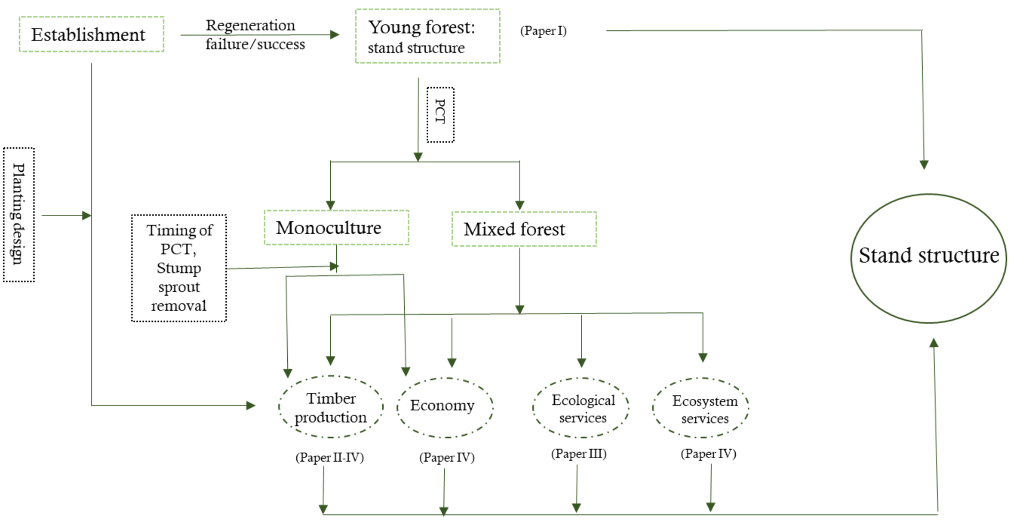

Figure 3. Conceptual framework of this thesis. The diagram shows how the individual research projects are interconnected to reach the aim of this thesis.

3. Materials and Methods

3.1 Study area

Data from field experiments and survey studies based in Sweden was used in this thesis. National inventory data from young forests was used in paper I (green points in Figure 4A). The spacing experiment used in paper II is located in three sites in northern, central, and southern Sweden (green dots in Figure 4B), and the PCT experiment used in papers III and IV is located in several sites in southern Sweden (orange squares in Figure 4B).

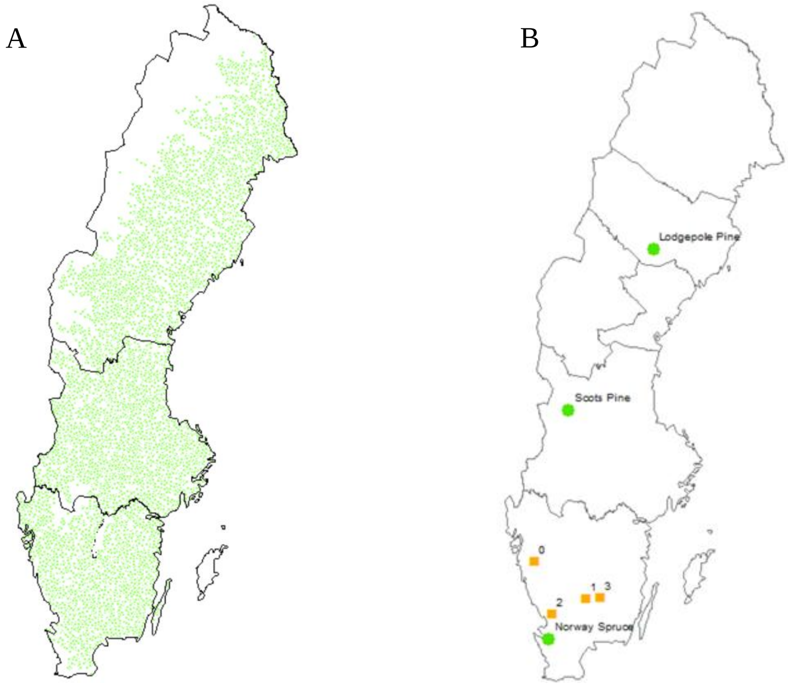

Figure 4. Location of inventoried stands (A) and experimental sites (B) used in this thesis. The points in panel (A) show annually-inventoried stands of the Äbin ungulate-browsing inventory used in paper I. The alpine zone was excluded because there were no inventory stands there. Panel (B) shows the location of experimental sites used in this thesis. Green circles show the spacing experiments with three different tree species used in paper II. The orange squares show the PCT experiments used in papers III-IV.

3.2 Materials and Methods

Materials and methods for each paper (connected to each research question) are described in the following section.

Paper I: The Äbin ungulate-browsing inventory

Research question one is addressed in paper I: Regeneration failure of Scots pine changes the species composition of young forest (published; Ara et al., 2021).

A national inventory dataset covering young forest (1-4 meters tall) known as "Äbin" (short for "Älgbetesinventeringen" in Swedish, meaning "moose browsing inventory") was used to answer research question one (paper I). It is an inventory of ungulate browsing damage. All annually-inventoried plot data from 2015-2018 was used in this study. The inventory was done within 3.5-meter radius sample plots. Occurrence of and damage to Scots pine, Norway spruce, and occurrence of birch and other broadleaves in each plot were used for data analysis.

Species composition used in regeneration was calculated using the field record collected by the field crew during the Äbin survey. Species composition of the young forest was calculated using the plot-level browsing damage inventory of Norway spruce, Scots pine, and occurrence of birch and other broadleaves. The proportion of species in each plot was scaled up to per-hectare values. Depending on the density of species per unit area, forest types were classified into five different categories: Norway spruce and Scots pine monoculture, mixed conifer, conifer-dominated mixed forest and broadleaf-dominated mixed forest (explanation of each class can be found in the abbreviations and terminologies section). In the analysis, it was assumed that 50% of the damaged trees will develop into crop trees. However, due to the uncertainty related to the percentage of damaged trees that will mature, a sensitivity analysis was performed where all, every second, or none of the damaged trees were included as future crop trees. Moreover, the proportion of young Norway spruce and Scots pine stands in the area regenerated with those respective species was calculated using both 1500 and 1000 trees ha^{-1} as definitions of dominance.

Paper-II: Spacing experiment

Research question two is addressed in paper II: Varying rectangular planting design yields no difference in forest growth and external wood quality of coniferous forest plantations (published; Ara et al., 2021).

A long-term spacing experiment established in the mid-1980s was used to address research question two in paper II. The experiment was established in three different sites with three different tree species (lodgepole pine, Scots pine, and Norway spruce; Figure 5). The experiment was established with five different planting designs (four different rectangular designs and one traditional square design) with three replicates in each site. The planting-spacing designs were 0.8 m x 5 m, 2 m x 2 m, 1 m x 4 m, 1.33 m x 3 m, and 1.46 m x 1.46 m x 4 m. The latter design consists of planting spaces separated by 1.46 m within rows, and rows alternately separated by 1.46 m and 4 m (Figure 5). Mid-rotational (stand age of 38-40 years) measurements of stand characteristics (diameter of all trees in the plots, height, height to the living crown, and diameter of branches near DBH of 20 sample trees per plot) were used for analysis.

