Comparison of native and introduced tree species in a range from low to high productivity sites in southern Sweden

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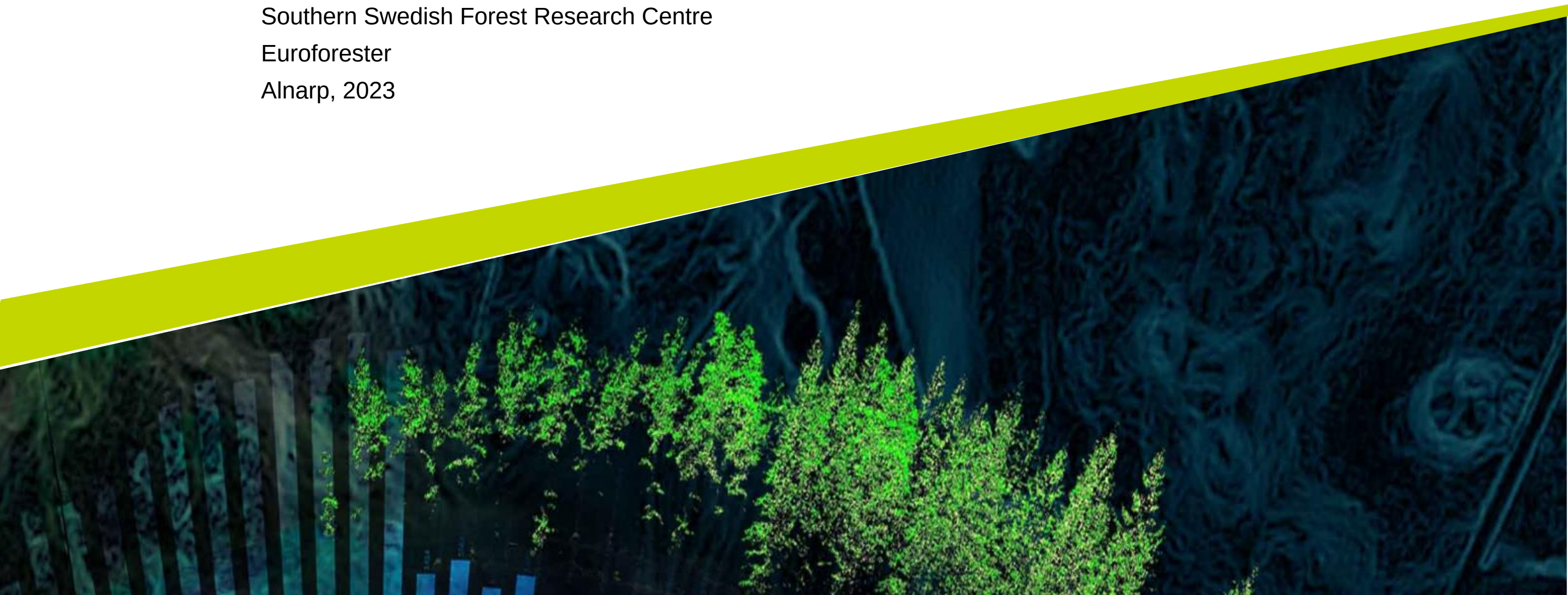

Comparison of native and introduced tree species in a range from low to high productivity sites in southern Sweden

En trädslagsjämförelse från låg till hög bonitet i skogliga försök i södra Sverige

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Abstract

The dilemma of climate change, biodiversity conservation and economic efficiency in nowadays forestry leads us to search for the new solutions. Introduction of non-native tree species becomes a more frequently explored field as a solution for the future problems. However, introduction is limited by adaptability, susceptibility and productivity which all together control the success and risks of their potential. This thesis studies three native and nine introduced tree species planted in tree species experiments across the low, moderate and high site productivity gradients in southern Sweden. Evaluated native species are Norway spruce, Scots pine, silver birch and introduced- white spruce, black spruce, Sitka spruce, lodgepole pine, Douglas fir, grand fir, balsam poplar, hybrid larch, hybrid aspen. The early growth of tree species provides us a better understanding of potential and expectations in the following growth periods. Besides the native tree species, a few of the non-native species such as lodgepole pine or Douglas fir have already been introduced in Swedish forestry. But for others, such as grand fir, black spruce or white spruce research is rather scarce.

Evaluation included a review of the species-specific literature on ecology, soil preference, growth and known biotic/abiotic risks as well as the early-growth analysis and comparison of diameter, height, basal area and total volume between and inside the low, moderate and high productivity sites in the southern Sweden.

Among the studied native species, based on total volume growth, Scots pine was most productive in low productivity, while Norway spruce- in moderate and high productivity sites. In comparison silver birch produced lowest total volume out of the three native species.

In the low productivity site volume growth of hybrid larch and lodgepole pine was higher than of the Scots pine, Douglas fir growth was similar to the growth of Norway spruce, while white spruce total volume growth was the lowest.

In the moderate productivity site Sitka spruce, grand fir and hybrid larch productivity was higher than of the Norway spruce. Hybrid aspen productivity was similar to Norway spruce. The lowest productivity was measured in black spruce and Douglas fir plots, not reaching either of the native species.

In the high productivity site, the highest production was measured by grand fir, there as Sitka spruce, balsam poplar and hybrid larch total volume growth were similar to the Norway spruce. Douglas fir total volume was slightly higher than of the silver birch, although was significantly lower than of the Norway spruce. Fast-growing hybrid aspen total volume by the age 18 was equivalent to the growth of Norway spruce by the age 30, showing the high suitability for short-rotation plantations.

Keywords: introduced tree species, low productivity sites, moderate productivity sites, high productivity sites, *Picea abies*, *Pinus sylvestris*, *Betula pendula*, *Picea glauca*, *Picea mariana*, *Picea sitchensis*, *Pinus contorta*, *Pseudotsuga menziesii*, *Abies grandis*, *Populus balsamifera*, *Larix x eurolepis*, *Populus tremula* × *Populus tremuloides*

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Abbreviations

B	Silver birch
BA	Basal area
BS	Black spruce
DBH	Diameter at breast height
DF	Douglas fir
GF	Grand fir
H	Height
HA	Hybrid aspen
HL	Hybrid larch
HP	High productivity site
LP	Low productivity site
LPP	Lodgepole pine
MP	Moderate productivity site
NOS	Number of stems
NS	Norway spruce
P	Balsam poplar
SP	Scots pine
SS	Sitka spruce
WS	White spruce

1. Introduction

1.1 Past and present- history of tree species introduction

First known efforts to introduce tree species to the European lands were driven by the necessity to provide food for humans and livestock animals (Zagwijn, 1994). Such introductions took place through Phoenician, Greek and Roman trading networks and led to the introduction of sweet chestnut (*Castanea sativa* Mill.), apple (*Malus pumila* Mill.), walnut (*Juglans regia* L.), quince (*Cydonia oblonga* Mill.), medlar (*Mespilus germanica* L.) and other similar fruit tree species widely known and grown nowadays (Nyssen et al., 2016).

In Europe tree species introduction on a larger scale began between 19th and 20th centuries as the rising industrialisation led to a higher demand of wood and reforestation of previously overexploited lands (Nyssen et al., 2016). Whilst mainly selected species for planting were native, in some rare occasions non-native tree species were introduced. This was accomplished after a thorough evaluation of economic benefits, productivity/cultivation or possible improvement to the soil conditions (Pötzelsberger et al., 2020). Throughout the years many tree species were introduced to European forests, however their success and prevalence varies between the different countries.

When analysing native tree species, it is impossible to overlook the importance and extensive usage of Norway spruce (*Picea abies* (L.) Karst.). Postglacial spread of Norway spruce extended across the northern Europe (Nota et al., 2022). Nowadays, it grows in Fennoscandia, Baltic countries, north-eastern Europe, parts of central Europe and mountainous areas in Alps and Carpathians (Nota et al., 2022). Scots pine (*Pinus sylvestris* L.) spreads from the far eastern parts to the western Spain (Durrant et al., 2016). Silver birch (*Betula pendula* Roth) is a native European tree species common throughout the continent- distribution ranges from northern Europe to the southern Mediterranean (excluding Greece, most of the Iberian Peninsula and Iceland) (Vakkari, 2009). However, it is most commonly found in mixed and pure stands of northern and eastern Europe, while in the south is more prevelant in higher altitudes (Vakkari, 2009).

1.2 Tree species range and distribution in both European and Swedish forests

Introduced tree species in Europe cover around 3% of the total forest area, most abundantly grown in the central-west Europe (introduced species take up 9%) and further increasing (FOREST EUROPE, 2020). A total of 145 tree species were introduced to European forests, of which most abundant are five- black locust (*Robinia pseudoacacia* L.), *Eucalyptus globulus*, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and lodgepole pine (*Pinus contorta* Douglas ex Loudon)- contributing to 77% of all grown introduced tree species. (Brus et al., 2019)

In Sweden tree species distribution percentage shows that the most abundant tree species are **Norway spruce** (39.7%) and **Scots pine** (39.3%), followed up by **silver birch** (12.9%) (Nilsson et al., 2021). Abundance of other species is considerably smaller. Aspen population reaches 1.8%, even lesser population has larch with only 0.1%. Among introduced species the most abundant is lodgepole pine with a total coverage of 1.3% (Nilsson et al., 2021).

Black spruce (*Picea mariana* (Mill.) B. S. P.) native range spreads over northern areas of North America- starting from the Atlantic coast forests from northern Massachusetts to the Northern Labrador spreading across all of the Canada towards the western coast of the Alaska (Viereck & Johnston, 1990). Most northern populations extend over the Arctic circle, while the most southern grow in the central Pennsylvanian bogs (OECD, 2010). Elevation ranges from the sea level coastal forests to the high elevation areas of Rocky Mountains (OECD, 2010). Compared with the **white spruce** (*Picea glauca* (Moench) Voss), both species range and distribution overlaps- white spruce growth ranges from the western Atlantic coast (parts of Newfoundland and Labrador) spreading over Canada, to the far lands of Alaska, both reaching Bering Sea and Gulf of Alaska, while in the south extending towards Montana Rocky Mountains, Wyoming and South Dakota Black Hills (Nienstaedt & Zasada, 1990).

Sitka spruce is native in the Pacific north-west of North America extending from the northern coast of California to the southern Alaska (Durrant et al., 2016). First introduction in Europe was made in the early 19th century (Lee et al., 2013). Nowadays Sitka spruce is most commonly commercially grown in Great Britain and Ireland, where the main focus for selection and breeding progress took place (Lee et al., 2013). Similar selection programs were started in Denmark, Germany, France and Norway, although due to the perceived small importance most had come to the close (Lee et al., 2013).

Introduction of **lodgepole pine** was common in northern Europe- Scandinavia, as well as some parts of Ireland and Britain (Critchfield, 1980). During 1950's lodgepole pine was planted in Finland, Sweden, Britain and Ireland in peat bogs to assist afforestation (Novotný et al., 2018). France had the most widespread planting of lodgepole pine, whilst in Netherlands, Denmark, Iceland, Norway, Germany and Poland planting was not common (Novotný et al., 2018). Lodgepole pine was introduced from the North America where it extends through Pacific coast regions and Rocky Mountains, growing from the northern areas of Yukon in Canada to the south Baja California, from the Pacific coast ranging to the east of South Dakota Black Hills (Lotan & Critchfield, 1990).

Douglas fir originated from North America- in native range spreads across western parts of North America starting from the central British Columbia it grows alongside southern Pacific coast (Hermann & Lavender, 1990). The first introduction in Europe dates back to approximately 150 years ago, beginning in the central parts and later spreading to the northern regions as well (Schmid et al., 2014). Nowadays largest Douglas fir populations in Europe are in France, Germany and United Kingdom (Da Ronch et al., 2016). On a much smaller scale grown in Sweden, Denmark, Switzerland, Austria, Poland and Netherlands (Da Ronch et al., 2016). The first Douglas fir in Sweden was planted in 1880's in state of Rössjöholms (van Loo & Dobrowolska, 2019).

Grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) originated from North America- from north-western forests in USA to southern parts of British Columbia provenance in Canada. Grows in coastal Vancouver Island, Washington, Oregon valleys, lowlands and north-west of California. Coming off from the coastline, common in more continental areas in north-east Oregon, north Idaho, west Montana, east Washington and southern British Columbia near the Okanogan and Kootenay lakes (Foiles et al., 1990). First seeds imported from the Pacific north-western regions were brought to Europe in 1830's and mainly planted in Germany (Konnert & Ruetz, 1997).

Balsam poplar (*Populus balsamifera* L.) is native to North America. It grows in south, west and central Alaska and extends through Canada's southern provenances- north and east British Columbia, spreads through Saskatchewan to the northern limit of trees, to the eastern coasts of Newfoundland, Quebec and Labrador. Covers northern states of USA, growing in Black Hills in South Dakota and Wyoming. (Zasada & Phipps, 1990)

Hybrid larch (*Larix x eurolepis* Henry) is a cross of Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and European larch (*Larix decidua* Mill.). As a hybrid of the two species, it does not have a native range, however it successfully grows in central and eastern Europe and few mountainous areas. In Sweden larch species are not considered to be native. Although based on radiocarbon-dated fossil findings Siberian larch (*Larix sibirica* Ledeb.) grew in Swedish mountains until the last glacial period. According to the statistics, hybrid larch is most commonly grown larch species in southern Sweden. (Larsson-Stern, 2003)

Hybrid aspen (Populus tremula L. × Populus tremuloides Michx.) derives from the European aspen (*Populus tremula* L.) and North American trembling aspen (*Populus tremuloides* Michx.). Species were first crossed in Germany in 1920's and since 1950's establishment of plantations in Finland and Sweden were started. (Tullus et al., 2008) In later years was planted in Nordic and Baltic countries often for experimental purposes as the commercial planting has not yet reached a huge significance (Tullus et al., 2012).

1.3 Climate change in southern Sweden

Climate change key indicators provide the undeniable proof of an already warmed climate as greenhouse gasses are at the all-time high of the last 800 000 years (Gulev et al., 2021). In the upcoming twenty-year period (2021-2040) global temperature is predicted to rise by 1.5°C (Lee et al., 2021). Reports forecast an increase of annual precipitation and uncertain weather patterns including the uprise of storms, frosts and droughts (Lee et al., 2021). In southern Sweden climate change is expected to adjust to a warmer climate with dry summers and more humid winters (Swedish Commission on Climate and Vulnerability, 2007). Annual mean temperature modelling of the later part of the XXI century (2081-2100) in southern Sweden suggest few adaptations- from minimal increase in mean annual temperature by 1-1.5°C to the highest of 4-5°C (IPCC, 2013). As a result of temperature increment, thermal summer and winter periods will shift. Summer period will elongate, ending in the early October, while winter period will shorten, starting in the early January and ending in the early February (Rousteenoja et al., 2020). To add on probability of winterless years increases by the mid-century (Rousteenoja et al., 2020).

The predicted climate changes are not expected to benefit native species, especially coniferous. Although, prolonged growth period increases total stem volume production and yield (Bergh et al., 2010), forest becomes more vulnerable to storms, fires, frosts and droughts which consequently often results in pest or pathogen outbreaks (Lidskog & Sjödin, 2016; Jönsson et al., 2004; Kronnäs et al., 2022). The growth of Norway spruce in southern Sweden is evidently efficient. However, the species is already facing few of the mentioned threats.

Mitigating climate change is an important part for reducing associated negative effects (Nicholls & Lowe, 2004). Carbon sequestration is a process that involves capturing and storing carbon dioxide from the atmosphere within trees, vegetation, soil or water bodies (Fawzy et al., 2020). Forestry has a significant part in contributing to the carbon storage (Canadell & Raupach, 2008). Both native and introduced tree species have a potential for carbon sequestration depending on species and growth conditions (Montagnini & Nair, 2004). In certain cases, introduced species have faster growth rates than the native ones, resulting in greater carbon sequestration over a shorter period of time (Nunes et al., 2021). While both native and introduced species contribute to carbon sequestration, it is important to consider long-term sustainability and resilience when selecting and planting tree species (Castro-Díez et al., 2019).

1.4 Biodiversity and ecological risks

Biodiversity. Nowadays, both Swedish and worldwide forest ecosystems are facing a decline of biodiversity instigated by the extensive forest management which has caused landscape fragmentation, decline of old-growth forests, lack of natural disturbances (gap dynamics, forest fires) and lack of deadwood (Elfving et al., 2001). The perspectives of introduced species influence on biodiversity and associated risks to the environment highly deviate (Gbedomon et al., 2020). Several studies emphasize the negative impact pointing out examples of the invasive species as an equivalent for all introductions (Simberloff, 2005; Yanci et al., 2002), while others highlight that the analysis of specific invasive species should not be generalised for all non-native species, as each should be evaluated separately (Guerin et al., 2018; Chalker-Scott, 2015). According to Essl et al., (2015) introduction is mostly concerning due to the unpredictable tree species impact on ecosystems. Currently harmless species, in the future could become damaging and weaken ecosystems. However, a few recent studies focus on the non-native tree species benefits to the native fauna (Packer et al., 2016) by providing food or shelter (Schlaepfer et al., 2011). In that respect, generalist species are better adapted to the ecosystem changes, contrary to the specialist species which are limited by specific ecosystem functions or species (Stigall, 2012). For example, introduction of the lodgepole pine in Sweden showed that vascular plant diversity in young stands is similar to the Scots pine forest species, while in mature- to Norway spruce (Engelmark et al., 2001). The diversity of invertebrates is comparable to that of Scots pine forests and is expected to further increases as insects adapt to the new habitats (Engelmark et al., 2001). However, no significant variation in vertebrate diversity between lodgepole pine and Scots pine forests was observed (Engelmark et al., 2001).

Pests and pathogens. The introduction of non-native species presents an ecological risk of unintentional introduction and transmission of pests and pathogens (Gougherty & Davies, 2021; Liebhold et al., 2012). Introduced species could act as a host for pests and diseases allowing them to establish and spread through the new ecosystems, resulting in the significant alteration of native ecosystem services (Vitousek et al., 1997) and destabilisation of local host-pathogen system dynamics (Dobson et al., 2003). Consequently, the damaged forest resources and its management efforts could result in a significant amount of economic expenses (Lovett et al., 2016; Pimentel, 2009).

Invasive species. Invasiveness is one the biggest threats for the native ecosystems. However, a correct terminology and understanding between invasive and introduced species should be a part of every discussion and action (Krum & Vitkova, 2016). Negative outlook forms due to the association of native forests being familiar, traditional, harmonious part of the nature, while humans tend to have the opposing point of view to the introduced species- negative connotations including unfamiliarity, hostility and modernisation (Eser, 2016). That said, if introduced tree species naturalize locally or spread beyond their confined range, they could become invasive. (Pyšek, 2016). Although, invasiveness of some species is inconclusive based on different sources. For example, according to Nunez & Medley (2011) lodgepole pine in Sweden had a non-invasive introduction, while Knight et al., (2001) reported that lodgepole pine is an invasive species. Contrary Jacobson & Hannerz (2020) concluded that lodgepole pine has naturalized, however, natural regeneration tends to take place in proximity to the seed tree. Invasiveness of Douglas fir in southern Sweden is considered to be of an intermediate-high risk due to its characteristics (early maturity, production of a large number of small seeds), although limiting factors include species vulnerability to frosts and high browsing risks (Felton et al., 2013). Based on the records Douglas fir has naturalized in two countries and has been labelled as invasive in seven (Richardson & Rejmánek, 2004). In comparison, Sitka spruce is considered invasive in three countries, while grand fir has naturalised in two regions and deemed invasive in one country (Richardson & Rejmánek, 2004). The risk of hybrid aspen becoming invasive is very high, while hybrid larch likeliness of invasiveness is medium (Felton et al., 2013). Additionally, in case of the hybrid aspen invasion or naturalisation the new risk of hybridization with native European aspen arises. Even in the short rotation plantations hybrid aspen has the risk of hybridisation. Short-rotation period plantations have risks for hybridisation due to seed production and flowering begins as early as 10-20 years of age (Landhäusser et al., 2019). Hybridization is a concern which poses a risk for future native tree species genetic material preservation, as the new introduced genes could dilute native genotypes (McKay et al., 2005).

1.5 Policy and legislations

European policies of introduced tree species planting in forests vary highly based on legislations of each country. National or regional country legislations have the greatest impact on the management, despite few international treaties, conventions or European Union response towards species introduction (Pötzelsberger et al., 2020). In countries such as Norway, Lithuania, Poland, northern region of Belgium, Slovenia, six regions in Spain, Portugal, Bosnia and Herzegovina, Moldova, Serbia, Bulgaria, Macedonia, Montenegro and Cyprus, legislations prohibit introduced species planting in nature unless permission is given (Pötzelsberger et al., 2020). More severe legislations are in Italy and in one central region in Spain- introduction to the nature is forbidden, in the later all imports and cultivations are prohibited. The contrasting absence of such restrictions are seen in other European countries, including Sweden.

In Sweden forest management is regulated by a few legislations and certification programmes. First established in 1903, the Forestry Act has been revised multiple times to suite the political or environmental movements (Nylund, 2009). First restrictions for the introduced tree species were put forward in 1979 as a response to a high increase of the lodgepole pine plantations (Karlman, 1981). As a result, southern Sweden permitted lodgepole pine planting only in the experimental sites, while planting in the harsh northern sites was banned in 1987 due to the fungal outbreak (Elfving et al., 2001). Limitations extended to the controlled annual afforestation area and forbid non-native tree species planting near nature reserves or national parks (Elfving et al., 2001). However, restrictions only regulated lodgepole pine regeneration. Contrary, the Bill issued in 2007 recognised upcoming challenges of the climate changes and suggested investigating a variety of solutions including broader introduction of exotic tree species as an alternative to increase wood production (Lindahl et al., 2017). The fast-growing introduced species are recognised for having economic benefits. The current forestry model in Sweden aims to fulfil multifunctional goals (Lindahl et al., 2017). In addition, forests could be voluntarily certified by Forest Stewardship Council (FSC) or Programme for the Endorsement of Forest Certification (PEFC) (Lidskog et al., 2013). The FSC standard regulations are more direct, for example introduced species have an area limitation of 5% (Brukas et al., 2013).

1.6 Tree species experiments and common gardens

The introduction of new species usually begins by establishing tree species experiments and common gardens. Tree species experiments examine potential growth, species characteristics, and their relations with various ecosystem functions, while common gardens provide a more controlled environment to determine species adaptation; although common gardens are more of a short-term evaluation, tree species experiments often extend to a full production length (Germino et al., 2019).

The beginning of tree species experiments in Sweden date back to the early 20th century (Laudon et al., 2011). Available research and literature broadly analyses few of the native species. Perhaps the most thoroughly studied species is Norway spruce with many experiments conducted to determine its growth and yield in different productivity sites (Bergh et al., 1999; Bergh et al., 2005; Hansson et al., 2011; Eriksson & Johansson, 1993). Research on growth trends in a gradient of site productivities in Scots pine (Hansson et al., 2011; Tamm et al., 1999; Ekö et al., 2008) and silver birch (Hansson et al., 2011; Karlsson et al., 1997) stands have also been evaluated. Between the non-native tree species, the number of experiments measuring growth and yield vary highly. The lodgepole pine growth has been analysed in a variety of soils with different nutrient availabilities (Engelmark et al., 2001; Kuznetsova et al., 2009; Varmola et al., 2000). Majority of the experiments were conducted between 1962 and 1979 to determine the most suitable lodgepole pine provenances for Sweden, with provenance trials established by companies and institutions across the country, serving as the foundation for seed transfer recommendations (Elfving et al., 2001). Similarly, research has been done on Douglas fir (Martinsson, 1990; Karlberg, 1961; Malmqvist, 2017), Sitka spruce (Karlberg, 1961), hybrid aspen (Fahlvik et al., 2021; Christersson, 1996), hybrid larch (Larsson-Stern, 2003; Johansson, 2012; Ekö et al., 2004) and grand fir (Eriksson & Jönsson, 1994;) growth on different sites. A bit less studied balsam poplar is mainly grown in the former agricultural lands (Dimitriou & Mola-Yudego, 2017). While there is insufficient research on black spruce and white spruce to draw any firm conclusions about their growth across the productivity gradient in Sweden.

