Growth and management of Silver birch and Hybrid aspen in southern Sweden

Mari Tuvikene

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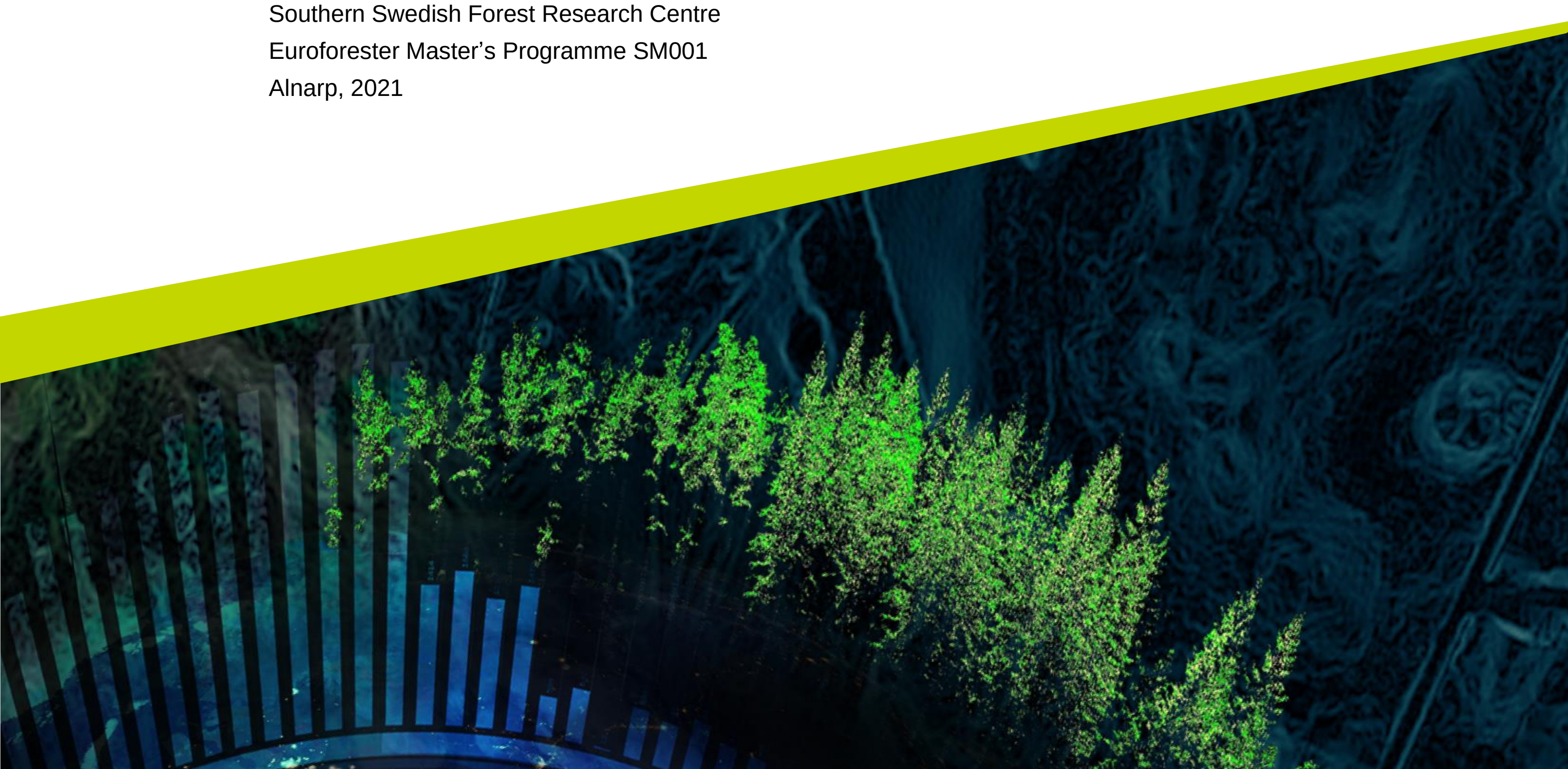

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Abstract

Nowadays, the changing climate and the risks associated with it urge us to re-evaluate our silvicultural practices. Due to the increasing demand for wood and good economy amongst other factors, Swedish forest landscape is dominated by two species – Norway spruce *Picea abies* (L.) Karst. and Scots pine *Pinus sylvestris* (L.) However, there are other species such as silver birch *Betula pendula* Roth and hybrid aspen *Populus* × *wettsteinii* Hämet-Ahti = *P. tremula* L. × *P. tremuloides* Michx. – two of the fast-growing tree species in Baltic sea region, including Sweden, that may complement the species composition in Sweden, providing various benefits, especially in the face of the changing climate.

The main objective of the thesis was to evaluate the early growth of silver birch and hybrid aspen depending on the management done so far. Also, to assess the growth and economy of full rotation birch stands in southern Sweden using a standard management regime. Data was collected from four experimental sites located in southern Sweden established on both forest land and agricultural land. Different functions were applied to estimate both early growth, e.g. height, basal area, volume, as well as future growth and development of silver birch stands. A statistical model was constructed to test the effect of fertilization.

Genetically improved silver birch (Ekebo 4) showed comparable growth next to hybrid aspen which is proved as one of the fast-growing tree species in Sweden. Statistical analysis revealed that fertilization has a significant effect on all growth parameters tested (height, DBH & volume) of both species, with differences between fertilized and unfertilized values being larger for hybrid aspen. Simulations of full rotation stands of silver birch showed that optimal rotation length of birch stands planted with improved material is between 36 – 40 years, while mean annual increment varies from 9.2 – 13.3 m^3 ha^{-1} $year^{-1}$ with the best performance delivered by birch planted on agricultural land.

Keywords: Betula pendula Roth, *Populus* × *wettsteinii* Hämet-Ahti = *P. tremula* L. × *P. tremuloides* Michx., plantation, young stand, simulation, fertilization

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Abbreviations

BA – Basal area

DBH – Diameter at breast height

DNA – Deoxyribonucleic acid

HA – Hybrid aspen

IRR – Internal rate of return

LEV – Land expectation value

MAI – Mean annual increment

NPV – Net present value

p – Pulpwood

PCT – Pre-commercial thinning

QMD – Quadratic mean diameter

SB – Silver birch

SEK - Swedish crown

SI – Site index

t – Timber

1. Introduction

Nowadays, the changing climate has risen many questions when it comes to species currently dominating the forest landscape in Sweden. The many potential risks arising in Norway spruce dominated forests in combination with the renewable energy directive (DIRECTIVE 2009/28/EC) is urging us to re-evaluate our silvicultural practices and think of possible solutions to the existing issues. Silver birch (*Betula pendula* Roth) and hybrid aspen (*Populus* × *wettsteinii* Hämet-Ahti = *P. tremula* L. × *P. tremuloides* Michx.) are two of the fast-growing species in the Baltic sea region, including Sweden, that can be used not only for pulpwood and quality timber but also as for woody biomass production primarily used for bioenergy. As a further matter, short rotation forestry and fast-growing species have an important part in global atmospheric carbon dioxide sequestration and mitigation of climate change (Borges *et al.* 2014).

1.1. Distribution, characteristics and history of silver birch and hybrid aspen

On the Eurasian continent, silver birch has a wide natural distribution from the Atlantic to eastern Siberia (Hultén & Fries 1986). It is a very important broadleaf tree species in northern and eastern Europe, which forms considerably high per centages of the total growing stock. Naturally, silver birch occurs in mixtures, but in Northern Europe it also grows in pure even aged stands which are most often regenerated artificially (Hynynen *et al.* 2010). Silver birch is a shade intolerant pioneer tree species (Hynynen *et al.* 2010) often comparatively straight and slender stem (Heräjärvi 2001; Dubois *et al.* 2020). In Sweden, birch is the third most common tree species in the country after Norway spruce and Scots pine. The growing stock of birch species (*Betula pendula* Roth & *Betula pubescens* Ehrh.) in Sweden is ca. 441 mill. m^3sk and it can be found throughout the country, however it shows better growth in southern Sweden compared to the northern part of the country. Growing stock is biggest in northern Norrland – 126 mill. m^3sk and smallest in Svealand - 97,2 mill. m^3sk, while the size of Götaland where the growing stock is 104 mill. m^3sk, is around 37 % smaller than size of northern Norrland. Mean annual volume increment for silver birch in northern Sweden (northern Norrland) is 388 x 10^4 m^3sk compared to south (Götaland) – 418 x 10^4 m^3sk, while in the central part of the country (Svealand) the mean annual volume increment is 356 x 10^4 m^3sk. (Skogdata 2020).

Hybrid aspen is artificial crossing which means it has no natural distribution. However, the parental species of the crossing have a large natural range of distribution (Tullus *et al*. 2012). Aspens generally are fast-growing, light demanding tree species that prefer fertile soils (Stanturf *et al.* 2001). Hybrid aspen has a longer growing season compared to its parental species (Yu *et al.* 2001).

In Sweden first crossing of hybrid aspen was made in 1939 (Johnsson 1953; Rytter & Stener 2005), same period the first trial was established (Johnsson 1953). In the beginning, the focus was only on high yield, with other factors, e.g. resistance, stem quality, etc. being considered only later (Stener *et al.* 2019). Experiments of hybrid aspen were established until the production of matches decreased - 1960´s (Elfving 1986; Stener & Karlsson 2004), however, in 1980´s, when the new project about production of commercially valuable timber for southern Sweden came into existence, the interest in planting hybrid aspen increased again (Stener & Karlsson 2004).

