Natural regeneration and management of birch

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Abstract

This thesis offers guidance for those who want to naturally establish, maintain and manage birch in monocultures and mixed stands. Silver and downy birch are the most common broadleaf tree species in northern Europe. In Sweden, the two species together make up approximately 12% of the standing forest volume. This thesis presents results from four studies (papers I - IV), with the aim to increase the level of knowledge about establishment and regeneration of birch, management of naturally regenerated birch in pure and mixed stands, and the distribution of birch over Sweden. The studies were based on experimental data from field trials, survey data from practical forestry, Swedish national forest inventory data and predictive modelling. On dry soil, mechanical site preparation is necessary in order to get a successful regeneration of birch; in wet soil moisture conditions, natural regeneration of birch will appear without effort. It is possible to manage the birch regeneration success if the soil scarification is adapted to the soil moisture conditions (paper I). The proportion of silver and downy birch varied in Sweden's young forests, and the temperature sum explained most of the variation (paper II). In dense, naturally regenerated stands of birch and Norway spruce, pre-commercial thinning (PCT) had a significant impact on the development of the future stand, and there are several profitable management strategies for the owner of this type of stand (paper III). The proportion of birch tends to decrease after canopy closure in mixtures of Norway spruce with stand age in southern Sweden, regardless of thinning (paper IV). Active forest management is key, in order to maintain the proportion of birch over the full rotation period. In conclusion, this thesis offers knowledge that can contribute to a more varied forestry, and forestry with a greater element of broadleaf trees.

Keywords: Betula pendula; Betula pubescens; Silver birch; Downy birch; Modelling; Forest management; Pre-commercial thinning; Direct seeding; Soil scarification; Mechanical site preparation.

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Naturlig föryngring och skötsel av björk

Sammanfattning

Denna avhandling är en guide till naturlig föryngring och skötsel av naturligt föryngrade bestånd med björk. Vårtbjörk och glasbjörk är norra Europas vanligaste lövträdslag. I Sverige står de två arterna för ca. 12% av den totala virkesvolymen. Avhandlingen baseras på fyra studier (I – IV), med målet att öka kunskapen kring naturlig föryngring och skötsel av björk i monokulturer och blandbestånd, samt björkarternas spridning över Sverige. Studierna baserades på data från fältförsök, inventeringar i det praktiska skogsbruket, riksskogstaxeringen och prediktiv modellering. På torr mark är det nödvändigt att markbereda för att få en lyckad naturlig föryngring av björk, på blöt mark däremot så etablerar sig björken oftast enkelt utan åtgärder. Det går alltså att styra över föryngringen genom att anpassa markberedningen efter de rådande markförhållandena (studie I). Fördelningen mellan de två björkarterna varierar signifikant över Sverige, förklaringen till detta är till största del temperatursumman (studie II). I täta naturligt föryngrade bestånd av björk och gran har röjning signifikant effekt på utvecklingen av det framtida beståndet. Det finns flera olika lönsamma skötselstrategier för skogsägaren till ett sådant bestånd (studie III). Andelen björk tenderar att sjunka i blandbestånd av gran och björk i södra Sverige över tid, oavsett om bestånden gallras eller ej (studie IV). Ett aktivt skogsbruk med medvetna val är avgörande för att kunna behålla andelen björk i ett bestånd under hela omloppsperioden. Sammanfattningsvis tillhandahåller denna avhandling kunskap för att skapa ett variationsrikt skogsbruk, och ett skogsbruk med en ökad andel lövträd.

Nyckelord: Betula pendula; Betula pubescens; Vårtbjörk; Glasbjörk; Modellering; Skogsskötsel; Röjning; Sådd; Markberedning.

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Preface

- *Sometimes it is hard to see the forest for the trees.*

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. Lidman, F.D.*, Karlsson, M., Lundmark, T., Sängstuvall, L., Holmström, E. Birch establishes anywhere! So, what is there to know about natural regeneration and direct seeding of birch? (submitted manuscript)

II. Lidman, F.D.*, Karlsson, M., Lundmark, T., Sängstuvall, L., Holmström, E. Birch in the Swedish forest: mapping and modelling. (Manuscript)

III. Lidman, F.D.*, Holmström, E., Lundmark, T., and Fahlvik, N., (2021). The Management of spontaneously regenerated mixed stands of birch and Norway spruce in Sweden. Silva Fennica, 55 (4), article id 10485.

IV. Holmström, E.*, Carlström, T., Goude, M., Lidman, F.D. and Felton, A. (2021). Keeping mixtures of Norway spruce and birch in production forests: insights from survey data. Scandinavian Journal of Forest Research, 36 (2-3), pp. 155-163.

Papers III & IV are reproduced with the permission of the publishers.

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The contribution of Felicia Dahlgren Lidman (FDL) to the papers included in this thesis was as follows:

I. FDL is the main author. FDL developed the research idea together with EH and TL. FDL established and managed the field trial. FDL compiled the data and did the statistical analysis. FDL wrote the manuscript in collaboration with the co-authors.

II. FDL is the main author. FDL developed the research idea together with EH and MK. FDL was in charge of the field survey, did the data compilation and statistical analysis. FDL wrote the manuscript in collaboration with the co-authors.

III. FDL is the main author. FDL compiled the growth & yield results and conducted the statistical analysis. FDL wrote the manuscript in collaboration with the co-authors.

IV. FDL participated in writing the manuscript, which was led by EH.

List of figures

Abbreviations

BI	Birch monoculture strategy, 1200 stems ha^{-1}
CTR	Control strategy, no biomass harvest
DBH	Diameter at Breast Height
FSC	Forest Stewardship Council
LEV	Land Expectation Value
MIX	Mixed strategy with 1200 stems birch ha^{-1} and 1300 stems Norway spruce ha^{-1}
NFI	National Forest Inventory
NS	Norway Spruce monoculture strategy, 1300 stems ha^{-1}
PCT	Pre-Commercial Thinning
PL	Planted Norway spruce monoculture strategy, 2000 stems ha^{-1}

1. Introduction

Globally, there are around 46 known species in the genus Betula, dispersed over the northern hemisphere. Birches are deciduous trees usually recognizable by their white paper-like bark texture, but far from all birches have white stems. *B. lenta*, *B. nigra* and *B. dahurica* are all examples of birches that have dark, almost black, bark (Ashburner & McAllister, 2016). The white colour in the bark comes from the compound betulin (Hayek *et al.*, 1989), which protects the tree from fungi, bacteria and insects and makes the bark resistant to decay (Ashburner & McAllister, 2016; Kuznetsova *et al.*, 2014).

The genus Betula comes in many different shapes and sizes, from larger species such as *B. utilis* and *B. pendula* that can reach 30 - 35 m in height, to dwarf shrubs like *B. nana* that only reach around 0.5 m in height. Leaf shape varies from small and round to larger triangular leaves with more or less serrate margins. All birches are monoecious and produce male and female catkins on the same individual. The pollen and seeds are wind-spread with the seeds being flat nutlets with small wings on either side.

Two of the most commonly cultivated birch species are silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescence* Ehrh.) (Ashburner & McAllister, 2016). In northern Europe, they are also the most common broadleaf species. For this thesis, both species were included in the studies so the term “birch” refers to both silver and downy birch, unless otherwise is specified.

1.1 Silver and downy birch - ecology

Birch is a pioneer species known to establish efficiently after disturbances such as fire (Dzwonko *et al.*, 2015; Ascoli & Bovio, 2010), storms (Vodde *et al.*, 2010; Ilisson *et al.*, 2007) or clearfellings (Götmark *et al.*, 2005; Karlsson & Nilsson, 2005; Karlsson, 2002; Holgén & Hånell, 2000). Naturally, this is dependent on there being seeds available (Holmström *et al.*, 2016a; Atkinson, 1992; Perala & Alm, 1990). Birch seed and pollen can travel long distances, and are produced in abundant and inter-annually varying amounts (Rousi *et al.*, 2019; Wagner *et al.*, 2004; Eriksson *et al.*, 2003; Hjelmroos, 1991; Koski & Tallqvist, 1978; Sarvas, 1952). To prevent a birch tree from pollinating its own flowers there is a self-incompatibility mechanism (Hagman, 1972). Even though silver birch has fewer (2n=28) chromosomes than downy birch (2n = 56), it is possible for the two species to pollinate each other, although it is rare (Raulo, 1987). The germination of birch is regulated by interactions between temperature and photoperiod. Temperatures of 10 - 20°C are required but the best conditions are around 17 - 35°C for birch germination, although variations depending on provenance exists. Apart from temperature and photoperiod, the soil moisture conditions are the most important factor that determines whether or not a birch seed will germinate, it should not be too dry and conditions should not fluctuate (Frivold, 1986; Palo, 1986; Sarvas, 1948).

The most beneficial sites for silver birch growth are sandy, fine sandy and silty soils. Silver birch is more sensitive to flooding than downy birch. Downy birch is the less sensitive of the two birch species, and establishes in less favourable conditions such as compact soils and peatlands to a greater extent. In the most northern parts of Europe, silver birch usually grows on drier sites suitable for Scots pine whereas downy birch can grow on more moist sites with fine, cool and poorly aerated soils (Mossberg & Stenberg, 2018; Sutinen *et al.*, 2002). In Sweden, silver and downy birch are usually not separated, they are both referred to as “birch” (Skogsdata, 2021). The phenotypes of silver and downy birch can be quite similar, especially when the trees are more than 20 years old (Lundgren *et al.*, 1995). Normally, silver birch has more triangular leaves with double serrate margins whose prominent teeth curve towards the leaf apex, and has resinous warts and lenticels, especially on the young twigs. Downy birch generally has more rounded leaves with single serrate margins whose teeth do not curve towards the apex of the leaf (Figure 1.) In addition, downy birch normally has smooth pubescent twigs, which lack resinous warts and have fewer or no lenticels (Ashburner & McAllister, 2016; Hynynen *et al.*, 2009; Atkinson, 1992). A definitive way to identify between the two birch species is by using a precipitate reaction, where detection of a phenol called platyphyllosid that exists in large amounts in the bark of silver birch but not at all in downy birch is used. A sample of birch bark is added to a fluid which causes a visible precipitate due to the reaction with the platyphyllosid (Eriksson *et al.*, 1996; Lundgren *et al.*, 1995).

Figure 1. Downy birch (*Betula pubescens*) on the left and silver birch (*Betula pendula*) on the right. Photo: F.D. Lidman

1.2 Silver and downy birch - regeneration

In many European countries, natural regeneration is the most common and preferred method for regenerating birch (Cameron, 1996). It is also the most common method of birch regeneration in Sweden (Skogsdata, 2021; Skogsstyrelsen, 2021). Seed supply is a key factor when naturally regenerating birch (Holmström *et al.*, 2016a; Karlsson, 2001). On sites where there are too few birches in the surrounding stands, a shelterwood can be used to secure the seed supply. An important thing to keep in mind when using a shelterwood is that it should not be too dense, since birch is shade intolerant (Hynynen *et al.*, 2009; Nilsson *et al.*, 2002; Nygren & Kellomäki, 1983). Around 20 to 40 trees per hectare is the recommended density in a shelterwood for birch regeneration (Cameron, 1996). Since the soil moisture conditions are so important when regenerating birch (Frivold, 1986; Palo, 1986; Sarvas, 1948), soil scarification is often recommended. This reduces the competition for water and nutrients from the surrounding vegetation (Johansson *et al.*, 2013; Karlsson, 2003; Örlander *et al.*, 1990), but on the other hand, soil scarification increases the cost of the regeneration (Skogsstyrelsen, 2021). Common types of mechanical site preparation are disc trenching and intermittent mounds (Sikstrom *et al.*, 2020; Örlander *et al.*, 1990). Besides creating an improved germination microsite for the birch seeds and a planting spot for the planted seedlings, the main reason for soil scarification on boreal soils is to reduce damage caused by pine weevil (*Hylobies abietis*). The reason is that the beetle is less prone to stop and feed on the seedling bark when surrounded by bare mineral soil (Wallertz *et al.*, 2018; Långström & Day, 2007). Pine weevils are a well-known problem when regenerating conifers (Wallertz *et al.*, 2014; Nordlander *et al.*, 2011), but birch is also a species in their diet and can be equally damaged when planted on former conifer clearfellings (Toivonen & Viiri, 2006). The preferred method for producing stands of high-quality birch timber is planting in monocultures, which is a more predictable, although also more expensive method, compared to natural regeneration. Perhaps the argument that is the most important when choosing planting is the genetic gain when using genetically improved seedlings, which have faster growth and better stem quality (Stener & Jansson, 2005). Planting is also recommended to be used in combination with soil scarification to secure the survival of the seedlings (Rytter, 2014). Other examples of regeneration methods for birch are coppice systems, where the regrowth occurs from stem sprouts, and can be used in short rotation and intense management, or direct seeding. Both these methods are less commonly used in the Nordic region (Hynynen *et al.*, 2009).

1.3 Forestry and the forest industry in Sweden

In Sweden, 28 million hectares, 69% of the terrestrial land area, is covered with forest (Skogsdata, 2021). Forestry has been of great importance for the Swedish economy historically, and remains so today. In 1870, timber accounted for 51% of Sweden's total export value; at present, products produced by the Swedish forestry sector account for approximately 10 % of the country's total export value (Skogsindustrierna, 2021; Jansson *et al.*, 2011; Söderlund, 1952). Up until around the nineteenth century, the forest resources were primarily used locally for household needs, firewood being the most important one by far, but also wood for construction and woodcraft. During the 18th and 19th centuries, there was increased pressure on the forest resources from the mining industry and because farmers in many regions produced wood-tar and potash (potassium carbonate from birch wood) for extra income (Josefsson & Östlund, 2011; Borgegård, 1996; Villstrand, 1996; Östlund, 1995). During the nineteenth century, the common harvesting method in the northern two-thirds of the country was selective cutting of the largest and most valuable coniferous trees. Forest harvests were undertaken without any active regeneration measures. Repeated cuttings were made until the stands, in some cases, had become rather sparse (Arpi, 1959). Since then, even-aged management with the primary goal of timber production has become the common practice, where entire stands are harvested at the same time. This is also known as a clear felling system or rotation forestry (Lundmark *et al.*, 2013; Josefsson & Östlund, 2011; Lisberg Jensen, 2011). This has resulted in a forest landscape characterized by stands of the same age with an even age-class distribution, allowing an even flow of timber from the forest to industry. At present, around 200 000 hectares of the productive forest land in Sweden is clearfelled each year. Some 85% of the clearfelled area is thereafter mechanically soil scarified and 80% of the area is then regenerated by planting. Almost exclusively two tree species are planted; either Norway spruce (*Picea abies* H.Karst.) or Scots pine (*Pinus sylvestris* L.), Sweden's two most common tree species. (Skogsdata, 2021; Skogsstyrelsen, 2021)

1.4 Birch in the Swedish forest and forest industry

The third most common tree species in Sweden is birch, more specifically silver birch and downy birch which accounts for approximately 12.4% of the standing timber volume (Skogsdata, 2021; Skogsstyrelsen, 2021). Birch trees and birch wood has always been an essential resource for farmers and the indigenous Sami population. Birch wood has been used for firewood and for tools, while birch bark was stripped from the trees and used as a protective layer on roofs. For the Sami population, birch wood and birch bark have been crucial to their survival in the high mountains for thousands of years (Östlund *et al.*, 2015; Liedgren & Östlund, 2011). In the 19th century, potash was produced in northern Sweden, sold, and then exported on a large scale (Östlund, 2005; Östlund *et al.*, 1998). Potash was used in industrial processes to produce soap, dye fabric and glass. During World War I and World War II, fuelwood from birch became very important due to the problems of importing fossil fuels to Sweden. Such wood was transported from rural areas to the larger cities and used for heating. Birch wood was also used to produce wood gas-fuel for cars (Sw. *gengas*) when gasoline was scarce. The intensive cutting of birch wood during the two wars had an important, but now largely ignored, influence on the forest structure, particularly in northern Sweden (Schön, 1992).

The development of the Swedish forest industry during the nineteenth century increased the demand for timber. This required efficient logistics for the mills and caused the forest industry to become dependent on timber floating in rivers, a method that goes back to the fifteenth century and the mining industry's demand for firewood. For several hundred years, timber floating was the main long-distance transportation method for timber in Sweden. Sawmills were established along the coast where rivers met the bay of Bothnia. The sawmills wanted high quality, large diameter logs of Scots pine and Norway spruce (Törnlund & Östlund, 2006; Nilsson, 1999) so birch was less desirable. In addition, birch tended to sink more easily during the floating anyway (Callin, 1948). When paper production started to use larger quantities of material from the timber market, around 1870 (Järvinen *et al.*, 2012), Norway spruce was the most in-demand timber species for making paper pulp, and remained so for a long time. The demand for conifer timber and the higher price on the market in comparison to, for example, birch, later led to active removal of the less desired deciduous species in the Swedish forests. Early on, birch was removed using manual pre-commercial thinning, but between 1950 and 1980, deciduous species were also treated with herbicides. The herbicides used contained the active substances di- and trichlorophenoxyacetic acid, in Swedish known by the commercial name “hormoslyr”, and in English known as Agent Orange. The herbicides were manually sprayed on young deciduous trees, poured into pockets made in the bark of older trees, and later dispersed over entire stands from airplanes. The active substances caused the broadleaf trees to grow to death, leaving the conifers with less competition. At least 700 000 hectares of productive forestland were sprayed with herbicides in Sweden between 1948 and 1984 (Östlund *et al.*, 2022). Large-scale use of herbicides was banned in the late 1980s because of the widespread protests from a growing environmental movement, which argued that the use of toxins damaged flora, fauna and people who worked with the herbicides (Östlund *et al.*, 2022; Lisberg Jensen, 2006; Lindewall, 1992).

Modern methods of paper pulp production uses both broadleaf and conifer fibres because of their different characteristics. The wood and wood fibre composition in conifer and broadleaf timber has different characteristics that are suitable for different types of wood pulp and products (Thörnqvist, 1990). In Sweden, birch is currently mainly used in the paper and pulp industry, with around 20 % of the wood consumed by the pulp industry being broadleaf species. There are very few sawmills for hardwood timber in Sweden. Out of the 16 million m^3 of products of sawn wood produced by the Swedish forest industry in 2013, only about 110 000 m^3 were from broadleaf species (Skogsstyrelsen, 2014; Woxblom & Nylinder, 2010).

