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Department of Forest Resource Management

Pine Production Comparison

– Production potential of Loblolly pine (Pinus taeda) and Slash pine (Pinus elliottii) in the southeastern USA in relation to initial density and forest management

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Abstract

The southeastern (SE) United States (US) produces more industrial timber than any other region in the world. Pine plantations in the southern US have increased from 1.8 million acres (728,400 ha) in the beginning of the 1950's to 32 million acres (13 million ha) in the beginning of the 21st century, and cover 17 % of the forest land. Both the increase in area and productivity over time is remarkable. The increase in productivity is due, in part, to more intensive silviculture methods. Both loblolly and slash pine are being managed intensively in plantations today. In Sweden, another country with large industrial pine timber production, the productivity also has increased over the past 100 years, mainly due to more efficient forest management.

Research about productivity in SE US pine plantations has since 1975 been done by the Plantation Management Research Cooperative (PMRC) at the University of Georgia. One of their culture/density studies evaluates how management intensity and planting density affect growth and yield of loblolly and slash pine. Evaluation was done using ANOVA analysis in R, and the results from the analysis were compared with trends from scots pine trials in Sweden through a literature study. Additionally, this study also evaluated whether or not these forest management practices are sustainable for production.

The results showed that loblolly pine performs better than slash pine across a range of different management intensities and planting densities. It also showed that the intensive treatment, and the 300 and 1500 trees per acre (TPA) planting densities (741 and 3,705 trees per hectare) had largest impact in terms of productivity of different stand-level measures in pine plantations. More intensive treatments could be applied in Sweden if the regulations would allow it, and those treatments would be sustainable from the perspective of reduction in greenhouse gas emissions, sources to bioenergy and biofuels, and for the economy.

Keywords: Loblolly pine, Slash pine, Scots pine, management intensity, planting density

Sammanfattning

Sydöstra USA producerar mer industriellt timmer än någon annan region i världen. Tallplantagerna i södra USA har ökat från 1.8 miljoner acres (728,400 ha) i början av 1950-talet till 32 miljoner acres (13 miljoner ha) i början av 2000-talet, och täcker idag 17 % av skogsmarken. Både ökningen i landareal och i produktivitet är anmärkningsvärd. Ökningen i produktivitet beror främst på mer intensiva skötselmetoder då både loblolly-tallen och slash-tallen är intensivt skötta i dagens plantageskogsbruk. Även i Sverige har produktiviteten i skogsbruket, och för tall, ökat under de senaste 100 åren, huvudsakligen tack vare mer effektiva skogsskötselmetoder.

Produktionsforskning angående tallplantagerna i sydöstra USA har sedan 1975 bland annat utförts av Plantation Management Research Cooperative (PMRC) på University of Georgia. En av deras anlagda forskningsförsök, som handlar om skötselintensitet och planteringstäthet, visar hur just dessa faktorer påverkar tillväxten hos loblolly- och slash-tallarna. Analyserna gjordes med ANOVA-analyser i programmet R, och sedan jämfördes dessa resultat med trender från svenska försök med tall, genom en litteraturstudie som också utvärderade huruvida dessa intensiva skötselmetoder kan tillämpas och vara hållbara för produktionen.

Resultaten visade att loblolly-tallen producerade bättre än slash-tallen vid en rad olika skötselintensiteter och planteringstätheter. Resultatet visade också att den intensiva skötselmetoden och planteringstätheter av 300 och 1500 träd per acre (TPA) (741 och 3,705 träd per hektar) hade störst inverkan på tillväxten i tallplantagerna. Mer intensiva skötselmetoder skulle kunna appliceras i Sverige om lagar och regler skulle tillåta det, och dessa skötselmetoder skulle vara hållbara om man ser till reduktionen av växthusgaser till atmosfären, med större möjligheter till bioenergi och biobränsle, samt rent ekonomiskt.

Nyckelord: Loblolly-tall, Slash-tall, tall, skötselintensitet, planteringstäthet

Table of Contents

Acknowledgement 2
Abstract 3
Sammanfattning 4
Introduction 7
Species Descriptions 9
Loblolly pine 10
Slash pine 11
Scots pine 12
Plantation Management Research Cooperative 14
Study objectives 14
Materials and Methods 15
Literature review 15
Previous studies in US 15
Previous studies in the Nordic countries 20
The culture/density interaction study in the SE US 25
Site descriptions 26
Soil Classifications 27
Data from the PMRC 29
Statistical analysis 29
Results 32
Productivity in relation to management intensity and planting density 32
Average diameter at breast height (DBH) 33
Average height 34
Crown length 35
Crown ratio 36
Survival rate 38
Stand density index (SDI) 39
Per-Acre basal area 40
Per-Acre outside bark total volume 41
Comparison between the 6 installations 42
Discussion 43
Loblolly versus slash pine 43
Scots pine in relation to loblolly and slash pine 44
Comparison with other studies 45
Sustainability of the management 46

Sources of error 47
Conclusion 48
Cited Literature 49
Appendix 54
Appendix 1 - Conversion tables 54
Appendix 2 - Graphs 56
Appendix 3 - Code 59

Introduction

The southeastern (SE) United States (US) produces more industrial timber than any other region in the world (Allen et al. 2005). Pine (*Pinus ssp.*) plantations in the southern US have increased from 1.8 million acres (see Appendix 1 for conversion to hectare) in the beginning of the 1950's to 32 million acres in the beginning of the 21st century (Fox et al. 2004). Stanturf (2003) reported that the pine plantations cover 17 % of the forest land in the southeast. Fox et al. (2004) state that not only the increase in area is remarkable but also the increase in productivity of the plantations over time. The increase in productivity is attributed to a range of reasons, such as improved genetics and more intensive silviculture methods such as site preparation, competing vegetation control, fertilizer, etc.

In the beginning of the pine plantation era, the plantations in the SE USA produced about 90 ft^3 ac^{-1} yr^{-1} (see Appendix 1 for conversions between the imperial and metric measurement systems). Today the productivity can be around 400 ft^3 ac^{-1} yr^{-1}. The rotation length of the plantations for southern pines has been reduced by 50 % or more compared to the 1960's (Fox et al. 2007). Part of this success of productive pine plantations in the south is due to the efforts from research cooperatives, the forest industry and universities. Nurseries for pine seedlings started in the 1950's, and at the same time research about genetic improvements of trees started in Texas. The focus was to promote good characteristics of the trees such as stem form, volume production and resistance against pests and diseases. The use of genetically improved seed material increased in the 60's and 70's, and those first-generation seeds produced 8-12 % more biomass than wild seeds did and gave an increased economic profit of about 20 %. This success led to second-generation seed orchards, which produced 14-25 % more biomass than the first-generation plantations. The production potential for genetically improved seed is large in the US, but currently the most common seed source used in todays' plantations is half-sib, open-pollinated seedlings (Fox et al. 2007).

Mechanical site preparation gained popularity in the late 50's, to reduce the problem with competing vegetation. This site preparation method was most popular during the 70's and increased the growth of the seedlings by 15-90 %. Even though the mechanical site preparation clearly improved the growth of seedlings, it wasn't considered good enough to remove competition from hardwoods. Therefore, chemical (herbicides) site preparation has seen a huge increase in application to forest plantations. In the 90's chemical site preparation had replaced mechanical site preparation on upland sites and is still today the most common method used in the upper coastal plain. On wetter sites in the lower coastal plain, bedding is used to increase the survival and growth of seedlings (Fox et al. 2007).

About 16 million acres of forestland were fertilized in the southeast between 1969 and 2004. In between 1991 and 1999, the acres being fertilized doubled every year. Today, an average of 1.4 million acres are being fertilized each year. Both the fertilization at establishment and mid-rotation has increased over the years. From 1969 to 1999 the increase was from 25,000-90,000 acres to 200,000 acres being fertilized at establishment and 1,000 acres to 150,000 acres at mid-rotation, for 1969 and 1999 respectively. From 2000 to 2004, at least 80 % of all fertilized sites were in the coastal plain region (Albaugh 2007). These drastic changes in forest management over the past have resulted in that well-developed management systems are routine for the most important pine species in commercial plantations (Jokela et al. 2010).

The forest land of the US amounted to 766 million acres in 2012 (8 % of the forest land in the world), from which 245 million acres were found in the South (USDA 2014). US produce today 28 % of the timber used for industrial products worldwide. Between 1953 and 1997 the timber market in the southeastern US increased from 41 % to 58 % of the total US production, which is equal to 6 % and 16 % of the world production of timber for each year, respectively (Wear & Greis 2002).

The industrial roundwood is the largest part of the US forestry market and the roundwood is used for pulp and paper, as well as solidwood products. Coniferous sawnwood, coming from e.g. pine plantations in the south, is often being used as construction material for housing, both locally and for export. The industrial roundwood production in the US was 17 % of the global production in 2013, meaning it was the largest producer in the world (Prestemon et al. 2015). The share of coniferous sawnwood was 17 % of the global market the same year.

Figure 1. The location of what is considered the south/southeastern US.

As a comparison, Sweden only has 1 % of the forest area in the world where about 70 % of the Swedish land area is covered by forests and about 80 % of the forests are being managed (Skogsindustrierna 2015). Sweden is the worlds' third largest exporter of pulp, paper and sawnwood, behind Canada and USA.

In Sweden, the forests are less productive compared to the SE US, due to a range of reasons. A colder climate is the most important reason, followed by the management of quiet low producing native species and not as intensive management practices - even if the management has developed to become more intensive over time also in Sweden. The growing stock per acre has doubled in Sweden over the past 90 years (Skogsdata 2018). In the 1920's the stock volume in Swedish forests were 58,550 million ft^3 and today it has reached 123,800 million ft^3 on the 58 million acres of productive forest land (100 million acres of total land area). The average growth is 81 ft^3 ac^{-1} yr^{-1} (Skogsstyrelsen 2014).

Planting after clear cutting and mechanical site preparation has been the dominating regeneration practice since the 1940's in Scandinavia. In Sweden the main system of regeneration has been planting, at the expense of decreased natural regeneration by seedling or seed trees, since 1948 (Savill 1997). In 2005 to 2009, 62 % of all regenerations was by planting and during the last 15 years about 371,000 acres on average have been planted annually (Skogsstyrelsen 2013). The natural regeneration of conifers declined during the same time, to about 22 % of total regenerated area between 2007 and 2009 (Skogsstyrelsen 2012).

Harrowing and patch scarification are commonly used mechanical site preparation methods and a large share of the clear-cut areas are being scarified (Esseen 1997). As in SE US, herbicides were used in Sweden to get rid of competing deciduous vegetation such as birch in conifer plantations. In contrast to US the use of herbicides was prohibited in 1987, due to environmental and health issues for the vegetation, animals and humans (Enander 2007). Pre-commercial thinning in young stands and commercial thinnings are practices widely used. Most forests are thinned at least one time during a rotation and about 1 million acres are annually thinned (Skogsstyrelsen, 2015a).

According to the Swedish forestry act (Skogsstyrelsen 2017), production goals and environmental goals should be equally important in Swedish forestry implying that production is not the only focus in Swedish forestry. The conservation of biodiversity is part of the daily forest management and there are regulations on how much forest land that must be set aside for nature conservation and that a proportion deciduous trees should be left in the forests to protect biodiversity. Certification also plays a large role in Swedish forestry, which makes the forest owners to take more responsibility for the environment than the law itself requires (Skogsstyrelsen 2015b). In 2012 there were 329,541 forest owners in Sweden (Skogsstyrelsen 2014), and today 45,296 forest owners representing 39 million acres forest land (productive and non-productive) are certified by PEFC (PEFC 2019) and 337 companies (29.5 million acres) was FSC certified 2017 (FSC 2019). Overall, this results in more restrictions on management and less intensive forest management in Sweden than in SE US.

From the 1970’s the use of bioenergy has increased in Sweden as a strategy to change energy sources from fossil fuels to renewable sources. In 2001 15 % of the energy used in Sweden came from bioenergy (Ericsson et al. 2004). Due to awareness of the changing climate, the interest in using biomass from the forest for bioenergy and biofuels has increased and in 2009 an investigation concerning more intensive forest management started (MINT 2009). This investigation was a commission from the Swedish government to the Swedish University of Agricultural Sciences (SLU) and aimed at evaluating the possibilities to implement more intensive forest management in the Swedish forestry to produce more timber for wood supply.

Species Descriptions

Loblolly pine (*Pinus taeda. L.*) and Slash pine (*Pinus elliottii. L.*) are two of the most important commercial timber species in the southeastern US. In this region, they are both commonly managed under a regime of intensive silvicultural practices. This includes different kinds of competing vegetation control, site preparation and genetic tree improvement (Xiao et al. 2003). Though both pines grow in the same region it is important to plant the best performing tree at a given site (Shiver 2004).

In Sweden, the two most important species for the forest industry are Scots pine (*Pinus sylvestris. L.*) and Norway spruce (*Picea abies. L.*), and pine and spruce cover 38 % and 40 % of the productive forestland of Sweden, respectively (Swedish NFI 2015).

Loblolly pine

Loblolly pine is one of the most important species for timber production in the SE US (CAB International 2002). Of the southern pines, loblolly pine has the largest natural range, which extends from southern New Jersey south to Florida and west to east Texas (Figure 2). Loblolly pine is also widely planted outside of its natural range and has been shown to be very adaptive to new areas as well as very responsive to silvicultural practices such as fertilization (Shiver 2004).

Figure 2. The natural range of loblolly pine.

The loblolly pine is used in plantation programs worldwide. It is a fast-growing tree and has the potential to get 90 to110 feet in height and 36 to 48 inches in diameter at breast height (DBH) (NC State, 2018), but it is not common to let the trees grow to that size. The trees can live up to 300 years, but normally loblolly pine is used in plantations and is in SE US harvested around the age of 30 with a tree height of about 60-100 feet and approximately 23 inches in DBH (CAB International 2002). The wood density is about 35 pounds per ft^3 (The Wood Database 2019a). In locations such as Brazil and South Africa the rotation can be as short as 20 years. The species can grow faster in these locations due to absence of natural enemies, and a mix of suitable climate and even more intensive management than in the US (Borders et al. 2001).

More intensive management will increase the growth and yield of loblolly pine in SE US as well, in fact, the increase can be from 0 to 225 ft^3 ac^{-1} yr^{-1} when applying herbicides and fertilization compared to non-treated sites (Borders et al. 2001) with a normal rotation of about 25 years.

Loblolly pine is planted with many different densities and a range of different silvicultural treatments, such as fertilizer and weed control. It is very adaptable and can be planted on many soil types, but it performs best on high fertile sites or on sites that are intensively managed (Fox 2004). Loblolly pine is more nutrient demanding than slash pine and does well on CRIFF (pp. 27-28) soil groups A, B, C, E, and F (Jokela & Long 2015).


Picture 1 (left). A loblolly pine stand at around the age of 25, in Georgia. (Photo: Åsa Ramberg)
Picture 2 (right). A cone from a loblolly pine tree. (Photo: Åsa Ramberg)

Slash pine

In contrast to loblolly pine, slash pine has the smallest natural range of the southern pines, and is native from Georgetown, South Carolina to central Florida and west to Louisiana (Figure 3) (Shiver 2004). Outside its natural range slash pine has been planted up north to Tennessee and west to eastern Texas and in Africa, South America and Oceania.