1.7 Aim of the study

The aim of this thesis was to gain a better understanding of native and introduced species growth and potential in southern Sweden, compared on the same sites.

I analysed and measured growth of, in total twelve, tree species on low, moderate and high productivity sites. The data I used comes from three species experiments. My research questions have been:

1. To compile the knowledge on tree species specific ecology, site preferences and known risks.
2. To analyse growth differences of common native and several introduced tree species within each site productivity gradient.
3. To compare native tree species growth with introduced species between the low, moderate and high productivity sites.

2. Methods

2.1 Study area

Measurements from three tree species experiments were used for this study, in a range from low site productivity, site 2298 (LP), moderate, site 2299 (MP) and high productivity, site 2297 (HP). The experiments are located in southern Sweden, in the region of Småland, Asa (low and moderate productivity sites) and in Skåne, Bullstofta (high productivity site) (Fig. 1). Establishment of the experiments by planting was done between 1993-1994.

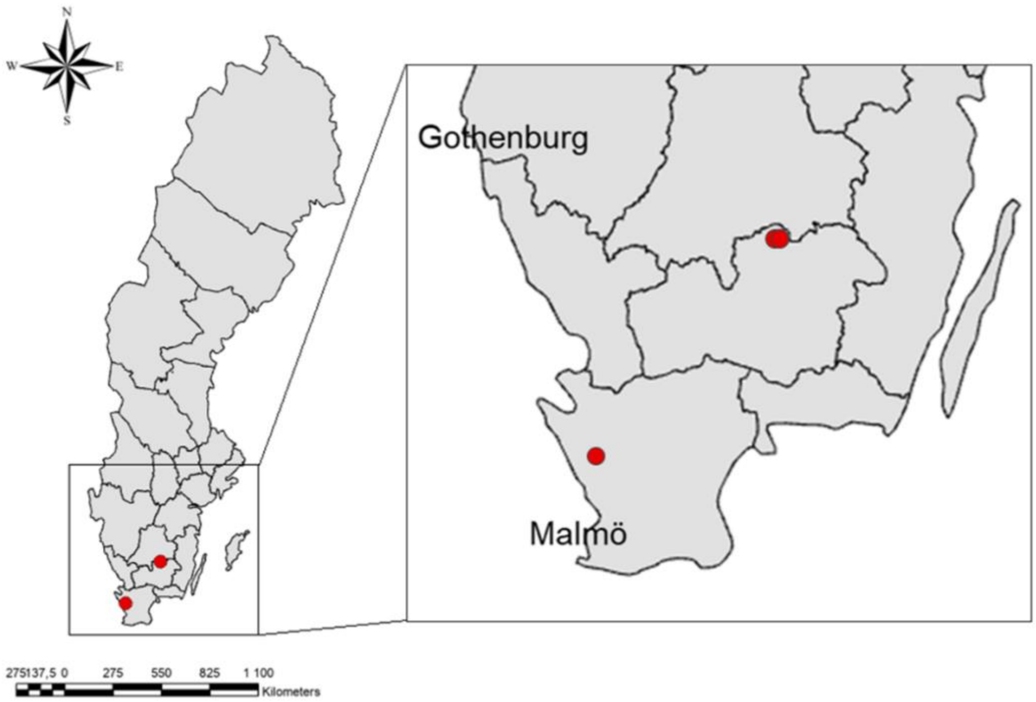

Figure 1. Location of experimental sites in southern Sweden

Experimental design in all of the sites was done similarly- all sites have been divided into three blocks. Each block was further divided into smaller 0.1ha plots.

Within the blocks, selection of tree species planting in the plots was randomised. Seedlings were planted following the layout of 2x2 meters spacing. Preparation for planting all three sites consisted of soil scarification- specifically using mounding method. All of the sites were fenced due to the high herbivore population in southern Sweden to avoid any browsing damage. Herbicides were only used in high productivity site due to the previous land use being an agricultural land with high fertility soil. In this case, herbicides were necessary to avoid high competition for seedlings with other site vegetation.

Table 1. Properties of the experimental sites

Site	Low productivity	Moderate productivity	High productivity
Site number	Site 2298	Site 2299	Site 2297
Soil fertility	Low fertility	Moderate fertility	High fertility
Year of establishment	1994	1994	1993
Previous land use	Spruce plantation	Spruce plantation	Agriculture land
Soil scarification	Mounding	Mounding	Mounding
Use of herbicides	-	-	Used
Fencing	Fenced	Fenced	Fenced

In total, twelve tree species were planted in the three experiments. During the establishment all tree species were planted using different number of seedlings. Different management practices were chosen to maximise each species growth potential. All species were planted during the same year inside each site. Most of the tree species were thinned (lodgepole pine was not thinned). Thinning intensities varied from species to species.

2.2 Design of the experiment

The low productivity, site 2298, has eight tree species planted in each block (Fig. 2). Three of the species are native- Norway spruce, Scots pine and silver birch. Other are introduced tree species- white spruce, black spruce, lodgepole pine, hybrid larch and Douglas fir.

The moderate productivity, site 2299, has eight species planted across different blocks (Fig. 3). Site has two native tree species- Norway spruce and silver birch, two hybrid species- hybrid larch, hybrid aspen, and four introduced- black spruce, Sitka spruce, Douglas fir and grand fir.

The high productivity, site 2297, in total has eight species planted across different blocks (Fig. 4). Of which two species are native- Norway spruce and silver birch. Four species are introduced- Sitka spruce, grand fir, Douglas fir and balsam poplar. And two are hybrid tree species- hybrid larch and hybrid aspen.

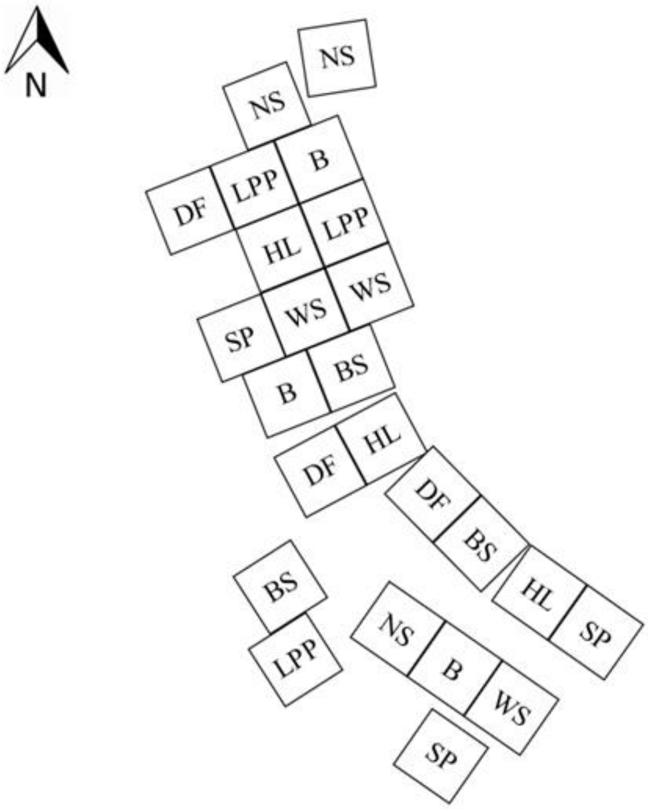

Figure 2. Experimental design of low productivity, site 2298. NS- Norway spruce, WS- white spruce, BS- black spruce, B- silver birch, SP- Scots pine, LPP- lodgepole pine, HL- hybrid larch, DF- Douglas fir

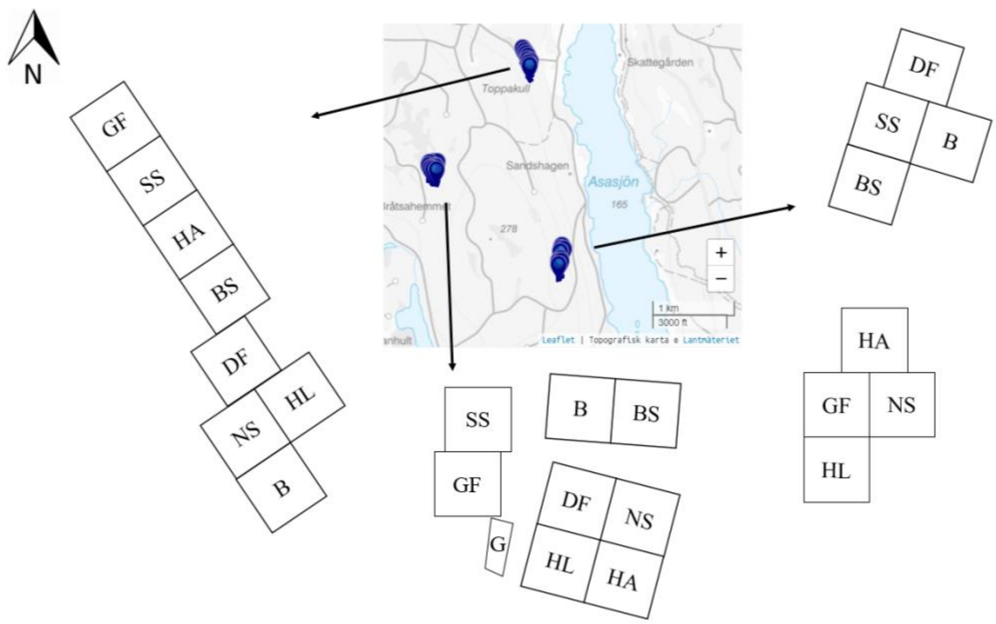

Figure 3. Experimental design of moderate productivity, site 2299. NS- Norway spruce, BS- black spruce, SS- Sitka spruce, B- silver birch, HL- hybrid larch, HA- hybrid aspen, DF- Douglas fir, GF- grand fir, G- Gran agallrad

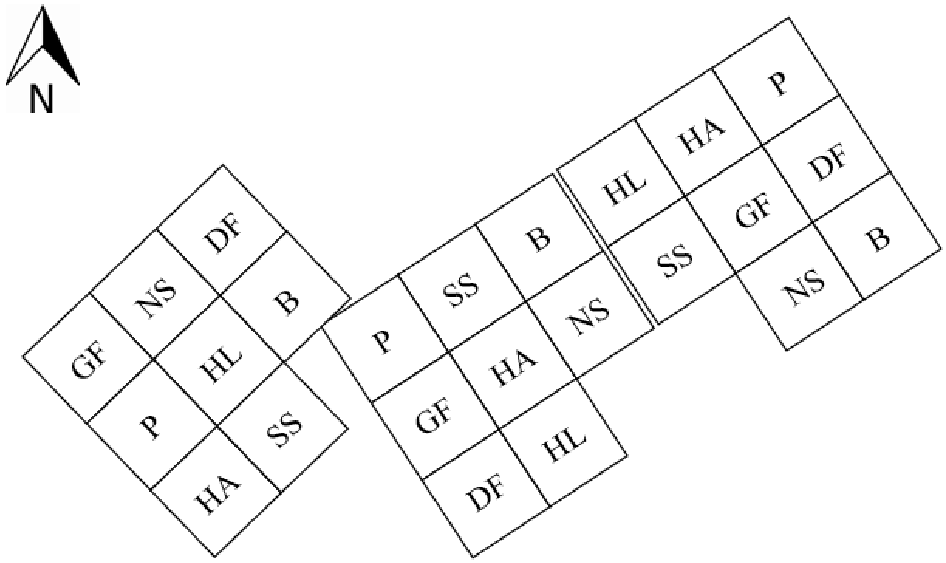

Figure 4. Experimental design of high productivity, site 2297. NS- Norway spruce, SS- Sitka spruce, B- silver birch, HA- hybrid aspen, HL- hybrid larch, GF- grand fir, DF- Douglas fir, P- balsam poplar

2.3 Data collection

All data was collected by the staff at the Unit for field-based forest research. In the low and the moderate productivity sites data was collected during 2010, 2016 and 2021 revisions. The high productivity site has total of six revisions in the years of 2003, 2006, 2009, 2012, 2016 and 2022. During the 2003 and 2006, data was collected only for four species- silver birch, balsam poplar, hybrid larch and hybrid aspen. Whilst the 2009 and later remeasurements included all eight tree species. Except the hybrid aspen and one of the balsam poplar plots, in which data was collected up to 2012. Hybrid aspen was managed as a fast-growing plantation and was felled at the age of 21. Similarly, felling was done in one of the balsam poplar plots, in the other two plots data was collected up to the 2022 revision.