Over the past decades, there has been a growing interest in biodiversity in the Swedish forest sector (Simonsson *et al.*, 2015). Retaining some of the naturally regenerated birch in pre-commercial thinnings, and then later thinnings to increase the amount of broadleaf species in a conifer stand, is one way to increase biodiversity (Felton *et al.*, 2021; Felton *et al.*, 2010). In 1994, the Swedish forestry act stated that biodiversity and production goals should be weighted equally in Swedish forestry (Skogsstyrelsen, 2019). In the current Forest Stewardship Council (FSC) standard (dated October 2020), the criterion for a forest owner to be certified is that they keep a minimum of 10% broadleaf stems in all stands (FSC, 2020).

1.5 Birch management

In Sweden at present, most of the birch is naturally regenerated, occurs in mixed stands (Skogsdata, 2021; Skogsstyrelsen, 2021), and is managed differently to planted birch. Apart from the regeneration method, birch plantations often have timber production as their main goal, as opposed to pulpwood or biofuel as the end product. Silver birch is used when the desired product is sawn timber, since it has higher quality and faster growth than downy birch (Heräjärvi, 2001). As a result, most of the birch planted in Sweden is silver birch (Rytter, 2014). However, out of the 453 million seedlings produced in Sweden in 2021, only 1.8 million were birch seedlings (Skogsstyrelsen, 2021). Pre-commercial thinning (PCT) is recommended to be carried out early in the rotation period when aiming for high quality birch timber, to avoid production losses due to competition and shading. Naturally regenerated or sown stands can be much denser than planted stands (Holgén & Hånell, 2000; Karlsson *et al.*, 1998) and often require several pre-commercial thinnings. A recommendation for birch is that 50% of the tree height should be covered by living crown in order to maintain vigorous growth. Small crowns (smaller than 50% of the tree's total height) are a sign of severe competition, and can lead to growth losses for individual trees which cannot be compensated for later in the rotation period (Rytter, 2013; Rytter & Werner, 2007; Niemistö, 1995a). On the other hand, a wide spacing may lead to increased branch diameter, which reduces the wood quality (Niemistö, 1995a). Pruning of branches solves this problem, although it can be both time-consuming and expensive (Stener *et al.*, 2017). The recommended stand density for an even aged birch stand in Fennoscandia is between 1600 and 2500 stems per hectare after PCT (Rytter & Werner, 2007; Cameron, 1996; Niemistö, 1995a; Niemistö, 1995b). According to silviculture recommendations, there should be two commercial thinnings in a birch monoculture intended to produce sawn timber, one when the stand is around 10 - 15 m dominant height and another thinning around 13 - 15 years later. At the first thinning, the aim is to reduce density to 700 - 800 stems ha^{-1} and, after the second thinning, 350 - 400 stems per ha^{-1}. The length of the rotation period is usually around 40 - 60 years in Fennoscandia, depending on site and quality of the stand. (Rytter, 2014; Oikarinen, 1983) For stands producing pulp or biofuel, the recommendation is one pre-commercial thinning to around 2500 stems per hectare at 4 - 6 metres height and another thinning to around 1000 stems per hectare at 13 - 14 metres height. The length of the rotation period for these types of stands are usually around 50-60 years (Hynynen *et al.*, 2009). However, forestry practices in Sweden for birch is not as well researched as those for Scots pine and Norway spruce, there is still much to be known.

1.6 Browsing

Browsing damage to seedlings and young trees is a widespread problem in Swedish forestry. Which ungulate species causes the most problems varies over the country. Moose cause the most problems in the northern parts, whereas in the southern parts moose, roe deer, red deer and fallow deer all cause problems (Pfeffer *et al.*, 2021; Skogsdata, 2021; Spitzer, 2019; Bergquist *et al.*, 2009). Broadleaf species such as rowan, willow, aspen and birch are in general favored by all herbivores but, during the winter, Scots pine is more preferred. Norway spruce, on the other hand, is one of the species that is least preferred by moose (Månsson *et al.*, 2007; Hörnberg, 2001; Cederlund *et al.*, 1980), making forest owners more likely to plant it in areas where the browsing pressure is high (Lodin *et al.*, 2017). Another way to avoid browsing damage is to use fencing (Löf *et al.*, 2010; Bergquist *et al.*, 2009; Taylor *et al.*, 2006; Ammer, 1996), something that is essential to ensure successful regenerations of some broadleaved species, such as oak (Bergquist *et al.*, 2009). On the other hand, fencing around naturally regenerated stands of birch is more difficult to encourage forest owners to undertake, since the expected income from the final harvest is predicted to be relatively low (Hynynen *et al.*, 2009), as fencing with its necessary maintenance increases the management costs (Bergquist *et al.*, 2009; Taylor *et al.*, 2006).

1.7 Birch in mixtures

A common type of birch mixture in the Swedish forest is birch in combination with Norway spruce. This mixture is especially used as a nursing stand over Norway spruce, and has been frequently studied (Grönlund & Eliasson, 2019; Bergqvist, 1999; Klang & Ekö, 1999; Andersson, 1985). Norway spruce is a secondary species that is considered to be semi-shade tolerant and can adapt to the less favourable light conditions in the understory (Andersson, 1985; Assman, 1970). During regeneration, a shelterwood can help prevent frost damage to the leading shoots of spruce seedlings in the understory (Langvall & Löfvenius, 2002; Langvall & Örlander, 2001; Andersson, 1985). A negative effect of keeping a birch shelter over Norway spruce is the potential loss in spruce volume growth, which is generally compensated for (Fahlvik *et al.*, 2011; Valkonen & Valsta, 2001), or exceeded by (Bergqvist, 1999; Klang & Ekö, 1999) the birch volume growth. Similar results have been observed in mixtures of birch and Norway spruce where there is less difference in initial height between the two species (Holmström *et al.*, 2016b; Fahlvik *et al.*, 2005). Other negative effects of mixing birch and Norway spruce are logging damage during the extraction of the birch which is harvested earlier than the spruce (Grönlund & Eliasson, 2019; Valkonen & Valsta, 2001), and whipping damage on the spruces when the two species have similar heights (Fahlvik *et al.*, 2011; Frivold, 1982).

However, there are also several positive aspects of combining birch with conifer species to produce mixed stands (Dubois *et al.*, 2020; Felton *et al.*, 2016). Challenges and disturbances due to future climate change in the northern European forests, such as increases in pests and pathogens (Lindner *et al.*, 2014; Lindner *et al.*, 2010), can potentially be dealt with by increasing the tree species richness (Jactel *et al.*, 2017; Brang *et al.*, 2014). Although it always comes down to which species are mixed and how these specific species handles the disturbances (Bauhus *et al.*, 2017). According to the insurance hypothesis by Yachi and Loreau (1999), a higher number of species in an ecosystem increases the chance that some of the species will maintain their function in a fluctuating environment. Different species have different functional traits and can adapt to different situations with varying levels of success. Currently, the Swedish forestry sector regenerates and depends on mainly two tree species (Scots pine and Norway spruce) (Skogsstyrelsen, 2021), implying a higher risk than regenerating and depending on, three species (Norway spruce, Scots pine and birch). Moving from conifer monocultures to broadleaf-conifer mixtures also provides several other benefits such as an increase in the amount of ecosystem services (Huuskonen *et al.*, 2021; Felton *et al.*, 2016). Another example is the increase in biodiversity, for example, bird species abundance and richness increase when broadleaves is mixed into a Norway spruce stand (Felton *et al.*, 2021; Lindbladh *et al.*, 2017; Felton *et al.*, 2011). In addition, sites planted with conifers in Sweden often have an ingrowth of birch or other broadleaves (Ara *et al.*, 2021; Holmström *et al.*, 2016a), which unintentionally creates conifer-broadleaf mixtures without additional costs.

Given the above, there are several reasons why the Swedish forestry sector and forest owners should look beyond the two conifers Norway spruce and Scots pine. This should motivate further research in the area of regeneration and management of Sweden's third most common tree species, birch, and in the long run, other broadleaves such as aspen (*Populous tremula* L.), rowan (*Sorbus aucuparia* L.) or sallow (*Salix caprea* L.) .

2. Thesis aim

The aim of this thesis was to contribute to the knowledge about establishment and natural regeneration of birch, management of naturally regenerated birch in pure and mixed stands, and the distribution of birch over Sweden.

2.1 Objectives

Two studies focused on birch regeneration with the main objectives:

I. To increase the understanding of interactions of regeneration management (soil scarification) and soil moisture, and how this will affect the seedling occurrence and seedling density of the two birch species *Betula pendula* and *Betula pubescens* in northern and central Sweden.

II. To investigate the spatial distribution of *Betula pendula* and *Betula pubescens* in Sweden.

Two studies focused on management of mixed forest, combining Norway spruce and birch, with the main objectives:

III. To develop and evaluate four alternative management strategies for mixed forest originating from natural regeneration.

IV. Investigating the composition and structure of the mixtures in practical forestry in southern Sweden.

3. Material and Methods

The basis of papers I-IV was field survey and experiment data, with predictive modelling included for papers II and III. The areas of data collection varied between the studies but together they covered most of the latitudinal range of Sweden (Figure 2.). This section provides a brief explanation of the material and methods used. Further details can be found in the individual papers.

3.1 Data collection

3.1.1 Experimental data from block design (Papers I & III)

Studies I and III were based on field experiments with randomized block designs, evaluating the regeneration of naturally regenerated and direct seeded birch. The focus was on the establishment of naturally regenerated and direct seeded birch (paper I), and management of naturally regenerated birch in combination with Norway spruce (paper III). The regeneration experiment (I) ran for four years, with the density of direct seeded birch seedlings and occurrence of naturally regenerated birch seedlings inventoried. The experiments were established on three different site types with four blocks on each site, and nine plots in each block. Two different soil scarification treatments and one control were repeated three times in each block. To quantify the annual variation of seed rain and seedling establishment, the soil scarification in one third of the plots in each block were repeated each year for the first three years of the experiment. In addition, restricted parts of the plots were direct seeded with a known number of silver and downy birch seeds. The regeneration experiment took place in two study localities, one in northern and one in central Sweden (Figure 2.).

The regeneration experiment was inventoried twice during each vegetation period, between 2018 and 2021.

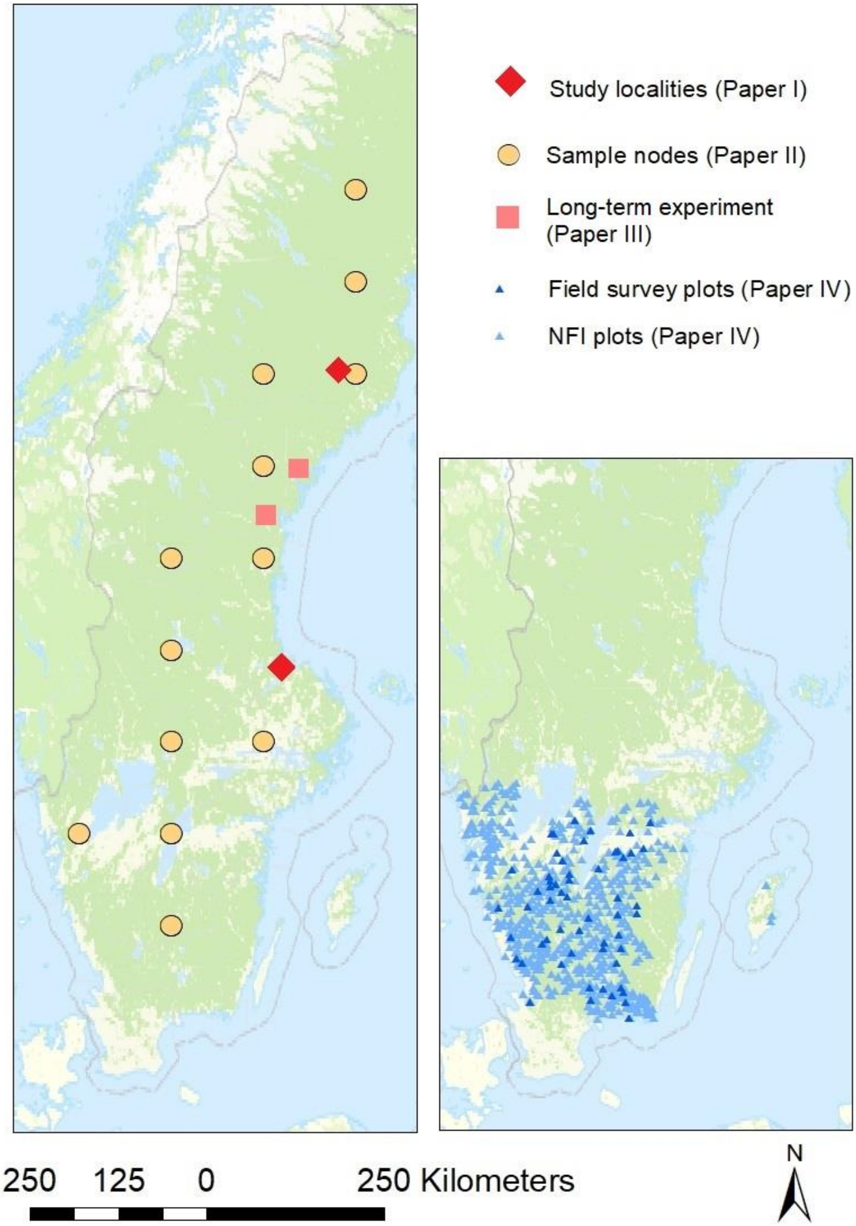

Figure 2. Locations of field surveys and field experiments in Sweden

The long-term experiment on management of naturally regenerated birch was established in 2007, on two sites with five blocks in total, on the east central coast of northern Sweden (Figure 2.). Neither of the two sites had been actively regenerated or otherwise managed since clearfelling, but the natural regeneration of both birch and Norway spruce had been prolific, hence the very high stem density (around 15,000 stems /ha). The two stands consisted of naturally regenerated birch, Norway spruce and a small share of other broadleaved species. The experimental layout consisted of four treatment plots in each block: three treatments of biomass harvest and one unmanaged control (CTR). The treatments aimed at retaining three different stand compositions: a monoculture of birch with 1200 stems ha^{-1} (BI), a monoculture of Norway spruce with 1300 stems ha^{-1} (NS) and a mixture of both 1300 stems Norway spruce ha^{-1} and 1200 stems birch ha^{-1} (MIX). Each plot was 20x30 m, and had a 5 m buffer with the same treatment as within the plot. The crop trees (1200 - 2500 stems ha^{-1} in each treatment) were permanently marked with numbers, equally 2500 stems ha^{-1} were selected in the control plots for comparison. The parameters of the long-term experiment (diameter at breast height and mortality on all trees, and tree height on sample trees) was measured five times between 2007 – 2019.

3.1.2 Survey of birch in practical forestry (Papers II & IV)

Papers II and IV both include surveys of birch in the Swedish forest. In both studies, the selection of stands was based on stand information and remote sensing data, before going out into the field to get representative stands i.e. with the right stand age or tree species composition. The layout of plots was made using a grid with pre-selected nodes in both surveys. The first field survey, described in paper II, was used to explore the distribution of silver and downy birch over Sweden. The survey took place at 13 selected sampling nodes from a grid with a side length of 130 km that was placed over a map of the country. The second field survey, described in paper IV, had a more local focus on the southern parts of Sweden, with an exception of Skåne and Kalmar counties (Figure 2.). The aim of the field survey for paper IV was to discover whether there was a correlation between stand variation in the proportion of Norway spruce and variation in basal area, thus indicating differences in management, growth rate or site differences in monocultures of Norway spruce and admixtures with birch.

For paper II, 123 stands, all harvested in 2014, were inventoried in the autumn of 2019 and summer of 2020, with 20 sample plots in each stand. All seedlings above 0.2 m in height within a 1.5 m radius from the plot centre were recorded, with silver and downy birch being identified based on the shape of the leaves and bark texture of the yearly shoots. Site variables were recorded for each plot, such as soil moisture class (dry, mesic, mesic-moist, moist or wet) and stand variables, such as planted tree species and soil scarification, were recorded for each stand.

For Paper IV, a total of 60 stands with five sample plots (10 m in radius) in each stand was inventoried with the purpose to investigate heterogeneity in birch-Norway spruce mixtures. Criteria for inclusion in the study was that the stand had ≥ 90% birch and Norway spruce combined, was over 60 years in age and larger than 2 hectares. Stands were divided into three categories, birch dominated with ≥ 80% birch, Norway spruce dominated with < 20% birch and admixture which was in between. In each plot, all trees over 40 mm in DBH was included, and DBH, damage and mortality was recorded for all trees. Tree height was measured on the two trees with the largest DBH and on one to three random trees of the most common tree species. Stand age and time since thinning were estimated for each stand and site variables was noted for each plot.

3.1.3 Test of method to distinguish between the two birch species (Paper II)

In addition, there was a test of the method used to distinguish between the two birch species carried out for paper II. In 2021, nine out of the 123 stands that were inventoried were revisited. At pre-set intervals along a transect in each stand, the nearest silver birch and downy birch seedling were identified using the bark structure of the yearly shoots and the shape of the leaves. A bark sample was collected from each seedling, with a total of 180 samples being collected. The birch species of each bark samples were thereafter validated using a precipitate reaction developed by Lundgren *et al.* (1995). The results showed that 180 out of 180 seedlings were identified correctly, using the yearly shoots and the shape of the leaves. The results of this trial were not included in paper II, but published as part of a master’s thesis (Nykvist, 2022).

3.1.4 National forest inventory data (Paper IV)

Data from the Swedish NFI were used for paper IV to examine whether there were differences in thinning intensity between tree species in Norway spruce and birch mixtures.

The growth performance of birch was compared to Norway spruce with increasing competition and stand age. The NFI and field survey plots, described in paper IV, were all located within southern Sweden, with the exception of Kalmar and Skåne counties (Figure 2.). The forest in the area was dominated by conifers and managed using a clearcutting system. All permanent plots inventoried between 1983 and 2016 by the NFI, and with atleast two repeated measurements, were included in the study. There was a total of 717 plots. Inventory of each 10 m radius plot included identification of the trees for comparison with previous measurements, mortality, growth or harvest, for each tree. All trees in each plot larger than 100 mm DBH were cross-calipered. Smaller trees 40 – 100 mm were measured on a smaller sample plot that varied in size, depending on the year of measurement. Tree height was measured for 1 or 2 trees per plot.