1.2. Growth of silver birch and hybrid aspen

Silver birch prefers forest sites with sandy soils and sandy silty till soils (Sutinen *et al.* 2002). In addition to fertile forest sites, it also occurs on afforested abandoned agricultural fields (Koivisto 1959; Raulo 1977; Oikarinen 1983; Niemistö 1995a). Fertilization promotes drought resistance and improves water uptake (Perala & Alm 1990). Silver birch is a nitrogen-limited tree species which means that lack of nitrogen can result in reduced growth (Keinänen *et al.* 1999). Nutrient cycling in birch stands is usually faster than in the conifer stands (Mälkönen 1977; Priha 1999) where birches can improve soil quality by cycling nutrients (Perala & Alm 1990). Notwithstanding, it is not common to fertilize birch stands (Oikarinen & Pyykkönen 1981).

Silver birch is the most productive native broadleaved tree species in the Nordic countries (Hynynen *et al.* 2010). Mean annual increment (MAI) on good sites of silver birch in Sweden can be around 10 m^3 ha^{-1} when the rotation period is between 30 and 60 years (Dahlberg *et al.* 2006). The growth and stem quality of the silver birch depends highly on the provenance of the seeds (Raulo & Koski 1977). Long-distance transfer of the seeds or seedlings can cause prolonging of growth period and higher risk for vitality (Eriksson & Jonsson 1986). To achieve vigorous growth, silver birch has to grow as a dominant tree in a stand with low competition (Hynynen *et al.* 2010). During the early stage, the growth of silver birch is usually rapid. It can reach a height up to 24 - 25 m in 30 years in good sites (Oikarinen 1983; Eriksson *et al.* 1997), however in poor sites, height can reach only 6 m in 30 years (Eriksson *et al.* 1997). The culmination of height growth is between 10 - 20 years and culmination of volume growth is reached 5 years later (Raulo 1977; Oikarinen 1983). Vigorous growth subsists until the stand is 40 - 50 years old (Koivisto 1959; Oikarinen 1983). In northern Europe, the growing season for silver birch is from the end of May until the beginning of August. When the growing conditions are favourable, the width of the annual ring is around 3 - 4 mm (Hynynen *et al.* 2010).

Hybrid aspen prefers light loamy sand or sandy loam textured soils which are nutrient rich, well aerated, moderately drained and water holding capacity is high (Tullus *et al.* 2007; Tullus *et al.* 2008; Tullus 2010). Former agricultural lands are suitable for hybrid aspen due to long-term tillage and fertilization which means that the physico-chemical properties in soil are different from the equivalent forest soils (Wall & Heiskanen 2003; Wall & Hytönen 2005). Concentration of gravel and clay may have a negative effect on growth of hybrid aspen (Tullus *et al.* 2007). In the boreal and hemi-boreal forest, nitrogen is the most important nutrient and the growth of tree species are highly dependent of it (Jacobson 2001). Hybrid aspen demands nitrogen more than most of the other tree species (Stanturf *et al.* 2001). Availability of other nutrients is also required because sometimes *Populus* species do not respond to additions of pure nitrogen (Blackmon 1976).

The potential of biomass production of hybrid aspen can be very high. Mean annual increment can reach up to 25 m^3 of stem wood ha^{-1} (Stener & Karlsson 2004; Tullus *et al.* 2012; Stener *et al.* 2019). The target yield of first rotation is 300 - 400 m^3 ha^{-1} while the production outcome is saw logs and pulpwood (Rytter & Stener 2005, Tullus *et al.* 2012). The origin of second rotation is from root suckers (Rytter 2006). The growth of root suckers is faster than first generation plants (Stener *et al.* 2019). The growth of hybrid aspen depends highly on the genetic material of clones, i.e. stem volume, height, mean annual increment, etc. are dependent on the quality of genetic material that is clone specific (Zeps *et al.* 2016).

1.3. Establishment and management of silver birch and hybrid aspen

Silver birch can regenerate abundantly naturally, but it is preferred to plant seedlings if the goal is to get high-quality timber. It is also possible to use stem sprouts as a regeneration method in short rotation forest management. Seeding is not so common practice when it comes to the establishment of silver birch stand. Normally, birch is being planted using a planting density of 1600 - 2000 seedlings ha^{-1} (Niemistö 1995b). Silver birch can grow in pure stands or in mixtures. Predominantly, it grows in mixed stands with conifers. Stands which are regenerated naturally are usually harvested for pulpwood. In case the stand is managed in a way that birch is favoured the outcome can also be high-quality timber. The goal of a pure silver birch stand is typically to produce plywood or high-quality saw timber (Hynynen *et al.* 2010). Silvicultural practices are aiming to grow straight and defect-free large diameter birch stems where the stocking is homogeneous and even-sized (Hynynen *et al.* 2010). Birch is a light-demanding tree species and an excessively high density reduces growth which requires intensive pre-commercial and commercial thinnings (Cameron *et al.* 1995; Niemistö 1995a, 1995b). Thinning benefits diameter growth and yield of sawn timber, hence it shortens the rotation age and increases revenues from cuttings

(Oikarinen 1983). Furthermore, the wood quality of silver birch does not get impaired when the diameter increment is fast, which is typical in conifer stands. Shorter rotation also decreases the risk of decay, which is a common problem in older birch stands (Hallaksela & Niemistö 1998). When the stand is unevenly-sized the dominant tree branch development is too vigorous and self-pruning very slow which causes the decrease of timber quality. Therefore, pre-commercial thinning (PCT) has to be done before the mean height of 7 m (Rytter & Werner 2007). Typically, during the rotation, silver birch stands have two commercial thinnings. To ensure high yield and good quality timber it is needed to remove 30 to 40 per cent during the thinning process (Oikarinen 1983; Rytter *et al.* 2008). Typical rotation of silver birch plantations in Finland varies between 40 and 60 years. Rotation length depends on site productivity and growing stock quality (Oikarinen 1983) but also depends on the stand purpose. When the aim is to produce high-quality timber, the rotation is longer (Hynynen *et al.* 2010).

Management activities of hybrid aspen depend on particular goals of a stand. When the aim is to grow pulpwood or material for the wood industry, the rotation is around 20 - 30 years (Tullus *et al.* 2012; Stener *et al.* 2019). The first rotation can yield between 300 - 450 m^3 ha^{-1} of pulpwood and logs. Higher quality can be achieved by performing pruning in hybrid aspen stands (Rytter & Jansson 2009). Thinning frequency depends on stand density and growing rate but typically it is 1 - 3 times during the rotation (Rytter *et al.* 2011). When growing energy wood, the rotation cycle can be down to 4 years. In regards to planting density for hybrid aspen plantations, it can range from 1000 - 1500 seedlings ha^{-1} (Stener *et al.* 2019; Rytter & Stener 2005; Tullus *et al.* 2007). When the purpose of a stand is to produce energy wood then the planting density usually is much higher (>4000 trees ha $^{-1}$) (Liesebach *et al.* 1999). Hybrid aspen is also good for coppicing (Stener *et al.* 2019). When the first plantation has been harvested, the stands usually regenerate from the root suckers (Rytter 2006; Rytter & Rytter 2017; Stener *et al.* 2019). Hybrid aspen can produce 50,000 - 100,000 suckers ha^{-1} after cutting the first generation (Rytter 2006; Rytter & Carthy 2016), meaning that the second rotation stands usually start off with very high densities (Rytter & Rytter 2017; Stener *et al.* 2019). When properly managed, stands from root suckers can become the first generation plantations, either for energy production or as large sized trees, as well as a combination of the two (Stener *et al.* 2019). According to Tullus et al. 2010, stands originated from root suckers usually have a higher yield compared to the first rotation stands. One major problem in growing hybrid aspen can be browsing by large herbivores, therefore it is recommended to fence the area to avoid damages (Rytter 2006; Rytter *et al.* 2011).

1.4. Breeding of silver birch and hybrid aspen in Sweden

In Sweden and Finland, the first initiatives for breeding and plus tree selection of silver birch were made in 1940´s (Johnsson 1974; Viherä-Aarnio 1994). In Finland, first crossing and progeny testing for quality started in 1960´s. (Raulo & Koski 1977; Koski & Rousi 2005; Stener & Jansson 2005). In Sweden, breeding for broadleaves lasted only for a relatively short period of time – 1960 - 1985. After 1985, the breeding was primarily focused on Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestis*). The breeding of silver birch restarted in 1988 with the purpose to improve regeneration material (Stener & Jansson 2005). Owing to the recent efforts, breeding has made significant improvements in both yield and stem quality of silver birch (Hagqvist & Hahl 1998). Breeding programs used to be based on testing plus trees. Nowadays there are new and more precise DNA and genomic selection tools that make the process of silver birch breeding faster. Although, the application of genomic selection is not so common yet due to the low interest in silver birch (Liziniewicz *et al.* unpublished).