Stand characteristics (mean volume production, ovality, branch thickness, PAI (periodic annual increment), living crown height, diameter distribution, Gini index by using individual DBH, height/diameter ratio) for each planting design were calculated from the inventory data and compared between treatments (through ANOVA analysis). The comparison was done to test the effect of planting design on different stand characteristics.

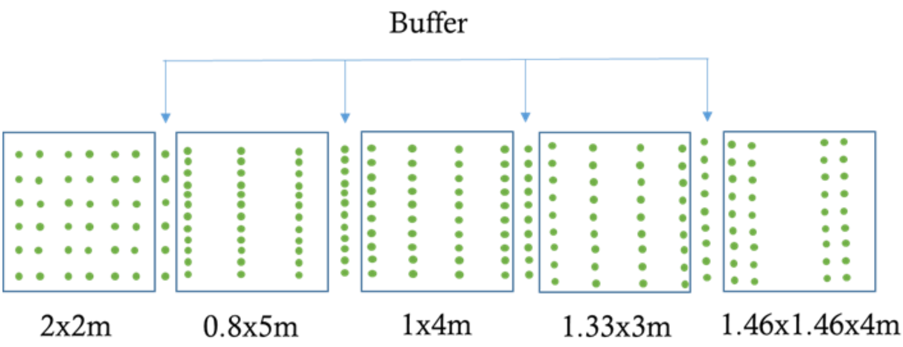

Figure 5. Planting designs used in the spacing experiment. Each plot was around 20 m × 30 m and the initial planting density was 2500 seedlings ha^{-1} for all treatments. To minimize the effect of neighbouring plots, one row of trees was planted as a buffer zone surrounding each treatment.

Papers III & IV: PCT experiment in Norway spruce and birch mixtures

Paper III

Research question three is addressed in paper III: Pre-commercial thinning in Norway spruce-birch mixed stands can provide abundant forage for ungulates without losing volume production (Under review).

A PCT experiment located in southern Sweden and replicated in three sites (numbers 0,1 and 3 in Figure 4B) was used in this thesis paper to answer research question three. The experiment was established in 2013-2014 in a planted Norway spruce stand where birch was regenerated naturally. The first PCT was done when the average height of planted Norway spruce was between 1-2 m and birch was 2-2.5 meters tall. The treatments were designed with both additive and substitutive levels of birch and Norway spruce competition. Four PCT treatments were established during the first PCT (Figure 6): no PCT (control), removing all broadleaves and retaining 2000 planted Norway spruce ha^{-1} (PCT-Total), removing all broadleaves within a 0.75 m radius of Norway spruce stems (PCT-Spot: 2000 Norway spruce ha^{-1}); and removing all broadleaves except 2000 birch ha^{-1} along with 2000 Norway spruce ha^{-1} (PCT-Mix).

After the PCT, the height and DBH of main trees within 3 m radius sample plots in each treatment were measured until the third growing season. Moreover, birch forage was inventoried within 1.78 m and birch browsing was inventoried within 3 m radius sample plots. Volume production of Norway spruce was estimated for each treatment using the inventoried data. The total amount of birch forage (leaves and branches of seed birch and stump sprouts) for ungulates was calculated using a regression model developed using destructive sampling. Moreover, browsed biomass for each treatment was estimated using the developed equation. All the target variables (volume production, total forage, and browsed biomass) were compared between PCT treatments. ANOVAs were done to compare the potential of different PCT methods to combine volume and forage production and also to assess the effect of PCT on browsing.

Paper IV

Research question four is addressed in paper IV: Pre-commercial thinning increases the profitability of Norway spruce monoculture and supports mixture of Norway spruce-birch in long term (Manuscript).

A PCT experiment (the same experiment used in paper III plus one additional site) located in southern Sweden and replicated in four sites (Figure 4B) was used in this manuscript to answer research question four. The description of the establishment and treatments of the PCT experiment has been described in the materials and method part of paper III. The first PCT was done in 2013-2014 (paper III) and three-six years later, a second PCT was carried out which was used in paper IV (connected to research question IV). In the second PCT, seven new treatments were established out of the four used in the first PCT. The purpose of new treatments was to develop Norway spruce monocultures and also to investigate the effect of PCT timing on the production and profitability of Norway spruce. Moreover, the treatments were also established to develop Norway spruce-birch mixed stands. In the second PCT, Norway spruce monocultures were prioritized in three out of seven new treatments. The treatments aiming for Norway spruce monoculture were early PCT (NS_EARLY; tree height 1-2m), late PCT (NS_LATE; tree height 4.5-6 m), and stump sprout removal (NS_COMB). Besides prioritizing Norway spruce, two treatments were aimed to develop Norway spruce-birch mixed forests with two different stand densities: MIX_DENSE (1000 Norway spruce and 1000 birch ha^{-1}) and MIX_ SPARSE (500 Norway spruce and 500 birch ha^{-1}). There was a control treatment (CRT) with no PCT and one with birch monoculture (birch monoculture was not used in this thesis due to missing data in one site) (see Figure 6 for all the treatments used in the 1st and 2nd PCTs). The stem density in each treatment after the 2nd PCT was 2000 trees ha^{-1} for all the treatments except for MIX_SPARSE and CRT. Norway spruce was 4.5-6 meters tall and birch was 6-7 meters during the 2nd PCT. Measured height and diameter from each PCT treatment from 2nd PCT were used as an input to simulate stand development over a full rotation.

A Swedish forest decision support system called Heureka was used to simulate stand development over a full rotation for different PCT stands. Heureka requires data about the site (e.g. latitude, site index, and vegetation type), the stand (age, management history), and the trees (tree species, diameter, and height). The Heureka system includes a large number of empirical models describing growth, mortality, and ingrowth (Elfving and Nyström, 2010; Fahlvik et al., 2014). In this thesis, the PlanWise application within the Heureka forestry decision support system (Wikström et al., 2011) was used for simulation. The treatment programme generator (TPG) included in this system was used to compute a set of thinning and final felling alternatives for each stand unit within frames set by the user. Therefore, the best management alternative was selected based on the highest LEV (land expectation value) for each treatment.

The mean annual increment (MAI) and land expectation value (LEV) were compared between mixed forest and Norway spruce monoculture after a full rotation. This was done to investigate the potential trade-offs between production, profit, and multiple ecosystem services in mixed forests. Moreover, production and profit were compared between Norway spruce monocultures with different PCT timing and control stands.