3.2 Predictive modelling

3.2.1 Modelling natural regeneration of birch (Paper II)

For paper II, a model developed by Karlsson (2001) and Holmström (2015) to predict natural regeneration of birch in southern Sweden was further developed by incorporating a digital soil moisture map (Ågren *et al.*, 2021) to allow predictions without filed inventories. The birch model (Holmström *et al.*, 2017) is built to predict birch regeneration success starting from seed supply and dispersal to seed germination and seedling survival. The first step produces a seed shadow, which is a raster with calculated dispersed seeds per m^2, by applying a seed distribution model on a raster layer with standing birch volume (m^3 ha^{-1}). The second step estimates the proportion of germinated seeds based on soil moisture conditions, soil disturbance (proportion bare mineral soil) and time since soil scarification. The third and final step estimates the survival of the seedlings, which is higher with efficient soil scarification and fencing against ungulate browsing.

A beta version of a new digital birch volume map was used to produce the seed shadow in this study. The beta map combines data from the Swedish NFI, aerial laser scanning and sentinel satellite information, and is still under evaluation (Egberth, 2022).

The germination probability was here estimated with a function which replaced the field visit classification of soil moisture, with a digital soil moisture map. The soil moisture map indicates the probability likelihood of a site being predicted as “wet”, and is a raster product developed using machine learning (Ågren *et al.*, 2021). The germination probability was then fitted as a linear function with interactions of soil moisture likelihood, time since soil scarification and soil disturbance level. The disturbance level was estimated based on the soil scarification method used, expressing the site proportion of bare mineral soil. The performance of the birch model using field based soil moisture classification or the digital soil moisture map was evaluated by comparing residual means.

The performance of the birch regeneration model was also tested for a larger extent of the Swedish forest, since it originally was validated on the most southern part of the country. The model output was compared with the measured birch density from the survey and the residuals was plotted against four regional climate features: average temperature sum of the first five years after clearfelling, average sum of precipitation annually and during the vegetation period of the first five years after clearfelling, and latitude.

3.2.2 Modelling future stand development and economic outcomes (Paper III)

The Heureka forestry decision support system (Wikström *et al.*, 2011) was used to simulate future stand development using empirical models. The three different management strategies and the untouched control (CTR) from the naturally regenerated field experiment described in paper III were evaluated. For comparison, the stand development of a fifth management strategy was simulated to reflect traditional management of a planted Norway spruce monoculture (PL). PL included planting of 2000 Norway spruce seedlings one year after clear-felling, followed by PCT to remove naturally regenerated seedlings, and three thinnings. Site data, stand variables and observed individual tree data from the first measurement in 2007 of the field experiment were used as input to Heureka. The five later measurements between 2010 and 2019 were used to calibrate the development of the Heureka models.

In addition, different rotation lengths were simulated for the different management strategies to maximize Land Expectation Value (LEV) at different interest rates. This was carried out using the cost of forest operations and different price levels for different timber assortments.

4. Main results and discussion

4.1 Natural regeneration and direct seeding of birch (Paper I)

The results from the block design field trial showed that soil scarification, soil moisture, and the interaction between the two, had significant positive effects on the occurrence of naturally regenerated birch (Figure 3.) and the density of direct seeded birch seedlings. This agrees with previous studies where positive effects of soil scarification (Nilsson *et al.*, 2002; Perala & Alm, 1990; Fries, 1984; Raulo & Mälkonen, 1976) and soil moisture (Frivold, 1986; Fries, 1984) were shown for direct seeded and naturally regenerated birch from seeds. The significant effect of the interaction between soil scarification and soil moisture is most likely because soil scarification itself decreases competition from the surrounding vegetation (Johansson *et al.*, 2013; Löf *et al.*, 2012), which makes water and nutrients more available to new seedlings.

However, there were also some contrasting results on one of the moist sites in Vindeln (Figure 3.), where soil scarification had a negative effect on naturally regenerated birch seedling density. Karlsson *et al.* (1998) found similar results, when soil scarification on mesic soil produced higher birch seedling density than soil scarification on moist soil. A possible explanation is that the soil moisture was too high, causing oxygen deficiency in the seedlings (Örlander *et al.*, 1990). However, the importance of sufficient soil moisture was shown in the experimental plots with direct seeding. Birch seedlings were found in control plots with an undisturbed soil surface, but only where the average volumetric water content was 28% or higher. This suggests that soil scarification was clearly beneficial for seed germination on mesic sites but was not needed for successful germination on wetter sites.

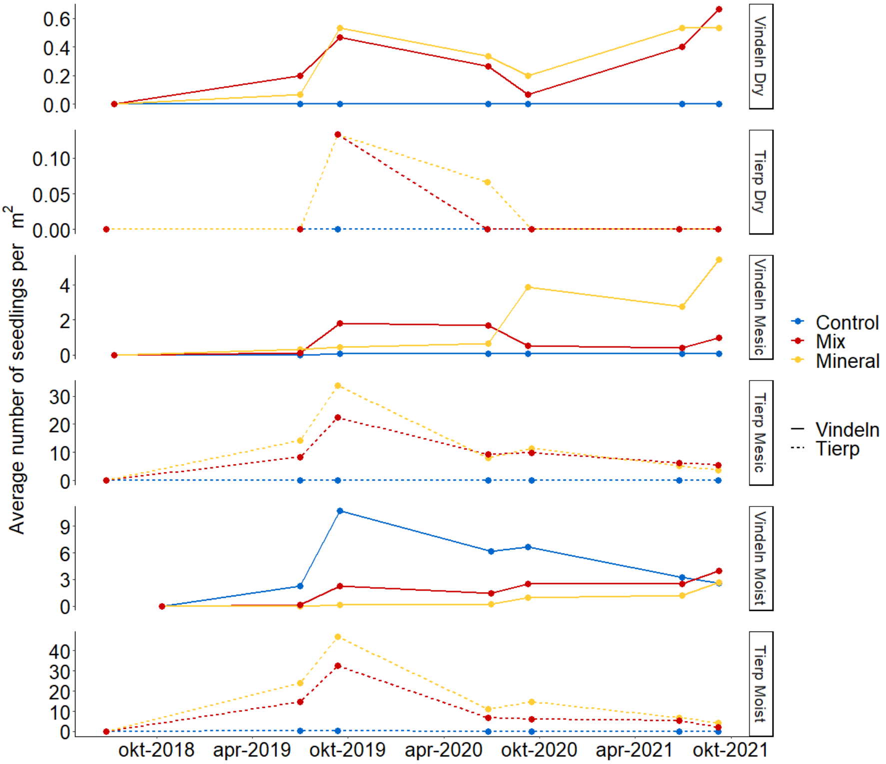

Figure 3. Average number of naturally regenerated (NR) birch seedlings (*Betula pendula* and *Betula pubescens*) per square metre for three different soil scarification treatments on dry, mesic and moist sites in northern (Vindeln) and central (Tierp) Sweden, between 2018 and 2021 for plots that were soil scarified in 2018. There are differing Y-axis limits. The soil scarification treatments were an undisturbed control (Control), a mixture of organic material from the humus layer and mineral soil (Mix) and bare mineral soil (Mineral)

Elapsed time since soil scarification was performed had a significant positive effect on naturally regenerated seedling occurrence in the plots that were soil scarified. A possible explanation for this was given by Sutinen *et al.* (2002); that the amount of seed rain that has fallen over a site increases over time.

There was considerable variation in seed rain between sites and years, but no significant effect of seed rain on direct seeded birch seedling density. Also, there was no significant effect of birch species on direct seeded birch seedling density.

4.2 Birch distribution and establishment predictions (Paper II)

There was a significant variation in birch species proportion over the country (Figure 4.). The silver birch proportion increased with the average temperature sum of the first five years after clearfelling, which explained 72% of the variation. Latitude, could only explain 47 % of the variation in birch species proportion. A possible explanation for this could be that the temperature sum decreases with increasing latitude, but also with other factors such as altitude, making it a more complex variable. The most common birch species in my study was downy birch, which is in line with the findings from the NFI (Riksskogstaxeringen, 2021).

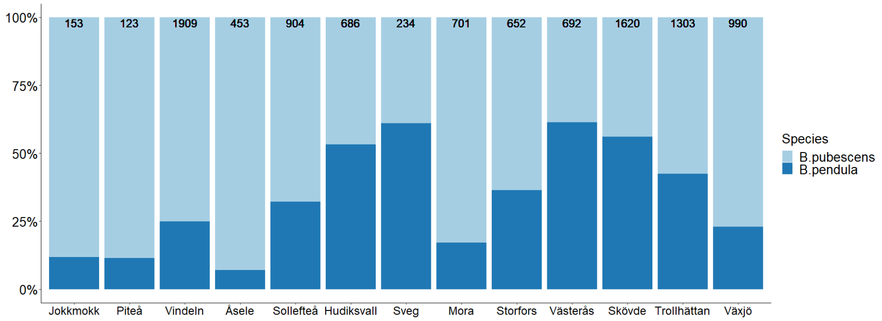

Figure 4. The percentage of silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) seedlings per sample node, going north to south. The number on top of each stack is the total number of birches found at each sample node

Currently, large parts of the tree volume in young Swedish forests is birch, and it has increased over the past 40 years (Figure 5.). This increase may be due to several different factors, such as that pre-commercial thinnings in the 21th century often is occurring later than before (Skogsdata, 2021; Skogsstyrelsen, 2014). Another reason could be the increase in mortality of planted Scots pine (Ara *et al.*, 2021), possibly caused by pine weevil damage (Wallertz *et al.*, 2014; Nordlander *et al.*, 2011) and/or browsing by ungulate species (Bergqvist *et al.*, 2018; Bergquist *et al.*, 2003), or other disturbances. Further explanations to the increase in birch proportion could be an increase in soil scarification intensity (Saursaunet *et al.*, 2018). Disc trenching, which is the most common type of soil scarification in Sweden at present (Hansson *et al.*, 2017; Bergqvist *et al.*, 2011), produces larger patches of bare mineral soil than the methods used previously (Örlander *et al.*, 1990). Larger patches mean that there are larger areas where birch seeds can potentially establish. Finally, another reason could be that the FSC scheme for a while has been stipulating at least 10 % broadleaf species of the total number of stems on stand level, and the requirement to leave more broadleaf retention trees (FSC, 2020; Boström, 2002). This might have contributed to a greater number of older birches in the landscape that can provide seeds, which in turn has caused more natural regeneration of birch.

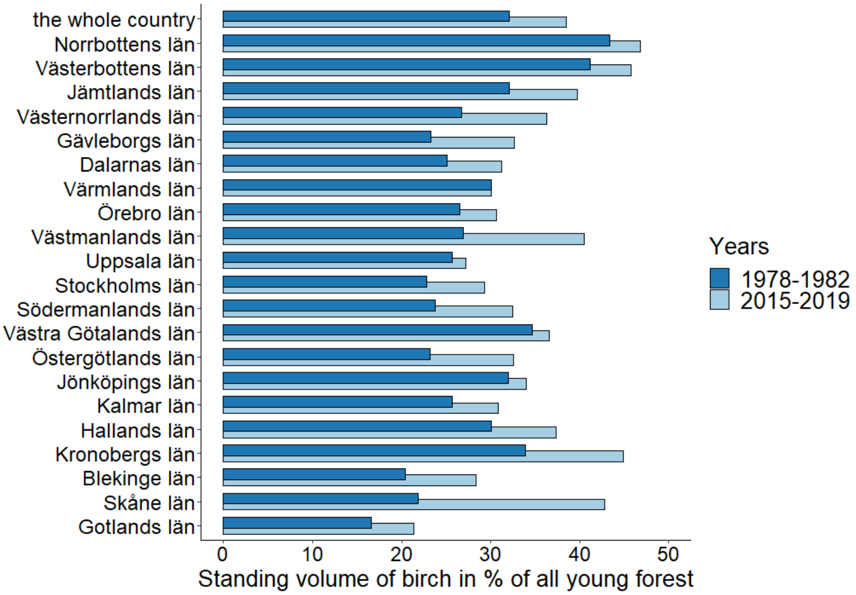

Figure 5. The estimated percentage of birch in young (1 - 79 mm DBH) forest in Sweden for the most recent measurement and 40 years ago, per county and for the entire country. Data from the Swedish national forest inventory (Riksskogstaxeringen, 2021)

The accuracy of the birch regeneration predictions tended to improve when the SLU soil moisture map was incorporated (Figure 6.). Using the soil moisture map also makes the model more user-friendly, since it becomes unnecessary to visit a site in order to estimate the soil moisture conditions.

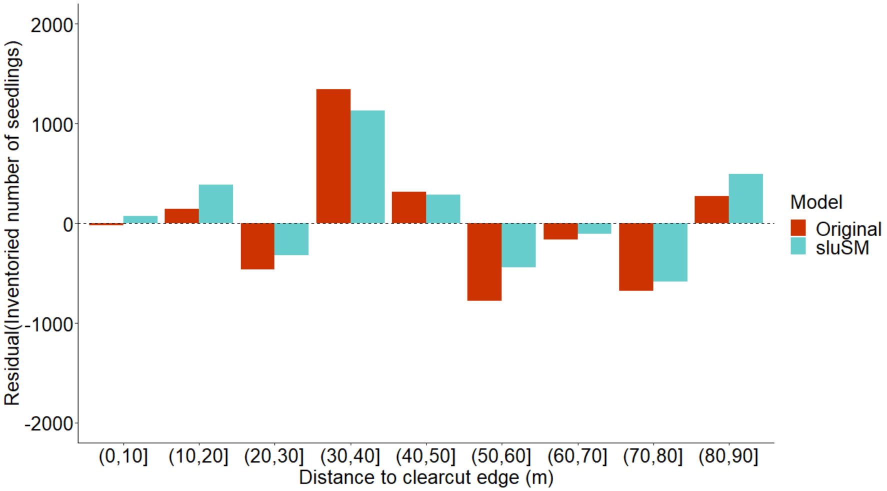

Figure 6. The residual mean of the inventoried number of seedlings per sample plot, using the modelled number of seedlings per sample plot as the explanatory variable, against distance to the clearcut edge in classes. Colours indicate the original birch regeneration model by Holmström *et al.* (2017) (Original) and the birch regeneration model but with soil moisture data from the SLU soil moisture map (Ågren *et al.*, 2021) (sluSM)

The model demonstrated a slight overestimation both for regions with low average precipitation during the vegetation period and low average annual precipitation (Figure 7B and 7C.). However, there appeared to be no such trend in the residuals for latitude or temperature sum (Figure 7A and 7D.).

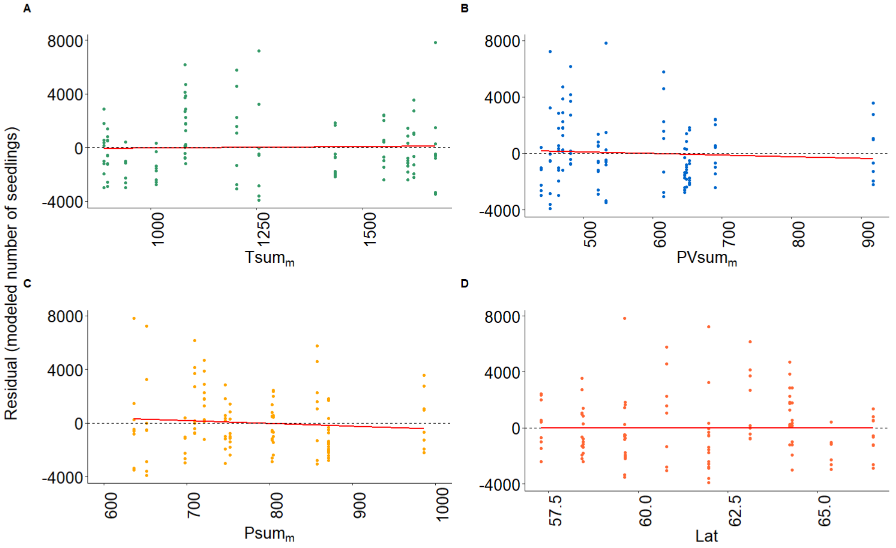

Figure 7. Residuals of average number of modelled seedlings per hectare, site and region, using the birch regeneration model developed by Holmström *et al.* (2017) with soil moisture data from the SLU soil moisture map (Ågren *et al.*, 2021), against four different regional climate features. Average temperature sum for the first five years after clearfelling ($Tsum_m$), average sum of precipitation during the vegetation period the first five years after clearfelling ($PVsum_m$), average sum of precipitation for the first five years after clearfelling ($Psum_m$) and latitude of each sample node (*Lat*)

4.3 Competition release of spontaneously regenerated Norway spruce and birch mixtures (Paper III)

In this study, we evaluated the effect of competition release, in the form of a biomass outtake, in two 30-year-old spontaneously regenerated mixtures of birch and Norway spruce on timber production and profitability. The competition release had significant effects on stem development and stand structure in these dense stands at mid-rotation. There was a significantly higher total stem volume production in the control (CTR) in comparison to the management strategies aimed for timber producing monocultures of birch (BI), Norway spruce (NS) and a mixture of the two (MIX) (Figure 8.). Other studies have shown similar results, where unthinned or denser stands produced higher total stand volumes than less dense stands (Pretzsch, 2020; Simard *et al.*, 2004).