Measurements of diameter (DBH), height (H), basal area (BA), number of stems was collected. Diameter was measured using calliper. Measuring two times- first with calliper towards the first point and second with calliper 90° from the point, both times at 1.3m breast-height. Each measured tree was appointed to different tree dominance classes, damages or plot treatment were described by using codes. Based on the collected data many descriptive values were calculated, both for stand and tree level.

2.4 Data analysis

Data was analysed and visualised using “Excel”. As the sites had different revision, data collection and tree species planting dates, data was analysed by comparing between the age groups (Table 2). The first age group was attributed to the revisions done in 2009 and 2010- stands were age 17-19. The next groups were chosen to be between ages 24-26, with all revisions being done in the year 2016. The newest data collection took place in 2021 and 2022, leaving age of the stands to be 30-31. Further data on the three revisions is presented as age 18, 25 and 30, respectively.

Table 2. Seedling age at the time of planting experimental plots

	LP	MP	HP
Norway spruce	3	3	3
Scots pine	2	-	-
Silver birch	2	1;2	2
White spruce	2	-	-
Black spruce	3	3	-
Sitka spruce	-	1;3	2
Lodgepole pine	2	-	-
Douglas fir	2	2	2
Grand fir	-	3	2
Balsam poplar	-	-	2
Hybrid larch	2	2	2
Hybrid aspen	-	2	2

3. Results

3.1 Comparison of ecology, growth, usage and biotic/abiotic threats

3.1.1 Norway spruce (*Picea abies*)

Characteristics. Large both pioneer and climax conifer species which grows in a cone like, columnar shape (Caudullo et al., 2016). Often forms a shallow root system. Branches are short and sturdy, at the bottom of the trunk slightly drooping while on the top ascending. Bark is brown, slightly orangish. Buds are reddish-brown up to 5mm long. Needles are usually coloured in a variety of green shades from lighter to darker, rigid 1-1.25cm with slimmer white lines. Often live up to 200-300 years, it reaches maturity at 20-30 years, in denser stands mature at 40 years. Norway spruce is monoecious- it produces unisex flowers. Male flowers are positioned at the base of the shoot, while the female flowers are at the tip. Male flowers vary from yellow to reddish colours and are 1-2.5cm length. Female flowers are usually darker red, 5cm length. Forms cylindrical cones the size of 12-15cm first green coloured, although with maturity turning brown. Opening in the autumn season and spreading 4mm. winged seeds. With the full growth it reaches up to 50-60m height.

Soil requirements. Tolerates wide range of soil conditions, although does not prefer salty spray of winds in the coastal areas, extreme drought or waterlogged conditions (Caudullo et al., 2016). The best growth could be expected on slightly acidic, moist and fertile soils. By itself has an ability of acidifying soil.

Wood usage/potential. Timber is light and easy to work with (Caudullo et al., 2016). Nowadays, the wood is used widely for many purposes- solid timber is used for construction, pulpwood for making paper, joinery, furniture, veneer and sound boards for various musical instruments, also every winter as a Christmas tree.

Risks. Due to the climate change Norway spruce populations in the southern distribution range had become more susceptible to biotic and abiotic threats- windthrows, fires, droughts and frosts (Caudullo et al., 2016). Detrimental effects are experienced during the bark beetle (*Ips typographus*) outbreaks, as well as various other pest infestations which could cause a massive die-back. Fungal pathogen damages are common, causing root or trunk rot.

3.1.2 Scots pine (*Pinus sylvestris*)

Characteristics. Scots pine is a pioneer medium sized conifer tree species (Durrant et al., 2016). The bark is easily identified for having brown-orange tones which become lighter in the upper parts of the trunk. Lower part often has deep fissures. Green-blueish 5-7cm needles often have a slight twist. It has a waxy layer on top of the epidermis and imbedded stomata's which attribute to the species high tolerance of droughts and frost as it serves a purpose of minimizing water loss. Scots pine is relatively a long-living tree on average reaching 400 years of age and in some rarer occasions is known to live past the average given age. Usually is monoecious, although some older and mature trees may only have one gender flowers. Male flowers are a yellow or pink coloured clusters located near the base of newly grown shoot. Female flowers located at the tip of the shoot are pink or purple. Pollination is done by wind. Oblong-conic cones are 5-8cm length and spread winged seeds after both dry and wet weather conditions result in its opening. Growth is rather slow, at the mature age reaching an average 23-27m height. As a light-demanding species it often grows in sunny and open areas, however it tolerates partially shaded sites.

Soil requirements. Grows in a gradient of soil fertilities, more often found on poorer sites as in fertile conditions is often outcompeted by other faster growing species (Durrant et al., 2016).

Wood usage/potential. Timber is known to be easily workable (Durrant et al., 2016). Its softwood is considerably very hardy and has high strength to weight ratio. Has a wide range of usage including construction work, furniture, pulpwood and paper making. For the great abilities to adapt to many varying poor site conditions species could be used for land reclamation and reforestation. In the past it has been widely used for resin collection particularly in eastern Europe.

Risks. As resilient as it is to the different soil conditions, its resilience is lacking in tolerance for atmospheric pollution and salty wind spray near the coastal areas (Durrant et al., 2016). The first threats in the forest plantations are often caused by browsing. It is susceptible to a few pests (*Hylobius abietis, Ips typographus, Mycosphaerella pini*, etc.) and diseases (various fungal pathogens causing rot or mortality of seedlings).

3.1.3 Silver birch (*Betula pendula*)

Characteristics. Pioneer broadleaf tree species (Beck et al., 2016). It has a light canopy of droopy branches with more separated course and serrated 3-7 cm leaves with a finer ending point. Bark of a younger tree is brownish. However, with maturity it becomes more bright white, grey or silvery, slightly shiny with the horizontal lenticels across. With the older age possibly developing fissures. Relatively a short-lived tree species in most cases reaching 90-100 years. Maturity in the denser forest stands is reached by the age 20-25, as the more free-standing trees tend to mature faster and start producing seeds by the age 10. Birch is a monoecious tree species. Male catkins develop during the summer into the hanging clusters. While female catkins are smaller, shorter and more erect. Pollination is done by wind, the following spring after female catkins emergence. It develops a cylinder shaped 1-4cm length and 6mm. wide fruit which around August disperses hundreds of small, winged seeds. Considered a medium sized tree species as in the best growth conditions height reaches up to 30m.

Soil conditions. Grows in a variety of soil conditions, tolerating even the poorest soils (Beck et al., 2016). Although, the best growth is expected in relatively fertile, lighter, acidic and well drained soils. Noted for having a moderate ability to acidify the soils.

Wood usage/potential. Timber is considered as one of the most significant hardwood sources in northern Europe (Beck et al., 2016). Although importance and usage exceed way beyond the timber production. Often planted alongside more common plantation conifer species to enrich and protect biodiversity by providing habitats for many lichen and bird species. The ability to tolerate poor site conditions could be used as an advantage to efficiently reclaim and reforest many land areas, and effectively prevent the erosion. Also, plantations are used for the sap collection- a fresh and sweet drink popular in many eastern European countries.

Risks. Has a high wind resilience and rarely is damaged by storms (Beck et al., 2016). However, is more susceptible to droughts. A lower resilience towards pest damages is apparent- leaves are a forage for many butterfly, sawfly and moth larvae species which often causes a cycle of repeated defoliation. Fungal disease infestations damage all parts of tree tissue causing leaf rust, deformations, defected shoot growth and more detrimental wood rot.

3.1.4 White spruce (*Picea glauca*)

Characteristics. In the native most productive sites diameter is measured up to 1m, height 15-25m (in exceptional cases up to 50m) (Navasaitis, 2004). Shallow root system- common depth is 90-120cm. Bark is brown with grey tone, scally. Crown has a cone shape, often narrow. Branches droop, shoots are lighter, more yellow grey. Buds are conic, light brown. Needles are quadrilateral, dense, green-blueish-greyish, 1-1.5cm length. Cones are rounded cylinder shape- 1cm. diameter with 3-6cm length, brown with yellow or red hue. Seeds shaped as scale-fan, brown or black, with 1cm wing. One cone produces ~60-70 seeds.

Soil requirements. Grows in wide variety- loamy, clay, sandy, both mineral and organic soils (Nienstaedt & Zasada, 1990). Not demanding for pH levels. Tolerates strongly acidic 4-5 pH soils and alkaline 7-8.2 pH. Soil fertility ranges from poor to rich. However, demands higher requirements for efficient growth and yield. In poor fertility soils is a secondary species. Prefers well-aerated and well moistened soils, although in higher fertility soils tolerates dry conditions.

Wood usage/potential. Wood is resistant and hardy, light in colour with straight grains (Nienstaedt & Zasada, 1990). Mainly used for either pulpwood or construction timber. Rarely, for musical instruments or utensils.

Introduction risks. In native range is susceptible to fire and frost damage in young stands due to slow root system development (Nienstaedt & Zasada, 1990). Susceptible to windthrows in moist or poor fertility soils, or after heavy thinning, heavy snowfall, browsing and has range of effecting diseases and pests. Equivalent risks could be expected in Swedish sites. Invasiveness potential is unclear.

3.1.5 Black spruce (*Picea mariana*)

Characteristics. Conifer tree species (Navasaitis, 2004). In height often reaches 20m, in exceptionally good conditions grow up to 30-33m. Mean diameter is measured to 0.5m. Crown is narrower and conic. Bark is reddish brown and scaly. Shoots are lighter reddish brown, densely hairy. Buds are oval shaped, brownish and pointy. Needles are 6-12mm length, both pointy or blunt, quadrilateral and green with blueish undertone. Needles grow densely and are slimmer and softer than the white spruce needles. Has small (2-3.5cm) oval cones coloured brown greyish. Cone scales are smooth, rigid, mostly rounded in some cases slightly pointy with jagged edges. Seeds are small 2-3mm in length, coloured brownish or slightly black and have 1cm long wings.

Soil requirements. Grows on a variety of soil types and conditions (Viereck & Johnston, 1990). In native range often prefers wet organic soil type, common in peat bogs or swamps. Rather intolerant to dry periods, droughts or dry soil conditions. Productive on both rich and poor fertility conditions. Suitable soil types include loamy, sandy, coarser till and clay soils.

Wood usage/potential. Timber is light, yellow or creamy-white with even and straight grains (Viereck & Johnston, 1990). Commercially used for pulpwood production, lumber and other wood products. Could be grown in the Christmas tree plantations. Historically was used for more specialized products such as resin production for healing salves, needles were used for aromatic essential oil creation and as binding material or for making canoes.

Introduction risks. Seedlings originating from southern provenances were susceptible to autumn and spring frosts, while northern provenance seedlings were hardier and less susceptible than Norway spruce (Ståhl & Persson, 1992). In native range is effected by several rust genus, and a few other diseases and pests (Viereck & Johnston 1990). In northern native range the biggest cause of mortality is windthrows and breakages (Viereck & Johnston, 1990).

3.1.6 Sitka spruce (*Picea sitchensis*)

Characteristics. Pioneer conifer tree species known for the fast growth (Durrant et al., 2016). Usually has a straight trunk with a conic crown, branches grow horizontally. The reddish-brown tree bark has larger scales and is relatively thin. Needles are 1.5-2.5cm long, sharp and often vary in colour- ranging from darker blueish green to lighter yellow- green. Seed production by wind-pollination begins at approximately 20 to 25 years. It produces both 2-4cm red pollen cones and 5-10cm papery, irregularly shaped scale seed cones. Seeds are small (2-3mm) with a larger (8mm) wing. In a native region of North America and Canada could reach up to 100m of height. However, in European forests maximum growth is reported to rarely surpass the height of 50m.