The area of slash pine has decreased since the 1980's, but the management intensity and productivity has increased. About 80 % of the acreage of slash pine is found in Florida and Georgia and those states had about 10 million acres of slash pine in the 80's and about 8 million acres 20 years later. Even though the area has decreased, the same volume is still produced. This, because of more intensive management practices, e.g. 69 % of the stands were planted in 2000 while 52 % were planted in the 80's (Barnett & Sheffield 2004).

Figure 3. The natural range of slash pine.

Slash pine has a rapid early growth and has good properties for a range of products such as fiber, lumber, poles and pine straw (Barnett & Sheffield 2004). Slash pine has good form and self-prunes, which gives the tree a short live crown (Fox 2004). The species has a straight stem and long needles and cones (7 to 10 in and 4 to 6 in respectively). Slash pine has higher wood density than loblolly pine. The rotation for slash pine depends on the aim of product class and a normal rotation for pulpwood is around 25 years, while sawtimber needs a rotation of 45 to 55 years depending on silvicultural treatments, conditions and genetics (CAB International 2002). Usually the tree grows 60 to100 feet high and approximately 23 inches in DBH. Slash pine is susceptible to fusiform rust, which is caused by the fungus *cronartium fusiforme* (CAB International 2002). Slash pine has higher wood density than loblolly pine (about 41 pounds per ft^3) (The Wood Database 2019b).

Slash pine doesn't grow well in the drier sandhills soils, but the species is less nutrient demanding than loblolly pine. Poorly drained flatwoods are optimal for slash pine but wet and sandy soils work fine, and slash pine has shown to grow best in CRIFF soil groups B, C and D (pp. 27-28) (Jokela & Long 2015).

Scots pine

Scots pine is one of the most important commercial forest trees in Eurasia and is used in plantations in the temperate zones of the world, mainly for its high-quality softwood production (CAB International 2002). The tree has the most extensive range of all Pinus, from Spain to eastern Russia (Figure 4). It has been introduced outside its native range but is no longer commonly planted because of the competition from more rapidly growing species.

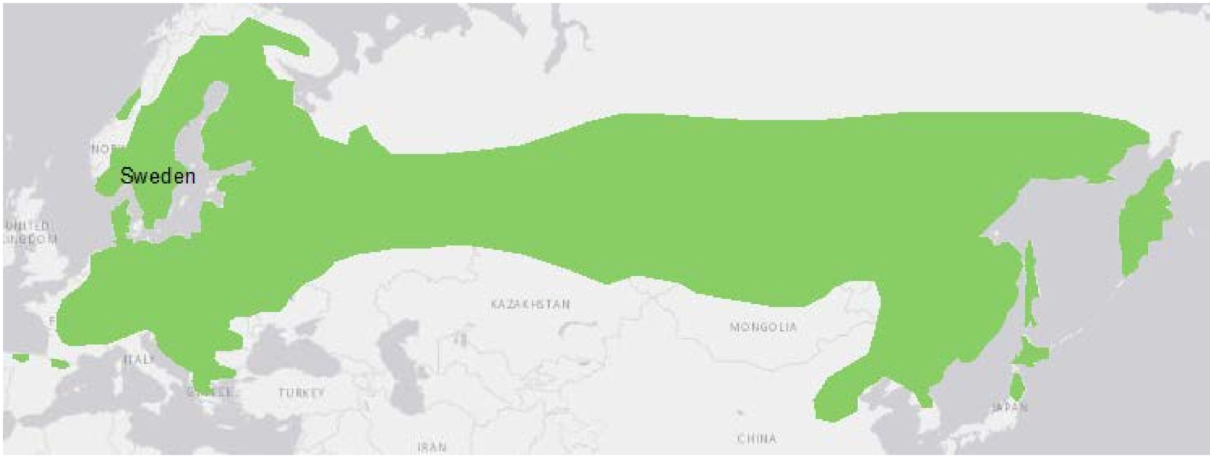


Figure 4. The natural range of scots pine.

In Sweden, scots pine accounts for 38 % of the standing volume (Swedish NFI 2015) and even though scots pine is not the most rapid growing species, there are breeding programs which have been running in Sweden for a long time, with a focus to increase the growth, wood quality and resistance against diseases. These genetically improved trees are currently used in operational plantations (Egbäck 2012).

Scots pine usually grows 65 to 98 feet. The rotation of sawtimber of scots pine is usually somewhere between 80 to 120 years, depending on the altitude and latitude. According to the Swedish forestry act (Skogsstyrelsen 2017), scots pine are allowed to be cleat-cut if older than the age of 60 on sites with site index 92 feet (at 100 years of age) in southern Sweden and at 65 years in northern Sweden, while the legal age for harvesting is 90 and 100 years respectively at site index 40 feet. Normally, no stands are established just for pulpwood production. The pulpwood production comes from thinning and smaller and lower quality trees in the final cutting. The mean annual increment is 40-140 ft^3 ac^{-1} yr^{-1} in Sweden. Scots pine grows on a wide variety of soils but are best adapted to sandy, dry soils, or on mires. Also, the recommended planting density should at least be 445 trees per acre (TPA) at site index 52 and 931 TPA on site index 92 and higher (Skogsstyrelsen 2017).

Picture 3. A scots pine tree forest in northern Sweden. (Photo: Åsa Ramberg)

Plantation Management Research Cooperative

The Plantation Management Research Cooperative (PMRC) is part of the Warnell School of Forestry and Natural Resources at the University of Georgia in the USA (PMRC 2008). In 1975 the PMRC started to do research to develop plantation management tools for modern forestry. The PMRC has since its start installed a broad range of studies in the southeastern United States. PMRC is financed by companies and organizations which are interested in research concerning pine plantations in the US. The PMRC mission statement is to "*Create value for its members by improving knowledge of southern pine plantation performance under different silvicultural regimes and by developing growth and yield systems and decision support tools that result in improved silviculture, management, and valuation of the plantation resource*" (PMRC 2008).

Study objectives

The PMRC has conducted research about the effects of management intensity and initial planting density, on a range of soil types in the southern US. As a part of that research, technical reports are compiled for the members of the cooperative.

The latest measurements of heights and diameters from the PMRC's culture/density study was collected at the stand age of 21. The PMRC's culture/density study evaluated the effects of initial planting density and management intensity of loblolly and slash pine growth and yield in southeastern plantations. The data from this study, through age of 21, was analyzed in this thesis.

The main objectives of this master thesis are…

… to compare the production of loblolly and slash pine in the SE USA and analyze where each species has its best productivity based on management intensity and planting density.

… to compare the results from the PMRC's culture/density study with results from similar studies made in the SE US and in Sweden on scots pine.

The thesis will answer and discuss these specific questions/statements:

Which factors have the largest impact on the production of loblolly and slash pine in terms of volume growth, diameter growth, height growth, and other stand-level measures?

Intensive silvicultural practices are often criticized for not being sustainable, but are they sustainable in terms of long-term production?

A discussion of options to apply similar intensive forest management practices in Swedish forestry.

Materials and Methods

This study includes two parts, an analysis of data from the PMRC's culture/density study and a literature study comparing results from the data analysis with other similar southeastern U.S. studies, as well as studies made in Sweden on scots pine.

Literature review

There are numerous studies made over the years, regarding pine plantations in the southern United States. These studies have been focusing on many different topics as improvements in genetics, resistance against diseases, insects, and fungi, growth and yield modeling, vegetation dynamics, fertilization, site preparation, competing vegetation, etc. It is and has been very important to understand how the plantations change over time, how the productivity can be maximized, and how the plantations can be managed in a sustainable way to contribute in a positive way to the global issues concerning climate.

In Sweden, similar research studies have been carried out. With the changing climate, there is a need to produce more environmentally friendly products from the forests. Lately, research has been done regarding the productivity of the boreal forests and what can be done to meet the demand for forest products. For example, there is an increased interest in how the Swedish forests can be managed and how the management can change towards more intensive methods (Hedwall et al. 2014). There is also an increased amount of forest ecosystem services required due to a growing human population and to minimize the effects of climate change. As part of this, increased need of biomass production on smaller area of land, at the same time as the competition of the forest resource is prevalent. Hedwall et al. (2014) states that the demand can be met by using genetically improved seed material, increased utilization, and fertilization, and this can be done even in northern Europe.

A brief summary of studies from the southeastern USA and from the Nordic counties is presented. These studies are similar to the PMRC culture/density study. Some words are frequently recurrent;

Intensity – high intensity means that the treatment is more intensive than commercial treatments are. There are levels of intensity.
Culture – aims to the different treatments, e.g. the intensive treatment is one type of culture.
Density – number of trees per area. High density means there are many trees, and low density means the opposite.
Interaction – how management intensity and planting density affects the growth, when both are applied.
Spacing – the distance between the trees in an area, e.g. 6x6 ft.

Previous studies in US

<u>Culture/density interaction studies</u>
A way to increase production is woody plantations, such as loblolly pine plantations, to sustainably produce biomass for renewable energy, but to get out as much biomass as possible from the plantations certain management regimes should be applied. To evaluate which management system is the most efficient in producing biomass, the key is to understand the stand-level biomass allocation within the trees, and production. In 2012, Zhao

et al. reported findings from a culture/density study on how biomass allocates and produces in 12-year-old loblolly pine. This study was established in 1997 in the Upper coastal plain and piedmont regions of Georgia, Florida, Alabama, Mississippi and South Carolina, on a total of 23 installations. The cultural treatments were intensive and operational and the planting densities were at six levels ranging from 300 TPA to 1800 TPA (740 to 4450 trees per hectare).

After the 12th growing season all trees were measured for DBH and 192 trees were sampled for weights. Two dominant or codominant trees, one average diameter tree and one tree less than average in diameter were sampled at each sampling plot. These selected trees were cut down and marked up in intervals along the stem and each section was weighed and measured for diameter. Then a sample disc from each section was cut to be dried and analyzed in the lab. The live crown was divided into three sections and two branches from each section was randomly selected, weighed, and sampled for the lab inside. All other live branches were only weighed. Two dead branches were sampled from each tree and weighted, and sampled for the lab. All other dead branches were only weighted. The foliage and bark were also measured (Zhao et al. 2012).

Both cultural intensity and initial planting density affected the aboveground biomass allocation (Zhao et al. 2012). The intensive treatment produced more biomass in stem, bark, dead and live branches and in total aboveground biomass than the operational treatment. The planting density of 300 TPA had less stem, bark and total biomass than all other planting densities. Higher planting densities had higher biomass in dead branches. Between the low and high planting densities the differences in partitioning and producing biomass was significant. Also, the foliage density was higher with higher planting density. In general, the biomass production was greater with more intensive treatment and higher planting densities.

Subedi et al. (2012) used the data from the same culture/density study (only data from the states of Georgia and Alabama) to evaluate the effects of cultural intensity and planting density effects on aboveground biomass of 12-year-old loblolly pine. After the analysis with mixed-effects models, the results showed that the cultural intensity had a significant effect on stem, bark, dead-branches and total aboveground biomass accumulation. The planting density had significant effects for all components of the tree. Trees planted at 300 TPA had a significant higher biomass than all other planting densities. The most intensive treatment combined with the lowest initial planting density resulted in the highest biomass accumulation, while the higher densities had no significant differences between one other. The interaction was significant only for dead-branch biomass accumulation. Dead-branches allocation was significantly affected by the management. Planting density had a significant effect to all aboveground components. Higher planting densities had more allocation of biomass to stem and bark than the lower planting densities. The intensive treatment produced 23 % more biomass than the operational treatment.

Another study was carried out by Zhao et al. (2016), were the authors analyzed the possibilities to optimize the productivity of loblolly pine plantations, to increase carbon sequestration and produce more biomass in shorter rotations. They wanted to see if there were ways of changing the silvicultural practices to reach these aims and address the variation in growth responses across southern US and how much the productivity can be increased with additional treatments and what the maximum achievable productivity for loblolly pine is. They used data from six long-term field studies (which were established in the southern US in the 80’s and the 90’s) with varying levels of management intensity, planting densities and site qualities. Three of the studies have similar management intensities and planting densities as the PMRC culture/density interaction study from 1995/96. Another study had 8-9 different levels of nitrogen fertilization, one study had fertilizer, irrigation and control treatments and the last study had control, fertilization, herbicides or a combination of both. They used linear regression and mixed-effects modeling to examine the effects of site quality, planting density and management intensity on tree growth. They calculated the expressed site index with the most recent measures from each study.

Zhao et al. (2016) found that a maximum expressed site index across the region was approximately 105 feet at age 25. Where the site index already was 105 feet the silvicultural treatments did not increase the productivity, but there was potential to increase the productivity due to silvicultural treatments on lower quality sites, and this was proportional to base site index. The response to the different treatments were higher in lower quality sites. Aboveground biomass in loblolly pine stands at age 15 was significantly affected by both planting density, cultural intensity and their interaction, but again, the higher quality of the soil, less effect of the treatment. Higher stocking generated more biomass in general too. Due to those findings, there is possible to change the management, reduce the use of fertilizer on high fertile sites for example, due to lack of response or even negative response.

Management intensity studies

Limitation in available soil nutrients is the factor that has largest effect on growth rates in southern pine plantations. With fertilization and optimal nutrient availability the growth rates of 360 ft^3 ac^{-1} yr^{-1} can be reached, and will be biologically possible, financially profitable and environmentally sustainable (for instance growth rates increases and more biomass can be used instead of fossil fuels) for a broad range of soil types. Many plantations in the southern US lack nutrients which in turn decrease the production of leaf area. Leaf area is essential for the trees growth and with nutrient availability the leaf area will increase and also the light interception which will generate in higher production (Fox et al. 2007). Both increased nutrients and water availability affect the leaf efficiency, and low nutrients reduces leaf area and therefore production.

The management of pine plantations should be site-specific and focus on both the soil and the trees. Current fertilization has shown that P-deficient sites increases the volume growth by an average of 40-50 ft^3 ac^{-1} yr^{-1} when being fertilized with 50 lbs ac^{-1}, and often has a long lasting effect (20 years and more). In general fertilization with a combination of N and P increases the production even more. 200 lbs ac^{-1} of N and 25 lbs ac^{-1} of P will result in an average increase in production by 55 ft^3 ac^{-1} yr^{-1} over an 8 year period (Fox et al. 2007).

Jokela et al. (2000) presents results from 5 and 8 years growth responses and interactions between fertilization and understory competition control treatments applied to young plantations of slash and loblolly pine. The experiment was established in Florida, Georgia, Mississippi, Alabama and North Carolina in 1987-1989. 11 of the installations were slash pine, and 10 were loblolly pine. 18 of the installations were on CRIFF soil groups A, B, C, and D which were mechanically site prepared and bedded, while three of loblolly pine installations were on CRIFF soil group E, and none of the sites had received fertilization before the experiment.

Four treatments were applied, none (control), competing vegetation control, fertilizer and a combination of fertilizer and competing vegetation control. After age 5 and 8, DBH and height measurements were taken for all living trees. The results indicated that soil type or treatment had no effect on the survival of slash pine after 5 years, while the soil type did matter for loblolly pine. CRIFF C had a survival rate of 73 % while the survival for other soil groups were 93-97 %. Both fertilization only and competing vegetation control had effect after 5 years, but after 8 years the effect was absent for slash pine. In general the combined treatment outperformed the other treatments for both the species and fertilization had a longer lasting effect than competing vegetation control.