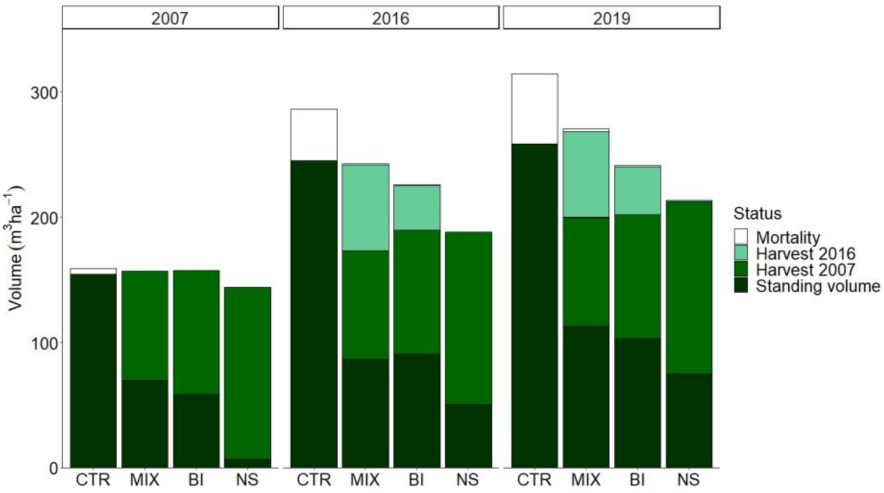

Figure 8. Total standing stem volume (m^3 ha^{-1}), biomass harvest in 2007, birch (*Betula pendula*) thinning harvest in 2016, and mortality between 2007 and 2019. The management strategies are a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (*Picea abies*) (NS), birch (BI) or a mixture of Norway spruce and birch (MIX)

For the initially suppressed Norway spruce crop trees, the competition release had a significant positive effect. For the birch, which started in the over-story, the competition release had no significant effect on the crop trees (Figure 9.). A probable explanation as to why there were no significant effects resulting from the competition release on the size of the birch crop trees is that the release came too late. Broadleaf pioneer tree species have been shown to start to develop diameter differences before the stand reaches 10 years old (Rytter & Werner, 2007). Later results from the same trial by Rytter (2013) indicated that diameter growth loss early in the rotation period cannot be compensated for later in the rotation period.

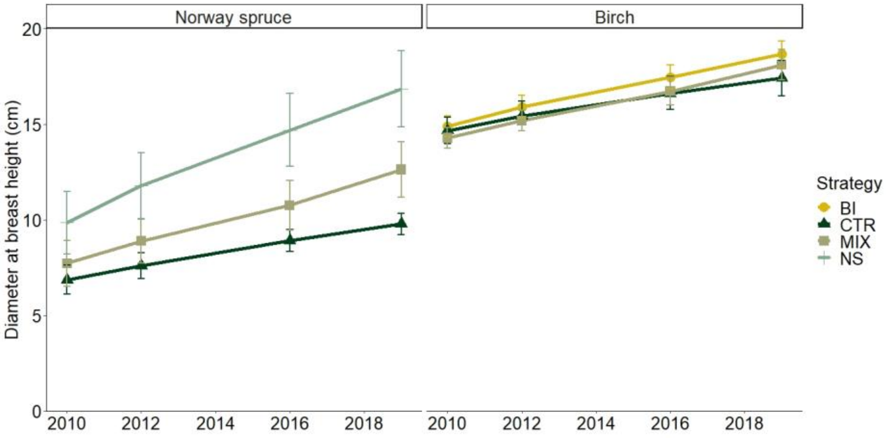

Figure 9. Average diameter at breast height (cm) for the initially largest crop trees (DBHdom) of Norway spruce (*Picea abies*) and birch (*Betula pendula*) (300 stems hectare^{-1}) between 2010 and 2019 for the different management strategies. The management strategies are a non-thinned control (CTR), and biomass harvest and thinning to promote pure stands of Norway spruce (NS), birch (BI) or a mixture of Norway spruce and birch (MIX). Error bars show standard deviations

The crown of the birch was significantly longer in BI than in CTR at the last measurement, which was not the case at the first measurement. Crown length is a significant indicator of competition and vitality, and should cover at least 50% of the stem to ensure that there is vigorous growth (Niemistö, 1991). The significant increase in crown length in the birch monoculture does perhaps lead to a significant difference in diameter growth between the birch management strategies in the future.

The production over the full rotation was simulated using measured initial data, and demonstrated that the competition release had long-term effects on the amounts of extractable wood and assortments. There, CTR produced the most extractable wood (over the full rotation period), with the highest mean annual increment of all management strategies. The strategy with the highest mean Land Expectation Value (LEV), on the other hand, varied depending on the interest rate (Figure 10.). Different biofuel and birch timber prices had little effect on the strategy rankings. At 1 – 2% interest rate, the planted spruce simulation (PL) had the highest LEV, whereas at 3 – 4% interest rate, CTR had the highest mean LEV. In summary, the differences in LEV between the different management strategies were smallest when the prices for biofuel and birch saw-wood were more competitive with Norway spruce saw-timber, and when there were low interest rates.

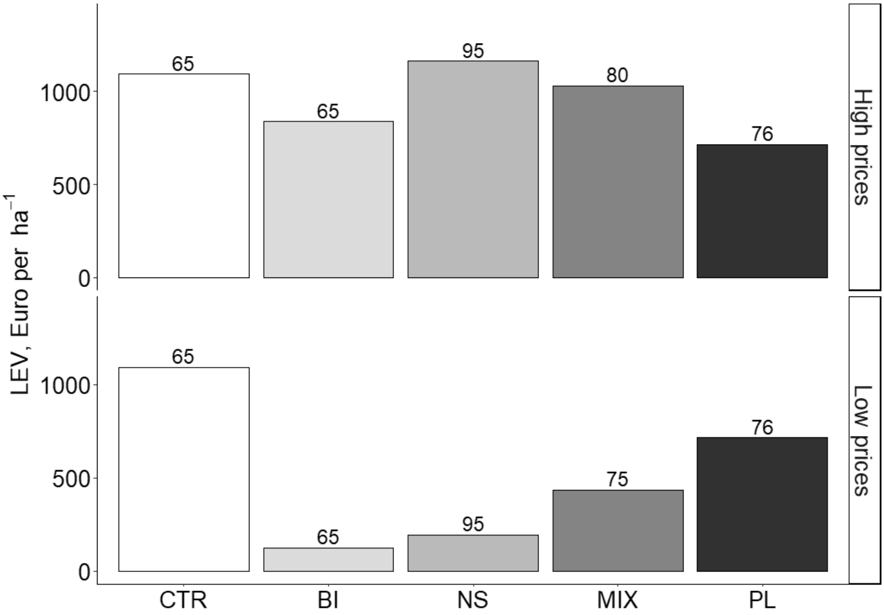

Figure 10. Simulated land expectation value (LEV) for five management alternatives (x-axis), at an interest rate of 3%, with biofuel and birch timber prices at high or low prices. Biofuel at low price = 14 € and high price = 42 € Mg^{-1} DW, birch timber at low price = 42 € and at high price = 57 € m^{-3}. The management strategies were a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (Picea abies) (NS), birch (Betula pendula) (BI), a mixture of Norway spruce and birch (MIX) and a simulated reference of planted Norway spruce with conventional thinning for roundwood production (PL). Age at final felling shown on top of relevant stacks

4.4 Development of birch and spruce mixtures over time (Paper IV)

The results from the NFI sample plots showed that the mean birch percentage by basal area (18%) and stem density (19%) remained consistent over the revision years, even though there were large variations between plots. Out of the 717 NFI sample plots, 295 were thinned in between revisions. Some plots were thinned more than once, resulting in 360 thinning events in total. For Norway spruce and birch, the average thinning intensity was 19% and 35% respectively of the basal area. Annual basal area growth was significantly lower for birch in comparison to Norway spruce trees of the same size, and the difference between the two species increased with increasing stand age and sample plot basal area. The same trend of decreasing birch tree size in comparison to Norway spruce was found when comparing the ratio of DBH for birch against the quadratic mean diameters of the plot (Figure 11.).

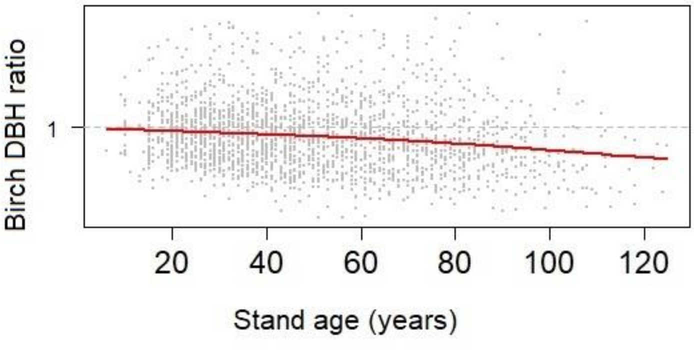

Figure 11. The diameter at breast height (DBH) of each birch divided by the quadratic mean diameter of all stems in the plot, over stand age. The red line shows the trend of the dataset.

These results confirm that mixed forest stands in southern Sweden are managed with similar intensity to Norway spruce production stands having little to no birch admixture at mid rotation age (40 - 80 years). This also indicates that the birch admixture in Norway spruce production stands is reduced over time, since birch is more prone to be harvested than Norway spruce. In addition, the birch that remains in the stands has a lower growth rate than the surrounding Norway spruce. In other words, in order to maintain the volume proportion of birch in a mixed stand, active management is required. Similar findings have been reported from previous experiments and scenario analyses (Huuskonen *et al.*, 2021; Holmström *et al.*, 2016b; Holmström *et al.*, 2016c; Fahlvik *et al.*, 2015).

Even though the admixtures of Norway spruce provided more within-stand heterogeneity in terms of species composition, in comparison to the Norway spruce dominated stands, they did not provide any significant difference in stand density. This is in line with Keren *et al.* (2019), who found low to moderate correlations between conventional stand characteristics such as stand density and indices of structural heterogeneity.

5. Conclusions and adaptability

(I) In moist soils with high volumetric water content ($\geq$ 28%), birch seeds germinate at high rates and seedlings survive without soil scarification. In mesic soils, birch seeds germinate with higher rates after soil scarification. In dry soils, birch seeds rarely germinate regardless of any disturbance of the humus layer. Hence, it is possible to manage the natural regeneration of birch if the soil scarification is adapted to the soil moisture conditions. This can be achieved by avoiding soil scarification in conditions that are too wet, and by undertaking soil scarification in dryer conditions where the competition from the surrounding vegetation is higher.

(II) Available open source mapping of soil moisture, increases the precision of birch regeneration predictions for both northern and southern Sweden. However, the percentage of silver and downy birch varies and the temperature sum explains the variation to a greater extent than the latitude does. The proportion of birch in young forest have increased in Sweden over the last 40 years. With management, this increase could possibly be maintained, and birch will increase also in the mature forest in the future. Birch is an important resource in the Swedish forest, and therefore, knowledge about natural regeneration and management of birch is important to the Swedish forestry sector.

(III) In stands with dense natural regeneration of birch and Norway spruce, pre-commercial thinning (PCT) has a significant impact on the development of the stand. The owner of this type of stand has several profitable management options to choose from, when deciding on the PCT strategy. The output from the first thinning is however also dependant on the length of the rotation period, the merchantable timber species, and the targeted timber assortments.

(IV) The proportion of birch tends to decrease with stand age in the current Norway spruce mixtures of southern Sweden, both with and without thinning. Active management is necessary to maintain the proportion of birch in a mixture with Norway spruce over the full rotation. To mix a second tree species into a stand dominated by one species does not necessarily increase the variation in stand density, so if the purpose of the admixture is to increase the number of species for biodiversity, the stand density should also be considered.

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Populärvetenskaplig sammanfattning

Björk är Sveriges vanligaste lövträd och står för ungefär 12 % av den totala virkesvolymen i våra skogar. Det vi i vardagligt tal refererar till som ”björk” är egentligen två olika arter, vårtbjörk och glasbjörk. Oftast görs inte skillnad på de två arterna, eftersom att det kan vara både svårt och tidskrävande att artbestämma dem.

Björken är ett pionjärträdslag, det betyder att den snabbt etablerar sig efter olika störningar, exempelvis efter en kalhuggning eller brand. Det betyder även att björken växer som bäst när den har tillgång till mycket ljus, eftersom att den är anpassad för att kunna vara konkurrenskraftig på öppna ytor. Björken producerar stora mängder pollen och frön som sprids över landskapet med vinden. Vad som avgör var björkfröna gror beror till stor del på markförhållandena. Det får inte vara för torrt eller för mycket konkurrens från växterna runtomkring, därför gynnas oftast björken av markberedning. Markberedning är en skogsskötselåtgärd där man på olika sätt blottar bar jord för att eliminera konkurrerande växtlighet och skapa gynnsamma förhållanden för plantering eller sådd. Majoriteten av alla hyggen som görs i Sverige markbereds och planteras därefter med antingen tall eller gran. De flesta björkarna i den svenska skogen är naturligt föryngrade, d.v.s. att de har etablerat sig naturligt med frön från träden runt omkring eller via stubbskott. Planterad björk förekommer också, men inte alls i samma utsträckning som den naturligt föryngrade. Fördelen med plantering är att plantorna då är genetiskt förädlade och därför växer snabbare och håller högre kvalitet. Nackdelen är däremot att plantering kostar och den naturliga föryngringen är gratis. I princip alla björkplantor som säljs och planteras i Sverige är vårtbjörk, detta eftersom att vårtbjörken producerar virke av högre kvalitet och växer snabbare.

Björken har varit en viktig resurs för människan i tusentals år. Brännved, virke och råmaterial till produktion av pottaska är några användningsområden genom åren. När papperstillverkningen började ta upp en större del av virkesmarknaden runt 1870-talet så blev granvirke det mest eftertraktade. Låg efterfrågan och ett lågt pris ledde så småningom till att björk och andra lövträd aktivt togs bort ur skogen för att ge plats åt de mer värdefulla barrträden. I dagens skogsbruk ser det annorlunda ut, intresset för lövträd har ökat, inte bara för att lövträd nu också används i pappersproduktion, utan även p.g.a. ett ökat intresse för biologisk mångfald. Och för att minska de risker som förväntas komma med klimatförändringarna. Ett ökat antal trädslag som den svenska skogsindustrin nyttjar ökar chansen att något av dessa står emot de skadegörare som förutspås komma med ett varmare klimat.

För att kunna öka mängden björk i den svenska skogen, samt kunna ta tillvara på de björkar som redan finns där på bästa sätt, krävs ökad kunskap om föryngring och skötsel av björk. Då björk som trädslag länge sets som ett problem mer än en tillgång så har forskningen inom området inte prioriterats i samma utsträckning som för ex. tall och gran. Målet med den här avhandlingen har varit att med fyra olika studier öka kunskapen kring etableringen av naturligt föryngrad björk och skötsel av naturligt föryngrad björk i kombination med gran. Samt att utforska spridningen av de två björkarterna över landet.

Resultaten från studie I, visade att det finns betydande interaktioner mellan effekten av markberedning och markfukten på förekomsten av naturligt föryngrade björkplantor. Mer specifikt så betyder det att skogsägaren kan styra den naturliga föryngringen av björk genom att anpassa markberedningen till de markförhållanden som råder. Detta genom att undvika att markbereda när det är för blött, och att istället markbereda när det är torrare och konkurrensen om vatten från annan växtlighet är högre. Studie II visade att de två björkarterna varierar i mängd över landet, och att variationen till största del beror på temperaturen (mer specifikt temperatursumman), och inte bara på latituden som man tidigare trott. Temperaturen i sin tur korrelerar med latituden men beror även på en mängd andra faktorer, exempelvis avstånd till närmaste kustlinje, och höjd över havet. Studie III i sin tur visade att i täta naturligt föryngrade skogar av björk och gran så har röjning (en typ av avverkning i en yngre skog där man inte tar reda på träden som fälls) stor betydelse för skogens utveckling. I den här typen av skogar har skogsägaren många alternativ och kan välja att anpassa skötseln efter de mål hen har. Exempel på olika mål är att skapa en skog som kan ge ekonomisk avkastning inom en kortare eller längre tidsperiod, eller att få högsta möjliga avkastning med en begränsad skogsskötselinsats. Slutligen visade studie IV, att man som skogsägare måste göra ett aktivt val för att kunna ha kvar björkarna i en blandskog med gran över tid. För om man inte aktivt väljer att spara björkarna och anpassar skötseln, så tenderar björkandelen att minska p.g.a. att björken exempelvis blir utkonkurrerad då den inte tål lika mycket skugga som granen.

Sammanfattningsvis, björken ser ut att ha en ljus framtid, så länge vi aktivt väljer att ta bort konkurrensen som skuggar när det behövs.

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P.S. Don’t forget to at least read the abstract before putting this thesis in the shelf for the next 20 years, Tack!

III

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Management of spontaneously regenerated mixed stands of birch and Norway spruce in Sweden

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Highlights

- The absence of forest management does not always mean economic loss.
- With dense spontaneous regeneration of birch and Norway spruce, the first competition release can have a high impact on future stem development.
- Significantly different effects on stand volume production and diameter development of Norway spruce can be expected with different biomass harvest strategies.

Abstract

Timber production and profitability were evaluated for spontaneously-regenerated mixtures on two formerly clearcut areas. The abandoned areas developed into birch-dominated (*Betula pendula* Roth and *Betula pubescens* Ehrh.) stands with successional ingrowth of Norway spruce (*Picea abies* (L.) H. Karst.). An experiment with randomized treatments within blocks was established, using three management strategies and one unthinned control, resulting in variation in optimal rotation age, merchantable volume and species composition. The management strategies were evaluated based on total production (volume) by using measured growth data 42 years after clearcutting and the modelled future stand development. The long-term effects of spontaneous regeneration and management strategies were evaluated based on land expectation value (LEV) and compared with a fifth management strategy using artificial regeneration and intense thinnings. 12 years after treatment, at a stand age of 42 years, the unthinned control had produced the highest total stem volume. At interest rates of 2% or higher, the unmanaged forest was an economically viable strategy, even compared to an intensive management strategy with a preferred merchantable timber species. Interest rates clearly impacted the profitability of the different management strategies. This study shows that when spontaneous regeneration is successful and dense, the first competition release can have a high impact on the development of future crop trees and on the species mixture.

Keywords *Betula pendula*; *Betula pubescens*; *Picea abies*; land expectation value; mixed forest; natural regeneration

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1 Introduction

For over a century, the forests of Fennoscandia have mostly been managed as even-aged stands, with the majority of productive forestland actively managed for wood production (Yrjölä 2002; Josefsson and Östlund 2011; Lundmark et al. 2013). Forestry has long been a cornerstone of the Swedish economy, which has resulted in laws and regulations to ensure sustainable timber production (Hagner 2005; Jansson et al. 2011). Swedish forest legislation requires reforestation measures to be applied directly after a final felling. In regenerated areas, two tree species are almost exclusively used: Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.). Depending on tree species, regeneration method, site conditions and region, new forest must be considered established within 5–15 years and be approved according to the Swedish Forestry Act (Skogsstyrelsen 2019a, 2019b).