Soil requirements. Sitka spruce grows in a range of soil fertilities (Durrant et al., 2016). Prefers high moisture humid soils. Intolerant to dry or water-logged soils. Grows well in wet coastal uplands due to tolerance for high salt exposures. Although does not tolerate high atmospheric pollution. As many other conifer species, has an ability to acidify the soil.

Wood usage/potential. Timber is pale, light, long fibered, has a good strength to weight ratio, usually is knot free (Durrant et al., 2016). Considering the good qualities it has, the usage of its timber is wide- paper production, general construction, fencing, pallets, soundboards for musical instruments. Its root tensile strength makes it applicable for bioengineering applications.

Introduction risks. Susceptible to wind damages and windthrows, although on certain soils is more resilient than Norway spruce (Durrant et al., 2016). It is prone to fungal diseases in case of injury and is highly susceptible to the damages of large pine weevil (*Hylobius abietis*).

3.1.7 Lodgepole pine (*Pinus contorta*)

Characteristics. Fast-growing conifer tree species (Lowery, 1984). Has a few geographical variations which have distinct differences. Var. *latifolia*, coming from the inlands of America, nowadays is commonly used for timber production due to the more productive characteristic. Trunk growth is straight and tall, at the age of maturity reaching from 13m to 27m of height, in excellent conditions could grow upwards to 50m. Bark is thin, scaly and has brown orang-greyish colour variations. The green-yellowish needles are long 3-7cm, twisted. Species has an average life span of 300-400 years. However, production of cones could begin as early as 10 years. Monoecious, produces both pollen cones (cylindric, orangish and 5-14mm long) and seed cones. Lightly coloured brown-yellowish seed cones are around 5cm long and have a recurved conic-rhombic like spiky appearance. Cones are serotinous and have a prolonged opening time (could stay closed for even 10-20 years). Seed release is triggered by high temperature upwards of 45°C which could be caused by solar radiation. Although often spreading of seeds is caused by the wildfires or controlled burnings.

Soil requirements. Grows on a variety of soils from very poor to very fertile, however the most productive growth is expected in well-aerated, acidic, sandy or loamy soils (Lowery, 1984).

Wood usage/potential. Timber has medium-fine and straight grained texture; sapwood is narrow and coloured slightly yellowish or white (Lowery, 1984). Heartwood is similar and often just slightly darker than the sapwood. Wood is light and soft. Timber could be used for construction work, manufacturing plywood or veneer, pulpwood or firewood.

Risks. In Sweden lodgepole pine is known to have a few damaging agents. On harsher sites *Gremmeniella abietina* damages younger trees causing mortality or stem defects (Karlman 1993). According to Lindelöw & Björkman (2001) is majorly effected by *Otiorhynchus nodosus*, *Strophosoma capitatum*, *Ankhonomus phyllocola*, *Hylobius abietis*, *Pissodes validirostris*, *Neodiprion sertifer*, *Rhyacionia buoliana* and *Actebia fennica*. Moreover, it is much more susceptible to wind or snow damage compared to the Scots pine (Elfving et al., 2001).

3.1.8 Douglas fir (*Pseudotsuga menziesii*)

Characteristics. Large-sized fast growing conifer species (Da Ronch et al., 2016). Has a column like shape with a short crown and a cylindrical trunk. Bark is thick and varies in colour from brown reddish to slightly grey, blackish. Older trees have a broad, scaly bark with deep ridges and furrows. Needles are 2-3.5cm long, located spirally around the twig with blueish-green top of the needles, while bottom has two distinct white-greenish lines. Long living species as is could reach well over 1300 years. Maturity and cone production begins approximately between 12-15 years. It is monoecious. Brown-yellowish pollen cones are around 10-20mm. Before pollination seed cones are longer (4-9cm), green and erect, after maturing-pendant brown-yellowish or purplish. Seeds are 5-7mm with a 10-12mm wing. In full potential height could grow to 60-80m. In the native north-western America occasionally grows over 100m. Often a pioneer tree species, spreads after forest fires. However, tolerates shade and grows well in secondary successional forests.

Soil conditions. Tolerates a range of soil conditions (Da Ronch et al., 2016). Although, most suitable are wet and well-aerated soils. It has an ability to acidify soil. In the similar conditions it has more resilience for droughts than Norway spruce.

Wood usage/potential. Timber is hard, relatively heavy and particularly strong (Da Ronch et al., 2016). Has a very clear distinction in colour between sapwood and heartwood. From light yellow-white sapwood to darker brown-reddish heartwood. Used for construction work, joinery, for making veneer, panel of fibres or particles and for pulpwood.

Introduction risks. Douglas fir has a few viable threats- many species of fungi causing rot, large pine weevil (*Hylobius abietis*) and other species such as woolly aphid (*Adelges cooleyi*) which damage younger trees and cause deformations (Da Ronch et al. 2016). Ecological risks are believed to be minimal due to its similarities in forming abiotic environment- forms similar habitat to native species, for example is similar to Norway spruce in ground-level vegetation and arthropod populations (Schmid et al., 2014).

3.1.9 Grand fir (*Abies grandis*)

Characteristics. Conifer tree species (Navasaitis, 2004). Commonly grows 30-60m in height and reach a diameter of 0.5-1m. Crown is wide 5-8m, conic. Bark on younger trees tend to be smooth, brown and with many resin halves, while the older trees have a smaller deeply splitter bark. Buds are small, round and have resin. Shoots are brown-yellowish and hairy. Needle 3-5cm length and 2mm width. The upper part of needles is glossy green colour, while lower has silvery white colour. On the branch, length wise, needles are located on the sides. Cones are brown-greyish, 5-10cm length and 4cm width. Seed production begins at approximately 20 years. Seeds are light brown and have a length of 5-8mm with a 2cm wings.

Soil requirements. Grows in various soil conditions and has little requirements for the site. In the North America coastal region grows best on fertile alluvial soils near water bodies and in the inlands best growth is achieved in fertile mineral or pure pumice soils (US Department of Agriculture, Forest Service, 1965).

Wood usage/potential. Wood of the grand fir is light colour, ranging from light almost white to the lighter brown with reddish undertones (Foiles, 1959). It has straight grains and is considered easily workable. Its softwood is a good source for a pulpwood production, as well as for producing timber. Due to its characteristic's species could be used in Christmas tree plantations.

Introduction risks. In the native range has shown a good adaptation for withstanding cold weather and resistance to frosts (Foiles, 1959). Younger stands are susceptible to some mortality accounted to snow. Generally, is resistant to storm damage, although some windthrows may happen in case the individual tree is effected by fungi damage. It is susceptible to a few types of fungi- *Echinodontium tinctorium*, *Armillaria mellea*, *Poria weirii*, *Poria subacida* and *Fomes annosus*. Pest damage include few species of budworm, bark beetles and moths. Has an intermediate resilience against forest fires.

3.1.10 Balsam Poplar (*Populus balsamifera*)

Characteristics. A hardwood species reaching around 20-25m height (Navasaitis, 2004). The crown is roundish or oval with ascending branches. Is a quick growing species and on average reach up to 0.5-0.9m diameter. Has a light grey or brown smooth bark which near the ground tend to have deeper fissures. Leaves are oval with heart-like base, tapered tip and jagged edges. In length grow to 6-10cm and in width 5-9cm. The upper side is bright green, glossy, leathery, the bottom is lighter, almost white with rust-coloured veins. The petiole is round and relatively hairy. The shoots are dark brown, glossy and round. Buds are very fragrant, yellow, glossy and sticky. The mature flower catnips have a length of 5-9cm. Regeneration often occurs by vegetative shoots.

Soil requirements. Grows in various soil types and soil moistures (Crist & Schlaegel, 1979). The best growth occurs in well moistened soils (e.g., river valleys), however the excess of moisture is not well tolerated, similarly with the dryer sites. Recommended soil types for the best production are deep sandy or gravelly soils.

Wood usage/potential. Sapwood is very light creamy or almost white, the heartwood is light brown or darker brown, almost reddish (Crist & Schlaegel, 1979). The wood is light in weight, soft, is easily workable (Zasada & Phipps, 1990). Lacks the ability to withstand exposure to weathering and tends to be non-durable. Used for timber production; in the northern regions is a good substitute for structural house development. Production for plywood, pulp and veneer is common. Species is valued for the aesthetic properties- common in city parks, during the spring flowering buds have a very fragrant scent. Fragrant buds and other parts could be used for making essential oils, ointments and salves.

Introduction risks. In the native range is rarely susceptible to uprooting during the floodings, premature trees could be killed or damaged by fires (Roe, 1958). Species has few associated pests- leaf eating caterpillars/bugs (*Malacosoma disstria*, *Tingidae*), poplar borer (*Saperda calcarata*), weevil (*Cryptorhynchus lapathi*). Leaves are effected by various pathogens causing spotting or rust (*Melampsora*). Wood is effected by heart (*Fomes igniarius*) and butt (*Armillaria mellea*) rot. Browsing is often a common issue, frequently gets damaged by moose, hares, deer and beavers.

3.1.11 Hybrid larch (Larix x eurolepis)

Characteristics. Morphological characteristics of hybrid larch are often indistinguishable from the parent larch species (Larsson-Stern, 2003). In other cases, hybrids tend to be a middle cross of both parent species, taking some characteristics from one and some from the other. Crown shape tends to be similar, slightly narrower, to the Japanese larch. Has ascending tips of the branches and brownish, slightly downy shoots. Buds do not have any resin and are yellowish brown colour. Blueish-green needles could be similar to the Japanese larch- longer and rather wide or could be smaller. Cones are small, conic. The hybrid rarely occurs naturally, and seed production is often done in the orchards.

Soil requirements. Moderately fertile soils are recommended (Larsson-Stern, 2003). Based on the site conditions in southern Sweden it grows best on the same sites as Norway spruce. Productive growth is seen in high fertility soils as well. However, it is noted that in such site conditions hybrid larch has poor stem quality. Moisture availability must be moderate.

Wood usage/potential. Wood is dense and has high hardiness (Larsson-Stern, 2012). Has an excessive amount of resin, in some cases making the sawing process harder. The usage is wide- plywood, pulp, timber for wall boarding both inside and outside the houses, flooring, window frames, furniture, play equipment and other.

Risks. The main insects which cause damage in Sweden are pine weevil (*Hylobius abietis* L.), *Coleophora laricella*, *Argyresthia laevigatella* and *Pristiphora erichsonii* (Larsson-Stern 2003). Susceptible to root and butt rot infections- it is an important factor to consider if the land was previously effected by root or butt rot pathogens (Stener & Ahlberg, 2002). Generally, has good frost and drought resistance, although suffers from early spring frosts and late summer droughts (Larsson-Stern, 2003). If compared with Norway spruce it has a lower risk of storm damage (Subramanian, 2016).

3.1.12 Hybrid aspen (*Populus tremula* × *Populus tremuloides*)

Characteristics. The parent species- European aspen and trembling aspen, genetically are very similar (Cervera et al., 2005). Despite the fact, hybrid aspen growth during the first 20-30 years is faster than the parent species (Tullus et al., 2012). In the northern Europe it is one of the fastest growing species. Phenotypically very similar to parent species and the only distinguishable difference is leaf shape. The leaves by shape are similar to trembling aspen- oval, tapering at the tip, lighter green, however hybrids have a coarser jagged-toothed edges. Similarly, to most *Populus* species hybrid aspen exhibits leaf dimorphism- more apparent during the early age leaf shapes vary by size and shape based on the earliness of growth.

Soil requirements. The best soils for the fastest growth could be achieved in fertile, nutrient rich soils (Tullus et al., 2012). Preferred soil types are lighter sandy-loams and loamy-sands. The soil moisture has to be moderate with good aeration. On the former agricultural lands tends to have a very productive growth.