Density studies

Dickens and Will (2004) was evaluating how slash pine was growing in different planting densities and spacings, and discussed that planting density has to be selected based on the products being produced and how it affects growth, yield and economics. Slash pine is actually used for pine straw production beyond fiber and lumber production. With higher planting density, each crown gets less space and the small canopy size depresses the stem growth, therefore should silvicultural activities focus on increasing the leaf area and at the same time the growth of the stem in the individual tree. A higher planting density accelerates the volume production early, and is attractive if employing intensive thinning regimes. In general, moderate planting densities produces a range of all product classes, and if the goal is a mixed product class, then a moderate density is good. For pine straw production, higher densities start the production earlier due to early canopy closure, but a wider density will produce more per tree and after some years, and the differences in planting density will not be affecting.

The product classes varied among planting densities, and when choosing a planting density for slash pine it is important to address what rotation age you want, aimed product class, prices for selling, treatments (thinning, fertilizer etc.), and access to the site. Higher planting densities will generate early canopy closure and potential for fast pine straw production. Lower planting densities will give more valuable individual trees for the solidwood market.

Amateis and Burkhart (2012) have reported similar trends from their study. All spacings and planting densities doesn’t fit all goals of production. To increase the understanding how spacing and planting density affect the growth of loblolly pine, Amateis and Burkhart (2012) did a spacing trial in the piedmont and coastal plain regions of Virginia and North Carolina in 1983, on four sites (two in each physiological region). They established a non-systematic block design, in which plots of different sizes and shapes contained equal numbers of trees. This resulted in a range of different spacings and densities (300-2700 TPA). The sites were cut-over areas that had received mechanical site preparation and burning after harvesting. The seed sources planted were from respective region. All sites received complete vegetation control the first two years, and then there were no more treatments during the study. At ages 1 to 5 the ground line diameter was measured, and then the DBH from the age of 5 and all other years. The total height was measured all years from 1 to 10 and every second year after. All trees were controlled for damages and at age 25 the crown class information was noted. The height and diameter measurements were used to estimate the outside bark volume.

The higher density and closer spacing plots outperformed plots planted with lower densities and wider spacings (Amateis & Burkhart 2012). The closest spacing (4x4 ft.) produced more total volume than any other treatment until age 13. At age 15, the mortality reduced the production for the highest density plot. But if biomass is the requested product class, the best strategy is to have high spacings and short rotation. If pulpwood production is the aim, a density of 680 TPA (8x8 ft.) produced most volume and can be harvested at 25 years. Even wider spacings will generate higher proportions of sawtimber. The 8x12 ft. and 12x12 ft. spacings produced more chip-n-saw than all other treatments for all ages. The 12x12 spacing (300 TPA) produced more sawtimber than all other treatments. By age 25, the 12x12 ft spacing treatment almost had twice the sawtimber that 8x12 treatment. If sawtimber is them aim and thinning is not part of the management regime, 300 TPA is the best density and a rotation of 25 years. The authors also found that rectangularity was not significant and does not affect the production. But most important, no single management will fit all goals. Biomass, pulpwood or sawtimber requires different densities.

Sustainability of plantation forestry

Stanturf et al. (2003) describes how the southern plantations have increased its productivity and area during the past six decades. The productivity can be led to genetic tree improvement, nutrient management and vegetation management. The growth and biomass production increase was as a start thanks to mechanical site preparation, and later on genetic tree improvements, further advancement in site preparation and also site-specific management and fertilization. The authors' states that genetic tree improvements is the most important change and will be the main focus in future development of the intensive plantations.

With repeated rotations of loblolly pine plantations being intensively managed, there are concerns that the management will degrade the site fertility (Stanturf et al. 2003). At harvesting, all aboveground components of trees are likely to be removed from the site followed by intensive site preparation which takes away the organic matter and nutrients from the soil. Therefore, it is important to adapt management practices that allow rotations to on-go without decreasing the productivity of the soil. An approach to do so, is to quantify the available nutrients in the soil and document the distribution of biomass and concentrations of nutrients.

Gresham (2002) established a study in two loblolly pine sites in South Carolina, to evaluate the sustainability of pine plantations. At the establishment of the study the two sites were 17 and 20 years old, and the sites were sampled for vegetation from litter and herb layer down to 12 inches depth in the soil, and sample trees were weighted and sampled for lab. After the biomass sampling, the stands were harvested and re-established. 10 years into the second rotation, the same sampling procedure was repeated. All samples were dried and weighed in lab and the components were analyzed for nitrogen and phosphorous.

The results from the first rotation showed that the soil was the major pool for N and P. The second rotation, one of the sites showed that organic matter, N and P in the soil was greater than in the first rotation, while the other site the same levels of P and greater amount of N in the soil. The first site had less available N, P and organic matter in the litter layer during the second rotation, but the same amount on the other site as the first rotation. The second rotation tree biomass was less than from the first rotation. Overall, the second rotation plantation are less productive than the first, but accumulates nutrients and can sustain nutrients up to 10 years into the second rotation without additional fertilization. However, the sites accumulated nutrients faster in the second rotation compared to the first, which indicates that these management practices will be sustainable, from this perspective.

With an increased interest in replacing fossil fuels with biofuels and reduce the greenhouse gas emissions to the atmosphere, removal of residues from harvested sites seem to be an option, but removal of these residues from sites might impact soil nutrient and functions in ecosystems. In the south USA, about 20-35 Mg dry weight per acre may be left after harvesting on a typical site. But it depends on site and also tree species, e.g. loblolly pine allocates more biomass to its stem and branches while slash pine allocates more biomass to bark and foliage. Forestry practices that do not replace the nutrient removal risk to reduce the long-term productivity of the site.

Eisenbies et al. (2009) conclude that 4-16 Mg ac^{-1} of residues could be used for biofuels and that replacement of the nutrients with fertilization could keep the productivity sustained. More research needs to be done, but based on the available information today, removal of residues seem not to have a negative effect on the long-term production as long as the forest floor keeps intact. This is particularly reliable on high fertile sites and fertilized sites.

Previous studies in the Nordic countries

With an increased interest in wood related products, the Swedish University of Agricultural Sciences (SLU) received a commission from the Swedish Government to investigate the possibilities for intensive forestry (MINT – Möjligheter till intensivodling av skog, the Swedish name) on abandoned agricultural land, and on forested land of low value for nature conservation (MINT 2009). Intensive forestry in MINT was defined as those silvicultural treatments that will increase the growth of the forests, but those silvicultural treatments may be limited by prevailing laws and regulations.

SLU reported their findings from the investigation in 2009. They concluded that intensive forestry is possible on about 1 million acres in Sweden and that it should be possible to implement more intensive treatments if some requirements are fulfilled, for example, there has to be an exception from the Swedish forestry act, and a new follow-up system has to be developed to implement these more intensive practices.

SLU think adaptive management (site-specific) is the kind of management that will be the best and easiest to adapt and implement in Sweden. This would include planting of the exotic species Contorta pine (*Pinus contorta*), adaptive fertilization, and development and planting of spruce clones. The researchers' states that intensive managed forests will not be at a higher risk of damages or affected by fungus or insects than operational managed forests. But, with higher rates of fertilizer, there will be higher rates of nitrogen emissions to streams and water, but still lower than from agriculture. An argument against this is that agriculture is essential for producing livelihood, but on the other hand, the forests are storing carbon and reduce emissions to the atmosphere. Intensive forestry can have a negative effect on the stand-level because of change in local ecosystems, and make recreation less attractive though availability and passability will decrease.

An implementation of intensive forestry in the Swedish forestry would be favorable for the production. The MINT (2009) investigation indicated that intensive forestry can double the growth, but it will take time due to long rotations. Overall, the economic return would be high for more intensive forestry. Intensive forestry would also increase carbon storing due to increased growth. The negative effects would be on biodiversity, on the aesthetics of the landscape, recreation and nitrogen leakage. But the largest dilemma is to come to an agreement of how to move forward. There are many different opinions regarding intensive forestry and it's important to evaluate which are most valuable for the environment before implementation.

Culture/density interaction studies

In 1983, a study was established in a 45-years-old, well stocked, even-aged scots pine stand in northern Sweden. The stand was thinned in 1972 and had an average height of 39 feet. Valinger (1993) evaluated the effects of nitrogen fertilization and thinning in this stand to see how biomass allocated in the trees for the first five years after the treatments were applied. The treatments were control, nitrogen fertilization, thinning with 40 % removal of basal area, and a combined treatment of fertilization and thinning. Before the treatments were applied, all trees were measured for DBH and sample trees in each measurement plot were defined. Sample trees were felled each of the five years and were measured for total height, and height to live crown. Discs along the bole were sampled and weighed, and branches were also sampled from the felled trees. In a laboratory the disks were dried and weighted.

The combined treatment resulted in a production of higher dry weight than the control and thinning treatments. The fertilization and combined treatment produced more than the control all five years. The dry weight increased by 5 % by thinning only, 29 % by fertilization only, and by 57 % with the combined treatment. The needle efficiency was higher for the combined treatment than for the control treatment, but fertilization as only treatment had the highest efficiency of all treatments after five years. After five years, the fertilization treatment allocated less proportion of growth to the needles, and the combined treatment allocated less proportion of the growth to stemwood than only fertilization. This shows that the combined treatment allocated more biomass to branches and needles to be efficient in producing more biomass. Per tree, all treatments generated more biomass than the control (Valinger 1993).

Another study was conducted 12 years after treatment, in the same scots pine stand. The purpose was to evaluate the growth response of scots pine to thinning and nitrogen fertilization (single and in combination) in below and aboveground components (Valinger et al. 2000). The results after 12 years showed that all treatments had effect of the growth compared to the control. After the 5-years-study the fertilization and combined treatment had a larger impact of production of volume. After 12 years, the authors could conclude that the fertilization treatment only had an active effect of growth for 8 years while the thinning treatment had an effect throughout the 12 years. The thinning resulted in lager total crown dry weight, total dry weight per tree, and larger crown length than the other treatments.

Bergh et al. (2014) did a similar study and were looking at long-term responses of scots pine stands in Sweden, to repeated fertilization and thinning. The experiment was established in the 1960's all over Sweden (altitude 56-66 degrees north) in uniform, even-aged scots pine stands. The 34 scots pine stands were located all over Sweden on different soil and vegetation types. In all locations, there were different treatments: no thinning, repeated thinnings, repeated thinnings and nitrogen fertilization, and repeated thinnings and both nitrogen and phosphorus fertilization. The amount of fertilizer was 92 lbs. ac^{-1} of nitrogen in northern Sweden and 138 lbs. ac^{-1} of nitrogen in southern Sweden. Phosphorus was applied at a rate of 92 lbs. ac^{-1} in both the south and north.

The results showed that scots pine responded well to nitrogen fertilization, but the response varied from site to site. Scots pine did not get an extra effect when being fertilized by both nitrogen and phosphorus. A shift in the diameter classes toward larger diameters was identified when the stand was fertilized compared to un-fertilized stands, resulting in more valuable timber. This result was not surprising, as other studies made in Sweden on scots pine has shown that scots pine is responsive to nitrogen fertilization. The repeated thinnings gave varied responses, but in general scots pine got higher growth rates per tree with repeated thinnings.

Another study located in central and southern Finland (altitude 61-63 degrees north) by Mäkinen et al. (2005) concerning intensive management of scots pine showed how intensive management pays off in scots pine plantations. The study was established in the early 1990's in young, even-aged scots pine stands, located on mineral soils.

Different silvicultural treatments were applied, a range of different thinning regimes and also fertilization. An operational treatment could consist of a thinning to 500 TPA and without any fertilization, while an intensive treatment could be thinned to 250 TPA and fertilized with ammonium nitrate with lime. The researchers simulated the stands in a growth and yield simulator (MOTTI) to mimic the full rotation of the stands. The results from the study showed that mean diameter, growing stock, basal area and standing volume were increased with decreased stand density. There was a significant difference in diameter between the fertilized stands and the non-fertilized stands. According to the simulation, the rotation of scots pine stands could be shortened by 15 years with intensive management, without losses in the mean annual increment. It is important to highlight that the lower densities in combination with fertilization will result in increased growth and yield, while a strong thinning without additional fertilization, can reduce the growth quite a bit (around 30%) (Mäkinen et al. 2005).

Ahnlund Ulvcrona et al. (2014) investigated the possibilities to produce biomass in young scots pine stands in northern Sweden. The authors wanted to study if high stand densities leads to slender stems, different allocation of biomass to the stem, fewer branches and reduced crown length. The experiment was established in 1997 at three sites in northern Sweden. These sites were naturally generated with scots pine but contained Norway spruce and birch as well. Before the treatments were applied in 1997, the sites contained 5800 to 7300 TPA. The treatments were control, pre-commercial thinning to 3000 stems per hectare, no thinning but annually fertilizer of 89 lbs. ac^{-1} of nitrogen, and pre-commercial thinning plus fertilization of nitrogen at 89 lbs. ac^{-1} in 1997 and 2003. A biomass sampling was done after the sixth growing season when the trees were 23-26 years old. About 30 trees from all diameter classes were harvested and DBH and total height were measured. Discs from the base, at DBH and at specific percentages of the heights of the stem were collected. The discs were measured for diameter. Branches were selected from the live crown. The discs and branches were weighed in field and later dried in the lab, where the foliar was separated and weighed. The stems and all live branches were weighed in field.

The results of the Ahnlund Ulvcrona et al. (2014) study showed that these treatments didn't had much effect of the slenderness of the stems, the allocation of biomass, branches and crown length. In general, the control treatment produced slender trees in the smaller diameters. The smaller trees were affected by the pre-commercial thinning and allocated the biomass to stem, branches and needles in different proportions compared to the control. With the pre-commercial thinning the crown length increased. The study showed that there are possibilities to get higher volume of biomass out of pine stands, but the treatments had not so much of an effect after six growing seasons and the density was quite unrealistic compared to normal operational treatments in Sweden.

Management intensity studies

The northern forests don't grow as fast as in south and typically react slowly to management practices. They are not likely to improve the growth during a short time period, but the use of fertilization could quickly increase the biomass production. The limiting factor in many forests is lack of nutrients. If there was no lack of nutrients (most importantly nitrogen) the forest could produce two to three times more volume. Other factors are also important, the more leaf area present the faster the tree will grow. The efficiency of adding nitrogen to a site also matters. This is dependent on the species, site fertility, the stand age and whether or not the stand has been fertilized before. To maximize the biomass production and the effect of fertilization the stands should be left unthinned (Hedwall et al. 2014).

The use of fertilization would increase the biomass production in the Swedish forest, but the usage of fertilization as a silvicultural treatment has varied over the years. In the 1970's Sweden reached its highest peak of fertilization treatment and 1 % (500,000 ac) of the productive forest land in Sweden was fertilized at that time. In the 90's the use of fertilizers declined but in 2010 it has increased to 200,000 acres (Hedwall et al. 2014).