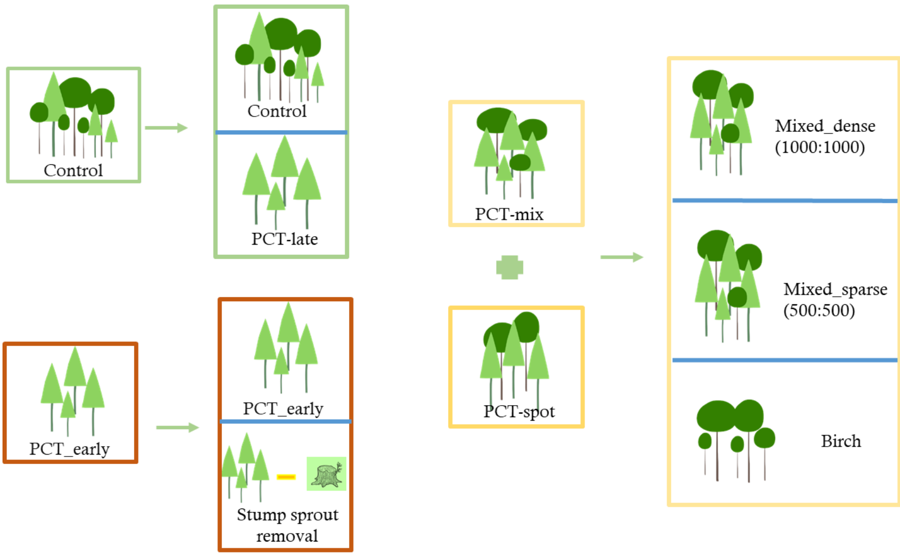

Figure 6. Treatments used in the 1st and 2nd pre-commercial thinnings. The same colour frame between 1st and 2nd PCT indicates that the new treatments in the 2nd PCT build

on 1st PCT treatment. For example, by combining PCT-mix and PCT-spot, three new treatments (Mixed_dense, Mixed_sparse and Birch) were established during 2nd PCT.

4. Results and discussion

4.1 Main findings and discussion

Results and discussion are described separately for each research question.

Research question-1 *Does species composition in young forest change from what was intended by forest owners during regeneration?*

Norway spruce and Scots pine were the dominant tree species used in regeneration, where Norway spruce was dominant in the south and Scots pine in the north of Sweden. However, in young forests, neither Norway spruce nor Scots pine was dominant. Instead mixed forests were dominant all over Sweden (Figure 7 & paper I). This indicates that species composition has changed in the young forest from what probably was intended at the time of regeneration.

Norway spruce regeneration resulted in more than 1500 Norway spruce trees ha^{-1} on more than 50% of the area in southern and central Sweden. The proportion of Norway spruce regeneration success was even higher considering 1000 trees ha^{-1} as a criterion to be dominant. In Scots pine regenerations, less than 35% of the area resulted in more than 1500 trees ha^{-1} but about two-thirds of the area regenerated with Scots pine had more than 1000 Scots pine trees ha^{-1} (Figure 8).

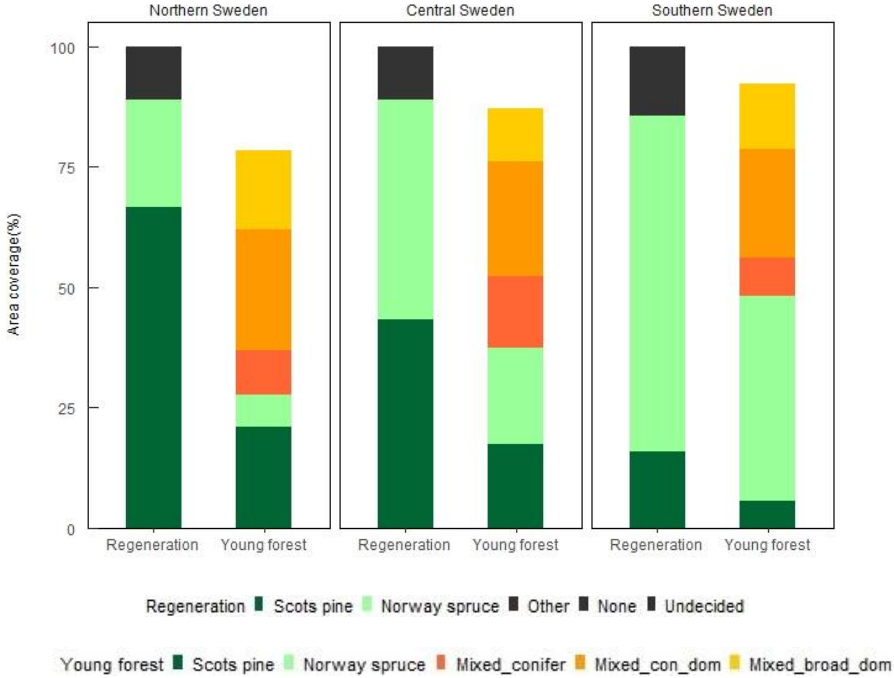

Figure 7. Species composition used in regeneration and species actually found in young forests in different regions of Sweden. Mixed_conifer means stands are dominated by mixture of Norway spruce and Scots pine. Mixed_con_dom means conifer-dominated mixed forest, and Mixed_broad_dom means broadleaf-dominated mixed forest.

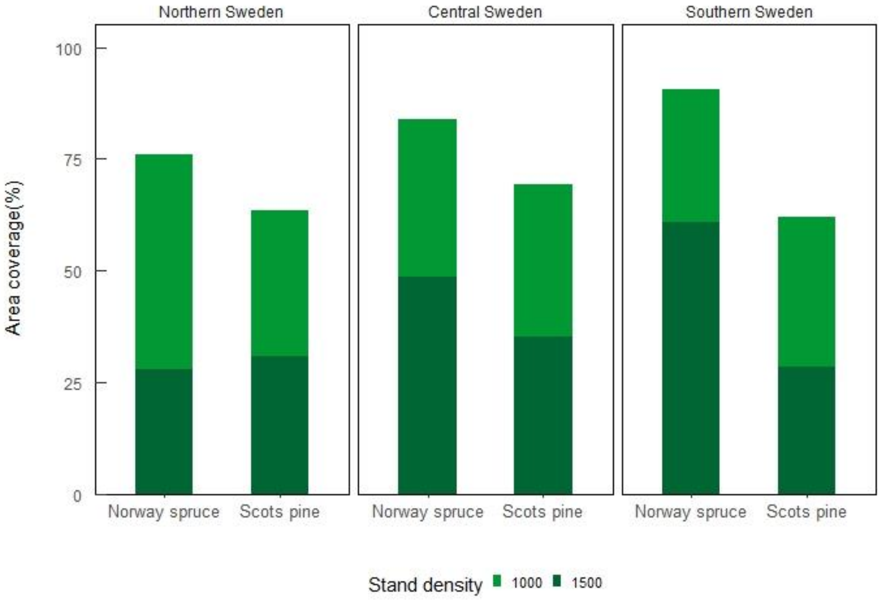

Figure 8. Area covered in young forests by species used in regeneration in sites regenerated with Norway spruce and Scots pine. The dark and light green colours show area coverage considering 1500 and 1000 trees ha^{-1} as the criterion to be dominant respectively.