Wood usage/potential. Wood is light, almost white in colour (lighter colour than European aspen) (Tullus et al., 2012). Commonly grown in the short rotation plantations. The wood is used for plywood, pulp, paper, biofuel and for making matches. Due to its properties wood is especially suitable for the paper production. Has a high concentration of cellulose, and the light colour allows the lesser usage of chemical making the paper production more environmentally friendly.

Risks. Damaged by pathogen outbreaks. Susceptible to canker causing fungi (*Neofabraea populi*, *Entoleuca mammata*, *Leucostoma niveum*, *Venturia tremulae*, *Xanthomonas populi*) (Tullus et al., 2012). However, damage of *Phellinus tremulae*, *Venturia tremulae* and *Melampsora pinitorqua* is less prevalent than in the European aspen stands. The most harmful insects are small poplar borer (*Saperda populnea*) and large poplar borer (*Saperda carcharias*). Younger plantations could be damaged by poplar leaf beetle (*Chrysomela populi*) which cause defoliation. The high risks include browsing by herbivores- roe deer, red deer, moose, several rodent species and hares. The common solution is fencing or repellent usage. Abiotic damages are not as prevalent, and highly depend on the hybrid parent species geographical origin regions.

3.2 Some comparisons between sites and total volume

Native species performance across all three productivity gradients showed that in the low productivity total volume yield was the highest for Scots pine (Fig. 5). Scots pine had 2.2 times higher total volume than Norway spruce and 1.8 times higher than silver birch. Moderate and high productivity sites had only two native tree species- Norway spruce and silver birch (Fig 6, 7). Both sites were better suited for Norway spruce. Norway spruce volume growth at the age 30 was higher than volume of silver birch (in moderate productivity higher by 23.1%, in high productivity higher by 58.1%).

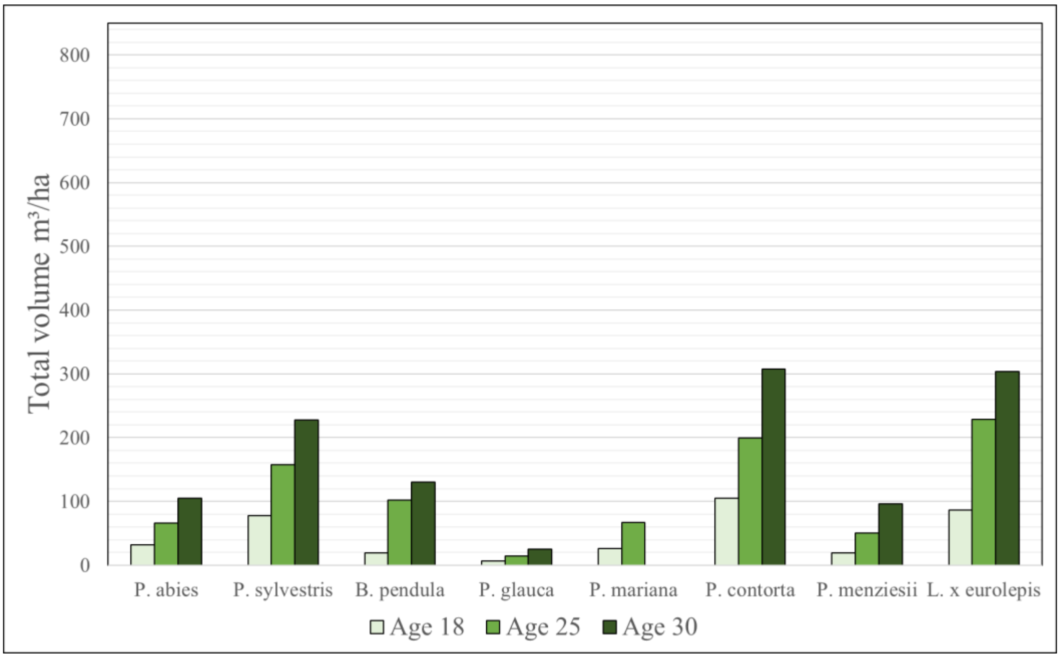

Figure 5. Total volume comparison between different tree species and age groups in low productivity sites

Silver birch in the low productivity produced less volume than Scots pine but yielded slightly higher volume than Norway spruce. Between the productivity sites, total volume of silver birch in the high productivity was the highest. Although, if compared with Norway spruce total volume, the high productivity had the biggest difference. At the age 30, in the high productivity silver birch volume was lower by 349.5 m3/ha, in the moderate- 55 m3/ha than Norway spruce. In the low productivity site silver birch total volume, compared to Norway spruce, was higher by 24.9 m3/ha. In comparison, by the age 30 silver birch out of all tree species grown in the high productivity site had the lowest volume.

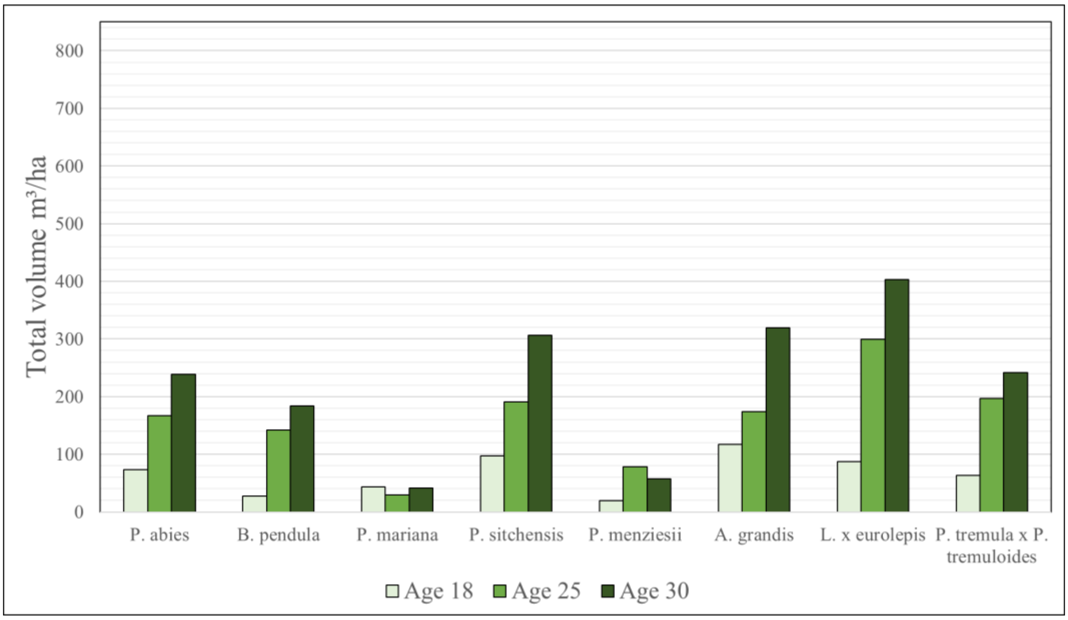

Figure 6. Total volume comparison between different tree species and age groups in moderate productivity sites

The introduced species total volume yield varied greatly between the different productivity sites. In the low productivity hybrid larch and lodgepole pine both exceeded the volume yield of Scots pine. Both species at the age 30 had reached the greatest total volume (hybrid larch lower by 1.1%). Lodgepole pine total volume was higher than of the Scots pine in all measured age groups. Although, high volume of the lodgepole pine correlated with the high number of stems in the sites (on average by the age 30 lodgepole pine had 2174 number of stems, while Scots pine had 867 number of stems). In the Scots pine stands a single tree has 1.85 times higher total volume than the lodgepole pine. While the hybrid larch by the age 30 had 534 number of stems which resulted in one stem of hybrid larch having 2.17 times more volume than one Scots pine stem and 4.03 times more volume than one lodgepole pine stem. Douglas fir, black spruce and white spruce total volume development was inferior to all of the native species. Douglas fir volume was slightly lower than the Norway spruce (on average was lower by 8.6 m^3/ha). Both black spruce and white spruce total volume was significantly lower in comparison to other both native and introduced species.

In the moderate productivity introduced species had a tendency to have a better performance than the native ones (4 of the 6 species yielded higher total volume than Norway spruce). Significantly higher volume growth was observed in the Sitka spruce, grand fir and hybrid larch yield (respectively 22.2%, 25.4% and 40.8% higher volume yield at age 30 in comparison to the Norway spruce). Generally, total volume of the hybrid aspen was nearly equal to the Norway spruce. The black spruce developed similarly as in the low productivity, although in the moderate productivity had the lowest total volume. While the total volume of Douglas fir was slightly better than of the black spruce, it yielded 40.4% less volume than in the low productivity site.

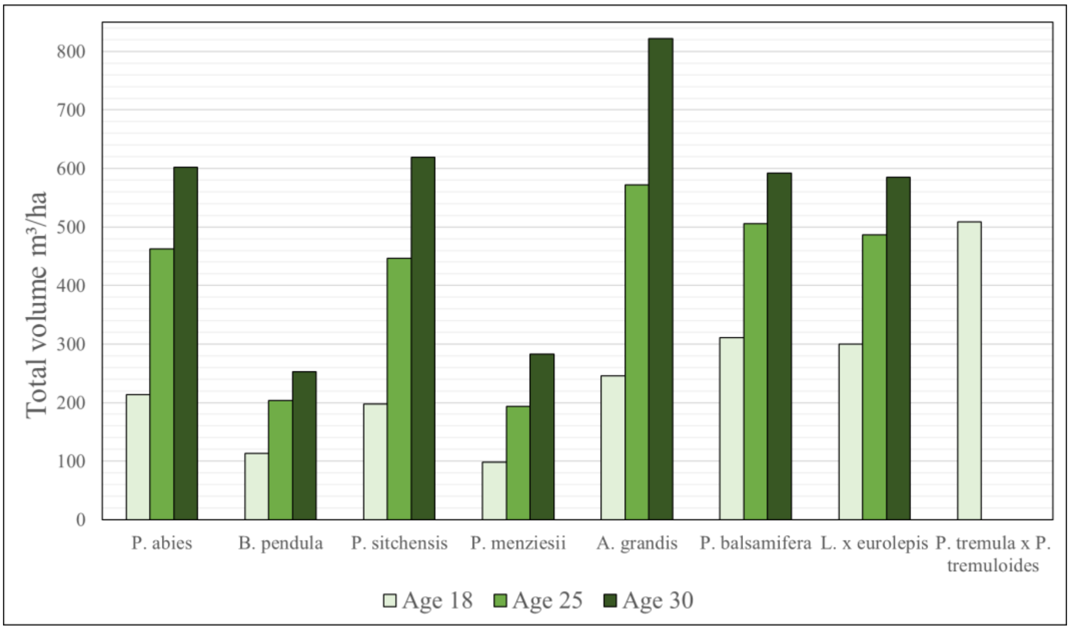

Figure 7. Total volume comparison between different tree species and age groups in high productivity sites

The high productivity site yielded the highest total volume within the whole productivity gradients. Exceptionally high total volume yield has been developed by grand fir. At the age 30 grand fir has 26.7% higher total volume than the Norway spruce. In comparison both Sitka spruce and Norway spruce had similar growth-Sitka spruce had slightly higher volume than the Norway spruce, although the difference was not significant. By comparing the results from both moderate and high productivity sites, it was evident that despite the higher volume, Sitka spruce performed better in the moderate productivity (in the moderate at the age 30 Sitka spruce yields 22.2% higher volume than the Norway spruce). The total volume of balsam poplar and hybrid larch was slightly lower (respectively 1.6% and 2.9% at the age 30), although the difference was not significant. By the age 18 both introduced species growth was the second highest, however the following two remeasurement showed an increment growth decline. Between all of the productivity gradients Douglas fir growth in the high productivity seemingly produced the best total volume. Regardless, in comparison with other tree species volume was on the lower end, often below the native species.