Hedwall et al. (2014) studied the effects of fertilization in northern Swedish forests based on biological, economic and environmental aspects. An application with 138 lbs. ac^{-1} of nitrogen increases the stem wood about 30 % over a 10-year period in mature scots pine stands. Young stands need more nutrients and respond better to fertilization than mature stands, but it is important to not fertilize too early due to competing vegetation. The biggest concern with fertilization is the aspect of leakage to freshwater and other water ecosystems. In general, the biodiversity of Nordic forests is low, and fertilization may not change that or it might even increase the number of species. There is a risk that there will be a reduction in biodiversity due to more leaf area in trees and less light for the plants on the forest floor.

However, fertilization of a forest will lead to a growing carbon stock and an increase in litter fall, which will increase sequestration of carbon. These fast-growing forests can be used for bioenergy and also positively contribute to the landowners' economy. It can increase the stock by 300-420 ft^3 ac^{-1} over 10 years. It is inexpensive and gives about 15 % more income than unfertilized stands. Optimized fertilization may reduce the rotation with 10-30 years in southern Sweden and 30-60 years in northern Sweden. Fertilization of northern forests will give good potential for carbon sequestration and biomass production which can reduce the use of fossil fuels. More intensive management will lead to higher risks, but also higher growth rates (Hedwall et al. 2014).

Density studies

Between 1966 and 1983 a nationwide study was established in Sweden, containing 35 uniform, even-aged, pure or almost pure sites of scots pine. The experiment was established to investigate the effect of thinning form, intensity, interval and timing of the thinning (Nilsson et al. 2010). The plots were established at the first thinning at each installation when the trees were 39 to 59 feet tall. The site index of these sites ranged from 65-98 feet at 100 years. The treatments ranged from unthinned control to several different grades of thinning expressed in percentage removal of basal area (20-63 %).

At the start of the experiments DBH was recorded for all trees, and also at every thinning and at irregular times between thinnings. Tree properties, damages, and cause of damage were recorded. Sample trees at each plot were recorded for height, height to live crown, and thickness of the bark. The sample trees were both retained throughout the whole study period if possible, and some sample trees were removed in thinnings. The measurements were used in volume models for predicting volume (Nilsson et al. 2010).

Total volume production was highest in unthinned control plots, and heavier thinnings resulted in lower total production than the weaker thinnings. The mean diameter was lower in the unthinned plots compared to thinned plots at the final measurements. The strongest thinning resulted in largest diameter trees. The results also showed that a delayed thinning did not affect the total production and that lower basal area gives reduced volume production. In general, the study showed that thinning decreased the total production by 65-80 % compared to the unthinned plots' production (Nilsson et al. 2010).

A study established in 1990 in southwestern Sweden compared the differences in growth and quality traits between half-sib families planted in single-tree plots and block plots, and also at different spacings (Egbäck et al. 2012). The experimental area was divided into single-tree plots and block plots. The single-tree plots were planted at 3.3x3.3 ft., 6.6x6.6 ft., and 9.9x9.9 ft. (1x1 m, 2x2 m, 3x3 m) while the block plots were planted by 6.6x6.6 ft. (2x2 m) and with a range of different half-sib families. No trees were removed throughout the study.

Measurements were taken at age 7, 9, and 21. At age 7 and 9 only total tree height for all the trees and at age 21 only sample trees were measured for height while all trees were measured for diameter. Quality traits were noted at this time too. The tree heights not measured were estimated using a height prediction model. Mixed-effects models were used for the statistical analysis (Egbäck et al. 2012).

The results showed that the 6.6x6.6 ft. spacing produced the tallest trees at all ages. At age 21 the 9.9x9.9 ft. spacing generated highest volumes and largest diameters. There were correlations between genetic family and the plot type (single-tree or block), and some families changed in behavior between the plots. This was explained by the thought that some of the families tolerate competition and others are not as tolerant of competition. Overall, families performed differently in single-tree plots and block plots, and the performance also differed among spacings (Egbäck et al. 2012).

The MINT (2009) report was partially based on opinion statements from stakeholders active in the Swedish forestry. Lidskog et al. (2013) evaluated the possibilities for intensive forestry in Sweden from those different stakeholders' point of view, concerning sustainable forest management. The expected benefits from intensive forestry in Sweden are increased production of raw material which can be used for energy, biofuels and industrial uses, and an increased carbon storage in tree biomass which will reduce the climate change, while the negative aspects are considered to be leakage of nitrogen, decrease in biodiversity, and lower values in recreation and cultural environments.

The authors used the 52 written sets of comments from different stakeholders that were submitted to the MINT report, and used a qualitative content analysis to analyze the benefits, risks and uncertainty concerning climate change etc. The interesting part was to see the stakeholders' standpoints and how they could justify them. The study showed that there was a large span of standpoints, which can be explained by the stakeholders' different interests in the Swedish forests. Most stakeholders were concerned about how the intensive forestry will be implemented and practiced. The stakeholders being positive to the intensive forestry are mainly interested in reduction in climate change and see intensive forestry as a step in the right way with carbon sequestration and higher production of biomass which can be used as biofuel and bioenergy. The stakeholders with a critical attitude believe that intensive forestry is harmful for the environment. The positive stakeholders believe that will not be an issue though the intensive forestry will be implemented in restricted areas, which already lack high values of biodiversity, and that the effect on recreation areas will not be huge.

However, all stakeholders agreed that the forests should be managed sustainable, and that the positive effects will be to the economy and climate, while there might be a negative effect in environment. Even though there are some agreements, there are conflicts about which values are the most important and the uncertainty in the outcome of intensive forestry, which may not be detected immediately (Lidskog et al. 2013).

The culture/density interaction study in the SE US

The PMRC installed a culture/density interaction study in 1995/96 in the coastal plain of southern Georgia and northern Florida at 17 locations with a range of different soil types (Zhao et al. 2015) to study the potential production of loblolly pine and slash pine, with different combinations of initial planting densities and management intensities (operational or intensive). These study sites have been measured and analyzed at ages 2, 4, 6, 8, 10, 12, 15, and 18. The data from age 21 is analyzed in this study.

The culture/density study consisted of 17 installations from the start, but only six installations contain complete data for both loblolly and slash pine for age 21, and therefore only those six installations are considered in this study. The 11 other installations have received treatments after establishment, or not been measured at all ages, and can therefore not be represented in this study. In the PMRC technical report from 2015, analyses from age 2-18 for seven installations are presented, and Zhao and Kane (2012) present findings from age 2-15 (six installations) in their paper.

In the culture/density study loblolly pine and slash pine was paired on a subset of installations, so there could be an opportunity to compare the performance of the trees at the same site conditions and treatments. The treatments were classified as operational or intensive and within both the treatments three subplots of loblolly pine and slash pine with densities of 300, 900 and 1500 TPA were randomly located and established. Loblolly pine was planted with six different densities, but slash pine only with three, the main focus will be on those three densities even though the 600 TPA and 1200 TPA is interesting for SE USA and Sweden. The 600 TPA and 1200 TPA (1500 and 3000 trees per hectare) represents common planting densities in the Swedish forestry.

The operational treatment is considered to be the prevailing practice in pine plantations in this region, while the intensive treatment is more intensive than what usually is applied in commercial forestry (Table 1).

Table 1. *The differences between the two management intensities*

Operational treatment	Intensive treatment
Bedding	Bedding
Fall banded chemical site prep	Fall broadcast chemical site prep
Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: at planting, 500 lbs per acre of 10-10-10; before 8th, 12th and 16th growth season, 200 lbs per acre N + 25 lbs acre P	Fertilization: at planting, 500 lbs per acre of 10-10-10; spring 3rd grow season, 600 lbs per acre 10-10-10 + micronutrients + 117 lbs/ac NH_4NO_3; spring 4th grow season 117 lbs/ac NH_4NO_3; spring 6th grow season 300 lbs/ac NH_4NO_3; spring 8th, 10th, 12th, 14th, 16th and 18th growing season 200 lbs/ac N + 25 lbs/ac P

The seedlings were all grown at one nursery. The loblolly pine was a first generation, open-pollinated family 7-56, which is a fast-growing family. The slash pine was first generation, open-pollinated family 5-61, an above average grower with significant resistance against cronartium rust. To make sure the initial density was correct and the same at all plots, each plot was double-planted again after the first growing season if plants were missing.

Site descriptions

All installations are located in the Coastal Plain of southern Georgia and northern Florida in the southeastern US (Table 2 and Figure 5). Six of the study sites from the culture/density study have been analyzed. These six sites contain data from all ages (2-21), for both loblolly and slash pine. Loblolly pine has been planted at six different densities while slash pine has been planted at three different densities. To make a comparison between the two species over all these six installations, the densities 300, 900, and 1500 TPA were used in the analysis.

Table 2. *The six installations' location, soil type and year of establishment*

Inst.	LAT	LONG	Location	NRCS Soil type	CRIFF	Year of Est.
4	30,1254	-82,1212	Columbia, FL	Pelham	B1	1996
9	30,702	-81,7756	Nassau, FL	Ocilla	B1	1996
11	30,5457	-81,9628	Nassau, FL	Ridgewood	D	1996/1997(sla)
12	31,2005	-82,6037	Ware, GA	NA	B2	1996/1997(sla)
13	29,6758	-81,7266	Putnam, FL	Pomona	C	1996
15	30,6464	-83,1448	Lowndes, GA	Albany	B2	1996

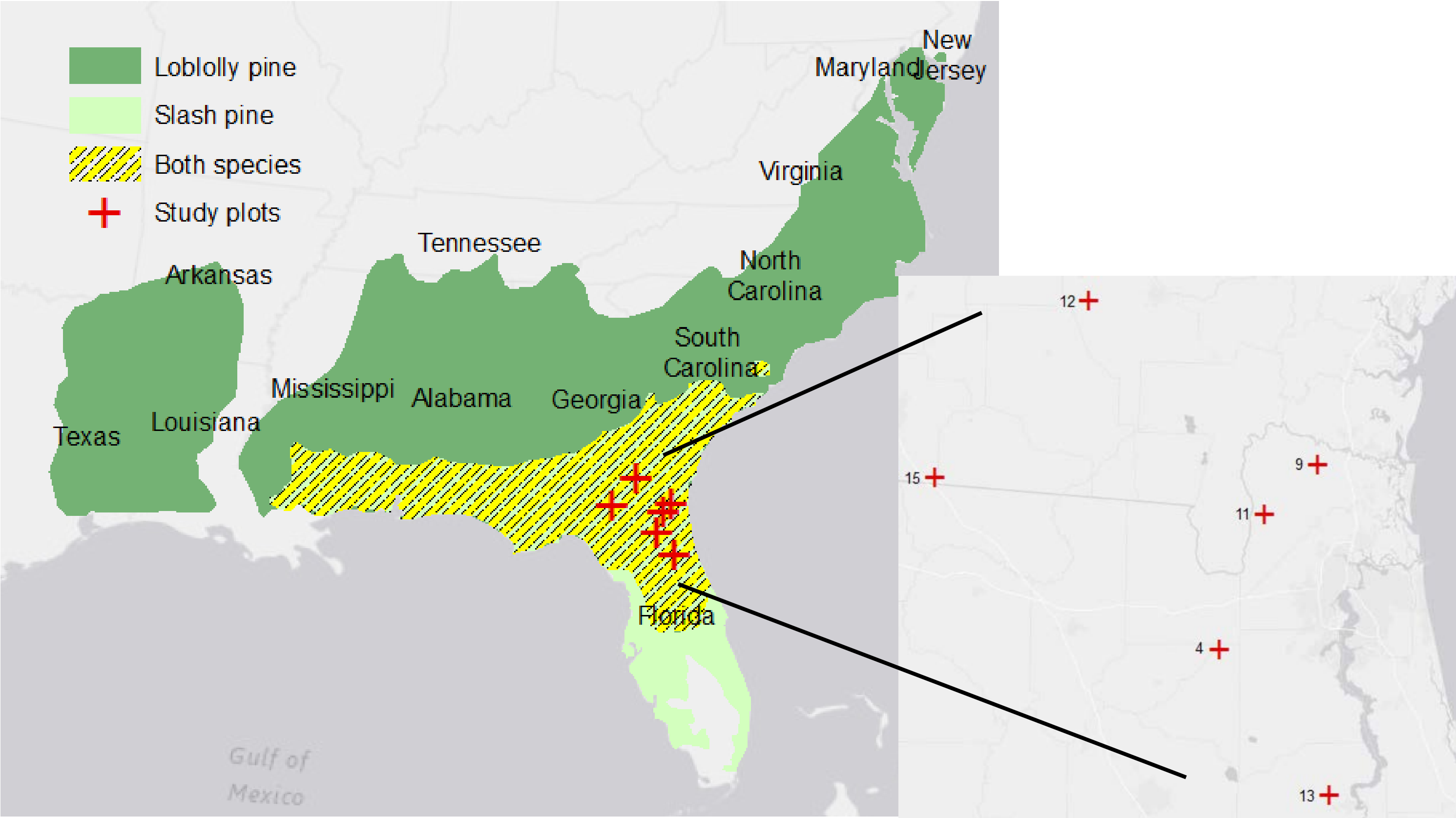


Figure 5. The location of the six installations.

Soil Classifications

In the Coastal Plain forests, often nitrogen (N) and phosphor (P) are limiting nutrients in the southern pine plantations. Therefore, soil classifications have been conducted. Researchers from the Cooperative Research in Forest Fertilization (CRIFF) program at the University of Florida developed during the 1970's a soil classifications system for grouping soils depending on how they respond to certain management activities (FFS 2017).

The soil orders can be divided into several individual soil series identified by Natural Resources Conservation Service (NRCS), based on the chemical and physical properties of the certain soil. This is complex and not easy, therefore the need of a simplified classification system for forest soils to use in practical forestry was requested and resulted in the development of CRIFF soil classification system. This system was made to help understand the distribution of forest soils in the Coastal Plain region (Jokela & Long 2015). The CRIFF classification system consists of eight soil groups, A-H (Figure 7), and is widely used as decision support for fertilization and other silvicultural treatments.

The soil groups are defined based on subsurface soil depth, drainage, and texture. Usually the recommendations are to plant slash pine on CRIFF soil groups A, B, C or D, while loblolly pine should be planted on CRIFF soil groups A, B, C, E or F. The culture/density study sites were planted on soils classified as B, C and D.

CRIFF soil groups A and B range from very poorly to somewhat poorly drained soils. They are usually very wet and lack phosphorus. Typically, these soils get flooded for some days during the growing season, and some organic matter in the surface horizon is common. Due to the lack of phosphorus, the growth is normally slow and can be as low as 40 to 45 feet after 25 years. The difference between CRIFF soil group A and B are from where the clayey subsoil can be found. CRIFF A has the subsoil within 20 inches from the surface while

CRIFF B has the subsoil deeper than 20 inches from the surface. Bedding and fertilization with nitrogen and phosphor at establishment is beneficial on these soils.

CRIFF soil groups C and D are very poorly to moderately well drained soils. They have a sandy to loamy sand texture, with low natural fertility. Under the surface horizon, a leached sand layer is found, followed by a spodic horizon where iron, aluminum and organic matter is accumulated. Below the spodic zone, the C soil group has an argillic zone (clayey) while CRIFF D has a sandy horizon. Bedding, fertilization and herbaceous weed control are treatments that can and should be done at establishment, which will increase the growth rates on those soils. Usually older plantations lack nutrients and will get higher growth rates from mid-rotation fertilization.