The breeding of hybrid aspen was initiated in 1985, when the first plus trees were phenotypically selected from existing experimental sites and stands within a project led by the Forestry Research Institute of Sweden (Skogforsk). The origin of the plus trees selected during the campaign of 1980´s were apart of crossings done during 1940´s and 1950´s. The material of 280 plus trees was planted on 14 sites in the period of 1986 - 1991 (Stener & Karlsson 2004). Based on the results of vitality, yield and quality (stem straightness), genetically best performing clones were selected (Stener & Karlsson 2004). Genetic breeding and selection have shown a great effect on the productivity of hybrid aspen over time. The productivity has improved from around 16 m^3 ha^{-1} yr^{-1} during 1940´s – 1950´s and 20 m^3 ha^{-1} yr^{-1} during 1980´s to 25 m^3 ha^{-1} yr^{-1} and more during a 20 – 30 year rotation during 2000´s – nowadays (Tullus *et al.* 2012).

1.5. Wood products market of silver birch and hybrid aspen in Sweden

On a global scale, Sweden has one of the biggest forest industries in the world. According to data from Swedish Forest Industries, Sweden is the world´s third largest exporter of pulp, paper and sawn timber (Swedish Forest Industries) Unsurprisingly, the largest contribution comes from the two species currently dominating Swedish forests - Norway spruce and Scots pine.

As mentioned earlier, when it comes to growing stock, birch is the third most abundant species in Sweden, however, the only end product of value of birch in the wood products market is pulpwood, with an approximate price of ca 300 SEK per m^3fub (solid volume excluding bark) (Sveriges officiella statistik). The market for timber or high-quality birch veneer is currently underdeveloped, but the rapid progress in breeding and promising results from the latest research activities (Liziniewicz et al. unpublished) might result in potential future changes in the market.

Hybrid aspen compared to birch, is not as extensively found and constitutes less than 2 % of the total growing stock in Sweden. In the past, the value of Hybrid aspen was associated with match industry as it was mainly used for match production (Johansson 2013a). Nowadays, the use of hybrid aspen has expanded as it is being grown for a combined production of sawn timber, pulpwood and raw material for energy purposes. That said, currently, hybrid aspen is considered as one of the most valuable sources for green energy production (National Commission for Fast-Growing Deciduous Trees)

1.6. Growth models in Baltic sea region and Fennoscandia

Models are tools that are constructed to assist in describing the complex process of growth of trees in the forest. Forests vary and growth of the tree depends on many growth influencing factors. Therefore, also growth models differ, e.g in terms of data used and construction method (Burkhart & Tome, 2012). First classification of forest growth models was presented by Munro (1974) where two primar types of models were recognized e.g. single tree and whole stand. Forest growth models have been developed continuously for even- and uneven-aged stands (Curtis 1981).

There are different older and more recent growth models developed in Baltic sea region and Fennoscandia which can be used to model growth and development of birch. Growth and yield research of silver birch in the Nordic countries has been very active hence, there have been developed several growth and yield tables and statistical growth and yield models for silver birch (Hynynen *et al.* 2010). For instance, In Norway, a stand level growth model for young mixtures of spruce and birch has been developed (Gobakken & Naesset 2002) and height–diameter relationship of Downy birch has been modelled (Sharma & Beidenbach 2015). In Sweden, a model predicting the risk of snow and wind damage for birch stands has been developed (Valinger and Fridman, 1999); growth model showing the effect of mixture of Norway spruce and birch on total production (Fahlvik *et al.* 2005), etc.

Hybrid aspen is a less common species (not as extensively planted), as well as it has younger history, which could be some of the reasons why the progress in growth modelling of hybrid aspen has not gone as far compared to birch. However, there are a several models developed in Fennoscandia e.g. site dependent dominant height growth model for hybrid aspen in Sweden (Johansson 2013b) and stand density dependent SI model for hybrid aspen in southern Finland (Lee et al. 2021); model developed in Sweden, describing MAI development (Rytter & Stener 2014) that can be used in hybrid aspen stands to estimate the growing stock; individual stem volume model for hybrid aspen cultivated on agricultural land in Sweden (Johansson 2014).

Modelling of stand development over time is a complex process as it usually consists of a set of models that model different variables of a stand, which is why, combined mathematical programming, i.e. using comprehensive and sophisticated decision support systems consisting of state-of-the-art growth models have to gain more interest and application. For instance, in Sweden, using Heureka Forestry Decision Support System, it is possible to perform stand, forest and regional analysis and planning. In the Heureka system the growth models concern two stand growth key stages, e.g. establishment period of the stand and the development of it, therefore, for different purposes various growth models are in use (Wikström *et al.* 2011). However, due to the lack of extensive and applicable models for birch and hybrid aspen in Sweden, it is not possible to use Heureka, to model the development of full rotation projections.

1.7. Aims of the thesis

The main objective of the thesis was to evaluate the early growth of silver birch and hybrid aspen depending on the management done so far. Also, to assess the growth and economy of full rotation birch stands in southern Sweden using a standard management regime. To be able to achieve all of the above results, three main aims were developed:

1. Compare the early growth of both species over a gradient of site conditions
2. Test the effect of fertilization on early growth of the two species
3. Simulate the development of full rotation projections of silver birch stands and evaluate their growth as well as economic potential

2. Methods

2.1. Study area – Tree species experiments

The main purpose behind the establishment of the “new” tree species experiments (also known as the Övergaards series) across Sweden has been to study and compare the long-term production of the different tree species, e.g. Norway spruce, Scots pine, poplar, silver birch, and hybrid aspen. The history of tree species experiments goes back to when the first tree species experiments were established between 1957 – 1994, whereas the experiments of the Övergaards series have been established between 2012 – 2014 (Böhlenius *et al.* 2016). Same as the “old” series, experiments of the Övergaards series have been established all across Sweden, however, only four of the sites located in southern Sweden will be included in this thesis, primarily because silver birch has been planted only in experimental sites located in southern Sweden, but also, these four sites were considered as the maximum due to limited time and time-consuming data collection stage.

The experimental sites were spread out across the southern Sweden in a certain soil fertility gradient – to include the variation in growth conditions and study in the potential effect of it on growth and production of different tree species. All experimental sites had undergone a soil preparation. In addition to the above mentioned, the effect of fertilization has also been tested in all experimental sites.

Experiment sites considered in this thesis were – Påarp, Sävsjöström, Tagel and Tönnerjöheden (Fig. 1).

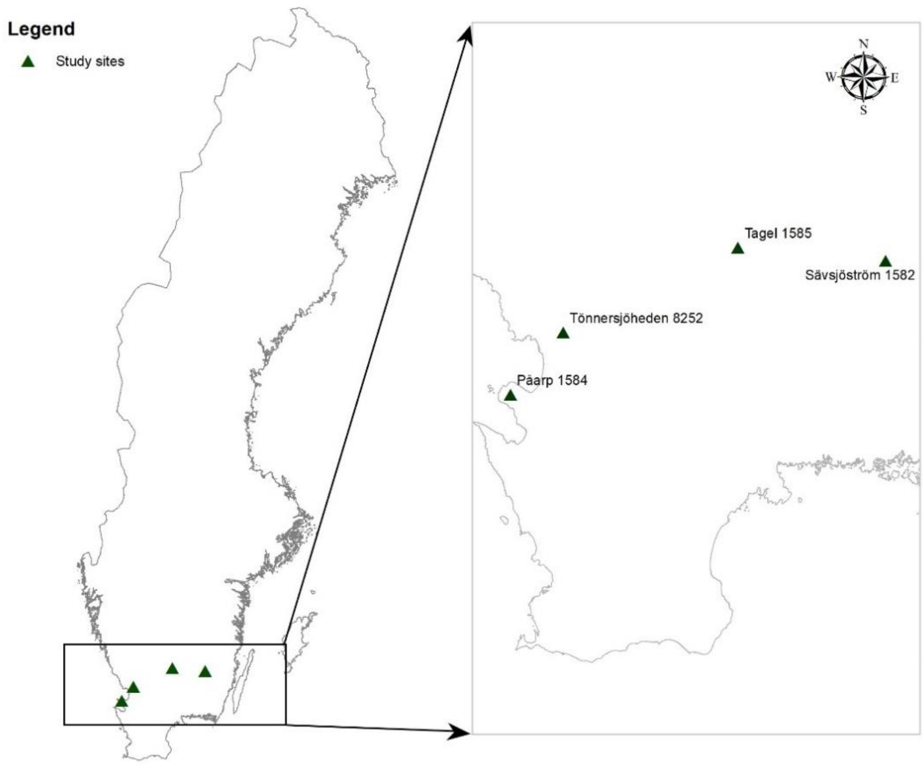

Figure 1. Location of the experimental sites

Sävsjöström, Tagel and Tönnerjöheden were established on forest land, while the experimental site in Påarp is the only one established on former agricultural land. Annual average temperature of experimental sites varies between 7 – 9 °C, while precipitation varies between 400 – 1000 mm y^{-1}. More detailed climate data, soil characteristics as well as geographical location of the experimental sites can be found in Table 1.

Table 1. Description of the study sites

Experimental site	Påarp	Sävsjöström	Tagel	Tönnersjöheden
Latitude	56.41743574	56.98469779	57.03901125	56.67887517
Longitude	12.71309706	15.48323955	14.37950442	13.08762832
SI	G36+	T22	T26	G32
Planting y/m	2013-06	2012-05	2013-06	2012-05
Planting material	SB - Ekebo 4, HA - 884012, 884015, 894012	SB - Ekebo 4, HA - 884012, 884015, 894012	SB - Ekebo 4, HA - 884012, 884015, 894012	SB - Ekebo 4, HA - 884012, 884015, 894012
Fertilization (summer)	2013, 2015, 2017	2012, 2014, 2016, 2018, 2020	2013, 2015, 2017, 2019	2012, 2014, 2016, 2018, 2020
Annual average temperature (°C)	9-10	7-8	7-8	9-10
Annual precipitation (mm/y)	600-800	400-600	800-1000	800-1000
Altitude (m)	82	225	210	95

Annual average temperature (SMHI 2020a); Annual precipitation (SMHI 2020b); Altitude (Free map tools 2021)

2.2. Experimental design

All experimental sites were divided into 4 blocks where each block consists of 8 plots (Fig. 2).