A central finding of this study was the overall discrepancy of species composition between regeneration and young forests. The discrepancy might occur due to mortality of seedlings as a result of pine weevil damage (Day et al., 2007; von Sydow, 1997; Örlander & Nilsson, 1999), browsing (Bergquist et al., 2003; Bergquist & Örlander, 1998; Bergström & Bergqvist, 1997; Edenius et al., 1994; Miller et al., 1982; Palmer & Truscott, 2003; Wallgren et al., 2014) and frost or drought (Burdett, 1990; Nilsson et al., 2006). One or more of these damage agents could result in a change of species composition in young forests. This could occur either by causing mortality of planted or otherwise intended seedlings or causing damage to those seedlings resulting in decreased competitiveness. However, the findings also showed higher regeneration success of Norway spruce compared to Scots pine. Higher food value and lower browsing tolerance of Scots pine compared to Norway spruce could be one explanation for this difference

(Bergquist et al., 1998). However, the observed difference in mortality may also be due to the differences in seedling type and scarification methods between Norway spruce in the south and Scots pine in the north.

The mortality of seedlings not only means a loss of future production but also indicates an immediate loss of money spent on regeneration. The cost of planting, including seedlings, scarification, and planting, is between 7,000-20,000 Swedish krona (SEK) (approx. 700-2000 Euro) and about 400,000 hectares are planted annually in Sweden. Thus, about 4 billion SEK is spent on planting each year and if more than 50% of the planted seedlings do not contribute to future production, more than 2 billion SEK is spent annually on seedlings that do not survive. Also, forest owners are using more genetically-improved materials to enhance forest growth, prepare for future climate change, and resist damage. However, the high mortality and regeneration failure indicates that forest owners are not benefiting from money spent on genetically-improved plants or seeds.

A possible solution to improve regeneration at a reduced cost might be complementing planted seedlings with natural regeneration. Moreover, site selection for planting can be done based on scientific evidence rather than following traditions. For example, in the case of seedling mortality and browsing pressure, mixed-species stands can be a form of insurance if one of the tree species is heavily damaged. Holmström et al., (2018) showed that mixtures of Scots pine and Norway spruce had almost the same production in medium-fertility sites as the best monoculture but other mixtures also could be tested in the future. Also, despite Scots pine being browsed in both northern and southern Sweden, it is mostly used in the north but avoided in the south. Recent studies have shown that contrary to current ideas, the production of Scots pine is better than Norway spruce on poor- and medium-fertility sites in southern Sweden and similar on relatively-fertile sites (Lula et al., 2021 unpublished). Therefore, increased use of Scots pine in southern Sweden will not only have biodiversity and risk management benefits, but also higher wood production. Scots pine seedlings might be protected from browsing by using repellent or fencing while reducing regeneration costs by relying on natural regeneration. Moreover, digital spatial data on, for example, soil moisture can be used to determine where to plant seedlings or to rely on natural regeneration. Also, prior information about site suitability and microsites for a species could be useful to improve regeneration success (Nordin et al., 2022).

Although young stands throughout Sweden tend to be of mixed species, the future of these stands depends on future forest management. It could be that all the broadleaves will be removed during PCT and the stand will develop into a low-density conifer monoculture due to conifer-oriented management. However, regeneration failure provides an opportunity to develop mixed forests providing multiple ecosystem services (Felton et al., 2016 and references therein). PCT could be a practical tool to manipulate the stand structure at a suitable stage either to create a monoculture or mixed forest. In the case of planted Norway spruce and naturally-regenerated birch stands in fertile sites, the stand can be developed as a Norway spruce monoculture by doing PCT which is profitable in long run (paper IV). Also, PCT can be used to create a mixed stand by keeping both Norway spruce and birch which could be a potential strategy to balance profit and other ecosystem services (paper IV).

Research question-2*: Can rectangular planting design be applied to facilitate forest regeneration success and young stand management without losing forest production?*

Planting design had no effect on any measured stand characteristic of coniferous plantations of three species in Sweden (Norway spruce, Scots pine, and lodgepole pine; paper II). The non-effect of rectangular planting is supported by other studies in European, North American, and Australian forest plantations (Gerrand & Neilson, 1998; Johnstone,2008; Sharma et al., 2002; Salminen & Varmola, 1993). In contrast to the spatial arrangement, there is strong evidence regarding the spacing effect on the growth of trees which confirms that the number of trees per unit area is important for their growth (Kellomäki et al., 1989; Liziniewicz et al., 2012; Pettersson, 1993). The non-effect of the spatial arrangement of seedlings (even at extreme rectangularity of 0.8 m x 5 m) from this study along with other studies shows that density but not spatial positioning is important for forest production.

There are some benefits of the non-effect of planting design for forest regeneration and young stand management. This paper shows that the regularity of seedlings within the regenerated area is not very important. This gives people planting seedlings much more freedom in searching for the best microsite, possibly increasing seedling survival and regeneration success (DeLong et al., 1997; Johnson & Yeakley, 2019; Jonson, 1999). Paper I indicates the consequences of regeneration failure in terms of stand structure and economic loss as well as sustainable wood materials. Implementation of a rectangular planting design will not solve the entire problem but may improve regeneration success and reduce economic losses. In both Finland and Sweden, cost efficiency has increased less in recent decades for regeneration measures than for forest harvesting operations (see references in Uotila, 2017). Therefore, there is a need to reduce the cost of regeneration and improve regeneration. Flexibility in planting spacing that can be obtained using rectangular planting design could be useful for Swedish and Finnish forestry to improve regeneration success. This will provide an opportunity for forest owners to choose and apply the appropriate measures to obtain the intended result from regeneration.

Almost all forest activities in Swedish forestry are mechanized except regeneration and PCT. The cost of PCT has increased quite steadily and alternative methods need to be developed to reduce the cost. Mechanized PCT could be a potential strategy to reduce its cost (Ligne et al., 2005; Uotila, 2019). Rectangular planting can make space for corridors through which machines can be driven during PCT. The use of a corridor could also reduce the stem damage due to mechanized PCT. In addition, the non-effect of spatial positioning also provides an opportunity to test group planting. Planting seedlings in clusters may be faster than traditional row planting. This would reduce planting costs and consequently will improve the profitability of the regeneration chain.