CRIFF soil groups E and F are moderately well to well drained. They are loamy sands and sandy clays. The E group has loamy sand to sandy loam surface, followed by clayey subsoil within 20 inches of the surface. The F group soils also have the same sandy surface layer, but the clayey horizon is found deeper than 20 inches from the surface. Fertilization at planting and in the already established stands will increase the growth of the plantations.

CRIFF soil group G is characterized by well drained sandhills and low nutrient reserves. Though these soils lack both moisture and nutrients, management practices that conserve the organic matter is needed, and therefore are these soils not well suited for intensive plantation management. CRIFF soil group H on the other hand is very poorly drained, often depressed areas in the flatlands and consists of organic matter. These soils should not be fertilized.

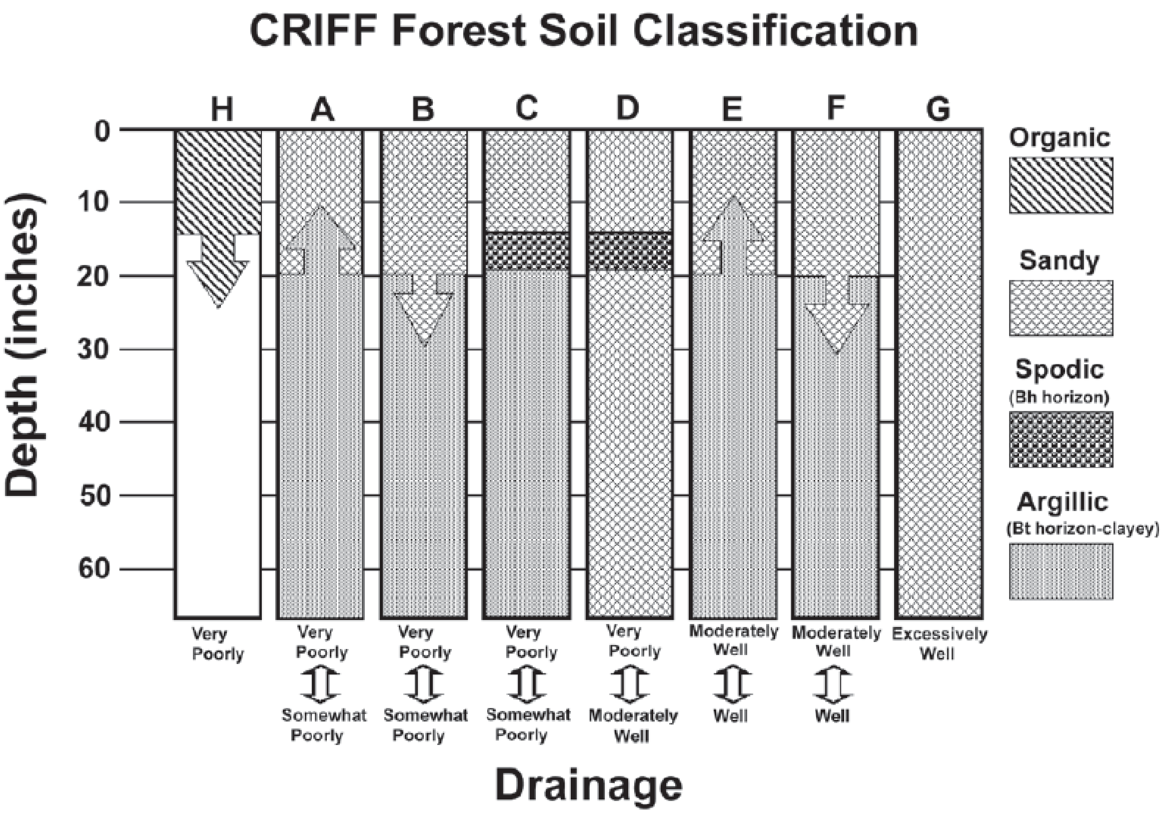


Figure 6. CRIFF soil classification (Jokela & Long 2015).

Data from the PMRC

Inventory data for the installations have been collected by staff from PMRC from the 2nd until the 21st growing season. All surviving trees at least 4.5 ft high was measured for diameter at breast height (DBH). All tree stems were inspected for cronartium infection. Every other tree was measured for total height (H) and height to live crown. The total height of the trees not height measured were estimated by two different height regression models. One model (1) was used for the smaller trees, for ages 2 and 4, while the other model (2) was fitted to ages 6 and older.

$$\ln(H) = b_0 + b_1 DBH^{-1} \quad (1)$$

$$\ln(H - 4.5) = b_2 + b_3 DBH^{-1} \quad (2)$$

Where

H = the total height in feet,
DBH = diameter at breast height (4.5 ft above ground level) in inches,
b_0, b_1, b_2, and b_3 = coefficients to be estimated.

The measurement plots varied in size depending on the initial planting density (Table 3). Note that the actual treatment plot size was larger to help buffer out the effect of adjacent treatments. Measurement plots were nested within larger treatment plots.

Table 3. *The measurement plots based on planting density*

TPA	300	900	1500
# of trees per plot	80	96	160
plot size (acres)	0.26	0.11	0.11

Statistical analysis

All statistical analysis was calculated using the statistical software R. R is an environment and language for statistical data analysis and graphics (Crawley, 2007). R is a free software to use and can be used for a wide range of statistical techniques, both for linear and non-linear modelling (The R Foundation, 2018).

First, summary statistics were calculated to see and display trends in data and how trends differed between treatments, planting density and tree species. Statistical analysis was made for each individual year, treatment, initial planting density, and species at each installation. To estimate height for non-measured trees, four height models were tested to the data to see which model that had the best fit. To determine the best fit, the R^2-values in relation to the data were compared. Two models had better fit than the other two and were therefore used, one for younger trees and one for older (model 1 and 2). The first model (1) fitted well to the data for age 2 and 4 while it didn't fit well at older ages, while the second model (2) did the fit for data from ages 6 and older but not for ages younger than 6.

To estimate volume production, different models were used for loblolly and slash pine. For loblolly pine the models from Pienaar et al. (1987) (4) were used and for slash pine the models from Pienaar et al. (1996) (3) were used. The models are using the top merchantable diameter outside bark (D_m) variable to be able to calculate to a certain top diameter, but because of interest in the total volume of the whole tree, and not just to a certain top diameter, the variable D_m was set to 0 to reduce this.

$$VOB_{slash} = \beta_0 DBH^{\beta_1} * H^{\beta_2} - \beta_3 (\frac{D_m^{\beta_4}}{DBH^{\beta_5}})(H - 4.5) \quad (3)$$

$$VOB_{loblolly} = \alpha_0 DBH^{\alpha_1} * H^{\alpha_2} - \alpha_3 (\frac{D_m^{\alpha_4}}{DBH^{\alpha_5}})(H - 4.5) \quad (4)$$

Where
VOB_{slash} = total volume outside bark in cubic feet for slash pine,
$VOB_{loblolly}$ = total volume outside bark in cubic feet for loblolly pine,
DBH = diameter at breast height (4.5 ft. above ground level) outside bark in inches,
H = total height in feet,
D_m = top merchantable diameter outside bark in inches (but because we want the whole tree, and not up to a certain diameter, we put this to 0)
β_{0-5} = coefficients from regressions,
α_{0-5} = coefficients from regressions.

The same equations (3 and 4) were also used in the previous technical report, making the results consistent.

When the summary statistics were done in R, the data was tested for significance. This was done with an ANOVA analysis and the differences between the two species were also analyzed at each year for each variable, and to determine the differences Tukey's test for pairwise comparison was used (Abdi & Williams, 2010).

The R-packages *nlme* and *emmeans* were used for the analysis (codes used are in Appendix 3), and both fixed, random and interactive effects were tested for significance.

The linear mixed-effects model was as follows:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + \delta_{ik} + e_{ijk} + \tau_l + (\alpha\tau)_{il} + (\beta\tau)_{jl} + (\alpha\beta\tau)_{ijl} + \varepsilon_{ijkl}$$

Where
$\mu =$ the overall mean,
$\alpha_i =$ the effect of the *i*th management intensity,
$\beta_j =$ the effect of the *j*th planting density,
$(\alpha\beta)_{ij} =$ the interaction effect of the *i*th management intensity and the *j*th planting density,
$\gamma_k =$ the random effect of installation with N(0,σ_δ^2),
$\delta_{ik} =$ the random effect of the *i*th management intensity in the *k*th installation with N(0,σ_e^2),
$e_{ijk} =$ the random effect of the *j*th planting density in the *i*th management intensity of the *k*th installation with N(0,σ_e^2),

τ_l = the effect of the *l*th time point,
$(\alpha\tau)_{il}$ = the interaction effect of *i*th management intensity with the *l*th time point,
$(\beta\tau)_{jl}$ = the interaction effect of the *j*th planting density with the *l*th time point,
$(\alpha\beta\tau)_{ijl}$ = the interaction effect of the *i*th management intensity with *j*th planting density at the *l*th time point,
ε_{ijkl} = the random effect of the *j*th planting density in the *i*th management intensity of the *k*th installation at the *l*th time point with N(0, Σ).

Results

To evaluate the effects of management intensity and initial planting density on productivity of the pines, graphs were first produced to illustrate the relationships, followed by the ANOVA analysis to determine the significant differences between loblolly and slash pine caused by certain factors. The ANOVA analysis was conducted at an α-level of 0.05, which means the results are 95 % reliable, but that 5 % possibly can be incorrect, because of type 1 error. Overall, loblolly pine performed better than slash pine.

Productivity in relation to management intensity and planting density

The ANOVA analysis showed the significant effects from both management intensity (Manage) in terms of how intensive treatment the plot recieved, planting density (Density) and their interaction (MxD) of the differences between loblolly and slash pine at each year (Table 4). For example the ANOVA analysis showed significance for planting density for DBH at age 6 to 21. Height (HT) followed the same trend but for both management intensity and planting density. Crown length (CL) showed significant results at almost all ages and all treatments. Survival was only significantly affected by planting density at age 15 and 18. Basal area was affected by planting density, and volume was between ages 6 to 15 affected by management intensity and from age 15 to 21 by planting density.

Table 4. *Fixed effects and interaction effects of the differences between loblolly pine and slash pine at each year*

Variable	Manage/ Density	Age 2	Age 4	Age 6	Age 8	Age 10	Age 12	Age 15	Age 18	Age 21
DBH (in.)	Manage	0.0820	0.8254	0.9040	0.9190	0.8307	0.1874	0.2171	0.5725	0.6606
	Density	0.5847	0.0530	**0.0065**	**0.0014**	**0.0001**	**0.0001**	**0.0003**	**0.0007**	**0.0003**
	MxD	0.6011	0.9471	0.5193	0.3798	0.5472	0.5146	0.2706	0.0525	0.0684
HT (ft)	Manage	0.9212	0.1149	**0.0001**	**0.0003**	**0.0010**	**0.0001**	**0.0002**	**0.0002**	**0.0232**
	Density	0.8893	0.1912	**0.0051**	**0.0008**	**<.0001**	**0.0001**	**<.0001**	**<.0001**	**<.0001**
	MxD	0.9780	0.4938	0.3054	0.0865	0.1222	0.2708	0.4414	**0.0326**	0.0771
CL (ft)	Manage	0.6214	**0.0040**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**<.0001**	**0.0225**
	Density	**0.0446**	**0.0284**	**0.0004**	**0.0101**	**0.0396**	**0.0419**	0.8957	**0.0001**	**<.0001**
	MxD	**0.0446**	0.2177	0.9170	**0.0137**	**0.0095**	**0.0021**	0.1050	0.3007	**0.0113**
CR	Manage	0.0505	**0.0006**	**0.0001**	**0.0016**	**0.0009**	**0.0250**	**0.0564**	**0.0169**	0.8410
	Density	0.2648	**0.0207**	0.0781	**0.0063**	**0.0038**	0.0632	**0.0002**	0.0593	**0.0001**
	MxD	0.5610	0.8706	**0.0212**	**0.0445**	0.4088	**0.0364**	0.4144	**0.0044**	**0.0003**
Survival (%)	Manage	0.4264	0.4460	0.6931	0.8183	0.5627	0.1769	0.9380	0.9808	0.9144
	Density	0.5216	0.5681	0.7914	0.7259	0.4810	0.5860	**0.0161**	**0.0106**	0.5738
	MxD	0.6581	0.5514	0.3347	0.3291	0.1684	0.2922	0.1104	0.1092	0.9868
SDI	Manage	0.0579	0.7863	0.5138	0.5539	0.2950	**0.0220**	0.0679	0.2414	0.5404
	Density	0.5970	**0.0461**	**0.0021**	**0.0063**	**0.0007**	**0.0011**	**0.0021**	**0.0028**	**0.0004**
	MxD	0.3231	0.8274	0.5752	0.3655	0.2745	0.1006	**0.0295**	**0.0057**	**0.0231**
BA (ft^2/ac)	Manage	0.0912	0.9377	0.1954	0.2148	0.2199	0.3278	**0.0768**	0.1861	0.3541
	Density	0.6695	0.0935	**0.0037**	**0.0138**	0.4707	0.4160	**0.0119**	**0.0021**	**0.0045**
	MxD	0.3682	0.8354	0.4847	0.2331	0.3239	0.4031	0.3207	0.6402	0.7397
VOL (ft^3/ac)	Manage	0.0732	0.4556	**0.0245**	**0.0051**	**0.0058**	**0.0145**	**0.0281**	0.0820	0.3234
	Density	0.4820	0.1325	**0.0524**	0.2323	0.6726	0.9527	**0.0294**	**0.0031**	**0.0050**
	MxD	0.4574	0.9125	0.1354	**0.0449**	0.1610	0.3053	0.3735	0.6585	0.7736

Average diameter at breast height (DBH)

Loblolly pine had a slightly faster diameter development than slash pine (Figure 7). The intensive treatment generated larger diameter than the operational treatment, and the lowest initial planting density led to larger diameter than the denser. At age 21 the 300 TPA initial planting density gave a dimeter of 10-11 inches while the 1500 TPA planting density gives around 7 inches, for both loblolly and slash pine. The DBH was significantly affected by the 300 TPA density from age 6 to 21 (Table 5). The intensive treatment was significant at age 15 only.