When choosing among different forest management alternatives, it is common to compare net present values (NPVs), which depend on interest rates (Simonsen 2013). The dominant forest-management strategy in Sweden is even-aged management (Albrektson et al. 2012), using planting, tending and commercial thinnings (often one or two), before a final harvest using clearfelling. In the last five years, more than 80% of clearfelled area in Sweden was regenerated by planting, around 10% was naturally regenerated, with the remaining part seeded or left without active measures. More than 85% of the clearfelled area was mechanically scarified to expose bare mineral soil (Skogsstyrelsen 2019b), helping to increase survival of planted and naturally-regenerated seedlings (Karlsson and Nilsson 2005; Holmström et al. 2017). The combination of birch and Norway spruce in young stands is well studied in Swedish forestry, especially using birch as a nursing shelter over Norway spruce (Andersson 1985; Mård 1996; Bergqvist 1999; Klang and Ekö 1999; Grönlund and Eliasson 2019). Birches are pioneer species and grow best in the overstorey since they are shade intolerant (Hynynen et al. 2009). Norway spruce is a secondary species that is considered semi-shade tolerant and can survive in darker understories (Assman 1970; Andersson 1985). Despite the majority of the clearfelled area in Sweden being artificially regenerated, around 2000–4000 hectares are still unmanaged and allowed to spontaneously regenerate each year, half of which is without soil scarification (Skogsstyrelsen 2019b). Such areas in Fennoscandia without any active regeneration methods, or where planting has failed, tend to spontaneously regenerate with birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) (Holgén and Hånell 2000; Götmark et al. 2005; Karlsson et al. 2010), and sometimes also with later ingrowth of Norway spruce (Nilsson et al. 2002; Hanssen 2003). These unmanaged clearfelled areas are usually considered to regrow slowly if at all, reducing future production. However, in areas where the spontaneous regeneration is successful, the stands can develop at full density.

This study evaluates different management strategies on land without investment in regeneration, but with spontaneous regeneration of birch and Norway spruce. The first objective was to test the relative impact of competition release on total volume production over time (which is expected to be low) vs. the development of the future crop trees (which is expected to be high). A second objective was to evaluate timber production and profit over the full stand rotation for different selection management strategies starting from the first competition release in dense mixed regenerations. The management strategies were compared both with an unmanaged control and with an intensive management-simulation starting from regeneration.

Table 1. Stand characteristics at each site before biomass harvest at the start of the experiment in 2007. Numbers inside parentheses are standard deviations. QMD = quadratic mean diameter.

Site	Species	Stem density (ha^{-1})	QMD (cm)	Dominant Height (m)	Basal area (m^2 ha^{-1})
A	Norway spruce	2473 (530)	3.9 (0.6)	7.3 (1.0)	2.9 (0.6)
	Birch	11 425 (4106)	5.2 (0.8)	13.8 (0.7)	22.9 (1.0)
	Other broadleaves	1040 (589)	3.7 (1.6)	-	1.1 (0.9)
B	Norway spruce	3158 (1251)	3.5 (1.0)	7.5 (2.0)	2.9 (1.4)
	Birch	10 642 (1023)	5.7 (0.4)	14.8 (0.7)	27.1 (2.7)
	Other broadleaves	1308 (1154)	2.3 (1.4)	-	0.8 (1.3)

2 Material and methods

2.1 Site and measurements

The experiment was established in the spring of 2007 on two sites where no active regeneration measures had been taken since final felling in 1977. Both sites are on the east central coast of Sweden and have mesic glacial till soils. Site A (long term experiment, SLU 1475) is at 62°56´N, 17°56´E with altitude 115 m and site B (long term experiment, SLU 1476) is located at 62°23´N, 17°11´E with altitude 140 m. At establishment, both sites consisted of naturally-regenerated Norway spruce (*Picea abies*) and birch (*Betula pendula* and *Betula pubescens*), with a minor proportion of other broadleaved tree species (mainly grey alder (*Alnus incana* (L.) Moench)). The stem density on each site was approximately 15 000 ha^{-1} of which almost 75% was birch (Table 1). Natural mortality had already begun at both sites at the time of experiment establishment and the basal area of dead trees was 0.3 m^2 ha^{-1} (site A) and 1.2 m^2 ha^{-1} (site B).

In total, five blocks were established, two at site A and three at site B. Using a randomized block design, each block was subset into four plots: three management strategies and one unmanaged control plot (CTR). All management strategies began with a commercial thinning of small-dimension trees used as fuelwood, hereafter called 'biomass harvest', but the selection of retained stems varied with treatment and strategy. In each strategy the target of the stand in final felling was set and the harvest selections were made to achieve these targets with the future crop trees, aiming for 1300 stems ha^{-1} of Norway spruce (NS), 1200 stems ha^{-1} of birch (BI) and a mixture with 1300 stems ha^{-1} of Norway spruce and 1200 stems ha^{-1} of birch (MIX) (Table 2). Out of all birches remaining after the biomass harvest, over 99.9% were silver birch.

Table 2. Stem density and quadratic mean diameter (QMD) after the establishment of the experiment in 2007. The management strategies are a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (*Picea abies*) (NS) and birch (*Betula pendula*) (BI) or a mixture of Norway spruce and birch (MIX).

Site	Treatment	Stems ha^{-1}			QMD (cm)			
		Spruce	Birch	Other broad-leaves	Spruce	Birch	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
A	CTR	2117	9842	842	4.0	5.4	26.9	134.4
	NS	1208	0	0	4.7	-	2.1	7.1
	BI	0	1167	0	-	9.9	9.0	52.7
	MIX	1267	1200	0	4.4	10.4	12.1	69.4
B	CTR	2983	11 300	1172	2.9	5.7	30.6	174.7
	NS	1406	0	0	4.2	-	2.0	6.3
	BI	0	1161	0	-	10.5	10.0	64.4
	MIX	1400	1183	17	3.3	10.5	11.5	70.6

The experimental plots were 20×30 m, surrounded by a 5 m buffer zone with the same management strategy as the plot. Dominant and co-dominant trees of good vitality (undamaged, well-developed and symmetric crowns) were retained during thinning, and other trees removed according to the strategies. Quality (stem straightness, branch diameter, lack of damage) and spatial distribution of the trees were considered subordinate to vitality when designating future crop trees. To compare the development of the future crop trees in thinned and unthinned stands, future crop trees of Norway spruce and birch were also selected and measured within CTR according to the same criteria as in NS, BI and MIX plots. In CTR an intended strip road was considered when selecting the reference crop trees to maintain the size of the selection pool, but no cutting was carried out. Later, the selected trees in CTR and the trees retained after the first thinning in NS, BI and MIX were all defined as crop trees.

After the applied management in spring 2007, all crop trees were permanently marked with individual numbers at breast height (1.3 m above ground). Trees were measured before treatment in Nov/Dec 2006 and in June 2007, Oct/Nov 2010, Aug/Sept 2012, March 2016 and May 2019. Diameter at breast height (DBH; 1.3 m above ground), species and damage were recorded for all trees. Tree height and height to the base of the living crown were measured on randomly selected sample trees. The number of sample trees per plot varied between 16–51 for Norway spruce and 11–44 for birch. In spring 2016 a second thinning was conducted but only in the two management strategies with birch crop trees, reducing the birch density in the MIX and BI strategies to 400 and 700 stems per hectare respectively, following birch thinning guidelines (Raulo 1987; Rytter et al. 2014). The database used for taxonomic nomenclature in this paper is Missouri Botanical garden (Missouri Botanical Garden 2021).

2.2 Calculations

DBH was used to calculate basal area (m^2) and the relationship of diameter and height for sample trees was used to estimate the height of all trees whose height was not measured, using species-specific height functions (Eq. 1), where $x = 2$ for Norway spruce and $x = 3$ for birch (Näslund 1947). The a and b parameters were calculated separately for each plot, revision and tree species.

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

The stem volumes of all trees were calculated using the measured diameter and the calculated estimated heights using species-specific volume functions for northern Sweden from Andersson (1954) for trees with DBH < 5 cm and Brandel (1990) for larger trees. However, non-crop trees in the control, whose stems were not all initially numbered, were not included in this calculation. The volume of dead trees in the control was instead estimated by multiplying the decrease in stem number between two measurements (Fig. 1) by the median volume of a measured tree in the control at that time. Total stand volume production (m^3 ha^{-1}) was summarized as the standing volume, the accumulation of harvested volumes and the estimated volume of dead wood.

Mean stem diameter (cm) in the treatment plots was estimated both for the stand mean, defined as the quadratic mean diameter (QMD) and the mean diameter of the 300 dominating trees (DBH$_{dom}$), corresponding to the 300 largest stems per hectare from when the crop trees first where numbered. Living crown ratio was calculated as the proportion of tree crown length in relation to the tree height for all sample trees.

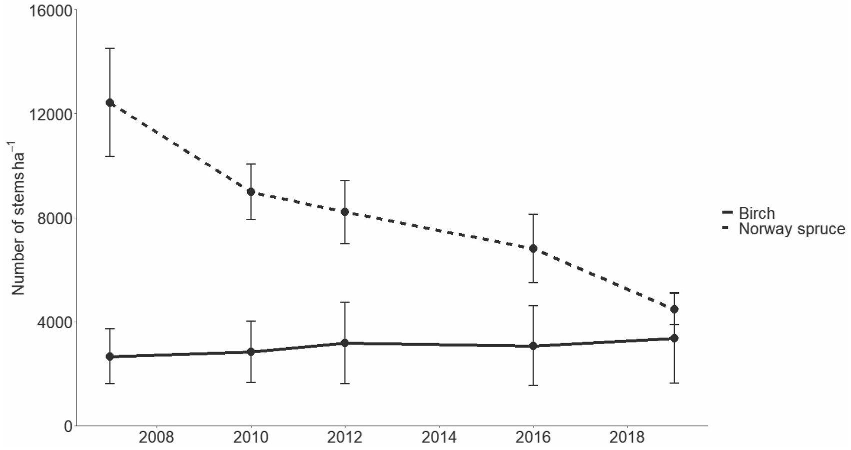

Fig. 1. Average stem density of birch and Norway spruce (*Picea abies*) (stems hectare^{-1}) in unmanaged control (CTR) plots. Error bars show standard deviations.

2.3 Statistical analysis of observed growth

The effect of competition release was tested for total volume production, DBH_{dom} and crown length using a linear model (Eq. 2).

$$Y_{19} = strategy + site + Y_0 \qquad (2)$$

, where Y_{19} is either volume production (m^3 ha^{-1}), DBH_{dom} (cm) or crown length (m) in 2019 per plot, the fixed factor strategy is the thinning strategy for the plot and *site* is one of the two sites A and B. Included in the equation was also a covariate Y_0 which was the initial estimate of standing volume (m^3 ha^{-1}), QMD (cm) or average tree height (m) for each plot, measured directly after the biomass harvest. Block was also tested as a fixed factor in the linear models and was excluded after comparisons of AIC, adjusted R2 and normality of residuals, since it did not have a significant effect and did not strengthen the model.

Tukey's tests were used, to test for significant differences between management strategies on total volume production, DBH_{dom} for Norway spruce and crown length for birch. All statistical tests were performed in R 3.6.1 (R Core Team 2019). The packages lmerTest (Kuznetsova et al. 2017) and TukeyC (Faria et al. 2019) were used to statistically evaluate differences between means, at significance level $p = 0.05$. Residuals of the linear models showed no indication of violating the assumptions of normality or constant variance.

2.4 Simulations and economic analysis of management alternatives

2.4.1. Forecasting stand development

Future stand development and management of the experimental plots after 2019 were simulated in the Heureka forestry decision support system (Wikström et al. 2011) to evaluate the management strategies over a full rotation. Inputs to Heureka included site data (e.g., latitude, site index, and vegetation type), stand characteristics (age, management history) and individual tree data (species, diameter, and height). The observed values from the first measurement of all individually-measured trees were used as inputs and the observations from the following years were used to calibrate the development in the Heureka models. Heureka simulates stand development using empirical models (Elfving 2010; Fahlvik et al. 2014) and calculates basal area development with a combination of stand-wise and tree-wise growth models. The stand-wise models determine the growth rate whereas the tree-wise models are used to distribute stand-wise growth of single trees (e.g., Fahlvik et al. (2014)). The Heureka system also includes models for estimation of mortality and ingrowth. Stand development in Heureka is estimated in 5 year periods. Treatment-specific thinnings in Heureka, were simulated based on decisions regarding the timing of thinning, the proportion of basal area removed, thinning form (size of removed trees in relation to the remaining stand) and the distribution of the removal among spruce, pine and broadleaves. Heureka also includes functions for bucking of commercial wood assortments.

2.4.2. Costs of forest operations

Time expended for pre-commercial thinning (PCT) and understorey cleaning prior to biomass harvest was based on time studies of motor-manual PCT (Bergstrand et al. 1986; SLA Norr 1991). The cost for motor-manual PCT was 33 € h^{-1}. Understory cleaning prior to felling in CTR was assumed to cost 189 € h^{-1}.

Felling costs were calculated from productivity norms of biomass harvest (selective tree-based multi-tree handling – $TMFF_{Sel}$), (Sängstuvall et al. 2012), thinning (Brunberg 1997) and final felling (Brunberg 2007). Forwarding costs were based on productivity norms of biomass harvest (Sängstuvall 2010) and forwarding of round wood (Brunberg 2004). The forwarder and harvester costs were 75 and 75 € h^{-1} at biofuel thinning, 66 and 94 € h^{-1} at thinning and 75 and 104 € h^{-1} at final felling, respectively.

The planting cost was 472 € ha^{-1} and the cost per sapling was 0.24 €. The cost for soil preparation was 214 € ha^{-1}.

2.4.3. Assortments and prices

The price list for spruce timber included two quality classes with maximum prices of 59 and 40 € m^{-3} for class 1 and 2 timber, respectively. The minimum top diameter of spruce timber logs was 14 cm and the pricing varied with the dimension of the logs. In all simulations, 87% of timber logs were assigned to class 1 and 13% to class 2. The pricing of birch timber was uncertain due to a limited market in Sweden. To handle the uncertainty, separate calculations were made for birch timber prices of 42 € m^{-3} (BirchLow) and 53 € m^{-3} (BirchHigh), respectively. The minimum top diameter of birch timber logs was 14 cm.

The price of pulpwood was 25 and 29 € m^{-3} for spruce and birch, respectively. The minimum top diameter of pulpwood was 5 cm. The market for biofuel in Sweden is uncertain as well, so we made separate calculations for biofuel prices of 14 € Mg^{-1} (BioLow) and 42 € Mg^{-1} (BioHigh) dry weight, respectively.

2.4.4. Management strategies

The strategies in the economic evaluation were the same as the four management strategies in the experiment. Inputs to the Heureka system were diameters and heights of both numbered and unnumbered trees in 2019 together with necessary site and stand data. A fifth strategy reflecting an intense management with planted Norway spruce (PL) and subsequent thinnings was also simulated as a reference. Simulations were carried out from the time of the last measurement until final felling according to the management strategies:

- CTR: Stand development was simulated with no further management actions, except for an understory cleaning right before the final felling.
- BI: Stand development was simulated with no further management actions.
- NS: Two thinnings were simulated 20 and 40 years after the start of the simulation.
- MIX: One additional thinning of both spruce and birch was simulated 15 years after the start of the simulation.
- PL: Reference reflecting traditional management of a planted monoculture of spruce. Stand development from regeneration to final felling was simulated in Heureka. The stand was planted in year 1 with 2000 spruce plants ha^{-1}. PCT to remove naturally-regenerated trees was carried out in year 15. The stand was thinned in years 40, 55 and 70.

Different rotation lengths were simulated and the rotation that maximized Land Expectation Value (LEV) according to Eq. 3 was selected for each management strategy and interest rates. The minimum stand age at final felling was restricted to 65 years for all strategies to prevent harvest of too weakly dimensioned forests and to consider the Swedish forestry act (Skogsstyrelsen 2019a). All simulated thinnings were carried out from below, removing trees in all diameter classes but more frequently from the smaller diameter classes, since we want to retain the larger, most vital stems. Thinning from below is the common practice in Sweden (Wallentin 2007) and has previously been shown to have a positive effect on net stem volume production of Norway spruce (Nilsson et al. 2010). Management strategies were based on guidelines for birch and Norway spruce in Sweden (Skogsstyrelsen 1985; Raulo 1987). Values from the experimental plots were used as site parameters in the simulations of PL.

2.4.5. Economic calculations

Costs and income from the biomass harvest in 2007 in the BI, NS and MIX treatments assumed that all trees < 5 cm DBH were motor-manually cleaned before thinning. The extracted biomass was assumed to include stems and living branches of thinned trees with DBH > 5 cm. The biomass of thinned trees was calculated with functions from (Marklund 1988).

The timber assortments, costs and income of simulated thinnings and final felling were calculated within the Heureka system. Also, the assortments and income from thinning of birch in 2016 were calculated within the Heureka system and costs of machinery were calculated using the same set of time consumption functions as in Heureka.

The reference year in the calculations of net present value was the year of final felling of the previous stand (t = 0 in Eq. 3) for all management alternatives. LEV was calculated according to Eq. 3, where *R* is the net amount in euro of cleaning, biomass harvest, thinning or final felling; *c* is the net present value of regeneration costs; *t* is time since last final felling (yr); *u* is rotation length (yr) and *r* is the interest rate. Regeneration cost was only relevant for PL.

$$LEV = \left(\sum_{t=0}^{u} R_t \times (1+r)^{-t} - c \right) \times \frac{(1+r)^u}{(1+r)^u - 1} \tag{3}$$

LEV was calculated for four different interest rates: 1, 2, 3 and 4%.

Table 3. Analysis of variance (type II Wald χ^2 test) for total volume production, diameter at breast height for the 300 largest stems ha^{-1} (DBH$_{dom}$) by tree species (*Picea abies* and *Betula pendula*) and living crown ratio for birch (*Betula pendula*). QMD = quadratic mean diameter.