In addition, the non-effect of spatial distribution can also be useful in other forest management operations. For example, strip roads for log extraction are usually created in the first commercial thinning. With a rectangular planting design, strip roads are not needed because machines can drive in the corridors. Avoiding new strip roads in commercial thinning may reduce storm damage since strip roads increase the risk of storm-felling (Gardiner et al., 2005; Satoo et al., 1971). However, there could be an abundance of natural regeneration in the corridor that would need to be removed during

PCT. Also, a rectangular planting design can reduce the area of disturbed soil after scarification which is beneficial for several ecosystem services. Overall, the non-effect of planting design can benefit forest management in multiple ways without losing timber production.

Research question-3*: Is it possible to use PCT strategies in a Norway spruce-birch mixture to combine forage for ungulates and volume production of Norway spruce?*

There was no significant difference in volume production of Norway spruce between stands with the PCT-total and PCT-mix treatments. However, there was a significant difference in volume production of Norway spruce in the PCT-total treatment compared to the PCT-spot and control treatments (paper III). This means a PCT strategy of keeping 2000 birch ha^{-1} along with 2000 Norway spruce ha^{-1} (PCT-mix) can supply forage for ungulates without losing volume production of Norway spruce. However, after three growing seasons, due to vigorous stump sprouting, there was no difference in total birch forage production between PCT-total and PCT-mix. There was significantly-higher birch forage in control plots compared to PCT-total and PCT-mix but PCT treatment did not affect actual browsing by ungulates. Therefore, a PCT strategy that provides sufficient birch forage without losing volume production of Norway spruce could be implemented. In this case, PCT-total or PCT-mix both can combine birch forage and volume production of Norway spruce. Forest owners can choose either of these options depending on their management goal. However, PCT-mix might have other advantages over PCT-total, for example, ecosystem services or development of mixed forest in full rotation for forest certification.

After three growing seasons, PCT had no effect on the birch browsing by ungulates. There was no significant difference in browsing between stands with and without PCT. Stump sprouts were used as a forage in the PCT-total treatment during the latter part of the study period. Although PCT reduced the total birch biomass, 5-15 MG ha^{-1} of birch biomass was found after three growing seasons depending on the PCT treatment (paper III). However, despite there being a high amount of birch forage, little was eaten by ungulates. After three growing seasons, a total of 60 kg/ha birch forage was browsed which was equivalent to the twelve days of food for a moose in the winter and six days in the summer (Persson et al., 2000). The unexpectedly low browsing pressure in this experimental area could be explained by several factors. First of all, a site with a high number of birch overtopping planted Norway spruce was needed to establish the PCT treatment; such a stand was difficult to find. Therefore, it could be that such sites were found in areas where browsing pressure is lower than average. This could lead to low browsing pressure in these experimental sites (Bergqvist et al., 2014; Månsson et al., 2007; Nygren & Personen, 1993). Moreover, birch (Månsson et al., 2007; Wam et al., 2000) and other hardwood (rowan, aspen, willow & oak – collectively known as RAWO) availability in forest landscape (Månsson et al., 2007) could reduce browsing on individual birches. However, the low use of birch forage in the experimental area doesn't limit the scope of practical implementation of this research finding because of the above-mentioned factors related to the low browsing pressure. Experimental sites used in this study do not represent the entire boreal forest landscape in Sweden or elsewhere. Rather, areas with high moose density might see greater forage use (Månsson et al., 2009). Moreover, in areas with high ungulate density, browsing damage might decrease with increasing forage availability (Månsson et al., 2009). In areas with high browsing pressure, combining forage production and the growth of crop trees can be useful. Therefore, PCT strategies (PCT-total or PCT-mix) can be implemented in Norway spruce-birch mixed stands in areas similar to this study site to reduce browsing pressure.

Research question-4: *How can different PCT strategies in mixtures with planted Norway spruce and naturally-regenerated birch be used to influence the long term outcome of timber production, profit, and other ecosystem services?*

The simulation results showed that PCT strategies in planted Norway spruce and naturally-regenerated birch stands can be used to alter the stand structure to develop a Norway spruce monoculture or Norway spruce-birch mixed stand. Results from tested PCT strategies/treatments to develop a Norway spruce monoculture showed that PCT had both positive and negative effects on the MAI of Norway spruce stands in full rotation depending on site characteristics (Table 1). However, PCT was always profitable in Norway spruce stands compared to no-PCT stands (Figure 9). The profitability of doing PCT in a stand was supported by other studies (Huuskonen & Hynynen, 2006; Pitt et al., 2013; Varmola & Salminen, 2004). Moreover, treatments with different PCT timing on the development of Norway spruce stands showed that early PCT tends to increase the MAI of the stand compared to late PCT. However, the timing of PCT had little effect on the economics of Norway spruce stands. Early and late PCT had nearly-equal full-rotation LEV in three out of four sites. There was a higher LEV under late PCT compared to early PCT in the fourth site, Tönnersjöheden (Figure 9). Moreover, the effect of stump sprout removal on the growth and profitability of Norway spruce varied between sites. It was economical in some sites and varied in other sites when compared with early and late PCT.

Table 1. Growth (Mean Annual Increment) of different stands with and without PCT at different sites after a full rotation. For the explanation of all the treatments see Figure 9

Treatment	Experimental site			
	Tagel	Tönnersjöheden	Tvarsjonas	Vartorp
CRT	12.67	16.95	14.71	13.24
NS_EARLY	12.53	13.52	16.16	13.86
NS_LATE	10.91	14.01	14.56	12.27
NS_COMB	11.66	13.24	15.51	12.10
MIX_SPARSE	7.33	9.71	10.97	8.46
MIX_DENSE	10.25	12.66	14.36	10.06

Based on previously-published literature, earlier PCT is expected to be more profitable because it increases the growth (Uotila & Saksa, 2014) and reduces PCT costs (Kaila et al., 2007). In this study, a high understory cleaning cost (6000 SEK ha^{-1}) was assumed in early PCT. Moreover, income from thinning was higher in late PCT compared to early PCT. Due to this, early PCT might not be more profitable than late PCT despite costing less, possibly leading to minimal impact of PCT timing on the profitability of Norway spruce stands. However, the higher LEV in late PCT compared to early PCT in the Tönnersjöheden site could be explained by within-site variation between treatments. The plot with late PCT was located lower on the slope compared to the early PCT plot. This could increase fertility and promote the growth of Norway spruce, leading to higher LEV.