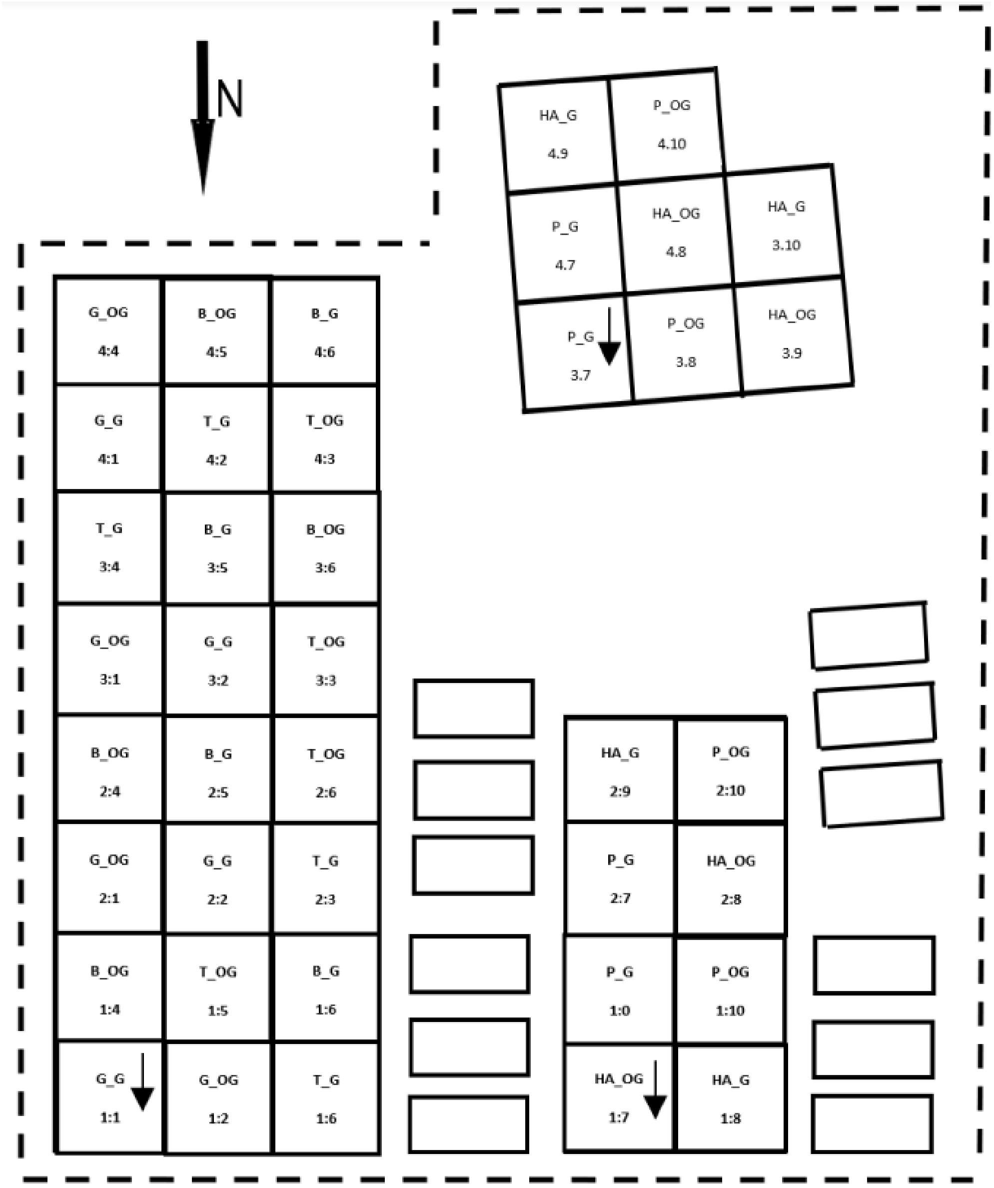

Figure 2. Experimental design in Sävsjöström. OG – unfertilized, G – fertilized, B – silver birch, HA – Hybrid aspen, G – Norway spruce, T – Scots pine, P - poplar

Plots has been assigned randomly, simultaneously considering the combination of tree species and fertilization. Seedlings has been planted in rows where soil preparation is done in every second row with the soil preparation method dependent of the site, i.e. rows with 11 seedlings were planted in a prepared soil, while the rows with 5 rows seedlings were established in unprepared soil (Fig .3)

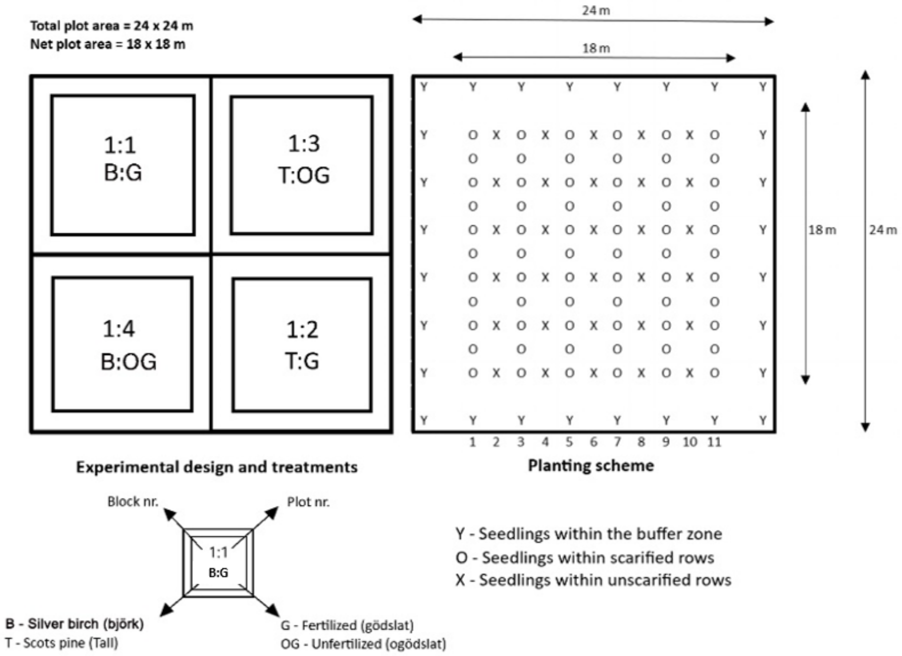

Figure 3. Example of an experimental design (plot level). Example for Scots pine and Silver birch.

The seedlings planted in rows with prepared soil were considered as the potential future crop trees, with seedlings planted in unprepared soil serving as reserve, in case of mortality, low quality of an initial crop tree. After PCT the plots consisted trees from both rows e.g. prepared and unprepared soil. All plots were surrounded with a 6 m buffer zone, consisting of with 28 seedlings. The total number of the planted seedlings per plot was 124, including the buffer zone, whereas all net plots initially consisted of 96 planted seedlings. Following planting, fertilization (SkogCan N27) was carried out immediately by spreading 75 kg N ha^{-1}. Thereafter, the fertilization was repeated according of the following scheme (1:a, 2:a, 3:e, 4:e) (Böhlenius *et al.* 2016).

Sixteen square plots of size 24x24 m were measured in every experiment site in which 8 were of silver birch and 8 were of hybrid aspen. For each species, half of the plots were fertilized. All fours sites were planted with same planting material ordered from the same suppliers, i.e. silver birch seedlings were bought from Södra (planting material "Ekebo 4"), whereas hybrid aspen seedlings were delivered by Sydplantor (planting material "884012, 884015, 894012") (Böhlenius *et al.* 2016). All experimental sites were surrounded by fence.

2.3. Data collection

The field measurements were done according to the field data system (Karlsson *et al.* 2012). Data was collected during a period of three weeks, lasting from the end of October till beginning of November 2020. Data in Påarp had been measured 2017.

In the experimental plots, diameter at breast height (DBH) of all trees was measured using a caliper. All trees were cross-calipering according to S - E directions. Heights of the sample trees was measured using the VL5 Vertex Laser hypsometer. All the data was recorded with the field computer.

Sample trees were selected using the algorithm built into the field data system, i.e. the sample trees were automatically determined by the field computer, after all diameters at breast height were inserted. In this algorithm tree height, height of first living branch and bark thickness at chest height were considered. Last too parameters were taken into account only for calculation of sample trees for silver birch. (Böhlenius *et al.* 2016). In addition to the primary data collection (heights and diameters) other notes and measurements on vitality, damages, etc., were registered in each sample plot, but this data will not be considered in this thesis.

2.4. Estimation of height of all calipered trees

As the heights were measured only for the sample trees, it was needed to calculate heights for the all the trees that had DBH registered. Height of all trees was calculated plot-wise in each stand using the height-diameter model (Eq. 1), which was developed by Näslund (1936). The calculation was based on the existing data of trees that had their height and diameter registered. The same initial function was used for both hybrid aspen and silver birch:

$$H = \frac{DBH^2}{(a + b * DBH)^2} + 1.3, \qquad (1)$$

The height-diameter model contains: H - hight of the tree (m), DBH – diameter at the breast height (cm), a and b – model coefficients.