Response variable	Tree species	Variable	F-value	df	P-value
Volume		Strategy	21.762	3	$1.546e^{-05}$
		Initial volume 2006	5.083	1	0.04
		Site	3.486	1	0.083
DBH$_{dom}$	Norway spruce	Strategy	29.623	2	$6.281e^{-05}$
	Norway spruce	Initial QMD 2006	2.168	1	0.172
	Norway spruce	Site	3.227	1	0.103
DBH$_{dom}$	Birch	Strategy	1.062	2	0.38
	Birch	Initial QMD 2006	1.2	1	0.3
	Birch	Site	3.74	1	0.08
Living crown length	Birch	Strategy	27.768	3	$4.005e^{-08}$
	Birch	Tree height	4.968	1	0.035
	Birch	Site	28.351	1	$1.613e^{-05}$

3 Results

3.1 Observed mid-rotation growth and yield

The competition release had a significant negative effect on total stem volume production until the last measurement 2019 at a stand age of 42 years (Table 3, Fig. 2). The total stem volume production was significantly higher in the unmanaged control (CTR) (315 ± 15 m^3 ha^{-1}; this and all subsequent error intervals are standard deviations) compared to the management strategies targeting different future crop trees: mixed (MIX) (269 ± 7 m^3 ha^{-1}), birch (BI) (239 ± 11 m^3 ha^{-1}) and Norway spruce (NS) (222 ± 10 m^3 ha^{-1}) . These values only differed significantly between MIX and NS (Table 4).

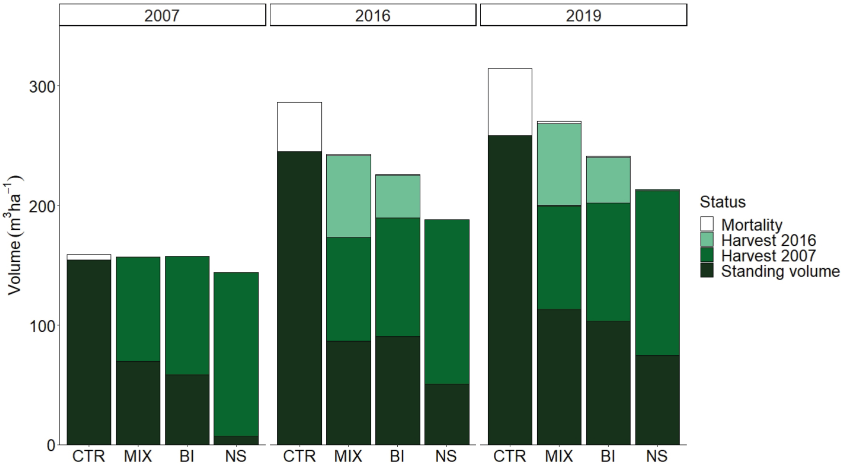

Fig. 2. Total standing stem volume (m^3 ha^{-1}), biomass harvest in 2007, birch (*Betula pendula*) thinning harvest in 2016, and mortality between 2007 and 2019. The management strategies are a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (*Picea abies*) (NS), birch (BI) or a mixture of Norway spruce and birch (MIX).

Table 4. Volume production in each strategy and control, diameter at breast height for the 300 largest stems ha^{-1} (DBH$_{dom}$) for Norway spruce (*Picea abies*) and crown length for birch (*Betula pendula*) in 2019. Letters in the final column indicate significant differences among strategies using Tukey t-test (within response variables) at p = 0.05.

Response variable	Tree species	Strategy	Average total stem volume production (m^3 ha^{-1}), average DBH$_{dom}$ (cm), average crown length (m)	Significance
Volume		CTR	315	a
		MIX	269	b
		BI	239	b
		NS	222	c
DBH$_{dom}$	Norway spruce	CTR	9.8	a
	Norway spruce	MIX	12.6	b
	Norway spruce	NS	16.9	c
Living crown length	Birch	CTR	6.08	a
	Birch	MIX	8.45	b
	Birch	BI	8.65	b

On the other hand, the competition release had a significant positive effect on the development of the future Norway spruce crop trees. DBH$_{dom}$ for Norway spruce differed significantly between the three strategies (NS, MIX and CTR) (Tables 3 and 4) and the variation among blocks was largest in CTR (Table 5, Fig. 3) in 2019. For birch there was no significant difference in DBH$_{dom}$ among the three management strategies BI, MIX and CTR at the latest measurement in 2019 (Fig. 3, Table 3) with an overall mean of 18.1 cm. (Table 5). However, the length of living crown for birch was significantly longer after competition release than in CTR in 2019 (Table 4), so was not the case at the first measurement of crown length in 2010. The living crown ratio of birch was 44 ± 5%, 46 ± 6% and 50 ± 7% for BI, MIX and CTR at the first measurement in 2010.

The quadratic mean diameter was 16.1, 13.3 and 12.4 cm for the BI, MIX and NS respectively and 6.5 cm for CTR (see Table 5 for species-specific QMD). Diameter distribution show the layering of Norway spruce and birch in MIX and CTR, with birch in the overstory and Norway spruce in the understory (Fig. 4). Birch mortality was highest in CTR. Between 2007 and 2019 an average of 610 stems were lost per hectare and year (Figs. 1 and 2) and the proportion of birch stems declined from 82% to 57% due to high mortality of birch and ingrowth of Norway spruce.

Table 5. Average stem diameter at breast height for the 300 largest stems ha^{-1} (DBH$_{dom}$), quadratic mean diameter (QMD), total stem volume production and basal area for all stems, and average living crown ratio for the sample trees of birch (*Betula pendula*) and Norway spruce (*Picea abies*) in the different management strategies at the latest measurement in 2019. Numbers inside parentheses are standard deviations. The management strategies were a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (NS), birch (BI) or a mixture of Norway spruce and birch (MIX).

	Birch			Norway spruce		
	BI	MIX	CTR	NS	MIX	CTR
DBH$_{dom}$ (cm)	18.7 (0.7)	18.1 (0.8)	17.4 (0.9)	16.9 (2)	12.6 (1.5)	9.8 (0.6)
QMD (cm)	16.1 (0.7)	17.4 (0.6)	9.5 (0.7)	12.4 (1.5)	9.2 (1)	5.6 (1.2)
Total stem volume production (m^3 ha^{-1})	239 (11)	139 (20)	257 (93)	222 (10)	39 (10)	33 (8)
Basal area (m^2 ha^{-1})	14.4 (0.4)	9.4 (0.8)	31.4 (2)	15.3 (1.8)	8.8 (1.3)	8.1 (1.4)
Living crown ratio (%)	57 (5)	53 (5)	42 (3)	90 (1)	89 (2)	79 (1)

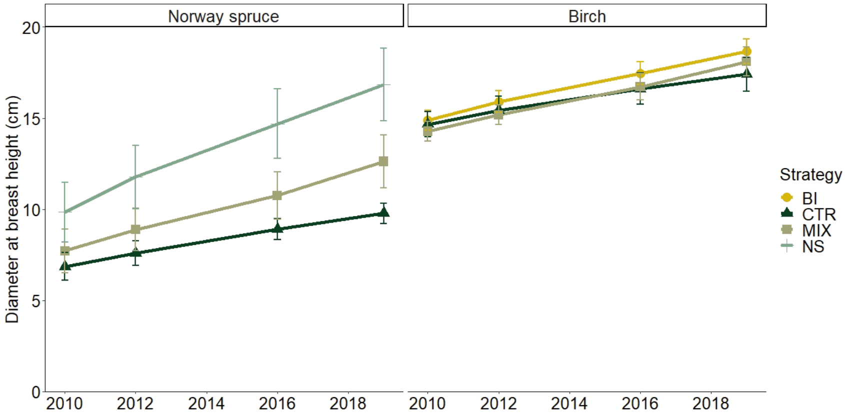

Fig. 3. Average diameter at breast height (cm) for the initially largest crop trees (DBH_{dom}) of Norway spruce (*Picea abies*) and birch (*Betula pendula*) (300 stems hectare^{-1}) between 2010 and 2019 for the different management strategies. The management strategies are a non-thinned control (CTR), and biomass harvest and thinning to promote pure stands of Norway spruce (NS), birch (BI) or a mixture of Norway spruce and birch (MIX). Error bars show standard deviations.

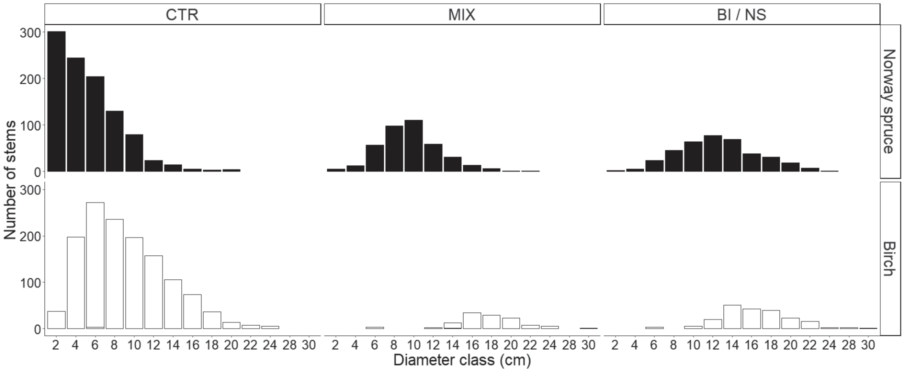

Fig. 4. Diameter distribution for Norway spruce (*Picea abies*) and birch (*Betula pendula*) in the different management strategies at the latest measurement in 2019. The management strategies included a non-thinned control (CTR), and biomass harvest and thinning to promote pure stands of Norway spruce (NS), birch (BI) or a mixture of Norway spruce and birch (MIX).

3.2 Full rotation simulations of yield and economy

The simulated production over a full rotation, based on measured initial data, demonstrated that competition release through the different management strategies had a long-term effect on assortments and amounts of extractable wood. The management strategy MIX with future crop trees of both birch and Norway spruce, resulted in the greatest total extraction of biomass (biofuel, pulpwood and timber combined) during a rotation period. The highest MAI (mean annual increment) was found in CTR, followed by PL, MIX, NS and BI. In CTR, MIX and BI the greatest share of the total removal of round wood was pulpwood, while in NS and PL the greatest share was timber (Table 6).

Ranking the different management strategies by land expectation value (LEV) gave different results depending on the interest rate. The influence of different biofuel and birch timber prices on strategy rankings were however minor (Fig. 5, Table 6). PL had the greatest mean LEV at an interest rate of 2% or less. CTR produced the greatest LEV at interest rates of 3% or more when the biofuel price was low, when the biofuel price was high NS had the greatest LEV. BI had the lowest LEV for all scenarios up to a 2% interest rate, while above a 2% interest rate the price of biofuel and birch timber determined if it was BI or PL that had the lowest LEV. The negative LEV of BI, NS and PL at high interest rates was caused by negative net revenue from the biofuel thinning in scenarios with low biofuel prices. CTR had the most stable LEV across the different scenarios. The differences among the five strategies were consequently smallest when pricing for biofuel and birch timber was more competitive with Norway spruce timber prices and under low interest rates.

Table 6. Simulated results of average annual stem volume production (MAI, $m^3\ ha^{-1}\ yr^{-1}$), net revenue (€ $ha^{-1}\ yr^{-1}$) and harvested assortments: Bio = Biomass (ton DW $ha^{-1}\ yr^{-1}$); Pulp = pulpwood ($m^3\ ha^{-1}\ yr^{-1}$); Tim = timber ($m^3\ ha^{-1}\ yr^{-1}$) for sites A and B. R = rotation length (yr). Mortality before the first measurement of CTR, BI, NS and MIX in 2007 was unknown and was not included in MAI. Biofuel prices were BioLow = 14 € and BioHigh = 42 € Mg^{-1} DW and for birch timber BirchLow = 42 € and BirchHigh = 57 € m^{-3}. The management strategies were a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (*Picea abies*) (NS), birch (*Betula pendula*) (BI) or a mixture of Norway spruce and birch (MIX) and a simulated reference of planted Norway spruce with conventional thinning for roundwood production (PL).

Strategy	Interest rate (%)	BioLow_BirchLow			Assortment			BioHigh_BirchHigh			Assortment		
		R	MAI	Net	Bio	Pulp	Tim	R	MAI	Net	Bio	Pulp	Tim
CTR	1	65	8.9	1029	0.0	4.4	0.9	65	8.9	1029	0.0	4.4	0.9
BI		65	5.6	505	0.8	2.7	0.6	70	5.6	770	0.7	2.8	0.6
MIX		97	7.3	1078	0.4	3.3	1.8	105	7.3	1257	0.4	3.2	1.9
NS		107	6.9	1200	0.7	1.1	3.1	110	6.9	1430	0.7	1.1	3.1
PL		93	8.3	1806	0.0	2.2	4.1	93	8.3	1806	0.0	2.2	4.1
CTR	2	65	8.9	1029	0.0	4.4	0.9	65	8.9	1029	0.0	4.4	0.9
BI		65	5.6	505	0.8	2.7	0.6	65	5.6	748	0.8	2.7	0.6
MIX		85	7.3	948	0.5	3.5	1.5	87	7.3	1136	0.5	3.5	1.6
NS		95	6.9	1065	0.8	1.2	2.9	97	6.9	1340	0.8	1.2	3.0
PL		85	8.2	1729	0.0	2.4	4.0	85	8.2	1729	0.0	2.4	4.0
CTR	3	65	8.9	1029	0.0	4.4	0.9	65	8.9	1029	0.0	4.4	0.9
BI		65	5.6	505	0.8	2.7	0.6	65	5.6	748	0.8	2.7	0.6
MIX		75	7.2	799	0.6	3.6	1.2	80	7.2	1053	0.5	3.6	1.4
NS		95	6.9	1065	0.8	1.2	2.9	95	6.9	1312	0.8	1.2	2.9
PL		75	7.9	1509	0.0	2.5	3.7	75	7.9	1509	0.0	2.5	3.7
CTR	4	65	8.9	1029	0.0	4.4	0.9	65	8.9	1029	0.0	4.4	0.9
BI		65	5.6	505	0.8	2.7	0.6	65	5.6	748	0.8	2.7	0.6
MIX		75	7.2	799	0.6	3.6	1.2	75	7.2	983	0.6	3.6	1.2
NS		95	6.9	1065	0.8	1.2	2.9	95	6.9	1312	0.8	1.2	2.9
PL		70	7.7	1367	0.0	2.6	3.5	70	7.7	1367	0.0	2.6	3.7

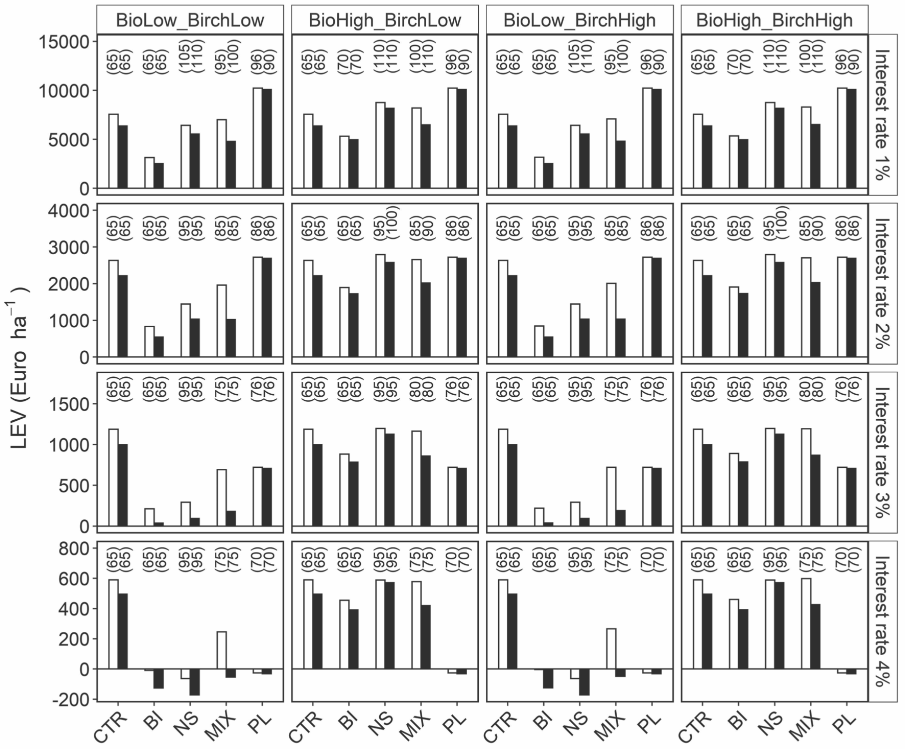

Fig. 5. Simulated land expectation value (LEV) for five management alternatives (x-axis), under four commodity price scenarios (names at the top of the figure) and interest rates between 1 and 4%. Bars show calculated LEV at sites A (unfilled) and B (filled). Biofuel prices were BioLow = 14 € and BioHigh = 42 € Mg^{-1} DW and birch timber prices BirchLow = 42 € and BirchHigh = 57 € m^{-3}. The management strategies were a non-thinned control (CTR), biomass harvest and thinning to promote pure stands of Norway spruce (*Picea abies*) (NS), birch (*Betula pendula*) (BI), a mixture of Norway spruce and birch (MIX) and a simulated reference of planted Norway spruce with conventional thinning for roundwood production (PL). Age at final felling within parentheses.

4 Discussion

4.1 Observed growth

Assuming the spontaneous regeneration is successful and dense, the first competition release can have a big impact on future stem development and on the species mixture. For Norway spruce, which was initially suppressed, the competition release had a significant positive effect (Figs. 2 and 3, Table 3).

Previous studies show similar patterns of dense and unthinned stands producing higher total stand volume compared to sparser and thinned stands (Simard et al. 2004; Niemistö 2013; Pretzsch 2020). However, one can argue that these are only mid-rotation values and the stands' future total volume may be more or less affected by mortality rates.

Competition release in the different strategies had a significant positive effect on DBH$_{dom}$ of Norway spruce in 2019 (Table 3). The NS strategy had the largest DBH$_{dom}$ followed by the

MIX and CTR (Table 4), indicating reduced growth of Norway spruce due to competition from the higher stem density in the MIX and CTR strategies. This is in line with the results from previous studies (Mäkinen and Isomäki 2004; Juodvalkis et al. 2005), where the diameter of Norway spruce increased with increasingly intense thinning. The large variation in standard deviation of DBH_{dom} for Norway spruce between the different management strategies and the control (Fig. 3) might be explained by the difference in stem density and patchiness, as seen in different standard deviations of stem density, between sites A and B at the establishment of the trial (Table 1). However, competition release in the different management strategies did not have a significant effect on DBH_{dom} of birch (Fig. 3). It is possible that an earlier competition release could have yielded a faster diameter development that could have resulted in the strategies having an effect on DBH_{dom} for birch. Rytter and Werner (2007) found that deciduous pioneer tree species in southern Sweden start to develop diameter differences before the stand is 10 years old. This could mean that the competition between the birches in the first 30 years of this study restricted growth to the extent that the competition release following biomass harvest didn't make any difference. Later results from the Rytter and Werner (2007) trial also support this interpretation by indicating that early rotation diameter loss can't be compensated for later in the rotation period (Rytter 2013). In addition, the birches had a more similar standard deviation of DBH_{dom} between strategies and the control than Norway spruce (Fig. 3). This could further imply that the competition release for the birches came too late, and that they had already self-thinned in the overstorey.