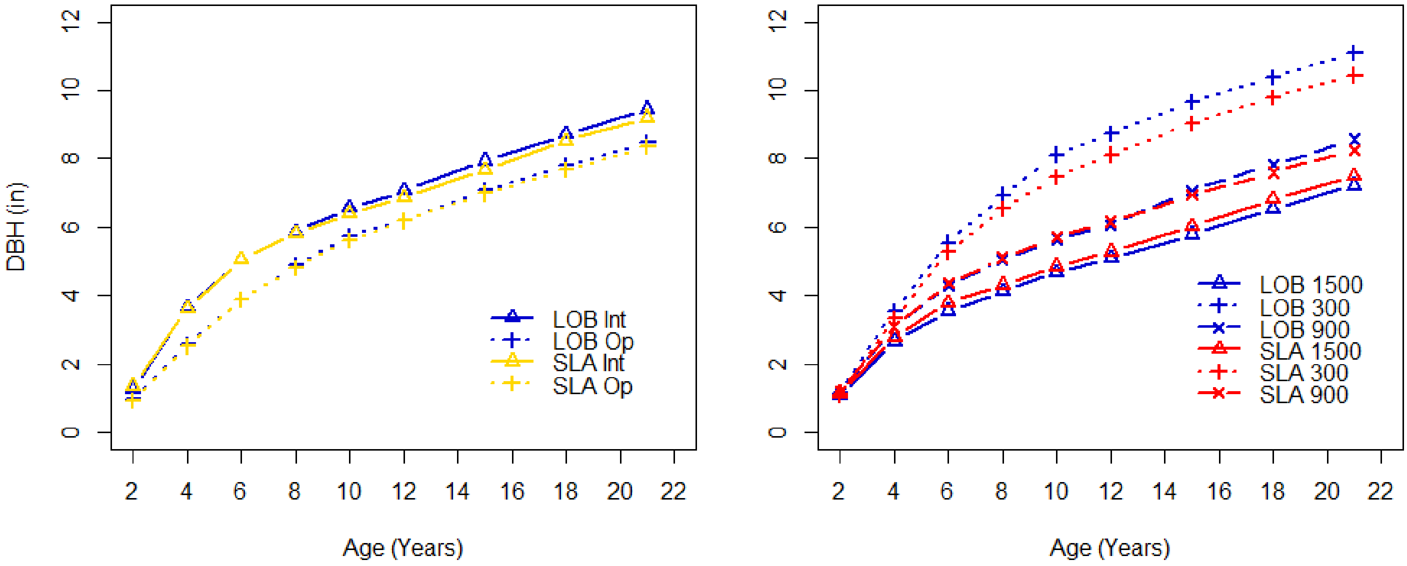


Figure 7. The average diameter at breast height for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Average height

The differences in height development between intensive and operational treatments, and planting densities are not large between the species (Figure 8). Loblolly pine gives just slightly higher trees than slash pine. At age 21 loblolly pine had an average of 78 ft for the intensive treatment while slash pine reached 72 ft. At the initial planting density of 300 TPA loblolly and slash pine reached 81 ft and 70 ft respectively and at 1500 TPA 69 ft and 67 ft respectively.

The intensive treatment results in taller trees than the operational treatment, and the initial planting density of 300 TPA contributes to taller trees than denser planting densities at the later ages. The initial planting density of 1500 TPA produces the shortest trees after 21 years.

Height was significantly affected by all densities and management intensities at all ages (Table 5).

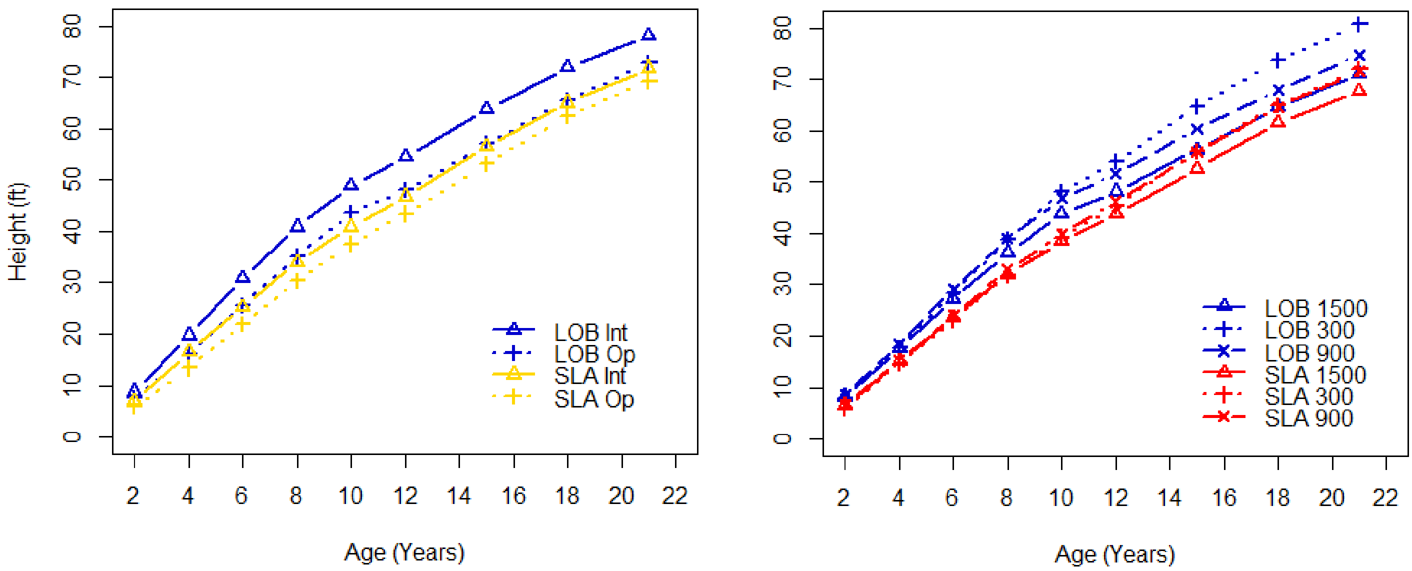


Figure 8. The average height for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Crown length

Loblolly pine has a longer live crown than slash pine for the intensive treatment and the operational treatment (Figure 9). The intensive treatment for loblolly pine generates the longest live crowns, while loblolly pine managed with the operational treatment performs on the same level as intensively managed slash pine. This trend is similar throughout the whole study.

Loblolly pine also has a longer live crown than slash pine in all planting densities. At the age of 21, loblolly pine at all planting densities performs at about the same level as slash pine planted at 900 TPA. While loblolly pine at 300 TPA has longer live crowns through the time series, 300 TPA for loblolly pine has the shortest crowns.

From around age 10, crown length was significantly affected by management intensity and planting density (Table 5).

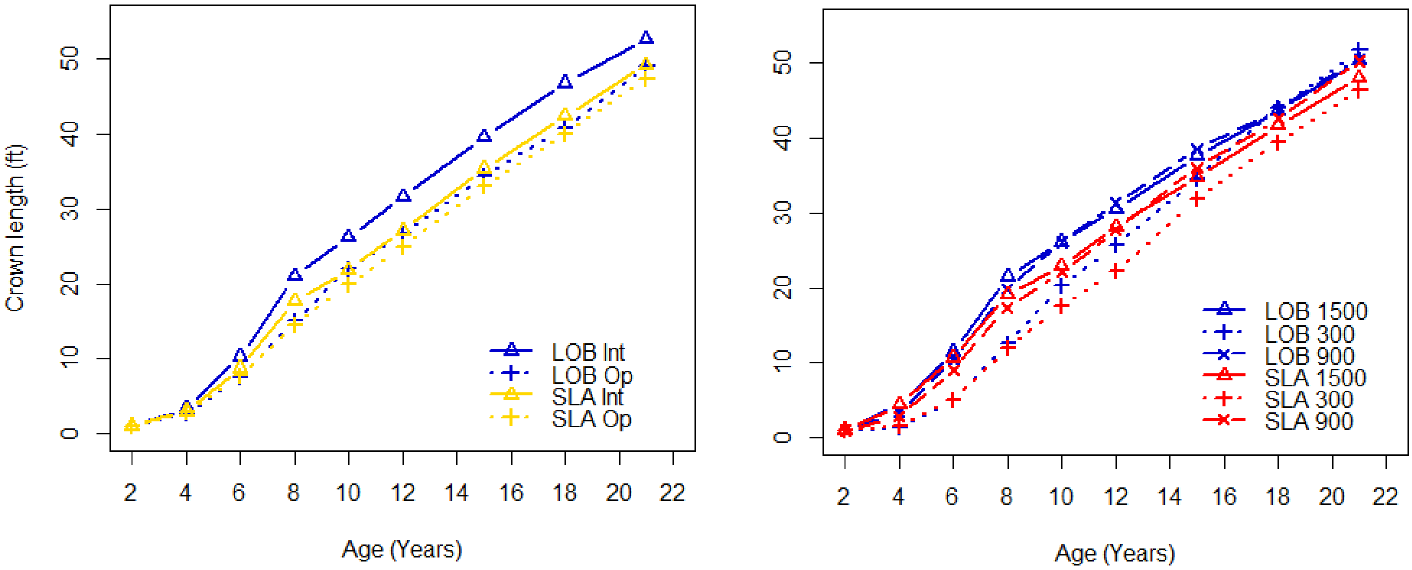


Figure 9. The crown length for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Crown ratio

The crown ratio is the relationship between the live crown length and the total height of the tree. High crown ratio means that the tree has a long crown length, while a low crown ratio means the opposite. With a planting density of 300 TPA, the crown ratio is higher (Figure 10), meaning each individual tree has higher potential to generate volume due to larger canopy.

The intensive and operational treatments follow the same trend and have similar ratios for both loblolly and slash pine. At age 21, both loblolly and slash pine have crown ratios of about 0.33 for the intensive and operational treatment.

The initial planting density of 300 TPA has through all ages the highest crown ratio, while the 900 and 1500 TPA performs on similar levels. Loblolly pine had a higher crown ratio for 300 TPA than slash pine, but on 900 and 1500 TPA the both species are similar to each other.

The crown ratio was affected by all planting densities and management intensities at age 2, but not after that (Table 5).

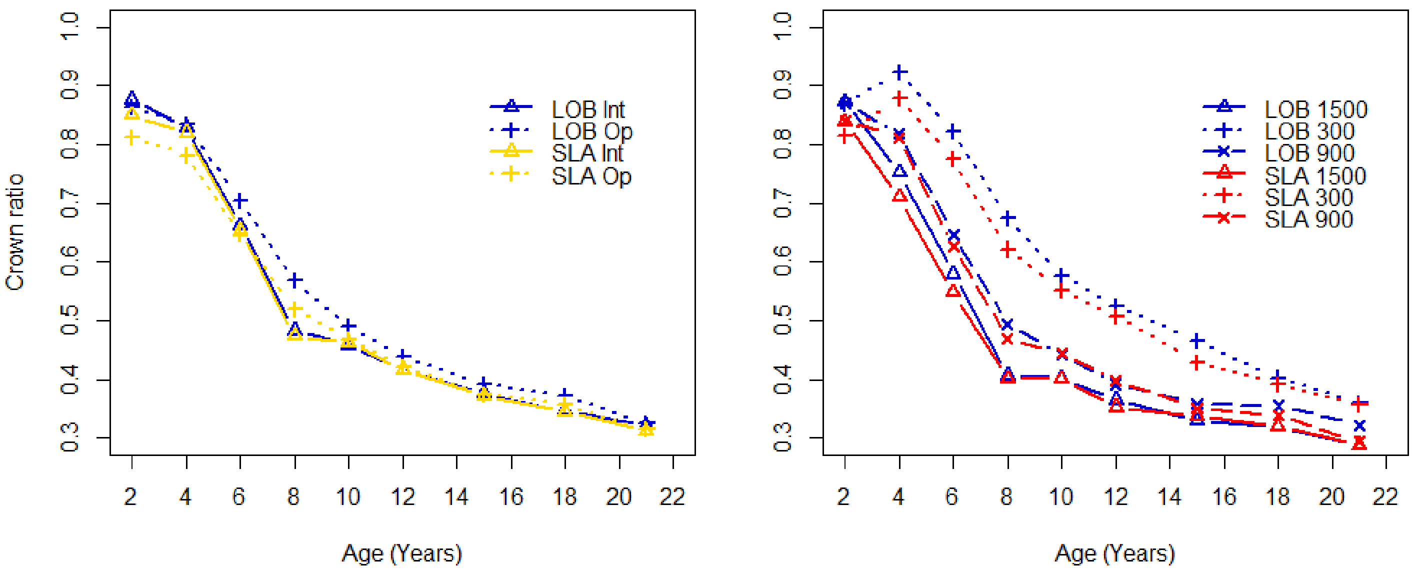


Figure 10. The crown ratio for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

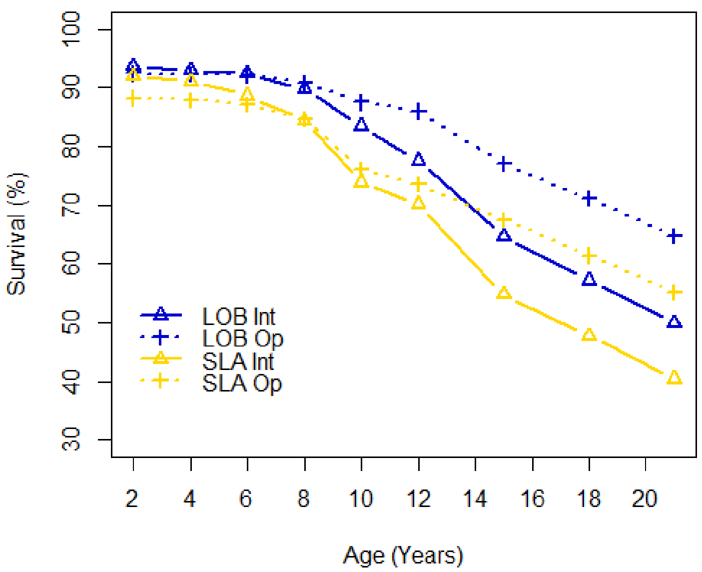
Table 5. *Differences in diameter (DBH), height (HT), live crown length (CL), crown ratio (CR) between loblolly and slash pine based on management intensity and initial planting density. The p-values indicate if there was a significant difference between the two specie during different management intensity and planning density*

Variable	Manage/ Density	Age 2	Age 4	Age 6	Age 8	Age 10	Age 12	Age 15	Age 18	Age 21
DBH (in.)	Int.	0.2560	0.8569	0.9331	0.6693	0.1978	0.0795	**0.0441**	0.1449	0.1549
	Op.	0.5938	0.7029	0.8225	0.5756	0.2839	0.7911	0.4171	0.3265	0.2932
	300	0.7556	0.1438	0.0705	**0.0130**	**0.0037**	**0.0028**	**0.0042**	**0.0079**	**0.0076**
	900	0.6542	0.9692	0.5808	0.5077	0.7033	0.4705	0.2878	0.2746	0.1657
	1500	0.4572	0.3767	0.0878	0.1375	0.2314	0.1586	0.1295	0.0971	0.0603
HT (ft.)	Int.	**0.0005**	**0.0006**	**0.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**0.0003**
	Op.	**0.0006**	**0.0014**	**0.0009**	**0.0002**	**0.0001**	**0.0002**	**0.0007**	**0.0024**	**0.0021**
	300	**0.0011**	**0.0009**	**0.0002**	**0.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**0.0001**
	900	**0.0011**	**0.0010**	**0.0003**	**0.0001**	**0.0001**	**0.0003**	**0.0010**	**0.0087**	**0.0188**
	1500	**0.0016**	**0.0026**	**0.0015**	**0.0006**	**0.0004**	**0.0007**	**0.0025**	**0.0072**	**0.0173**
CL (ft.)	Int.	0.5110	0.1160	**0.0058**	**0.0019**	**0.0001**	**0.0002**	**0.0002**	**0.0006**	**0.0016**
	Op.	0.9999	0.2957	0.7130	0.4353	**0.0014**	**0.0113**	**0.0293**	0.1832	**0.0170**
	300	0.9999	0.3040	0.9994	0.3375	**0.0008**	**0.0009**	**0.0031**	**0.0006**	**0.0003**
	900	0.0701	0.1138	**0.0125**	0.1192	**0.0002**	**0.0008**	**0.0045**	0.1759	0.8973
	1500	0.2122	0.8349	0.0829	**0.0096**	**0.0005**	**0.0056**	**0.0026**	**0.0201**	**0.0163**
CR	Int.	**0.0280**	0.4307	0.4787	0.4995	0.5507	0.8450	0.4929	0.9351	0.1854
	Op.	**0.0019**	**0.0039**	**0.0047**	**0.0093**	**0.0249**	0.0557	**0.0187**	0.0892	0.1298
	300	**0.0040**	**0.0145**	**0.0128**	**0.0088**	**0.0171**	0.0821	**0.0028**	0.2444	0.5286
	900	**0.0389**	0.5739	0.2063	0.1142	0.8351	0.5212	0.3286	0.1243	**0.0079**
	1500	**0.0226**	**0.0162**	0.0577	0.6634	0.9302	0.1954	0.2387	0.9032	0.7418

Survival rate

Loblolly pine had higher survival rate than slash pine (Figure 11). The operational treatment results in higher survival than the intensive treatment. At 300 TPA the survival was highest for both species throughout the study. At 1500 TPA at age 21 the survival was as low as 30 % for slash pine, while the survival at 300 TPA was about 70 %. For loblolly pine the survival rate was about 45 % at 1500 TPA and 85 % at 300 TPA at age 21.