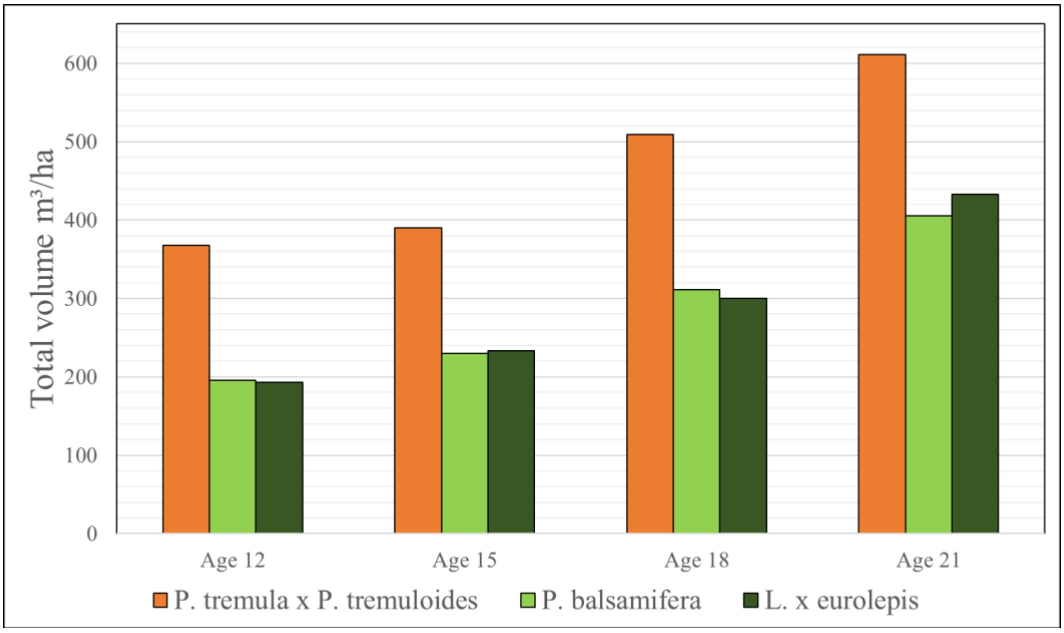

Figure 8. Total volume comparison between different tree species and age groups in high productivity

The early development of hybrid aspen, hybrid larch and balsam poplar in the high productivity demonstrated fast-growing species comparison (Fig. 12). The total volume of hybrid aspen was substantially higher in all age remeasurements. At the age 21 hybrid aspen has reached the total volume equivalent to the age 30 Norway spruce. The total volume of balsam poplar and hybrid larch developed correspondingly. Both of the species had fast-growth in the earlier age, although the total volume of the hybrid aspen was significantly higher in all of the age measurements. In comparison between the gradients, the high productivity was best suited for the hybrid aspen as total volume of the age 12 in high productivity was higher than of the age 30 in moderate productivity.

3.2.1 Norway spruce basal area

The results of Norway spruce basal area development provide two insights (Fig. 5). First, it demonstrates a trend of higher BA values as the site productivity increases. Norway spruce in the moderate productivity has higher basal area values than in the low productivity, similarly as the high productivity has higher basal area values than the moderate productivity. Second, with the higher site productivity basal area of Norway spruce increases faster and requires more intense management measures. For example, in five years between the age 25 and 30 in the high productivity sites basal area on average increased by 33.35m^2/ha. While in the low productivity average increase was 4.17m^2/ha, leading to 8 times higher basal area growth in the high productivity sites. Evidently, the rapid increase in the high productivity leads to a more frequent and more intense thinnings which where the case for most of the species grown in high productivity site.

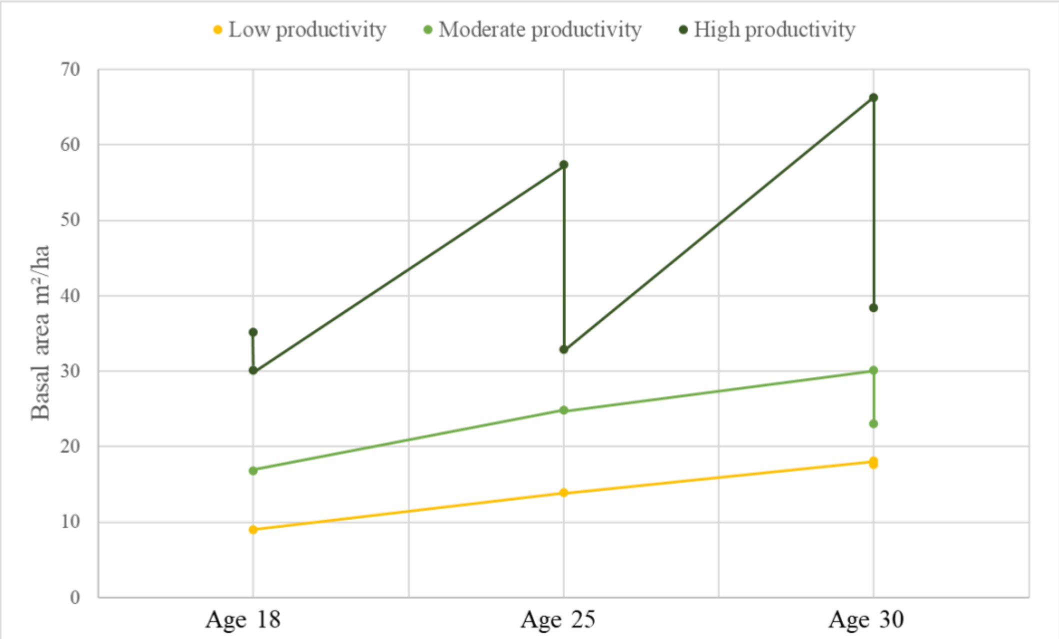

Figure 9. Basal area development of Norway spruce in three productivity sites

3.2.2 Norway spruce, Scots pine and lodgepole pine

In comparison Norway spruce basal area development in the low productivity sites were lesser than of Scots pine or lodgepole pine (Fig. 6). Scots pine development followed typical management practices. Optimally thinned Scots pine by the age 30 formed stands with around 830-886 number of stems/ha. Contrary, lodgepole pine was managed by excluding the stands from thinning which resulted in higher basal area with almost equal values between total and standing basal area lowered by self-thinning (2099-2289 number of stems at age 30).

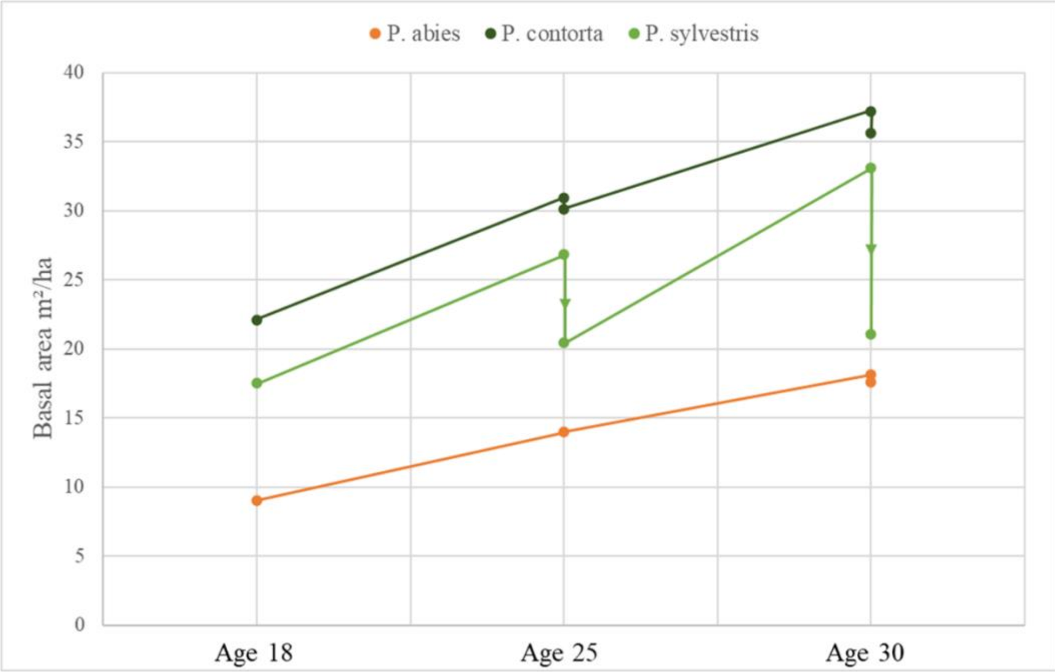

Figure 10. Basal area development of Scots pine, lodgepole pine and Norway spruce in low productivity

3.2.3 Norway spruce, Sitka spruce and black spruce

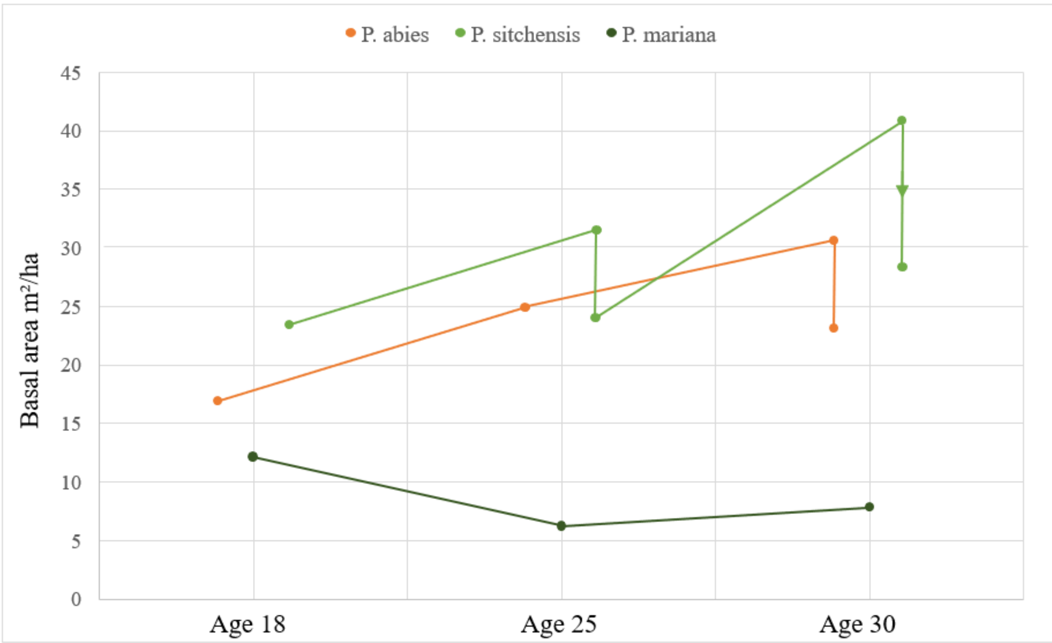

Figure 11. Basal area development of Norway spruce, Sitka spruce and black spruce in moderate productivity

In the moderate productivity an average basal area development of Sitka spruce surpassed the growth of Norway spruce (Fig. 7). Between the age 18 and 25 growth increments were similar (Norway spruce- 8m²/ha, Sitka spruce- 8.2m²/ha), contrary to the basal area growth between the age 25 and 30 (Sitka spruce growth was 3.2 times higher: increment of Norway spruce-5.3m²/ha; Sitka spruce- 16.8m²/ha). On the other hand, if we looked at the black spruce basal area development and growth an opposite effect was observed. During the early growth between the age 18 and 25 basal area dropped by 5.9m²/ha. At the age 18, BA was higher than of the latest measurement in the age 30.

3.2.4 Grand fir, balsam poplar and hybrid larch

Besides Norway spruce, in the high productivity sites both introduced and native species basal area developed somewhat similarly. The three fast-growing introduced species between the remeasurements had a significant basal area growth (Fig. 8). Despite different growth outcomes, growth increments were consistent. The growth of basal area between the ages 18 to 25 on average reached 31-33.5m²/ha, while growth between the ages 25-30 varied slightly more (33-48m²/ha).