2.5. Effect of fertilization

Statistical analyses were done to test the effect of fertilization on height, DBH as well as volume. A linear mixed effects model consisting of response variable and a set of predictors was constructed and run for each species separately. Three different models were run using height, diameter and volume as response variables. The predictor variables were constructed to describe both fixed and random effects of the model (Eq. 6)

$$y_{ijk} = \mu + b_i + c_j + \ \alpha_k + \varepsilon_k \tag{6}$$

where y_{ijk} is the response variable (height, DBH and volume), μ = mean value, b_i = fixed effect of fertilization, c_j = random effect of site, a_k= random effect of block nested to site and y_{ijk} = random error term for observation ijk.
The model was constructed and tested using R (R core Team 2019), lmerTest package (Kuznetsova *et al.* 2017). Model assumption (normal distribution) was tested using Shapiro-Wilk test (Shapiro & Wilk 1965).

2.6. Estimation of basal area and volume

Basal area (BA) of a tree is the cross-sectional area at breast height measured over the bark and recorded typically in square meters ha^{-1} (Edwards 1998). BA was calculated by using sample plots method (Eq. 2) which means that BA of all trees was calculated from its diameter at breast height.

$$BA = \frac{\pi \times DBH^2}{10\ 000}, \tag{2}$$

where BA – basal area in m^2, DBH – diameter at breast height in cm.

Volume function (Eq. 3) by Brandel 1994 was applied to calculate volume of each tree.

$$V = 10^a \times DBH^b \times (DBH + 20{,}0)^C \times H^d \times (H - 1{,}3)^e, \tag{3}$$

where coeficents a (-0.89363), b (2.23818), c (-1.06930), d (6.02015), e (-4.51472), DBH – diameter at breast height in cm, H – height of a tree.

2.7. Simulations of further stand development

The simulation of further stand development was applied only for silver birch. Different functions were applied to obtain the results e.g. basal area development, volume development and economy of the stands. The simulations were carried out using R (R core Team 2019).

2.6.1. Basal area development function for silver birch

In order to perform full rotation projections, three different functions were used. First function was a site index function where site index was calculated based on top height of the 100 thickest trees ha^{-1}, subtracted by the time trees reached height at breast height (Fig.4). Then the second function – a stand basal area starting function was used to estimate the starting basal area of a stand ha^{-1}. Subsequently, using the estimated starting values (Table 2), a basal area development function was used to estimate basal area over the whole rotation period. Finally, a fourth function that estimates volume was applied (Fig. 4) (Liziniewicz *et al.* unpublished).

Table 2. Stand initial data

Variable	**Treatment**	**Stems**	**Mean basal area**	**QMD**	**Mean height**	**Age**	**Volume**
Unit	F/UF	trees ha^{-1}	m^{2}ha^{-1}	cm	m	yrs	m^3 ha^{-1}
Experimental site	**Hybrid aspen**						
Påarp	F	1216	2.3	4.6	6	8	8.6
	UF	1216	1.9	4	5.8	8	6.7
Sävsjöström	F	1217	4.9	6.7	6.9	11	18.4
	UF	1217	3.1	5.3	6.3	11	11.8
Tagel	F	1217	6.7	7.8	8.3	10	27.6
	UF	1217	4	6.1	7.2	10	15.6
Tönnersjöheden	F	1217	8.9	8.9	9.1	11	37.8
	UF	1217	7.3	8.2	8.9	11	31.3
Experimental site	**Silver birch**						
Påarp	F	1216	4.3	6.2	6.8	8	15.3
	UF	1216	3	5.2	6	8	10.4
Sävsjöström	F	1217	5.1	6.8	6.8	11	18.2
	UF	1217	4.9	6.6	6.6	11	17.4
Tagel	F	1217	4.5	6.4	6.9	10	16.3
	UF	1217	2.7	5	6.1	10	9.5
Tönnersjöheden	F	1217	6.1	7.5	7.8	11	23.5
	UF	1217	5.6	7.2	7.8	11	21.8

Overall approach of following functions was to forecast the stand development of the silver birch stands considered in this study. The first model calculates site index of birch at the base age of 50 years by using following parameters e.g. asi (7), beta (394) and b2 (-1.387). Second model predicts starting values of stand basal area by using estimated parameters e.g. β_0 (- 7.3193), β_1 (0.2138), β_2 (0.0643) and β_3 (0.1555) (Liziniewicz *et al.* unpublished). Third model was basal area projection function which is dynamic equation derived from the base model of Korf (1939) which was the best model for describing basal area development of the silver birch stand, according to Liziniewicz *et al.* unpublished. Estimated parameters which were applied in basal area projection function were b_1 (91.3397) and b_3 (0.7054). The fourth model was used to estimate total volume production by calculating stand form height which is a ratio between basal area production and total volume. a_1 (0.4286), a_2 (0.0085) and intercept (-0.4044) were the estimated parameters for the model converting basal area into volume (Liziniewicz *et al.* unpublished). All four models are visualized in Figure 4 and parameters used in the models are visualized in Table 3.

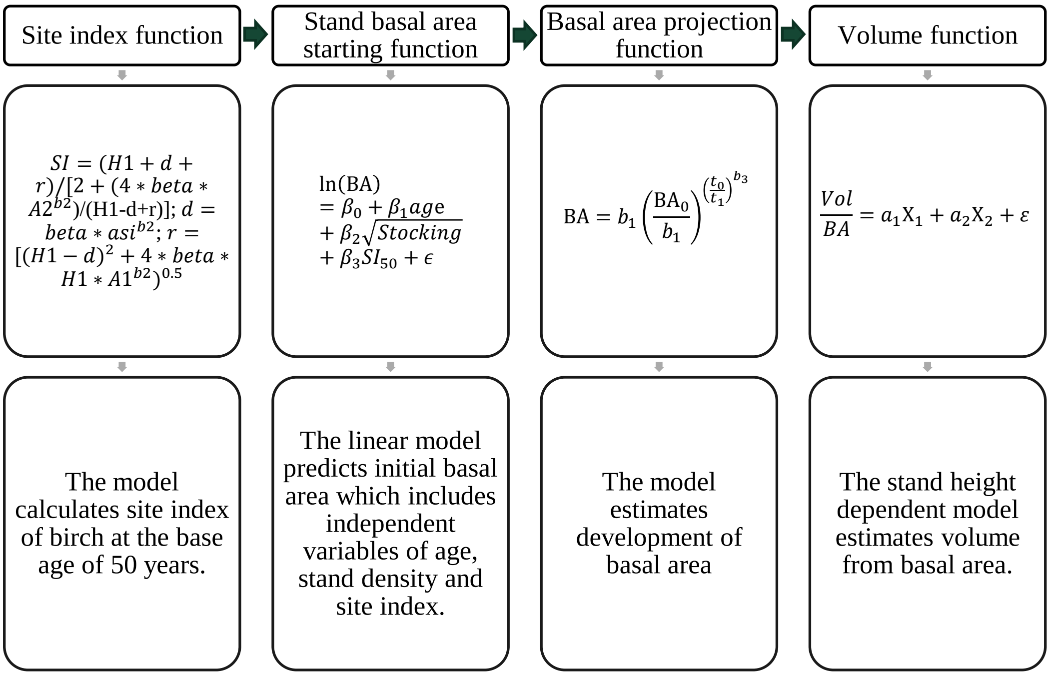

Figure 4. Schematic diagram of simulation of full rotation projections of birch stands

Management which was chosen for the development function contained PCT at age 10 and two thinnings at age 20 and 25. PCT was applied due to the model structure where the number of the trees has to be at least 2000 ha^{-1}. While the PCT has been done in all experimental sites before the measurements then stands had less than 2000 trees ha^{-1}. In order for the model function properly, one PCT was simulated to get as close as possible to the measured stand values, reducing the stem number around 1200 trees ha^{-1} for each site.

Table 3. Table of parameters

	Parameter	Value		Parameter	Value
1. Site index function	asi	7	**3. Basal area projection function**	b_1	91.3397
	beta	394		b_3	0.7054
	b2	-1.387		BA_0	ln (BA)
	H1	Starting height		t_0	Stand age
	A1	Starting age		t_1	Simulation time
	A2	Base age 50			
2. Stand basal area starting function	β_0	-7.3193	**4. Volume function**	a_1	0.4286
	β_1	0.2138		a_2	0.0085
	β_2	0.0643		X_1	Top height
	β_3	0.1555		X_2	Age of the trees
	Stocking	Trees per hectare		Intercept	-0.4044
	Age	Stand age		ϵ	Random error
	SI_{50}	Mean height of the 100 thickest trees per hectare at 50 years			
	ϵ	Random error			

2.6.2. Economic analysis of full rotation stand projection

Mean annual increment was estimated based on the respective site indices which were derived from the development of the untinned stands where the initial planting density was at least 2000 trees ha^{-1}. Land expectation value (LEV) was estimated using a 2.5% discount rate which is often the assumed discount rate in Sweden. Two commercial thinnings which were applied had removal of 30% of BA (Liziniewicz *et al.* unpublished). To calculate LEV, net present value (NPV) was calculated (Eq. 4; 5).

$$NPV = \sum_{t=0}^{n} \left(\frac{R_t}{(1+i)^t}\right); \tag{4}$$

$$LEV = NPV \times \frac{(1+i)^U}{(1+i)^U - 1}; \quad (5)$$

Where Rt – net cash inflow-outflow during a single period t, i – discount rate, n – number of time periods, u – rotation age.