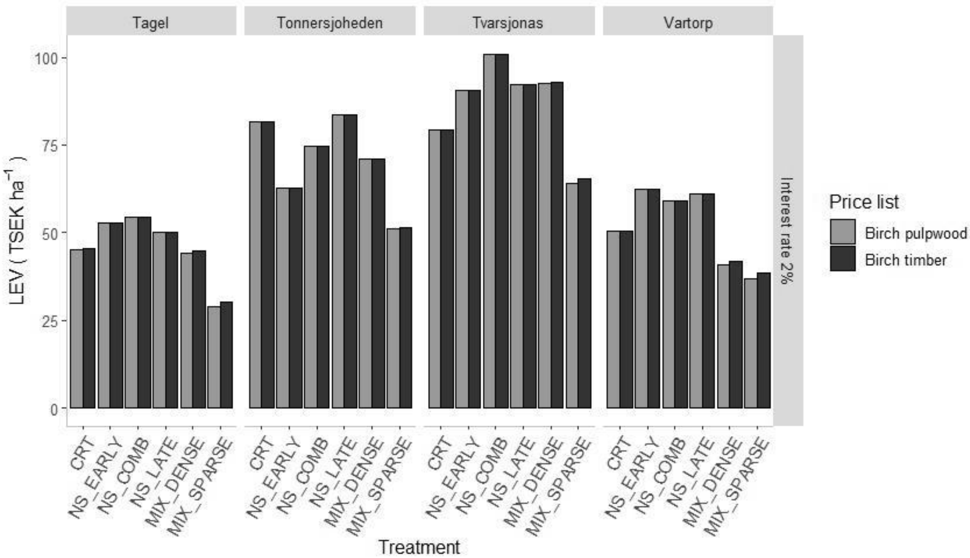

Figure 9. Land expectation value (LEV) of stands in full rotation with different PCT and no PCT (control) treatments. The LEV was calculated using a 2% interest rate. The treatments were; control (CTR), late PCT (NS_LATE), early PCT (NS_EARLY), early and late PCT (NS_COMB), mixed sparse (MIX_SPARSE), and mixed dense (MIX_DENSE). Here, TSEK in Y axis means thousand SEK (Swedish Krona).

Besides Norway spruce stand development, two PCT strategies were tested to develop Norway spruce-birch mixed forest with two different stem densities. Results of simulations showed that both strategies supported Norway spruce and birch in full rotation. This means the mixed stands can provide a wide range of ecosystem services. These include increased biodiversity, climate change adaptation, stand stability, soil carbon accumulation, nutrient cycling, protection from pests and pathogens, ecological, cultural, and other ecosystem services (Felton et al., 2016; Huuskonen et al., 2021 and references therein). All the services mentioned above are higher in mixed Norway spruce-birch stands compared to Norway spruce monocultures (Felton et al., 2016; Huuskonen et al., 2021).

However, the growth of Norway spruce-birch mixed stands is often lower in full rotation compared to Norway spruce monocultures, something consistent with results of this study (Table 1). A possible explanation could be the different growth patterns of Norway spruce and birch. Birch is a pioneer tree species and grows faster early in the rotation while Norway spruce does the opposite. This often leads to higher growth in Norway spruce-birch mixtures compared to pure Norway spruce in early rotation (Fahlvik et al., 2004; Fahlvik et al., 2011; Frivolt & Frank, 2002; Valkonen & Vlasta, 1999). In the latter part of the rotation, the growth pattern shifts, Norway spruce starts to grow faster and birch growth slows. This creates high competition between Norway spruce and birch and consequently self-thinning of birch increases. This could lead to lower MAI in Norway spruce-birch mixed stands. However, despite having lower MAI in mixed forest, LEV in the mixed_dense treatment was almost equal or higher compared to Norway spruce monoculture in three out of four sites. The lower profit in the fourth site could occur due to the lower volume production of Norway spruce in that site compared to other sites (according to the simulation data for volume production). This study result indicates that during PCT, by keeping 1000 Norway spruce and 1000 birch ha^{-1}, it is possible to obtain a wide range of ecosystem services with no or little economic loss.

However, it is not possible to translate all different forest ecosystem services obtained from the mixed forest into monetary outcomes. Mixed stands can get benefits like stand stability and protection from biological agents which can increase the LEV in practical forest management. Moreover, with lower planting costs of mixed forest and uncertainties related to the future timber market, the mixed forests could be more profitable in the long run than Norway spruce monocultures. Therefore, a PCT prescription of keeping 1000 Norway spruce and 1000 birch ha^{-1} could be a potential strategy to balance profit and other ecosystem services in long term. Although it seems uneconomical, the mixed_sparse treatment could be beneficial for game animals and other biodiversity because of the sparse stand. A low stem density helps accessibility for game animals to move and light-demanding understory vegetation might get benefit from the open canopy. Overall this study showed that PCT can be a tool to alter the stand structure at an early age to meet the long-term goal of forest management. This study also showed the different possibilities of tailoring management alternatives to management goals.

4.2 Constraints of the thesis

The Äbin data used in paper I was designed to inventory ungulate browsing but was repurposed to calculate species composition. This means it is not possible to predict the future stand structure with a high degree of confidence based on this data analysis alone. Young stands are mostly of mixed species, and it is difficult to predict their future trajectories. Forest composition depends on future forest management as well as ecological and environmental interactions. Broadleaves may be removed during PCT and commercial thinning, resulting in conifer-dominated stands. Moreover, low-density Norway spruce and Scots pine plantations can also result in low-density monocultures or conifer mixtures that are managed without thinning.

In paper II, mid-rotational field-measured data was used to investigate the effect of planting design on the stand characteristics of planted forest. Because this data represents a single snapshot of a stand's development, no time series analysis was possible to check if the planting design affected early development. However, other studies in young stands and time series data showed no effect of planting design on the growth and external wood quality of different tree species (Sharma et al., 2002; Salminen & Varmola, 1993).

The main objective of paper III was to simultaneously estimate forage and volume production of Norway spruce-birch stands. During the experimental design, it was anticipated that ungulates would move freely, necessitating a relatively large area for each treatment to test the effect of PCT treatments. Due to this, it was not possible to replicate the treatments within each site. This could adversely influence the statistical analysis. Moreover, although we used relatively large areas for each treatment, the overall size of each area was still smaller than the average home range of a moose (Neumann, 2019). This could also influence the lack of effect of PCT on ungulate browsing.

In paper IV, a forest decision support system was used to simulate stand development which is built based on several empirical models. These models are mostly regression functions, where dependent variables are estimated from easily-measured tree, stand, or site variables. However, this is a general weakness of the empirical model because it is highly dependent on the data used for parameterization (Peng, 2000; Porte & Barterlink, 2002). The growth models in Heureka have been found to provide reliable results for long-term projections in even-aged forests (Fahlvik et al., 2014). However, the uncertainties related to the interpolation and extrapolation could make the model less certain for mixed forests (Drössler et al., 2013). Another general problem related to long-term forecasting of growth which becomes less accurate with increasing prognosis length. This is partly due to the forecasts being made recursively, updating the independent variables in each fifth year and error compounds from one period to the next. Moreover, long-term forecasts require a reliable estimate of natural mortality (Fridman & Ståhl, 2001). However, mortality prediction is very difficult due to its stochastic nature. Also, long term simulation of unthinned forest is indeed a challenge as it is not well represented in the data used for model construction. Moreover, all the uncertainties related to future climate change (e.g storm effects, bark beetle outbreak, and higher tree growth in southern Sweden; Erikson et al., 2015) were not considered during the simulation. This is important to keep in mind while interpreting the results. Also, all the benefits associated with mixed forests were not included in the simulation, which creates uncertainty while interpreting the profitability of mixed forests. The cost of planting seedlings was considered the same for establishing both monocultures and mixed forests. However, during practical implementation, the lower cost of planting mixed forest might increase profit. Together, these factors can overestimate the profit from Norway spruce stands and underestimate the profit of mixed forest.