At age 10, all planting densities and management intensities were significantly affecting survival between the two species (Table 6). At age 12 all treatments but the 900 TPA were significant. For age 15 and 18 only 300 and 1500 TPA had a significant effect on survival.



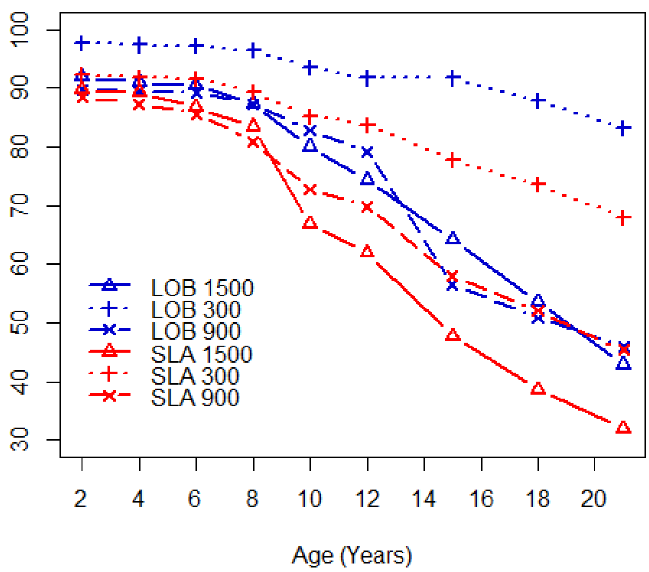


Figure 11. The survival rate for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Stand density index (SDI)

Stand density index (SDI) is a measure of stocking of a stand, based on the trees in this specific area and DBH of an average tree in this area. The index converts a current stand's density into a measure that is comparable with other areas and densities. SDI is commonly used USA. SDI is calculated as equation 5 shows.

$$SDI = TPA(\frac{D_q}{10})^{1.6} \tag{5}$$

Where

$D_q = \sqrt{\frac{\sum DBH^2}{n}}$ = square quadratic mean diameter.

Denser initial planting density results in higher SDI. Slash pine has higher SDI than loblolly pine at TPA 1500. The intensive and operational treatments show no difference between slash and loblolly pine. The intensive treatment gives higher SDI than the operational one (Figure 12).

SDI was significantly affected by 1500 TPA at age 6, 8, 15, 18, and 21, and by 300 TPA at age 10 (Table 6).

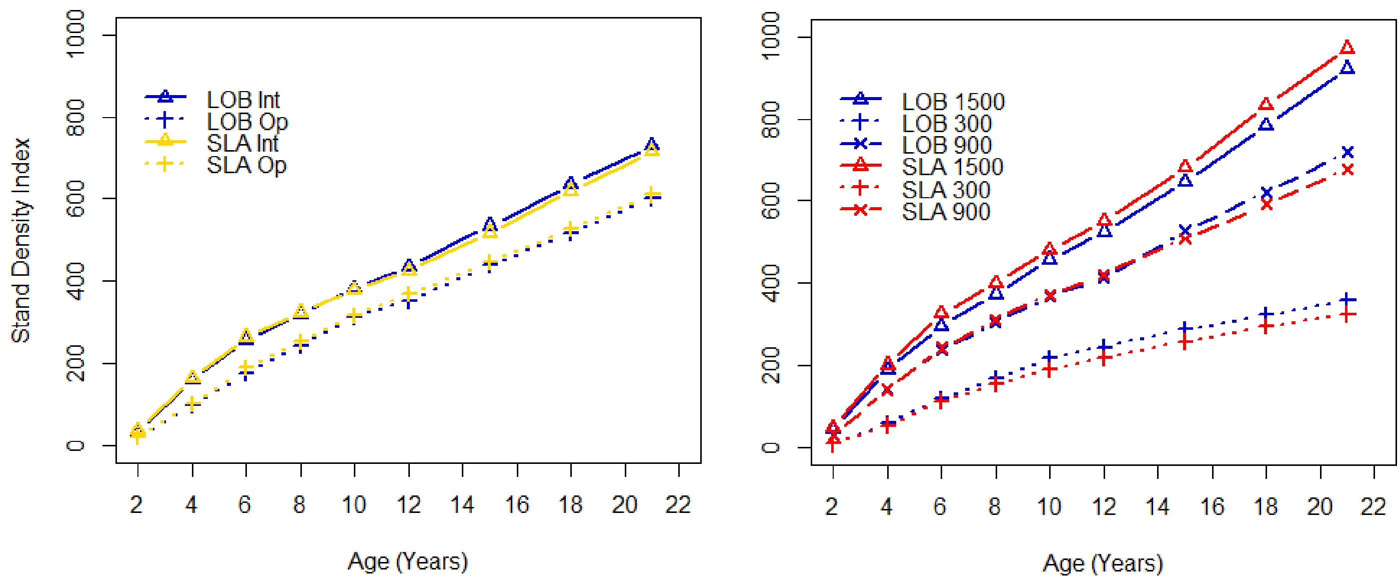


Figure 12. The SDI for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Per-Acre basal area

Generally, loblolly pine had higher basal area per acre than slash pine (Figure 13). The operational treatment gives higher basal area than the intensive treatment after 21 years, but the intensive was higher to an age of 12 for slash pine and to an age of 18 for loblolly pine.

With denser planting density, the basal area was higher, but with increased age, the initial planting density of 300 TPA is getting a higher basal area and has the same basal area as the plots with the initial planting density of 1500 TPA for loblolly pine at the age of 21. The basal area for loblolly pine planted at 900 TPA decreases in basal area after 10 years and then rises again. The decrease in basal area can be explained by the increased mortality.

Almost all treatments affected the basal area from age 10 (Table 6). The intensive treatment, 300 TPA, and 1500 TPA had affect from age 10 to 21.

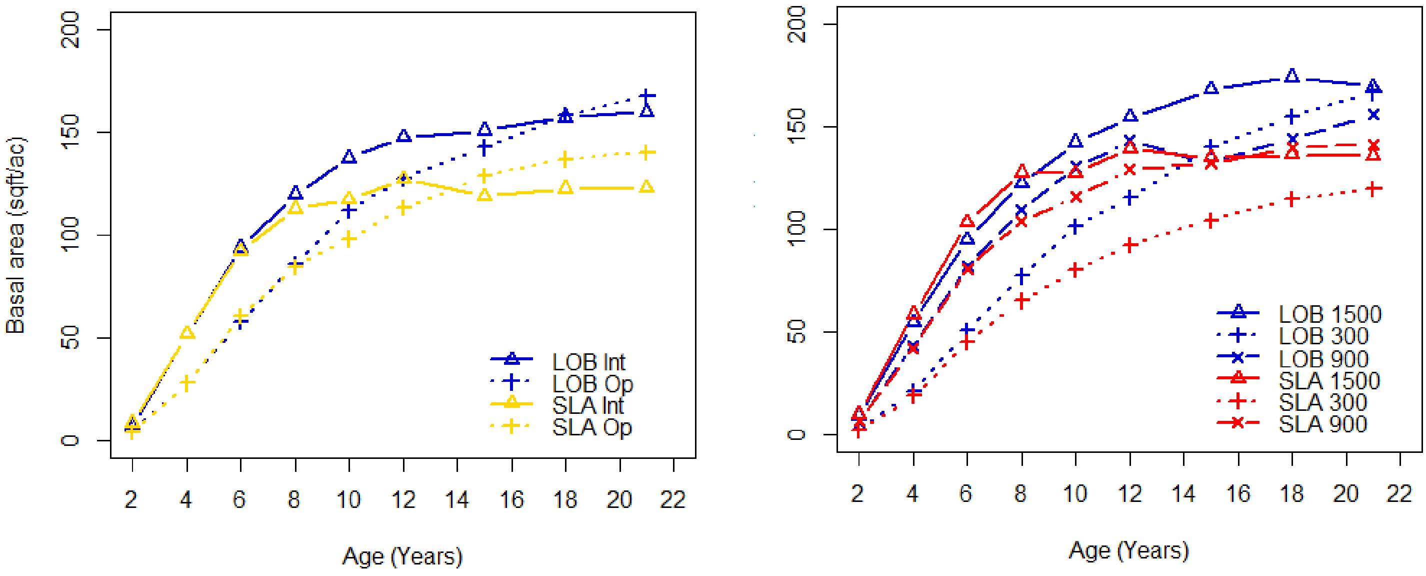


Figure 13. The basal area per acre for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Per-Acre outside bark total volume

Loblolly pine has a higher per acre volume production than slash pine overall (Figure 14). Both the operational and the intensive treatments results in higher total standing volume outside bark for loblolly pine than any of the treatments for slash pine. The intensive treatment results in highest total volume production at the younger ages, but at age 21 the two treatments have the same volume production for loblolly pine. For slash pine, the operational treatment makes a higher total volume outside bark from age 14.

In all the three planting densities, loblolly pine has a higher total volume production than slash pine. Slash pine has its highest total volume production in the planting density of 900 TPA at age 21. 300 TPA and 1500 TPA produces highest volumes for loblolly pine after 21 years.

Volume was significantly affected by the intensive treatment from age 8 to 21 (Table 6) and by 300 TPA and 1500 TPA between age 10 to 21. The operational treatment had significant effect age 10, 12, 18, and 21 while 900 TPA affected the volume at age 8 to 12 and at age 21.

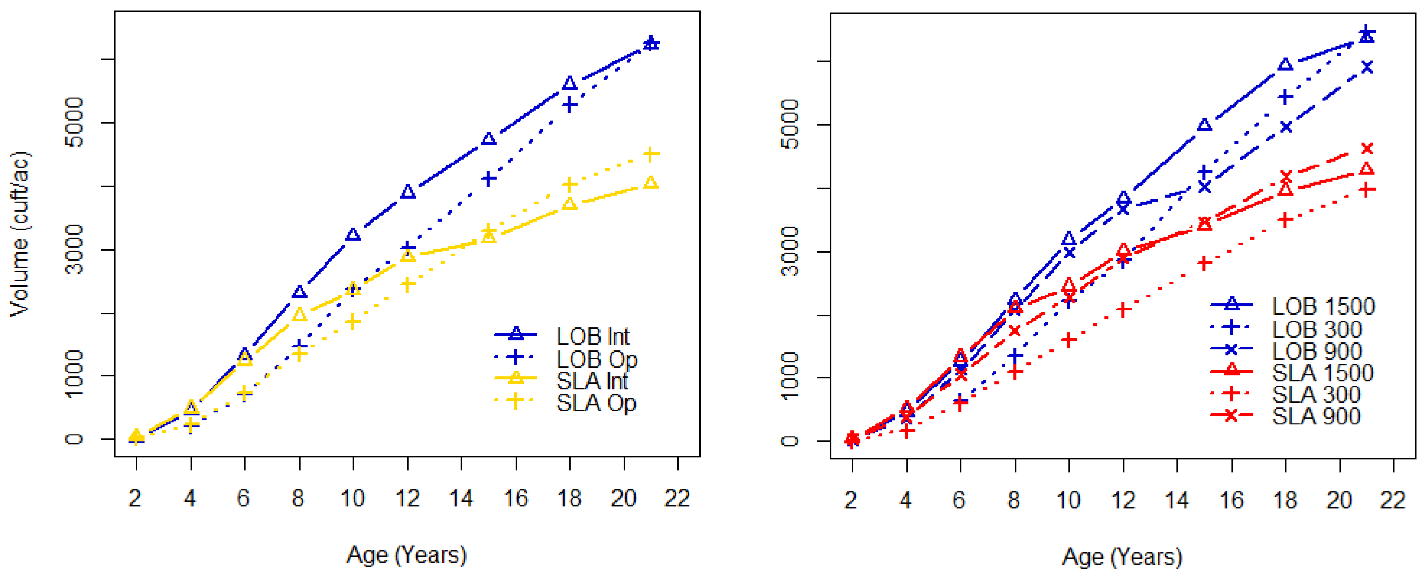


Figure 14. The per-acre total volume outside bark for loblolly and slash pine for the two management intensities (left) and the three planting densities (right).