3. Results

3.1. Effect of fertilization

The assumption of normal distribution for the model constructed in this study was tested using a Shapiro-Wilk test, but a high p-value ($P > .049$) indicated that the model assumption is not violated and thus can be used in further analysis.

Statistical analysis showed that effect of fertilization was significant for both species regardless of the response variable tested. The significance Pr (>F) values as well as other model output values are found in Table 4.

Table 4. Model output values and pairwise comparisons between fertilized and unfertilized Silver birch and Hybrid aspen.

Response variable	Species	α	lsmean	Group of means	SE	P-value
Volume	SB	0.05	18.3 (fertilized) 14.8 (unfertilized)	a b	2.39	$P < .049$
Mean height	SB	0.05	7.06 (fertilized) 6.67 (unfertilized)	a b	0.33	$P < .049$
Mean DBH	SB	0.05	6.67 (fertilized) 5.92 (unfertilized)	a b	0.398	$P < .049$
Volume	HA	0.05	23.0 (fertilized) 16.3 (unfertilized)	a b	5.82	$P < .049$
Mean height	HA	0.05	7.58 (fertilized) 7.04 (unfertilized)	a b	0.692	$P < .049$
Mean DBH	HA	0.05	6.81 (fertilized) 5.69 (unfertilized)	a b	0.899	$P < .049$

Note: SB is Silver birch; HA is Hybrid aspen; α is significance level used. Different letters mean significant differences between treatments using a pairwise comparison of least square means.

As it can be seen in Table 4, fertilized blocks had significantly higher volume, DBH as well as mean height for both species compared to unfertilized blocks. However, the analysis also revealed substantial variation in terms of effect of fertilization between the sites. For better visualization, pairwise comparisons of the tested response variables are also depicted in Figure 5.

3.2. Mean height

Mean height of both species showed slightly greater growth rates on fertilized plots than on unfertilized ones. Mean height of hybrid aspen was evidently affected more by soil fertility as it performed considerably better on more fertile soils than silver birch hence hybrid aspen had better mean height in Tagel and Tönnerjöheden. Silver birch, on the other hand outperformed hybrid aspen on former agricultural land (Påarp), i.e. it showed better growth in terms of mean height than hybrid aspen both in fertilized and unfertilized plots. Hybrid aspen and silver birch had a rather similar mean height in Sävsjöström, where the soil is poorer compared to the other 3 experimental sites. Mean height in forest land in fertilized plots varied between 6.9 m to 9.1 m and 6.8 m to 7.8 m for hybrid aspen and silver birch respectively, whereas on unfertilized plots the height varied between 6.3 m to 8.9 m for hybrid aspen and 6.1 m to 7.8 m for silver birch (Fig. 6). The best performance in terms of mean height of hybrid aspen (12.3 m) and silver birch (9.3 m) was reached in Tönnerjöheden. In 2017, maximum height of silver birch in Påarp was also 9.3 m.

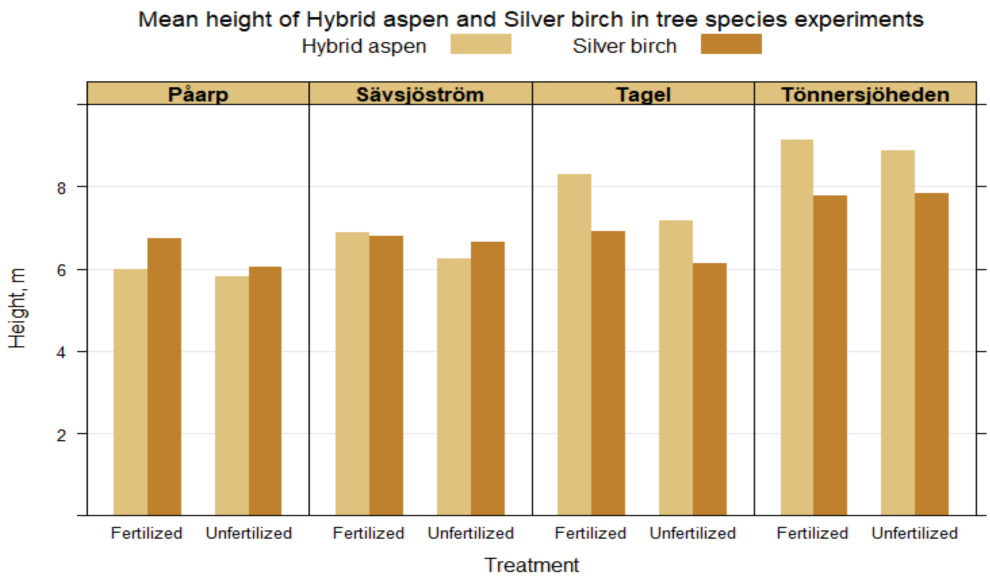

Figure 5. Mean height growth of hybrid aspen and silver birch in tree species experiments. Data from Påarp was measured 2017, other three experiments 2020.

3.3. Diameter distribution

As it can be seen in Fig. 7, diameter growth of both species was affected by fertilization, i.e. fertilized plots resulted in bigger proportion of trees with larger diameters (DBH). Diameter distribution of silver birch was more uniform compared to hybrid aspen, which showed greater stem variance (Fig. 7).

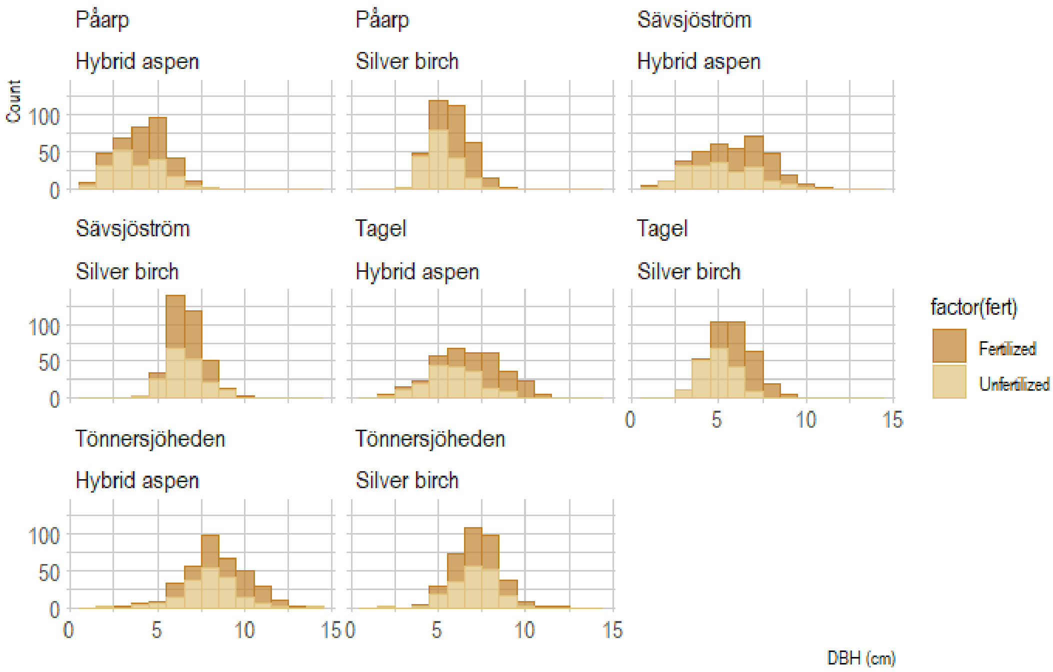

Figure 6. Diameter distribution of hybrid aspen and silver birch in tree species experiments

Quadratic mean diameter (QMD) at breast height showed that Hybrid aspen was more affected by fertilization than silver birch in all sites. Fertilization of silver birch showed positive effect in Påarp and Tagel but only a minor effect in Sävsjöstöm and Tönnerjöheden. QMD was more uneven in unfertilized sites in Påarp and Sävsjöstöm while in Tagel and Tönnerjöheden it was conversely opposite (Fig. 8).