4.3 Future research

The stand structure and species composition of the young forest were evaluated in paper I using the Äbin inventory data. Future studies can be done by simulating stand structure over a full rotation based on Äbin data. From paper I, we came to know how young stand structures look, though it was not possible to predict what mature stands or stands during final felling will look like. Future simulation studies can forecast the stand structure as a consequence of seedling mortality and browsing. Moreover, stand structure can also be simulated assuming that no seedlings will die during regeneration. This will provide us an indication of the structure and composition of a stand if there is no seedling mortality. Moreover, an earlier study in mid-Sweden showed the potential of Norway Spruce-Scots pine mixtures to improve regeneration where browsing pressure is high. More studies can be done testing other mixtures.

The effect of planting design on the production and external wood quality of coniferous plantations in Sweden was evaluated in paper II. The non-effect of planting design on the characteristics of plantation forest is supported by earlier studies conducted on different species and in different parts of the world. However, the reason for not having any effect of planting design has not yet been investigated. In my opinion, future research should be prioritized on finding out the reason for non-effects of spatial arrangement of trees. I expect that the explanation has to do with below-ground interactions between trees through their root systems rather than above-ground competition, and would encourage studies into this topic.

In paper III, browsing was found to be exceptionally low compared to the total forage availability. Based on earlier literature, I would expect that one of the reasons might be the overall lower density of ungulates in this area. This could be tested experimentally using identical PCT treatments in sites with greatly differing ungulate densities. However, it could be extremely difficult to find stands at different moose densities where birch is not heavily browsed. In that case, fencing can be used during regeneration. Fencing can be removed during PCT when the average height of Norway spruce is 1-2 meters. Moreover, ungulates are very selective in browsing even in winters when their twig-based food is relatively nutrient-poor and difficult to digest. Their selectivity could be different between (Andren & Angelstam, 1993) and within the stands or even between shoots from the same species (Shipley et al., 1999). Ungulates are also selective in browsing between silver and downy birch shoots (Danell et al., 1985). Therefore, there is an obvious reason to expect a difference in the selectivity of shoots from birch and birch sprouts, which varies greatly between different pre-commercial thinning strategies. In this paper, seed birch and stump sprouts were not separated in the dataset during forage utilization. At the end of the three growing seasons, we found no difference in total forage availability and utilization between the PCT-total and PCT-mix treatments. However, relative preferences for seed birch and stump sprouts could be different when both are present in a stand, something that can be tested in further studies of ungulates' relative preferences.

In paper IV, empirical forest modelling was used to simulate stand development of Norway spruce monocultures and mixed forests over a full rotation. However, the growth models used in this study were mostly developed from empirical data sourced from homogeneous forests. With a growing interest in and reality of mixed forest, I think the model should be developed to simulate these kinds of stands. Other variables could be considered, such as abiotic drivers of production, soil characteristics, and climate variables.

Mixed forests are beneficial for multiple forest services, though we know very little about mixed forest management compared to monoculture forest management. Mixed forest management requires additional considerations due to the distinct ecological traits of multiple tree species. However, in Sweden, there are more than 1600 long-term silvicultural experiments and only 3% of them are mixed forest experiments (www.silvaboreal.com). Due to the resultant lack of local knowledge regarding suitable silvicultural prescriptions, the tree species found in mixtures are often managed using recommendations designed for monocultures. More experiments need to be established to develop management strategies of mixed forest and more research with alternative strategies need to be tested to balance production and other ecosystem services.

Moreover, the mixed forest experiment used in this thesis was established by planting 2000 Norway spruce ha^{-1} during regeneration. Therefore, it was not possible to reduce the regeneration cost during simulation. The regeneration cost could be reduced if the species proportion is pre-set at regeneration and a lower number of Norway spruce plants are supplemented by naturally-regenerated birch in mixtures. Studies can be done by reducing species' proportions during regeneration and analysing its influence on future profits. Also, mixed forest stands can be exposed to future climate trends and changes, for example drought and storms, and more studies can be done on how these climate changes and trends affect mixed forests compared to monocultures.

Also, earlier literature discusses the advantages of mixed forest in terms of stand stability against storm and wind damage, pests, and pathogens. Moreover, the mixed forest might also be advantageous given long-term uncertainties related to timber markets. In this case, scenario analysis with advantages of mixed forest for stand stability, pests and pathogen resistance, and sensitivity analysis to increasing timber prices for mixed forest could be done. In addition, mixed forests are usually studied in terms of stand productivity in comparison to monoculture. However, future studies can be done on how mixed forest influences external wood quality, allometry, etc. So far, most studies in Sweden and elsewhere have focused on mixed forests with only two species. New experiments need to be established with more than two species to quantify the mixing effect on the growth and production of the stands.

Lately, climate change has arisen as a challenge that puts new demands on forest management. With ever-changing growing conditions, it is more challenging to make plans for sustainable forest management. Sustainable forestry needs to estimate the effects of climate change accurately on the forest. With ongoing and predicted changes in the boreal climate, tools for management planning and predicting forest development need to be flexible and respond to these changes. Forest models need to be updated with climate data that can influence forest productivity. Future studies need to focus on incorporating climate data into existing models. In this case, hybrid models (combining empirical and processed-based models) could be used to model future stand development.

Also, despite the significant use of PCT in Norway spruce, little research has been done on the long-term profitability of PCT in Norway spruce stands. To my knowledge, paper IV is the first scientific evidence to study the profitability of doing PCT in Norway spruce stands over a full rotation. There was variation in growth and profitability between sites. Future studies can establish experiments in different site conditions and investigate how PCT influences production and profit in different kinds of sites. Moreover, the timing of PCT on the growth and profit of Norway spruce (paper IV) differs with findings from earlier studies on Scots pine. Future studies can establish side-by-side experiments between Norway spruce and Scots pine with PCT treatments and doing modelling to investigate how PCT influences these species in identical site conditions.

4.4 Practical implementation of this thesis findings

- **New possibilities for forest operation & management**: Machinery operation is very common in Swedish forestry in thinning operations and final felling. During thinning, strip roads are created for harvesting trees. In a rectangular planting design, there is no need to create strip roads in later stages, as machines can drive along the corridors between rows of trees. Moreover, in Scandinavian countries, machines are not often used to do PCT, while a rectangular planting design provides the opportunity to do PCT using machines along the corridor.