Further, the competition release through the management strategies had a significant positive effect on crown length (Tables 3 and 4), with BI having the longest crown followed by MIX and CTR in 2019 (Table 5). Crown length is an important indicator in silviculture of birch, and it should be at least 50% of the tree length to ensure vigorous growth (Niemistö 1991). The significant positive effect of competition release through the different strategies suggest that there perhaps in the future will be a significant difference in diameter growth of DBH_{dom} for birch between strategies.

4.2 Economy & simulations

At interest rates of 2% or higher (Fig. 5), the unmanaged forest (CTR) was an economically viable strategy, even compared to intensive management with a preferred merchantable timber species (PL). At higher interest rates, high initial costs and long rotations of intensive management are more difficult to overcome, even with more lucrative timber assortments and higher yields. The intensive management strategy with artificial planting was only a better economic choice at a low interest rate (1%) (Fig. 5). Artificial regeneration using planting with soil scarification requires a larger investment, but ensures more predictable survival and stand development, and also offers the opportunity to use improved plant material (Nilsson et al. 2002; Simonsen 2013; Sikstrom et al. 2020).

Biofuel prices affects the LEV (Fig. 5). This and the timber assortment differences between strategies (Table 6) imply that the profitability of different strategies can depend on local conditions, since the prices for roundwood varies across the country (Skogsstyrelsen 2021). Age is an important parameter in the growth model and is negatively correlated to growth at a given basal area or tree size. This correlation is logical in single-storied and even-age stands. However, understory spruce in NS might respond to a release cutting in relation to tree size rather than to the age (Ferlin 2002). Production in NS might be underestimated if released Norway spruce growth depends more on tree size than age. This needs to be evaluated as additional data about the stand development becomes available in the future.

4.3 Adaptability

Although artificial regeneration practices in boreal forest, with soil scarification and planting of conifers, have proven highly efficient (Örlander et al. 1998; Hjelm et al. 2019) and profitable (Sikström et al. 2018), there is a need for management practices in areas where mixed forests spontaneously regenerate (Coll et al. 2018; Löf et al. 2018). Spontaneous regeneration is an opportunity for the forest owner to combine production and biodiversity on the same clearcut by leaving different tree species during pre-commercial thinning to create a mixed-species stand (Felton et al. 2016; Holmström et al. 2016). An expected positive effect of mixing birch into a spruce stand is an increase in bird biodiversity (Jansson and Andrén 2003; Felton et al. 2011; Lindbladh et al. 2017). Replacing a monoculture with a mixed-species stand can also be a type of risk spreading (Yachi and Loreau 1999); by combining species with different functional traits the chance that at least some maintain their long-term function increases (Morin et al. 2014). A mixed-species stand also increases forest owners' management alternatives when climate change causes difficult-to-predict disturbances (Millar et al. 2007).

The type of forest management evaluated in this study – spontaneous or natural regeneration, without active cultivation in combination with or without biomass harvest at a later stage – is a viable management strategy for both profit and volume production as long as the spontaneous regeneration is vigorous. However, the dense spontaneous regeneration that occurred at these sites is no guarantee at another site with similar traits. Multiple variables needs to be aligned for a dense and vigorous regeneration to occur (Karlsson et al. 2010; Holmström et al. 2016; Holmström et al. 2017; Tiebel et al. 2020) . The different management strategies show very clearly that it is possible to create different types of stands to meet various objectives through strategic biomass harvest. This type of strategy could be a solution for regenerating sites where planted seedling survival is expected to be low. Factors reducing planted coniferous seedling survival include wet soils (Holmström et al. 2019) and incomplete soil scarification due to factors like rocky soils (Berg 1986; Sundblad 2009; Luoranen et al. 2011). Today there are several digital tools available for locating sections of a clearcut unsuitable for planting conifers before going out to the field. Soil wetness maps and digital elevation models (Murphy et al. 2011; Ågren et al. 2014; Lidberg et al. 2020) are two examples. The biggest challenge of using spontaneous regeneration without active cultivation is predicting the success of regeneration on a specific site (Holmström et al. 2017). With further development of predictive models for spontaneous regeneration, less intensive cultivation can be an option, in combination with the low-investment management strategy to promote economic profitability, biomass production and birch mixtures. Ultimately, the naturally-regenerated mixed forest of birch and Norway spruce is a possible alternative when it comes to meeting the Swedish FSC standards' (FSC 2020) recommendation of aiming for 10% deciduous trees in all stands across Sweden.

Declaration of openness of research materials, data and code

The data that supports the findings of this study is available at www.silvaboreal.com.

Authors' contributions

TL and NF designed and established the experiment. NF conducted the simulations and economic analysis, FDL conducted the growth, yield and statistical analysis. All authors contributed to the writing of the manuscript.

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IV

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Keeping mixtures of Norway spruce and birch in production forests: insights from survey data

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Keeping mixtures of Norway spruce and birch in production forests: insights from survey data

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ABSTRACT

Admixtures of birch in Norway spruce plantations are being promoted as a means to increase habitat and species diversity. The implications of this mixture were analysed with regional survey data from southern Sweden. Permanent sample plots from the Swedish National Forest Inventory (NFI), with Norway spruce and admixture of birch, were used to describe the temporal trends in the admixture, regarding species composition and competitive strength. Observations from thinned plots show a higher harvest removal in birch (35%) than for Norway spruce (19%). Observations without thinnings in the period before measurement showed that individual birch tree growth was lower compared to Norway spruce and it decreased even more with increasing stand age and competition. In addition, a complementary field survey, with multiple distributed sample plots in each stand, was used to detect within-stand variation of species composition and density. Although within-stand heterogeneity was larger in mixed stands in terms of species composition, it was not different from Norway spruce monocultures in terms of stand density. These two surveys show that the admixture of birch, for several reasons, decreases over stand age and although birch increases tree species diversity, it does not necessary imply a change in density.

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Introduction

Sustainable production of wood for fibre and construction is an important driver of the Swedish economy. The management of production forest lands is regulated, in terms of both harvest restrictions and regeneration obligations. Most of the productive forest land is managed by rotation forestry systems with soil scarification and planting as primary measures to secure new forest growth. Thirty years ago, a new forest act was implemented which emphasized the need to balance multiple objectives for forest lands (Gustafsson and Perhans 2010). Mixed forest of planted conifers and naturally regenerated broadleaves are suggested as a measure to combine both a sustainable wood supply and a high level of biodiversity conservation (Bergquist et al. 2016; Felton et al. 2010; Felton et al. 2016) and in Fennoscandia, mixed-forests represent less than 20% of forest land area (Huuskonen et al. 2021). The definition of what counts as a mixture versus a monoculture varies across studies (Bravo-Oviedo et al. 2014). For example, the Swedish national forest inventory (NFI) sets the limits as a tree species composition for which no more than 65% of the basal area is dominated by one species (Drössler 2010; Nilsson 2013), whereas other studies use a threshold of 70% (Felton et al. 2016). The retention of at least some broadleaf trees throughout a stand's rotation (5–10% of basal area) is also a requirement of some certification standards (FSC 2010).

Surveys, with spatial and/or temporal distribution of sample plots, can be used to describe the status of the forest structure within or between sample plots. Variation, in terms of tree species diversity or stand density, provides insights into the function of managed mixtures as forest habitats (Hedwall et al. 2019). Furthermore, comparisons of tree growth rates in mixtures across gradients of stand density and/or inter vs, intraspecific competition (Brunner and Forrester 2020; Manso et al. 2015), or stand age, will contribute to the understanding of how to continue manage mixtures over the full rotation, in order to retain tree species composition and habitat quality. Likewise, survey plots have been important for the understanding of the interaction effects of tree size inequality, stand density, resource availability and resource use efficiency on stand growth (Forrester 2019).

Norway spruce (*Picea abies* (L.) Karst) is the most commonly planted tree species in southern Sweden (Bergquist et al. 2017) and most of the associated clearcuts are soil scarified prior to planting with methods that also provide for the natural regeneration of birch spp. (*Betula pendula* Roth, *Betula pubescens* Ehrh) (Holmström et al. 2016a; Holmström et al. 2017; Nilsson et al. 2010). The combination of high survival rates of the planted Norway spruce seedlings and sometimes a high density of naturally regenerated birch (Holmström et al. 2019) has led to the manual pre-commercial thinning (PCT) of young stands to select and favour

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the future crop trees. This is the development stage at which time the land owner decides whether or not to keep and maintain a mixture in the future stand (Agestam et al. 2006; Felton et al. 2016; Holmström et al. 2015). Among the many decisions taken during PCT is not only the choice and proportion of tree species to retain, but also the magnitude of competitive release provided by selecting the size and stem density of the retained tree species (Fahlvik et al. 2015; Holmström et al. 2016b). Forest experiments with the specific aim to evaluate the growth of spruce–birch mixtures provide strong evidence that density of the stand, after PCT and the height relation between the tree species, will affect the possibility to keep both species in the mixture over a full stand rotation (Fahlvik et al. 2005; Fahlvik et al. 2011; Fahlvik et al. 2015; Holmström et al. 2015). However, very few experiments are available for this specific forest mixture type in later stages, after the first commercial thinning until final harvest. Instead survey data of existing stands are at the present time one of the best sources of information regarding how these stands behave in older stages. The Swedish national forest inventory (NFI) has repeatedly measured temporary sample plots across the country for almost a century, from which regional and national estimates of standing volume and periodic growth can be obtained (Fridman et al. 2014; Nilsson 2012). In addition, permanent sample plots with a re-measurement frequency of 5–7 years were added to the NFI in 1983.

The main objective of this study was to use forest inventory data to describe the current status of Norway spruce production forests in which birch occurs and how these stands tend to develop. The following forest conditions in southern Sweden were investigated using two surveys, one with temporally – and the other with spatially – repeated measurements. Two questions were addressed using permanent sample plots of the NFI and based on the change in management and growth between repeated measurements over time: (1) Is the thinning intensity the same in both tree species, indicating a preservation in mixed species composition after thinning? (2) How is the growth performance of birch compared to Norway spruce when stand age and competition increase? A third question was addressed using a field survey with replicated sample plots within stands: Is there a correlation between stand variation in the proportion of Norway spruce and variation in basal area, indicating differences in growth rate, management or site differences in monocultures of Norway spruce compared to admixtures with birch? For both surveys, the selected interval for a sample plot to be defined as "mixture", the species proportion of birch was defined as at least one birch in the sample plot and at most 70% of the basal area. This definition was used specifically for the purpose of addressing the questions raised above, for which mixed forest response per se was not the key issue, but rather how forest practices interact with tree – and forest growth.

Material and methods

NFI, survey selection

The study area was confined to Götaland, an administrative region in southern Sweden which is also used as the geographical delineation for the southern sampling design within the Swedish NFI (Figure 1). Not included in the study was the southernmost county (Skåne), where Norway spruce is only partly native, and Kalmar County, which also has relatively low proportion Norway spruce forests historically (Lindbladh et al. 2014). The forest in the study area is predominantly coniferous forests, and most of the commercial forests are managed with a clearcutting system regenerated with either Norway spruce or Scots pine. The climate is in the border of the boreal region with annual mean temperature 5–8°C and average annual precipitation ranging between 500 and 1000 mm year^{-1} (SMHI 2015).

We evaluated all permanent NFI sample plots from the study area, if measured between 1983 and 2016 and providing two or more repeated measurements. Every repeated measurement is defined as a "revision" and the number of revisions varied between plots (2–6), depending on when they were established. The time period between revisions varied from five to seven years, depending on the inventory scheme at the time (Fridman et al. 2014). We restricted our analysis to plots with at least one revision in which there was a living birch tree in the plot and for which birch and Norway spruce trees together accounted for more than 90% of basal area. In addition, we removed sample plots in which birch exceeded 70% of the basal area. From here on, we refer to this final selection as the NFI survey, which consisted of 717 permanent sample plots in total (Figure 1). This sample corresponded to 52% of the sample plots from the study region that were dominated by Norway spruce.

NFI, measurements and data retrieval

NFI measurements involve all trees within the radius of 10 m from plot centre being registered and measured. For the repeated measurements, trees are first identified from

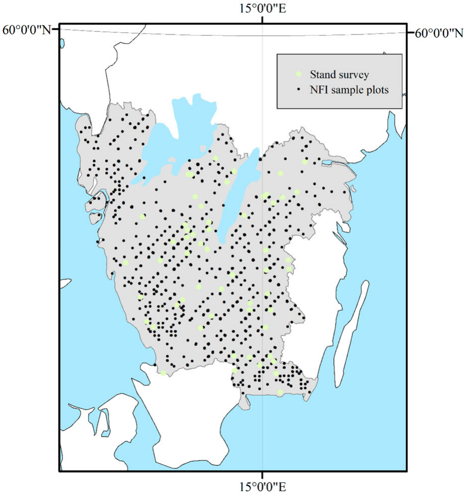

Figure 1. Location of NFI sample plots and the stand survey, framed within the shaded study area in southern Sweden.

earlier inventories so that individual tree changes can be calculated or registered (e.g. mortality, growth or harvest). Trees with a diameter at breast height (dbh) exceeding 100 mm were measured on the whole sample plot, whereas trees with dbh between 40 and 100 mm were measured on a smaller plot with an area of 38.5–78.5 m^2 depending on the year of inventory. Trees growing into the tree population in subsequent inventories are registered as new sample trees. In this study, basal area per hectare (G) was calculated as the sum of all trees' basal area weighted with the sample plot area and individual tree and sample plot basal area growth was calculated based on the difference in between two measurements. In order to adjust for the unknown prior basal area of the new sample trees, the dbh in the previous inventories ($\text{dbh}_{t1\text{-}1}$) were derived as a linear function of time between measurements, age and the next measured dbh where dbh and species were derived from the NFI database for the individual trees and age was derived from the sample plot estimated age.

Tree height is only measured for a low proportion of trees in every sample plot (approximately 1–2 trees per sample plot), but individual tree height is provided in the NFI database using Söderbergs height functions (Söderberg 1986) with corrections from the sample plot height measurements (Fridman et al. 2014).

Stand survey, survey selection

The second survey was initiated as a stand survey database for investigations of Spruce–birch mixtures, including habitat – and species diversity-studies (Hedwall et al. 2019). The same study area as for the NFI selection was delineated and within this geographic range forest stand information from the Swedish state company Sveaskog and from the forest owner association Södra skogsägarna, was compiled (Figure 1). The information contained a shape file with the geographic position and stand borders for every stand and a few stand descriptive values such as tree species proportion, stand age, density and estimated basal area. Age, density and species proportion were supplemented and corrected with field observations. Only stands with ≥90% of Norway spruce and birch combined were used in the survey. Other criteria for inclusion were based on age ≤ 60 years, stand size ≥ 2 hectares, and stand form, whereby the majority of the stand must be wider than 100 m, in order to minimize edge effects from surrounding stands. In an attempt to ensure a balance in the number of stands included in the survey, the stand database was stratified into three categories of species proportion according to the stand data base; birch dominated (B.dom) = Birch dominated ≥ 80% birch, Spruce dominated (S.dom) < 20% birch, and in between Admixture with birch (Mix), and four age categories: 20–29 years, 30–39 years, 40–49 years and 50–59 years, resulting in a total of 12 strata. A random priority was assigned to all stands within each strata and the inventory was then made in the priority-order until five stands in each strata were measured. The minimum distance between two selected stands was 1 km. Stands were first assessed using orthophotos, and a GIS layer for the stand borders. This was necessary because of uncertainties regarding actual tree species proportions, and broadleaf species identifications, as listed in the stand database. If it was clear from the orthophotos that the broadleaf species were not birch (e.g. large heritage oaks) the stand was excluded. All selected stands were visited and measured with a grid of 10 m radius sample plots, 5 per stand. The distribution of the sample plots was made prior to the field visit, distributed systematically over the stand but centralized to reduce edge effects. The stand attributes provided by the data base were predominantly consistent with field assessed descriptions: The stands were located on medium to fertile sites, and consistent in terms of their stem density, which decreased with age and thinnings. Most stands had signs of thinnings (stumps and strip roads), with the exception of 15 stands. The lack of thinning in these stands understandably affected resultant stem density and standing volume (Table 1). Of the unthinned stands, 10 were in the youngest age class, and were predominantly classified as birch dominated stand types in the database. The other unthinned stands were stands occurred among stand type mixtures in age class 30–39 years, which had a higher average stem number compared to the other stand types in the same age category (Table 2). As the birch dominated stands had a high proportion of birch (on average 70% of the basal area), there was difficulty to find "typical birch monocultures with the purpose of wood production" in older age classes and therefore the comparison with the other stand types in terms of heterogeneity was not further explored.

Stand survey, measurements and data retrieval

All trees within the sample plot were cross calipered for dbh and included if the dbh exceeded 40 mm. The tree species, observed damage, and mortality were recorded. Heights were measured for the two trees with the largest dbh, as well as for one random tree of the dominant tree species. If the sample plot included more than one tree species, up to three random trees were measured in height. Stand age was assessed and compared with the stand database by counting branch whorls on Norway spruce (one year per

Table 1. Stand mean and standard deviation of stem density and standing volume for age categories and stand types ($n = 5$).

Age class	Stand type	Stems ha^{-1}	Volume m^3 ha^{-1}	Site index
20–29	Birch dominated	1427 ± 801	78 ± 16	38 ± 2
	Mixed stands	1504 ± 237	136 ± 45	36 ± 2
	N. spruce dominated	1593 ± 598	146 ± 21	36 ± 1
30–39	Birch dominated	707 ± 208	97 ± 22	34 ± 4
	Mixed stands	1471 ± 851	172 ± 62	34 ± 1
	N. spruce dominated	917 ± 193	182 ± 39	35 ± 1
40–49	Birch dominated	820 ± 398	131 ± 41	35 ± 5
	Mixed stands	893 ± 303	195 ± 30	36 ± 1
	N. spruce dominated	838 ± 385	327 ± 70	36 ± 2
50–59	Birch dominated	796 ± 238	161 ± 61	31 ± 2
	Mixed stands	994 ± 430	263 ± 88	34 ± 2
	N. spruce dominated	691 ± 192	354 ± 56	35 ± 1

Table 2. Summary statistics of the NFI sample plots between revisions. Basal area (m^2 ha^{-1}) corresponds to the total sample plot basal area and birch proportion is the percentage birch basal area in the sample plot.