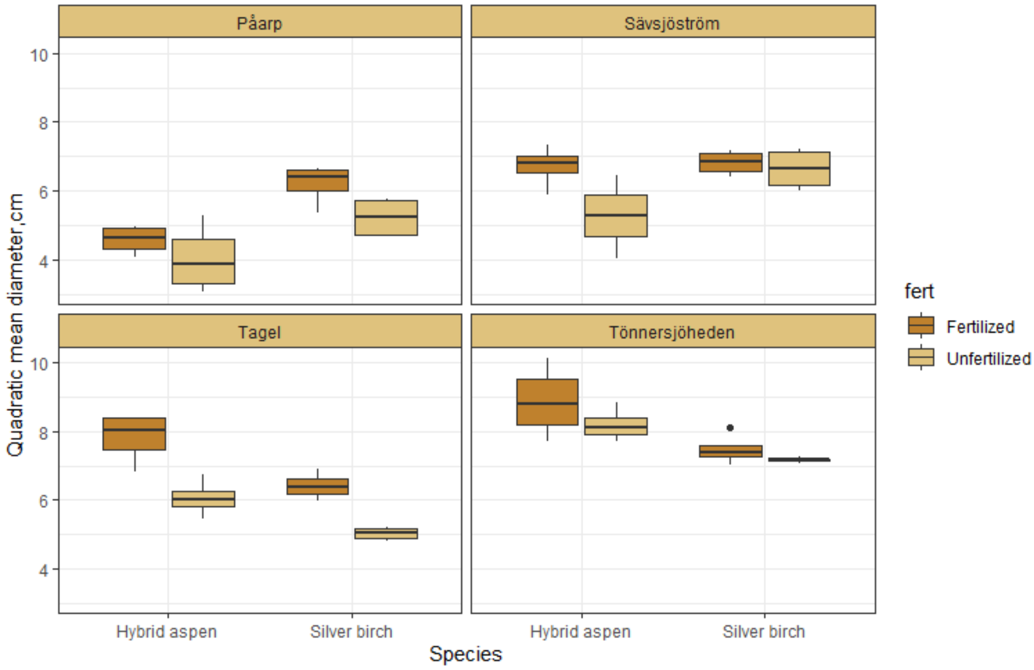

Figure 7. Quadratic mean diameter of hybrid aspen and silver birch in tree species experiments

3.4. Volume

Starting values showed that hybrid aspen has mostly greater volume than silver birch, especially on better soils on forest land and fertilized sites. Unfertilized silver birch stands showed similar or greater volume growth than hybrid aspen. In Påarp which is former agricultural land, silver birch had almost twice as great volume growth at early age than hybrid aspen (Table. 2).

3.5. Stand basal area

Basal area of hybrid aspen in fertilized plots was considerably higher than in unfertilized sites. Fertilization had a lesser effect on silver birch and a larger effect on hybrid aspen. Greatest difference between treatments appeared in Tagel, where basal area of hybrid aspen on fertilized sites was 6.7 $m^2 ha^{-1}$, whereas on unfertilized sites 4.0 m^2ha^{-1}. Basal area of silver birch on fertilized sites was 4.5 $m^2 ha^{-1}$, on unfertilized sites 2.7 m^2ha^{-1}. For hybrid aspen, the smallest difference occurred in Påarp (2.3 m^2ha^{-1} – F, 1.8 m^2ha^{-1} – UF) and for silver birch in Sävsjöstöm (5.1 m^2ha^{-1} – F, 4.9 m^2ha^{-1} – UF) (Fig. 9).

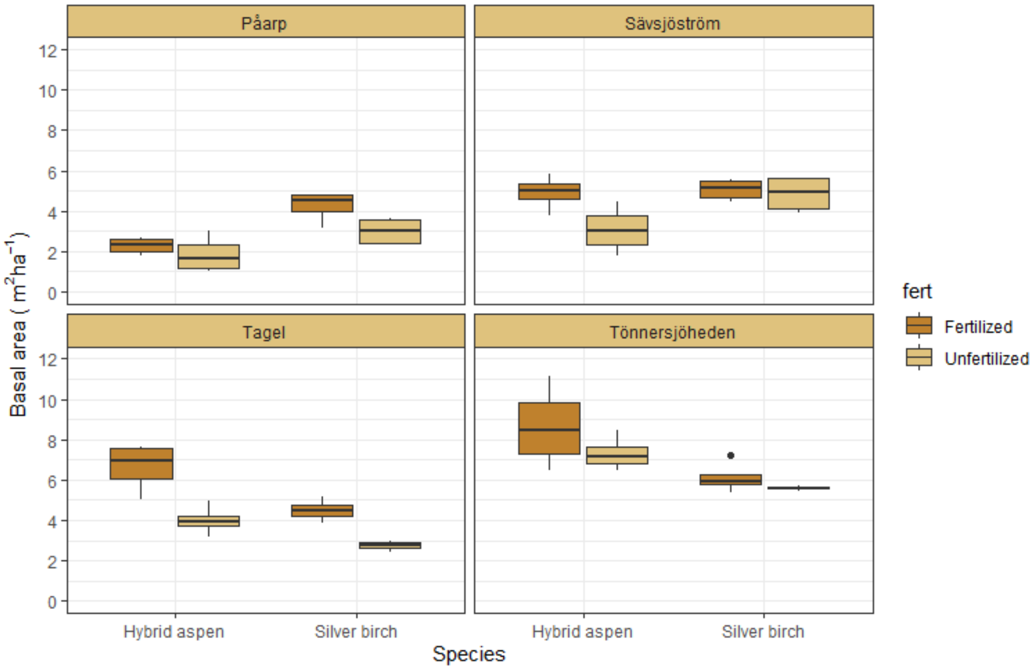

Figure 8. Basal area of hybrid aspen and silver birch in tree species experiments

3.6. Simulations of full rotation projections

Economic analysis based on volume development showed that highest mean annual increment (13.2 m^3 ha^{-1} $year^{-1}$) and highest maximum land expectation value (48463.7 SEK (pulpwood) and 95023.0 SEK (timber)) appeared in Påarp, wherein the optimal rotation age arrived in 34 years for pulpwood production and 36 years for timber production. While the least productive area was Sävsjöström where the optimal rotation length was 40 years hence maximum mean annual increment (9.2 m^3 ha^{-1} $years^{-1}$) and maximum land expectation value (21942.6 SEK (pulpwood) and 52861.6 SEK (timber)) were lowest between all sites. Tönnerjöheden and Tagel showed more close results to Sävsjöström as all these three experimental sites are growing on forest land (Table. 5). Volume from final felling of silver birch during the full rotation was highest in Påarp (290.2 m^3ha^{-1} (pulpwood) and 312.0 m^3ha^{-1} (timber)) and smallest in Sävsjöström (265.2 m^3ha^{-1}). As the optimal rotation length in Sävsjöström was same for pulpwood and timber then the volume from final felling was also equal (Table. 5).

Table 5. Simulation results

	Site	**Påarp**	**Sävsjöström**	**Tagel**	**Tönnerjöheden**
Variable	Unit				
Trees	trees ha^{-1}	1216	1217	1217	1217
Site index		33.4	27.6	28.8	29.5
Optimal rotation length (pulpwood) p*	yrs	34	40	38	39
Optimal rotation length (timber) t*	yrs	36	40	40	39
Volume (thinnings)	m^3ha^{-1}	109.5	62.5	71.8	76.6
Volume (final felling)	m^3ha^{-1}	290.2 (p) 312.0 (t)	265.2	268.8 (p) 285.8 (t)	287.5
LEV_{max} (p)	SEK	48463.7	21942.6	27278.6	30038.4
LEV_{max} (t)	SEK	95023.0	52861.6	61525.0	66106.0
MAI_{max}	m^3 ha^{-1} yrs^{-1}	13.3	9.2	10.1	10.5

4. Discussion

4.1. Effect of fertilization

The linear mixed effects model used in this study revealed that fertilization has an effect on mean height, mean DBH and quite reasonable also on volume production for both silver birch and hybrid aspen. The linear mixed effects model was constructed using random effect of block nested to site as this his would give more observations in the model and possibly a greater chance of detecting a treatment difference compared to if we ran a model for each site separately. However, the downside is that the model became weaker since there were substantial differences between sites; however, no violations of model assumptions were detected.

4.2. Early growth of silver birch and hybrid aspen

Height growth of trees on forest lands depends highly on soil fertility, especially for hybrid aspen. When the soil is fertile, hybrid aspen shows greater height growth than silver birch, however on poorer sites the height growth is similar. Thereby, silver birch, which is a native broadleaved tree species in the Nordic countries, is less dependent on soil quality. Simultaneously non-native hybrid aspen requires special treatment (ie. Fertilization) to achieve optimal height growth. It is important to bear in mind that the material of silver birch was genetically improved and therefore naturally regenerated or unimproved material could have different results.

Diameter development of hybrid aspen varies more than the diameter development of silver birch on all sites considered in this study. It could be caused by different planting material, which varies between three different clones planted randomly on the sites. Planting material of silver birch was singular Ekebo 4. It is also possible that diameter development was affected by fertilization.

Basal area development of hybrid aspen tended to be highly dependent on fertilization. As it is one of the most nitrogen demanding tree species (Stanturf *et al.* 2001), the soil nutrient requirements of hybrid aspen are quite high which explains why it grows especially well on former agricultural lands (Wall & Heiskanen 2003; Wall & Hytönen 2005). While silver birch is a nitrogen-limited tree species (Keinänen *et al.* 1999) fertilization could also have great effect on silver birch growth, it showed minor impact on basal area development. Nonetheless, fertilization had a positive growth effect on both species. Based on silver birch studies in Finland, Hynynen & Niemistö (2009) state that due to weak growth response, fertilization of silver birch is not a profitable silvicultural action. Although, Nilsson *et al.* (2021) recommends the fertilization of juvenile silver birch stands for increasing the growth rate, as the reduction of wood density was relatively small.

Certainly, management activities affect previously mentioned parameters. Based on Zālītis & Zālītis (2007), early (at the mean stand height 3 m $<H_0 < 12$ m) PCT has great effect on the diameter growth of birch stands when the stand density remains 1500 - 2000 trees ha^{-1}. A heavy PCT was applied also on experimental study sites in this study where the stand density remained ca. 1200 trees ha^{-1}. Similarly to what Zālītis & Zālītis (2007) reported, Simard *et al.* (2003) stated that mean diameter growth was significantly higher, when the birch stand was thinned. In addition to this, based on Simard *et al.* (2003), the increment of basal area and increment of volume was also significant when the thinnings were applied, however, mean height, height increment and top height were unaffected.