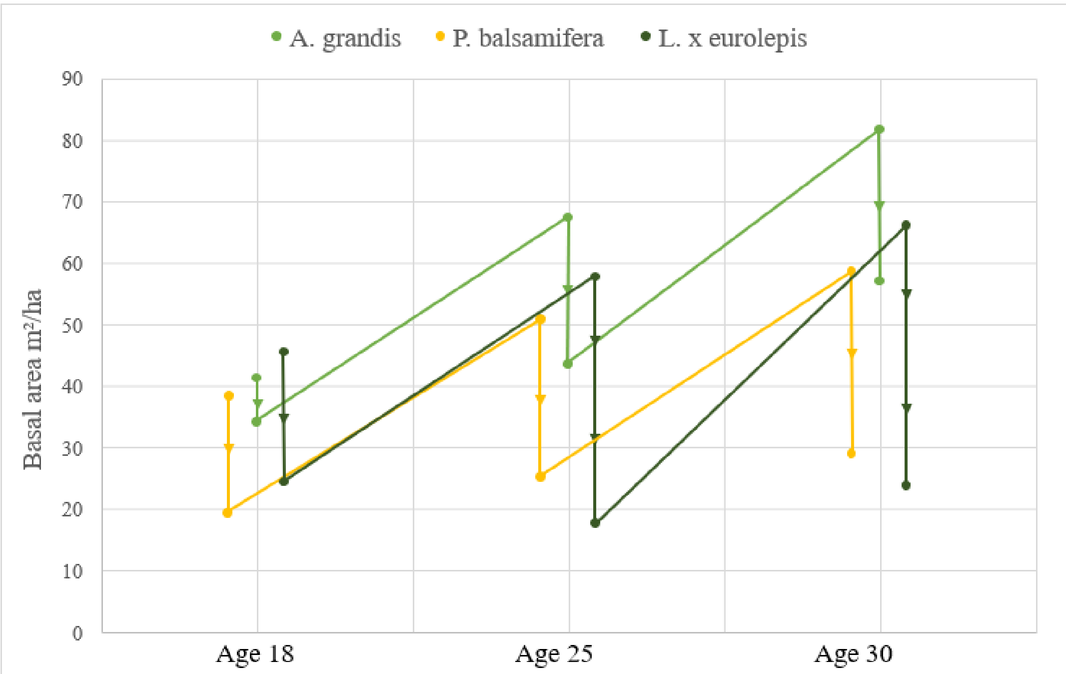

Figure 12. Basal area development of grand fir, balsam poplar and hybrid larch in high productivity

3.3 Average diameter and height

The greatest average diameter was measured for the balsam poplar in the high productivity (Table 3). Similarly, height was the highest (30.50m), except in the age 18 remeasurement in which the highest height was measured by the hybrid aspen (27.03m). Unlike in the low and moderate productivity sites, all species in the high productivity by the age 30 had reached diameter over 20cm. In comparison, hybrid larch in the low productivity was the only species which diameter measured above 20cm. During the latest remeasurement hybrid larch height between the moderate productivity (23.23m) and high productivity (23.60m) had no significant difference, although in the low productivity was slightly lower (19.67m). Notably hybrid larch had the highest average height and diameter between all of the species in the low and moderate productivity sites. In the low productivity hybrid larch diameter measurements are followed up by the Scots pine, while the height measurements between Scots pine, lodgepole pine and silver birch were relatively identical (respectively 15.60m, 15.67m and 15.40m). Interestingly, both average height and diameter of silver birch in all of the productivity sites was superior to the Norway spruce. Though the Norway spruce remained in the middle, having neither the highest nor the lowest measurements. Rather the worst development of both height and diameter was measured for white and black spruces (in the moderate productivity by age 30 black spruce average height reached only 3.47m).

Table 3. Average diameter measurements in different productivity sites at age 30 (cm)

Species	Low productivity	Moderate productivity	High productivity
Norway spruce	10.3	15.5	25.5
Scots pine	17.6	-	-
Silver birch	14	16.1	26.3
White spruce	8.4	-	-
Black spruce	-	3.9	-
Sitka spruce	-	19.7	24.3
Lodgepole pine	14.5	-	-
Douglas fir	12	8.4	21.1
Grand fir	-	19.9	29.7
Balsam poplar	-	-	38.2
Hybrid larch	21.7	28	29.7
Hybrid aspen	-	20.8	-

Norway spruce, Sitka spruce, silver birch, hybrid larch and grand fir height developed gradually and grew higher with the more productive sites. Although Douglas fir proved to be an exception to the rule as the development in the moderate productivity was comparably slower than in the low productivity.

4. Discussion

The tree species introduction is a relevant discussion topic in the forestry field. Nowadays, introduction of the non-native tree species is recognised for the potential to be both profitable and effective solution in the climate change and ecology context (Vacek et al., 2021; Hanewinkel & Knook, 2016). Although, the benefits are often considered with the precaution and highlight the downsides with a more sceptical outlook (van Wilgen, 2016; Ennos et al., 2019; Simberloff et al., 2005). At the moment, tree species introduction in Sweden is limited by the legislations and forest certifications (Rytter et al., 2016), which resulted in smaller non-native species percentage.

The research results revealed a potential of a few studied native and introduced species. Site productivity is one of the key factors contributing to the successful maximisation of yield. While most of the species performed better with increasing fertility, all displayed different tendencies towards the growth increments.

In Sweden Norway spruce takes up 39.7% of the total forest land area and is one of the most economically important species (Nilsson et al., 2021). However, due to the climate change Norway spruce vitality and maladjustment is becoming more and more concerning- root rot infections, bark beetle (*Ips typographus*) attacks and major storms combination will cause a reduction of land expectation value (Subramanian et al., 2015). In 2005 storm Gudrun drastically damaged southern Swedish forests resulting in the approximately 70 million m3 felled trees, majority of which were Norway spruce (Valinger et al., 2019). The amount of felled timber was equivalent to the yearly timber production of Sweden. The forecasted future climate implies an increase in the occurrence of severe storms, potentially resulting in significant financial damages. Many strategies for the climate change adaptation support the non-native tree species introduction (Mason et al., 2012; Bolte et al., 2009). However, the species introduction implementation should not be considered as a “one size fits all” solution- non-native species, similarly as native, may have various adaptability to changing climate conditions and each species should be evaluated separately (Sousa-Silva et al., 2018). A great example is the two introduced species- white spruce and black spruce. Several factors, including warmer winters (Egorov & Afonin, 2018) and low productivity site conditions (Nienstaedt & Zasada, 1990), may explain the poor growth of white spruce. Due to the changing climate conditions, even in their native North American forests, both species are facing adverse effects, suggesting that they may no longer be suitable for southern Sweden (Sniderhan et al., 2021; Billah & Goldblum, 2019). A more coastal North American Sitka spruce appears to be well adapted for the southern Swedish climate. Prior study of Sitka spruce suggests that it could be a suitable and productive alternative to Norway spruce in south-western Swedish coast (López-Andújar Fustel, 2019). To add on, results of Norway spruce and Sitka spruce early growth implicate that in the moderate productivity Sitka spruce growth was superior. Previous research by Karlberg (1961) of Douglas fir and comparison with Norway spruce in southern Sweden determined that total yield of Douglas fir in poorer, sandy soils with low clay consistence was much higher than of Norway spruce. In contrast results obtained from the three productivity sites demonstrate that Douglas fir yield was lower, although the difference between the two was lowest in the low productivity site. Unfortunately, the comparison was not possible on the moderate sites due to damage in the Douglas fir plots, leading to a complete elimination of one plot between age 25-30. A recent analysis of Douglas fir growth and susceptibility in Europe revealed that growth performance has declined due to changing climate (Nicolescu et al., 2023). Douglas fir is more sensitive to the longer drought periods, windthrows as much as Norway spruce and various pests and diseases common in Norway spruce and Scots pine forests (Nicolescu et al., 2023). On the other hand, there is a lack of available research on the growth of grand fir in southern Sweden. Conversely, the grand fir demonstrated exceptional yield results in both moderate and high productivity sites. While in the moderate productivity grand fir grew similarly as Sitka spruce, in the high productivity it yielded highest values. According to Rytter et al., (2016) growth of grand fir, Sitka spruce and Norway spruce in the later growth stages becomes more productive. Grand fir growth becomes more productive after 50 years, while growth of Sitka spruce has most efficiency between 70-115 years (Rytter et al., 2016). Longer rotation period might be suitable for grand fir, in fact previous studies highlight higher yield (by 65-70%) compared to Norway spruce.

In Sweden, comparisons between Scots pine and lodgepole pine are common, with the latter often being determined as superior in regard to yield growth (Norgren, 1996; Varmola et al., 2000), while the climate change appears to have significantly increased risks for damages (Dempster, 2022). Prior research on the forestry adaptation to climate change suggests that management of shorter rotations with reduced thinning intensity minimises the associated risks (Dempster, 2022). Such practises were applied to the management of lodgepole pine in low productivity site. In my study, the low productivity out of the three native species was best suited for the Scots pine. Comparably, the growth of the two pine species differed as Scots pine was thinned, while lodgepole pine was left unthinned. The higher yield of lodgepole pine was reflected by high stand density which resulted in smaller tree diameter. Further development of lodgepole pine in the second half of rotation period is expected to slow down therefore resulting in a higher yield of Scots pine (McCarter & Long, 1986).

In the past few decades silver birch has become a valuable part of Swedish forestry. Yet, based on the results yield of silver birch often is lower compared to both Norway spruce and Scots pine. Although, more recent studies provided promising results from tree breeding and genetically improved plantations (Liziniewicz et al., 2022; Gailis et al., 2020). In addition, silver birch is deemed as a resilient species, well-suited for the impacts of climate change and advantageous for biodiversity (Mielikäinen & Hynynen, 2003; ALRahahleh et al., 2018). As a result, one of the recommended approaches to mitigate the effects of climate change and enhance biodiversity is to plant a mixtures of Norway spruce and silver birch (Felton et al., 2016). Overall, the most potential was seen in low and moderate productivity sites as in high productivity silver birch produced nearly two times lower yield than other native and introduced species. Notably, the two deciduous species, balsam poplar and hybrid aspen, exhibited high yield production in high productivity. Specifically, the fast early growth of hybrid aspen is notable for usage in short rotation plantations in previous agricultural sites in Sweden (Karacic et al., 2003), Finland (Hytönen, 2018), Estonia (Tullus et al., 2007; Tullus et al., 2009), Germany (Liesebach et al., 1999) and other. Based on the results hybrid aspen appears to be the most suitable species, out of the twelve analysed, for the short rotation period plantations.

Hybrid larch showed rapid early growth in all three productivity sites. The available previous research provides extensive analysis of growth in southern Sweden. Discussions of the species potential (Larsson-Stern, 2003; Larsson-Stern, 2012) and growth in different productivity sites (Johansson, 2012; Ekö et al., 2004) have been examined. As reported by Larsson-Stern (2003) the best growth occurs from moderate to high fertility sites, while growth in the low productivity was deemed as too limiting to yield higher volume. Similarly, results of hybrid larch demonstrated that the most efficient and highly potential growth was in moderate and high productivity sites. Ekö et al. (2004) acknowledges potential and suggests that hybrid larch could be an excellent substitute for Norway spruce. Regarding the low productivity sites, the early growth of hybrid larch at the age of 30 shows great potential. My results from the low productivity sites revealed that hybrid larch had one of the highest total volume, surpassing Scots pine. Although the best growth was achieved in moderate and high productivities, the overall broader evaluation between a few native and introduced species suggests a great potential in low productivity.

5. Conclusion

This study provides a better understanding of native and introduced tree species potential. Tree species experiments are a valuable tool to gain an insight of strengths and weaknesses both between and within each of the low, moderate and high productivity sites. In light of the upcoming challenges posed by climate change, it is important to explore all viable options, including introduction of the non-native tree species. The early growth of non-native Sitka spruce, grand fir, balsam poplar, hybrid larch and hybrid aspen showed mostly promising results. Introduced species, similar to the native, have certain site characteristics in which the most productive growth is expected. The highly suitable sites resulted in superior growth compared to native Norway spruce, Scots pine or silver birch. While other introduced species showed opposite tendencies. The growth and yield limitations are already evident for black spruce, white spruce, lodgepole pine and Douglas fir. However, to support the estimations of each species potential, future evaluations during the second half of the rotation period will be necessary.

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