- **Improvement of regeneration**: Seedling mortality in regeneration is one of the biggest issues in Scandinavian forestry. Very often at the end of regeneration, target stand density is not reached due to seedling mortality. Implementation of a rectangular planting design could be one piece of the puzzle. As it is possible to select the best microsite in flexible planting designs, survival of seedling can improve. Moreover, rectangular planting makes clustered planting possible, which can reduce the time and cost of regeneration compared to row planting. Moreover, as most young stands contain a mix of species, relying on natural regeneration rather than planting seedlings could reduce regeneration costs by requiring less planting and improving regeneration.

- **Possibility to influence forage:** Browsing damage is one of the major problems in forest management in Sweden and other boreal forests. With increasing ungulate density, there is always a great value in finding adaptive management strategies to reduce browsing damage. Forage availability has a relation to the browsing intensity. In this regard, creating extra forage in the forest landscape without losing forest production might lower the overall browsing pressure. PCT strategies (keeping only 2000 Norway spruce ha^{-1} or keeping 2000 Norway spruce and 2000 birch ha^{-1}) in Norway spruce-birch mixture could be a potential way to create extra forage in the landscape.

- **PCT in Norway spruce stands:** Pre-commercial thinning is recommended in Swedish forestry but many forest owners ignore it because of its cost. This thesis' findings indicate the positive effect of PCT on the early growth and long-term profitability of Norway spruce on fertile sites. Therefore, forest owners can invest in PCT for young Norway spruce stands for higher income from thinning and final felling. Moreover, it is often debated when PCT should be done to balance growth and external wood quality of the stands. This thesis' findings indicate less effect of PCT on the profitability of Norway spruce stands. Therefore, forest owners and managers might be flexible to choose when they want to do PCT (early or late) in their Norway spruce stands. However, more research needs to be carried out for concrete recommendations.

- **PCT to manage unintended mixed forests**: Most of the forest area in Sweden is regenerated either with Norway spruce or Scots pine. Southern Swedish forests are dominated by Norway spruce and birch is abundant in the planted stand due to natural regeneration. In such unplanned stands in fertile sites, PCT can be useful to modify the stand structure and composition toward the management goal. This thesis' findings suggested that based on the management goal, PCT can be useful to develop either Norway spruce monocultures or Norway spruce-birch mixed forests.

- **Flexibility to choose forest management strategies:** Forest management goals are different for different forest owners. Therefore, it is valuable to offer them multiple forest management options for stand development. This thesis has shown that both Norway spruce monocultures and mixed stands can supply forage for ungulates without losing volume production of Norway spruce during early growth stages. Forest owners and managers can choose either of the PCT strategies to supply forage for ungulates and develop their future stand based on their management goals. Also, it is possible to develop mixed forests containing Norway spruce and birch over the long term based on different management goals. If forest owners want profit, more ecosystem services compared to Norway spruce and also consider forest certification, keeping 1000 Norway spruce and 1000 birch ha^{-1} could be an option. Otherwise, the development of Norway spruce monocultures remains an option.

- **Development of mixed forest:** Current forest management should be improved to attain multifunctional and sustainable forest management. Mixed forest is often considered to be able to meet these demands. This thesis' findings indicate that both strategies used to develop mixed forest during PCT (keeping 1000 Norway spruce: 1000 birch $ha^{-1}$and 500 Norway spruce:500 birch ha^{-1}) can support both Norway spruce and birch in full rotation. Stands with keeping 1000 Norway spruce and 1000 birch ha^{-1}during PCT, has the potential to provide both profit and high levels of several ecosystem services in the boreal region (Jonsson et al., 2019). However, the density of birch in the mixture is important to get the highest level of ecosystem services (Jonsson et al., 2019), which needs to be kept in mind during the interpretation of this finding. Keeping 500 Norway spruce and 5000 birch ha^{-1}during PCT could be beneficial for other biodiversity and ecological services as there is a more open canopy, though it is very unlikely to be economical. This finding showed different possibilities to manage mixed forests with different outcomes. This could serve as a guideline for forest owners to select management strategies based on their management goals. However, this is just one case study, so more studies in different mixtures need to be carried out for concrete conclusions.

5. Conclusion

This thesis' findings indicate that the failure or success of regeneration, establishment and young forest management determines the future stand structure, production, profitability, and other ecosystem services. Paper I showed how regeneration failure across Swedish young forests changes their species composition and structure. Forest owners aimed to have either Norway spruce or Scots pine in their stands. However, the young forest was dominant by a mix of species as a consequence of regeneration failure of planted seedlings.

Findings of papers II-IV showed the potential of alternative silvicultural management strategies to combine production and other ecosystem services as well as the implementation of new management possibilities. Paper II showed that rectangular planting does not negatively affect the production and external wood quality of coniferous plantations in Sweden. This provides the opportunity to select microsites that can improve regeneration. Moreover, it can also improve soil scarification, facilitate machinery operations, and also can provide an opportunity to do PCT using machines.

Moreover, the alternative PCT strategy (keeping 2000 birches along with 2000 Norway spruce ha^{-1}) tested in paper III didn't negatively affect the volume production of Norway spruce and also supplied forage for ungulates. However, after three growing seasons, the traditional PCT strategy (keeping 2000 Norway spruce ha^{-1}) also provides the same amount of forage as other PCT strategies did because of lots of stump sprouts. These means forest owners can use any of the PCT strategies that maximises the production of Norway spruce and also supplies enough forage for ungulates.

Also, the long-term effect of different alternative PCT strategies on a planted Norway spruce and naturally-regenerated birch stand was simulated over a full rotation in paper IV. The result showed that doing PCT in Norway spruce stands is economical in the long term. The timing of PCT and stump sprout removal has less effect on the profitability of Norway spruce stands. However, more studies considering site variation need to be conducted to make concrete recommendations for practical implementation. Moreover, during PCT, keeping 1000 Norway spruce and 1000 birch ha^{-1} might be a potential strategy to balance profit and other ecosystem services in long term.

Overall, it can be said that multiple ecosystem services along with production and profit can be combined using alternative management strategies. Moreover, it is also shown that alternative forest management can offer new possibilities without losing production. This finding can be a guide for forest owners, forest managers, and policymakers to make the right decisions in early forest management considering the shift from one value of the forest to multiple values.

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The success or failure of regeneration, establishment, and young forest management determines the future stand structure, production, profitability, and multiple ecosystem services. In this thesis, stand structure was described as a consequence of regeneration failure and showed the effect of planting design (during establishment) on the production of coniferous plantations. This thesis also contributes to the knowledge of young forest management using PCT in a Norway spruce-birch mixture to combine production, profit and multiple ecosystem services.

Mostarin Ara received her first MSc from Khulna University, Bangladesh and second joint MSc from Lund University, Sweden and Twente University, The Netherlands. Her undergraduate degree is from Khulna University, Bangladesh.

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