4.3. Simulations of full rotation stands of silver birch

Simulations of full rotation stands of silver birch showed that optimal rotation length varies up to 6 years between stands on forest land and former agricultural land. Lower optimal felling ages allows us to maximize production (MAI) and achieve better economy over continuous rotations.

Management regime which was chosen to include two thinnings with 30% of basal area removal gives plenty of light for the remaining trees to improve the growth and avoid damages. With birch, a pioneer of broadleaved species, it is recommended to take into account early stand development which means that thinning in early stage is needed to improve diameter growth, especially on fertile sites. Delayed thinning can cause slow diameter growth which increases the risk of wind and snow damages. The aforementioned damages are common in dense birch stands in southern Sweden (Rytter & Werner 2017).

The applied model to simulate full rotation provided useful estimates of full stand basal area development but it did not take into account mortality. This means that the MAI was the same irrespective of different thinning scenarios (Liziniewicz et al. unpublished). In addition, the model required a stand density of at least 2000 trees ha-1 while in the experimental sites studied in this thesis the density was less than 2000 trees ha^{-1}. To use the simulation imaginary PCT was applied in the model.

4.3.1. Economy of full rotation stand projections

Full rotation of stands depends highly on the origin of seedlings, silvicultural practices and site conditions. Seedlings on experimental sites studied in this thesis were genetically improved which has great effect on different factors e.g. quality, growth and mortality (Liziniewicz *et al.* unpublished). Genetically improved seedlings can increase land expectation value, hence shorter rotation length of stands (Jansson *et al.* 2017). For selection of the most productive genotypes breeding programs are applied. Study made in Latvia showed that planting material from breeding programs is much more costly than natural regeneration which causes high establishment costs of planting when the material originates from a breeding programs (Gailis *et al.* 2020). However, the results of a study by Gailis *et al.* (2020) showed that the internal rate of return (IRR) was remarkably higher when silver birch seedlings were selected from the best-performing families. According to Gailis *et al.* (2020), IRR in case of high timber price for the best-performing families was 9.4 %. For all families it was 8.1% and in case of low timber prices the IRRs were 8.3 % and 6.7 %, respectively. Which means that the difference between best-performing families and all families were correspondingly 13.8 % (high timber prices) and 19.3 % (low timber prices). However, silver birch can also successfully regenerate naturally, and genetically improved material is not always available for the forest owners. According to Rytter & Werner (2007), well-timed and thorough silvicultural activities in naturally regenerated silver birch can improve the growth and result in good quality stands.

Fertilization was applied in all four experimental sites. Up to now the frequency of fertilization was done every second year (Böhlenius *et al.* 2016). The frequency of fertilization affects the growth of trees, but it is not decided if the frequency stays the same (every second year) or is reduced to every 5 years, when the stand reaches a height of 10 meters. Hybrid aspen is more dependent on fertilization while silver birch can have quite good growth without the use of fertilizer. Considering the above said, fertilization was not included in the simulations since there is no knowledge of how it may affect the stand development in the future. Last but not least, soil fertility showed great effect on both tree species, indicated by greater growth in the experimental site located on former agricultural land.

Based on Dahlberg *et al.* (2006), managed silver birch stand MAI varies between 6 and 9.3 m^3 ha^{-1}, even ca. 10 m^3 ha^{-1} when the rotation length is between 30 and 60 years. MAI in unmanaged stands varies between 4 and 6.75 m^3 ha^{-1}. In this study where genetically improved silver birch material was in use, MAI varied between 9.2 m^3 ha^{-1} and 10.5 m^3 ha^{-1} on forest land and 13.3 m^3 ha^{-1} on former agricultural land. These results support the research of Liziniewicz *et al.* (unpublished) where simulation of further stand development of silver birch showed better growth when the plant material had a higher genetic improvement level. The results of LEV connect with MAI, hence the biggest LEV appeared also in former agricultural land and optimal rotation age arrived earlier. To compare LEV based on assortment, LEV for timber was more than 50 % higher than for pulpwood in all experimental sites.

Damages and insufficient management cause a loss of timber quality (Hynynen *et al.* 2010) which influences the economical outcome. Measurements and analysis used in the current thesis did not take into consideration the damages and quality of trees. Selected management regime influences the economy and conditions in forest change after different silvicultural actions. Two thinnings were applied in full rotation simulation with 30 % of removal. First thinning was inserted in a 20 year old stand and the second one 5 years later. Rytter & Werner (2007) stress that it is important to not delay with early silvicultural processes in silver birch stands because it affects the growth of the future stand. As silver birch is a light demanding tree species and crown competition influences growth, early and high intensity thinning is recommended (Cameron *et al.* 1995; Niemistö 1995a, 1995b; Rytter & Werner 2007).

4.4. Future management considerations

Fast growing tree species like silver birch and hybrid aspen could be an alternative to Norway spruce and Scots pine which are two of the most planted tree species in Sweden and the Baltic sea region. Silver birch is commonly regenerated on forest land while hybrid aspen is planted mostly on former agricultural land, therefore most of the studies are also based on these sites and only a few studies are made of hybrid aspen growing on forest land (Hjelm & Rytter 2018).

To maximize economical outcomes in the future, it is suggested to use birch seedlings with higher genetic improvement level (Liziniewicz *et al.* unpublished). Although establishment cost is higher when the planting material is selected from best-performing families, the IRR is also greater (Gailis *et al.* 2020). Current studies showed that MAI of genetically improved birch can catch up with spruce which makes it a potential alternative tree species to spruce. The origin of the seedling is important for growth and fertilization aspects. It is not decided what the frequency of fertilization in experimental sites will be in the study but if it continues with two year intervals then the growth might be different at a reduced interval of five years. Fertilization affects the structure of a tree. With fertilization, a tree has wider growth rings and thinner cell wall thickness due to the more rapid growth, which means a lower wood density. Nevertheless, fertilization is still recommended in young birch stands (Nilsson *et al.* 2021).

The study was based on pure silver birch stands. Silver birch grows not only in monocultures but very commonly also in mixtures (Hynynen *et al.* 2010). Valkonen & Valsta (2001) studied a mixture of birch overstory in a young Norway spruce stand. The results showed that an overstory of naturally emerged birch in a spruce stand is more profitable than growing a monoculture of Norway spruce. This presumes that the removal of overstory has to be done with minimal logging damages due to the sensitivity of spruce, otherwise it is economically not profitable.

Hybrid aspen is a highly preferred tree species by ungulates (Edenius & Ericsson 2015) which means high browsing pressure, hence at establishment fencing is recommended (Persson et al. 2015). To protect hybrid aspen against moose browsing fencing is the only option according to Tullus *et al.* (2012). Fencing was also applied on experimental sites. Fence protects damages from ungulates but not from other factors like competitive vegetation, insects and voles. Damages by voles are dependent on the amount of competing vegetation, if it is kept down vole damages could be decreased (Hytönen & Jylhä 2005; DesRochers & Sigouin 2014). Silver birch is usually not the first choice for the browsers but when game is overpopulated, browsing damages can be found in silver birch stands (Dubois *et al.* 2020).

Mortality and resistance of hybrid aspen are highly dependent on genetic material but also on soil treatment. Soil treatment has an effect on tree growth and various methods have a different effect (Hjelm & Rytter 2018). Based on Hjelm & Rytter (2018), mounding is the best way to establish hybrid aspen on forest lands, also patch scarification should be avoided, especially on soils which are mesic to moist. In Tagel, Sävsjöström and Tönnerjöheden inverse soil preparation methods with an excavator were applied. Mounding could be the best method on mineral soils but as the experimental sites studied in this thesis were located mostly on relatively rocky soils then mounding may not be the best way to scarify the area.

For hybrid aspen, the fatal issue can be a serious pathogen for the species called *Entoleuca mammata* which causes Hypoxylon canker. Recent studies showed that the mortality rate of infected trees during a few years was 100 % (Lutter et al. 2019). To reduce the risk, it is recommended to plant the hybrid aspen on less acidic soils because acidic soils present a higher risk of infection. While forest soils are usually more acidic than former agricultural soils (Wall & Hytönen 2005) it is not suggested to plant hybrid aspen on forest land (Bruck & Manion 1980). One suggestion is to plant hybrid aspen at a lower density to decrease the risk of infection (Ostry 2013). This risk gives a great advantage to silver birch for it does not have such mortal pathogens registered.

5. Conclusion

In this thesis, two fast-growing tree species were compared, and the results showed that genetically improved young silver birch stands demonstrated similar or in some conditions even greater growth than same aged hybrid aspen, which is recognised as one of the fastest growing tree species in Sweden. The study showed that fertilization has an effect on early growth for both species but particularly so for the hybrid aspen. For silver birch, soil fertility appeared to play a more important role than fertilization. Silver birch stands had more growth than hybrid aspen on former agricultural land (which had a more fertile soil compared to the forest sites), independent of additional nutrient supplement. This was also recognisable from the simulation development of full rotation projection, where the optimal rotation length arrived earlier on former agricultural land than on forest lands. Values of MAI and LEV in both scenarios e.g. pulpwood and timber were also higher for birch planted on former agricultural land. Further studies including genetically improved silver birch and natural planting material comparison on the same conditions would be required for the economic analysis to show silvicultural profitability of birch dependent on origin of the seedlings. One way to estimate the full rotation projection of hybrid aspen with the measurements collected during the field inventories is to develop a similar model as was applied to silver birch.

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