Revision	Inventory years Interval	Stand age Mean	Basal area Mean, St. dev	Birch proportion Mean, St. dev
1	1983–1987	51	23 ± 10	17 ± 17
2	1988–1992	50	24 ± 10	17 ± 17
3	1993–2002	50	26 ± 12	17 ± 17
4	2003–2007	49	29 ± 13	17 ± 17
5	2008–2012	49	28 ± 15	18 ± 17
6	2013–2017	49	29 ± 17	19 ± 17

whorl), and tree ring counting some of the height measured trees using cores at breast height.

Site variables were taken at every sample plot using the classifications according to Lundmark (1974). If the stand had stumps from thinning operations, the time since thinning was estimated as 1, 3, or 5 years, using the decay stage of the stumps and retained twigs as indicators. The mixtures were classified using descriptive measures of mixed structure: Composition structure was either stem-by stem mixture or grouped tree species mixture. The canopy structure was categorized as involving either the two tree species coexisting in the same canopy layer or segregated in distinct sub-layers. The succession structure of the stand was categorized according to whether the stand was regenerated at the same time, as opposed to two distinct regeneration periods within the stand. The descriptors were assigned from the centre of every sample plot, subjectively assessed based on the surrounding view. Stand heterogeneity was also evaluated using the coefficients of variation for basal area and species proportion of the basal area between plots. The species proportions were assessed and based on the Norway spruce percentage of the total sample plot basal area. Heterogeneity was tested by Anova two-way statistical tests using the stand age and stand type categories.

For all calipered trees an estimated height was calculated using a standard method for height functions $H = DBH^x/(a + bDBH)^x + 1.3$, where H = tree height (m), DBH = diameter at breast height, a and b are coefficients, and x has the value of 2 for birch and 3 for Norway spruce with separate functions per stand and tree species (Holmström et al. 2015; Naslund 1947). This was possible to do when the number of height-measured trees exceeded 10 per stand. For cases in which the presence of tree species other than Norway spruce and birch, the Söderberg height functions was used (Söderberg 1986), which is also the standard for height estimations used by the Swedish NFI.

Both surveys, data management and statistical design

In both surveys the individual tree volume and standing volume per hectare (the sum of the tree volumes in the sample plot weighted on plot area) were calculated using species-specific volume functions for southern Sweden (Brandel 1990). Quadratic mean diameter (QMD) was also calculated, as a species-specific measure and as based on all stems in the sample plot. Thereafter the ratio of QMD for birch vs. Norway spruce was calculated for each sample plot.

Periodic annual basal area growth (ABA) (m^2 $year^{-1}$) for individual trees was estimated from the NFI data using the difference in DBH between two periods. A linear mixed model was used for the analysis of growth difference, as well as for ABA of Norway spruce and birch trees, with *i* replicates of measurements nested within *j* sample plots (Plot) as random effect, using *R* statistics software package lme4 (R Core Team 2013):

$$\begin{aligned} \mathrm{ABA}_{ij} &= \mu + \beta_0 \mathrm{DBH}_{ij} \times \beta_1 \mathrm{DBH2}_{ij} \times \mathrm{TS} + \beta_2 G_{ij} \times \mathrm{TS} \\ &\quad + \beta_3 \mathrm{Age}_{ij} \times \mathrm{TS} + \varepsilon_{ij}, \quad \mathrm{Plot}_j N(0, \sigma_{ij}^2) \end{aligned} \tag{1}$$

where μ is the model intercept and the fixed effects included in the initial model were initial and squared DBH of the tree (DBH, DBH2), sample plot basal area (*G*) and estimated stand age of the sample plot (Age). Tree species (TS) was implemented as a dummy variable in the model for either birch (*B*) or Norway spruce (NS). The survey material used in the statistical test was reduced to only include sample plots with birch proportion less than 70% of the basal area but still possessing at least one

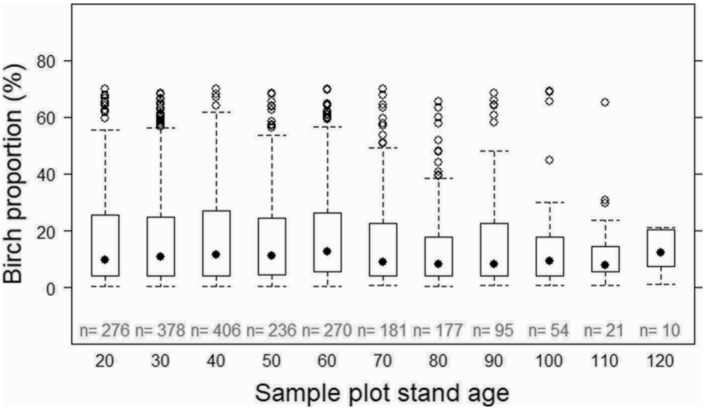

Figure 2. Box and whisker plot of the birch proportion in basal area (%) in each sample plot, grouped by stand age at the time of the revision. The number of observations is stated (with *n* = *j*) in red above the stand age presented in black, in age classes of 10 years where "20" corresponds to age 16–25, etc.

birch tree, within a minimum of one of the revisions. Furthermore, only those revisions were included that were without documented thinnings since last measurement, with stand age below 150 years and basal area corresponding to between 10 and 40 $m^2 ha^{-1}$ and testing only trees with DBH between 10 and 40 cm. The reduction in observations was made to ensure a sound proportion of sample trees of both species and reduce outliers which could be large measuring errors, (542 sample plots used in the model). To reduce heteroscedacity of the data, the response variable was transformed prior to model fit by a reciprocal square root transformation. All fixed effects and interactions with tree species (TS) were initially kept but removed if proved non-significant, using a *p*-level $p > 0.05$ in combination with reduction of AIC.

Table 3. Statistical characteristics of Equation (1).

Fixed effect variable	Fixed Effect Parameter	Estimate	Std. Error	ρ
Intercept	μ	9.999e-01	2.337e-05	<2e-16
Intercept TS_B	μ	−2.550e-04	4.451e-05	<2e-16
DBH	β_1	−8.174e-06	1.954e-07	<2e-16
DBH: TS_B	β_1	5.072e-06	4.745e-07	<2e-16
DBH2	β_2	9.821e-09	4.477e-10	<2e-16
DBH2: TS	β_2	−7.986e-06	1.121e-09	1.044e-12
G	β_2	1.126e-05	4.607e-07	<2e-16
Age	β_3	6.792e-05	3.290e-07	<2e-16
Age:TS_B	β_3	−2.872e-06	2.193e-07	<2e-16
	Random Effect	**Std.Dev**		
	b	0.0002299		
	Residuals	**Std.Dev**		
	ε	0.0003343		

Results

For all revisions the mean birch proportion in terms of basal area and stem density was 18 and 19%, respectively, while median birch proportion of the stem density was 11 and 13%, respectively, (Table 2) (Figure 2). Although the variation between plots was high, the inventory remained constant over the revision years, in regard to basal area and birch proportion.

Thinning intensity

Thinning operations were made in the period between two revisions in 295 sample plots, resulting in 360 thinning events in total, due to repeated thinnings in some plots. The species-specific thinning intensity was for Norway spruce on average 19% and for birch 35% of the basal area. Of the thinning events, 69 occurred in sample plots with one birch, which was removed in 33% of the events.

Species growth rate

The individual tree annual basal area growth (ABA) was evaluated for all sample plots and revisions without thinning, in between the two measurements. The dummy variable TS for tree species was significant for all fixed effects except for basal area (G), and the model was reduced accordingly, ending up with species-specific coefficients for stand age (Age) and DBH. Birch ABA was significantly lower compared to Norway spruce and the difference increased with stand age and with the sample plot basal area (Table 3). Based on the model prediction, birch tree ABA was 69% of Norway spruce at sample plot basal area 10 m^2, and 55% in plots with a basal area of 30 m^2, given the median-sized dbh 15.3 cm and median sample plot stand age of 40 years. The same tendency of decline in birch tree size compared to Norway spruce was also visible in the ratio of quadratic mean diameter for birch vs. Norway spruce (Figure 3).

Within stand variation

In the stand type Mixture all, except 8 sample plots, had a single layer in the canopy structure of the species mixture, but the composition structure, however, was equally stem wise and group wise categorized in sample plots and stands (Figure 4).

Basal area variation between sample plots within stands was high; 23 and 19% for the mixed and Norway spruce dominated stand types, respectively although the coefficient of variation for basal area within the stands was not significantly different between stand types (Figure 5). However, the coefficient of variation for proportion of the Norway spruce basal area within stands was significantly higher in the mixed stands (30%) compared to the Norway spruce monocultures (9%), ($p < 0.05$) (Figure 6). The stand age had no effect on either of the two coefficients of variation.

Discussion

The presence of a birch stem in the Norway spruce forest seems to be as common as absence, considering the proportion of Norway spruce sample plots with birch presence sometime during the rotation was 50%. Data from the NFI showed that some Norway spruce forests with intermixed birch remain in the southern Swedish forestry even after commercial thinnings. The high frequency of thinnings confirms the assumptions that such mixed forest stands in mid-rotation age (40–80 years) in southern Sweden are managed to a similar intensity as the Norway spruce production stands with little or no birch retained. However, based on the NFI findings, there are indications of a reduced birch admixture in production stands later in the rotation. Firstly, the proportion of birch is more intensively harvested in thinnings compared to Norway spruce. Secondly, the growth rate of the individual trees is slower than that of the surrounding Norway spruce. These findings indicate that the birch proportion in mixtures demands active management in order to retain the mixture over the full rotation, which is a finding likewise supported by independent results from experiments and scenario analysis (Fahlvik et al. 2015; Holmström et al. 2015; Holmström et al. 2016b; Huuskonen et al. 2021). Active management to preserve spruce–birch mixtures may involve heavier thinning in Norway spruce stands, reducing the overall competitive pressures in the stand. Many deciduous species like birch require wider spacing than Norway spruce to maintain vitality and growth capacity in a stand, and to avoid self-thinning

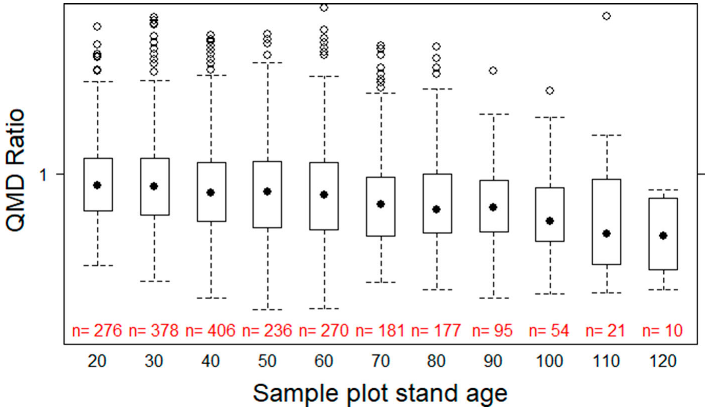

Figure 3. Box and whisker plot of the ratio of birch vs Norway spruce quadratic mean diameter in each sample plot, grouped by stand age at the time of the revision. The number of observations is stated (with $n = j$) in red above the stand age presented in black, in age classes of 10 years where "20" corresponds to age 16–25, etc.

(Hynynen et al. 2010; Maleki and Kiviste 2016; Vanhellemont et al. 2016). The apparent decrease in competitive strength of birch over the rotation needs to be taken into consideration during future management if an admixture of birch is to be maintained over the full stand rotation.

The results from the field survey and specifically, the replication of sample plots within the same forest stand make it possible to further elaborate on the ways by which mixed forest also can increase heterogeneity. Forest diversity, in terms of tree species mixture, is currently used as a measure to combine multiple objectives in plantations. In other words, using an increase in forest tree species composition to correspondingly increase forest structure and function, might theoretically be a way forward for forest plantations managed to provide for a wider variety of species habitat requirements and ecosystem services (Felton et al. 2016; Felton et al. 2020). Results from the field survey showed that heterogeneity, described as variation within the stand, clearly increased with the mixture if measured as tree species proportion. We suggest this is probably an artefact of the stand's origin, as many of these mixtures are not intentionally created but have occurred due to variation in birch regeneration throughout the stand, and as a result of the patchy success in Norway spruce regeneration.

Importantly however, within-stand heterogeneity did not increase if measured solely as basal area. In this regard there was no significant difference in basal area variation between Norway spruce monocultures and Spruce–birch mixtures. This is in line with other studies where conventional stand characteristics, such as density, show low to moderate correlation with indices of structural heterogeneity (Keren et al. 2020). The implications of this may be that for some forest taxa the addition of another tree species will not be sufficient as habitat improvement, if these additional benefits are not sufficient to override the habitat limitations imposed by high stand densities (Hedwall et al. 2019). If the objective with growing the Norway spruce stand together with admixture of broadleaves is to increase nature conservation values, then this issue needs to be considered from the outset of the thinning regime. Simulations of thinning approach in mixtures demonstrate positive effects of maintaining clustering tree structures for maintained or increasing within-stand heterogeneity (Cannon et al. 2019) as well as a general increase of species richness with increasing forest heterogeneity (Felton et al. 2016; Latif et al. 2020).

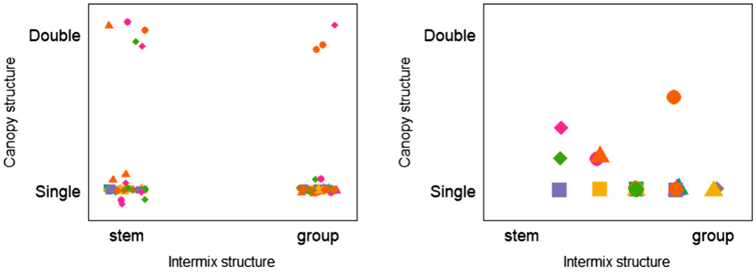

Figure 4. Visualization of the composition and the canopy structure in plots (left panel) and as mean values over stands (right panel). The combination of colour and symbol is representing a unique stand.

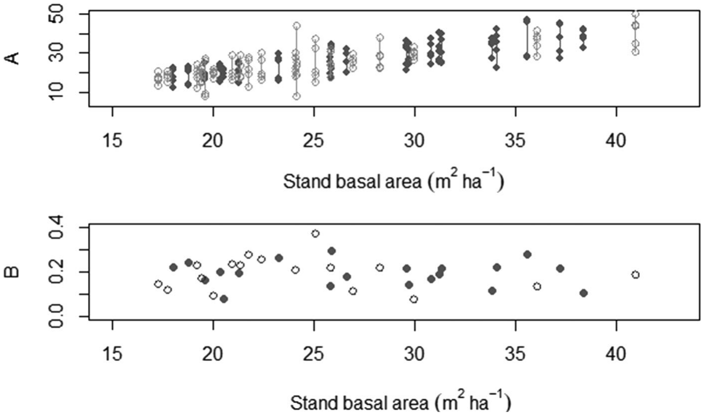

Figure 5. Top panel: Sample plot basal area vs the mean basal area for the five sample plots. Each line corresponds to the min and max value from each stand. Lower panel: Coefficient of variance of basal area between sample plots in the same stand. Dark grey and light grey symbols correspond to Norway spruce monoculture and birch stand, respectivley.

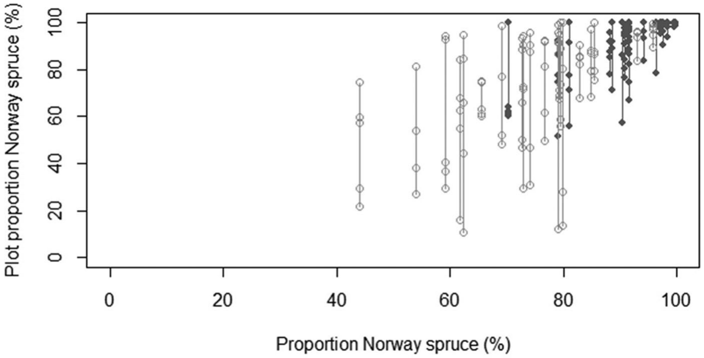

Figure 6. The basal area proportion (%) of Norway spruce in sample plots vs the stand mean value. Lines correspond to the stand max and min value. Dark grey and light grey symbols correspond to Norway spruce monoculture and birch stand, respectively.

Conclusions

Due to the lack of established experiments and empirical data on growth performance in older Norway spruce–birch mixtures, we exploited NFI data and targeted field surveys to fill important remaining knowledge gaps. The permanent sample plots from the NFI, with repeated measurements on the same trees, made it possible to both quantify and provide statistical support for theoretical expectations that birch would decrease in percentage within Norway spruce plantations with time and over the course of the rotation. Birch in these forests tends to have more difficulties to maintain its proportion over the length of the rotation in southern Sweden and this regardless of thinnings or no thinning occurring. Furthermore, the repeated measurements of our field survey made it possible to disentangle the contradictory results regarding forest diversity. Specifically, although mixed stands have a high variation in tree species composition, this did not translate into a corresponding increased variation in stand density. Whereas experiments conducted in younger stands have repeatedly demonstrated the reduced growth rate of birch compared to Norway spruce (Fahlvik et al. 2011; Holmström et al. 2015), our efforts emphasize the importance of also considering the trajectory of birch decline later in the rotation.

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Sveaskog and Södra forest owner association, has approved that information extracted from their forest properties can be published in anonymous summarized results, as managed in this manuscript. We are thankful for their data contribution. We are thankful to the Swedish National Forest Inventory, especially to Bertil Westerlund, who guided us with metadata and data delivery, and to all the forest technichians measuring the forest every summer.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability

Data from the national forest inventory (NFI) are open source and available from the SLU webpage: https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/. Detailed information regarding exact coordinates of sample plots from both stand survey and NFI is not open source but may be retrieved after written agreements have been made with the original data supplier. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request (excluding exact location of the plots).

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