Table 6. *Differences in survival, stand density index (SDI), basal area (BA) and total volume outside bark (VOL) between loblolly and slash pine based on management intensity and initial planting density. The p-values indicate if there was a significant difference between the two specie during different management intensity and planning density*

Variable	Manage/ Density	Age 2	Age 4	Age 6	Age 8	Age 10	Age 12	Age 15	Age 18	Age 21
Survival (%)	Int.	0.5798	0.5111	0.2105	0.1223	**0.0144**	**0.0405**	0.0910	0.0595	0.1781
	Op.	0.1988	0.1782	0.1217	0.0871	**0.0069**	**0.0056**	0.1014	0.0537	0.1293
	300	0.1537	0.1447	0.1142	0.0909	**0.0421**	0.0589	**0.0482**	**0.0230**	0.0632
	900	0.7130	0.5187	0.2843	0.1127	**0.0224**	**0.0346**	0.7880	0.9110	0.0631
	1500	0.5419	0.5994	0.2651	0.2955	**0.0078**	**0.0121**	**0.0274**	**0.0192**	0.0632
SDI	Int.	0.2171	0.6431	0.3864	0.6903	0.6047	0.3386	0.1355	0.4065	0.7210
	Op.	0.6700	0.8050	0.1501	0.2807	0.5331	0.1596	0.3996	0.4987	0.6327
	300	0.9346	0.5334	0.3827	0.1446	**0.0381**	0.0561	0.0639	0.1337	0.1304
	900	0.6992	0.9597	0.5512	0.4807	0.6946	0.4981	0.1820	0.2087	0.1300
	1500	0.3721	0.1385	**0.0130**	**0.0296**	0.0523	0.0529	**0.0350**	**0.0285**	**0.0136**
BA (ft^2/ac)	Int.	0.2917	0.9698	0.6289	0.1382	**0.0024**	**0.0047**	**0.0252**	**0.0155**	**0.0092**
	Op.	0.7159	0.9801	0.5068	0.7472	**0.0120**	**0.0187**	0.2299	0.0579	**0.0187**
	300	0.9064	0.4450	0.1862	**0.0468**	**0.0045**	**0.0066**	**0.0256**	**0.0091**	**0.0035**
	900	0.6736	0.7219	0.6928	0.2598	**0.0206**	**0.0432**	0.9809	0.8631	0.2560
	1500	0.4795	0.2754	0.0768	0.3052	**0.0194**	**0.0313**	**0.0323**	**0.0113**	**0.0129**
VOL (ft^3/ac)	Int.	0.1449	0.3164	0.2146	**0.0073**	**0.0001**	**0.0003**	**0.0048**	**0.0025**	**0.0021**
	Op.	0.9850	0.6297	0.5503	0.2912	**0.0016**	**0.0040**	0.0523	**0.0101**	**0.0034**
	300	0.8996	0.9812	0.4601	0.0497	**0.0017**	**0.0028**	**0.0100**	**0.0026**	**0.0012**
	900	0.4192	0.6905	0.2419	**0.0195**	**0.0009**	**0.0026**	0.1858	0.1288	**0.0300**
	1500	0.2289	0.1282	0.3414	0.2164	**0.0008**	**0.0020**	**0.0074**	**0.0024**	**0.0027**

Comparison between the 6 installations

Over the six installations, loblolly pine performed better than slash pine. Over the 21 years, loblolly pine had generally a larger DBH than slash pine. Slash pine had the same diameter as loblolly pine in installation 9 (CRIFF B) after 21 years and almost the same in installation 12 (B). In installation 15, slash pine starts producing higher DBH than loblolly pine after 15 years, but from age 21 not all measurements are available for slash pine. In installation 13 (C) slash pine has larger DBH than loblolly pine to age 12 and then it shifts.

Overall, the differences in DBH are not large, only about tenth of an inch (see Appendix 2). The total volume production is higher for loblolly pine than slash pine throughout all installations. The total volume production over the installations at age 21 ranges from about 6000 ft^3 ac^{-1} to 7000 ft^3 ac^{-1} (420-495 m^3 ha^{-1}) for loblolly pine and 3800 ft^3 ac^{-1} to 4500 ft^3 ac^{-1} (266-314 m^3 ha^{-1}) for slash pine, which is equal to 105-122 US ton and 78-92 US ton for loblolly and slash pine respectively. These volumes generate an economic value of $2500-3000 per acre for loblolly pine and $1860-2200 per acre for slash pine according to the latest prices for pine sawtimber in the South (TimberMart-South 2019).

The first years (age 2-8) both pines are producing the same amount of volume. After 8 years it starts to differ. The largest differences were found in installation 4 (B) and 9, where loblolly pine produces about 7000 ft^3 ac^{-1} while slash pine produces about 4000 ft^3 ac^{-1}, at age 21. The smallest difference was found in installation 13 where is differs about 1500 ft^3 ac^{-1} between the two species (Appendix 2).

Discussion

Loblolly versus slash pine

Overall, loblolly pine performed better than slash pine in terms of volume production and growth and yield in general across the variables tested in the analysis. The only time slash pine performed better than loblolly pine was at initial planting density of 1500 TPA for DBH. At all other variables, ages and treatments, loblolly pine performed better than slash pine. Loblolly pine performed better among all installations too. The installations were located on CRIFF soil groups B, C, and D, which are the most suitable soil types for slash pine (Jokela & Long 2015). Loblolly pine does not perform best on CRIFF D, but the analysis show that loblolly pine performs better than slash pine in installation 11 too, which is the CRIFF D installation. Over the six installations loblolly pine produces more total volume than slash pine, and also a larger DBH (slightly). On the CRIFF B soil groups, loblolly and slash pine had about the same DBH after 21 years. The higher volume production in loblolly pine can be because of the higher mortality for slash pine, though their diameter developments is similar.

The differences in growing stock between the species in the different installations are large, with about 6000 ft^3 ac^{-1} to 7000 ft^3 ac^{-1} of total volume for loblolly pine and 3800 ft^3 ac^{-1} to 4500 ft^3 ac^{-1} of total volume for slash pine at age 21. At early ages (age 2-8) both the pines produce about the same amount of volume. In terms of economic profit for the forest owner, slash pine generates higher profit in those cases loblolly and slash pine produces the same amount of volume due to the higher wood density slash pine has. But as we can see (Appendix 2), loblolly pine produce much more volume than slash pine does at the end of the rotation (age 21). This would mean quiet large differences in economic gain for the forest owner depending on what species that is planted on what soil type, and therefore it is important from this economic perspective to choose the best suited species. For example, in installation 13, the volume difference between loblolly and slash pine is about \$384 per acre in economic value, while the difference between loblolly and slash pine in installation 9 is \$1055 per acre in terms of economic value (if we assume all volume is sawtimber).

As the results from the analysis show, intensive forest management and initial planting density can increase the growth of pine plantations, but the largest affect is caused by planting density for each tree species, and in the end of the rotation, the operational and intensive treatments do not differ significanly. After 12 growing seasons in loblolly pine stands Zhao et al. (2012) reported the similar trends. The more intensive management, the higher biomass production to a certain point. They also found that higher planting densities resulted in higher biomass production in a stand, and this can be seen in the analysis too, that loblolly pine at age 12 produces more biomass at 1500 TPA than other planting densities (Figure 14). The study only lasted over 12 years, but the findings are in line with the analysis from this master thesis and the treatments used are the same which shows consistency between the two studies and makes the results reliable. Subedi et al. (2012) also concluded that intensive treatment generates more biomass production than operational treatment, using the same study design as Zhao et al. (2012).

Actually, all of the American articles reviewed showed that more intensive management results in higher production of volume or biomass. For example, Fox et al. (2007) stated that fertilization can increase the volume production by 55 ft^3 ac^{-1} yr^{-1} over an 8 year period. This was also confirmed by Jokela et al. (2000). They reported that fertilization affected the production positively for both slash and loblolly pine, but they saw they CRIFF soil group didn’t affect survival for slash pine, but CRIFF C affected the survival for loblolly pine negatively, which it doesn’t do in the analysis. Jokela et al. (2000) questioned this too and address the low survival to flooding during the first growing season on those sites. However, at the end of the rotation (age 21) the two management intensities generated about the same amount of volume for loblolly pine which can be addressed to the high mortality (Figure 11) for the intensive treatment. For slash pine, the operational treatment generates more total volume after 21 years.

Initial planting density also influences production of the plantations. For slash pine, higher planting density accelerates the volume production of the plantation early (Dickens and Will 2004), which is consistent with the analysis (Figure 14). Amateis and Burkhart (2012) are reported similar trends from their study, including loblolly pine.

None of the studies reviewed showed results that were completely different from the analysis, and that might be due to the similarities in study designs, management treatments, geographical region etc., and this most importantly indicates that the results can be general and what to expect in the SE US on similar sites and conditions. Even though the articles reviewed and the results from the analysis show consistent trends, I think the PMRC culture/density study would have given a better overview of the production potential of slash and loblolly pine if control plots (plots without any management at all) were included in the study and not only plots with different managements, to show how stands without active forest management develop and grow in comparison to managed stands.

Scots pine in relation to loblolly and slash pine

The Nordic studies have less intensive management than both the operational and intensive treatments from the analysis, and from other SE US studies. Even though the management in Sweden is less intensive than the management practices in SE US are (mainly due to regulations that doesn’t allow more intensive treatments in Swedish forestry (MINT 2009)), it shows a large potential to increase the growth in Swedish scots pine stands as well. For example, scots pine reacts to fertilization as slash and loblolly pine do, but not on the same level because of lower amount of nitrogen applied and colder climate. As an example, nitrogen fertilizer can increase the volume by 300-400 ft^3 ac^{-1} over a 10-years period (Hedwall et al. 2014). Valinger (1993) also showed that fertilizer can increase dry weight in scots pine stands by almost 30% and by almost 60 % with a combined treatment of fertilizer and thinning. This shows that scots pine has a great potential to increase its growth with more intensive management which is not too intensive according to the Swedish forestry act.

All the Nordic articles related to management intensity (Ahnlund Ulvcrona et al. 2014; Valinger et al. 2000; Bergh et al. 2014; Mäkinen et al. 2005) showed that scots pine has potential to grow at higher rates if the stands are being managed with fertilizer compared to control plots.

The study Mäkinen et al. (2005) made with scots pine under different management intensities and thinning regimes showed that diameter increased for the individual tree with decreased stand density, which are similar to the trends SE US studies have shown for loblolly and slash pine (e.g. Dickens and Will 2004) and from the analysis presented in this thesis. The results from Mäkinen et al. (2005) showed that stand volume increases with higher stand density (Figure 15) which is consistent with the analysis of loblolly and slash pine, which follows the same trends.

The trends seen from density studies can be somewhat similar in USA and Sweden, e.g. that higher initial planting density leads to higher biomass production. Egbäck et al. (2012) showed that larger spacings generated individual trees with higher volume production and wider diameter than trees planted at high density, but the total volume production on stand level is highest in unthinned stands and stands with high initial planting density (Nilsson et al. 2010) while stronger thinnings reduce the total volume production. This is seen in SE US too (Amateis and Burkhart 2012; Jokela et al. 2000) and shows that scots pine follows the same trends to planting density as loblolly and slash pine, although it goes faster in the SE US stands.

It is hard to compare the southeastern US pines with scots pine due to their very different rotations and management regimes. Scots pine rotations are longer in all Nordic studies and it also takes longer time to do research and evaluate the results in Sweden because of the rotations. Anyhow, all the species are affected by planting density and management intensity and have potential to produce more biomass and volume if the regulations allowed more intensive managements.

Comparison with other studies

The results from the analysis matched well with results from other studies made in the SE US. Zhao et al. (2012) found in their study that both management intensity and planting density effects allocation of biomass in 12-year-old loblolly pine. Intensive management results in higher production of biomass while planting density of 300 TPA produces the least amount biomass per acre. At the age of 12 years, the production of volume in the PMRC's culture/density study indicates the same result. The findings from Subedi et al. (2012) study also show the same pattern.

Zhao et al. (2016) showed with their study that productivity can be increased by different treatments and that responses are most noticeable on low quality sites. They found that 15-year-old loblolly pine stands was affected by planting density, management intensity and their interaction, but less response the better quality site. Higher stocking generated more biomass, and that's in line with the volume production at 15 years from the analysis.
Dickens and Will (2004) found that slash pine produces more volume per tree in a wider planting density and more volume per acre in denser plantings. Higher planting density accelerates the volume production. All spacings and planting densities doesn't fit all goals of production. Amateis and Burkhart (2012) concluded that too. Wider spacings generated larger trees and higher planting density produces more volume than lower densities. 300 TPA produces higher quality trees while denser stands produce more biomass.

The Scandinavian studies also showed results that responded positive to fertilization and thinnings. Valinger (1993) found that fertilizer and fertilization in combination with thinning produced more dry weight 5 years after treatment in 45-years-old scots pine stands than control plots. Bergh et al. (2014) concluded that scots pine responded well to fertilization, and they saw a shift in diameter classes toward larger diameters when the stand was fertilized compared to un-fertilized stands. The response to thinnings was overall positive too. Mäkinen et al. (2005) showed that stand density has an effect on individual tree and stand growth and fertilized stands increased the diameter growth significantly. The volume production increases after fertilization (Hedwall et al. 2014).

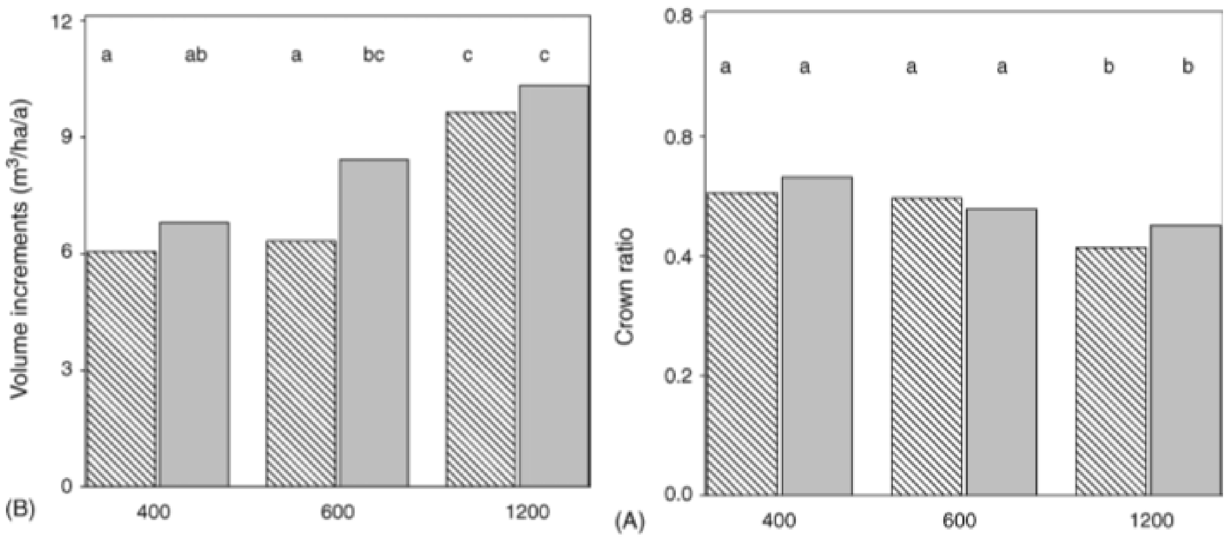


Figure 15. Volume increments and crown ratio at stand density of 400, 600, and 1200 trees per hectare (160, 240, 485 TPA) (control and fertilized, left-slanting and grey respectively) (adapted from Mäkinen et al. 2005).

Two studies (Nilsson et al. 2010; Egbäck et al. 2012) reported findings about density and growth where they showed that volume production was highest in unthinned control plots and stronger thinnings lead to lower total production. Egbäck et al. (2012) also showed that a spacing of 9x9 ft generated high volume.

Overall, the results from the analysis and from the literature show consistency with each other.

Sustainability of the management

According to the MINT-investigation the possibilities to implement more intensive forestry is realistic on 1 million acres in Sweden and without higher risks of damages (MINT 2009). Higher rates of fertilizer might lead to leakage to streams and freshwater, but will increase the growth of trees and at the same time increase the capacity of carbon sequestration in the forests. In general the implementation of intensive forestry in the Swedish forestry would be favorable for the production, economic growth and for the climate. The volume growth can doubled and the greenhouse emissions can be reduced. According to simulations made in Finland on scots pine, the pine stands rotation can be shorten by 15 years with intensive management (Mäkinen et al. 2005), which would result in higher production of and possible use of more renewable building material, bioenergy and biofuel sources.

When Lidskog et al. (2013) evaluated the possibilities for intensive forestry in Sweden based on opinions from active stakeholders in Swedish forestry, they concluded that the opinions were many because of different interests. However, a general trend showed that the stakeholders positive to implementation of intensive forestry were the ones which were interested in reduction in climate change while the negative responses came from stakeholders concerned about the environment and biodiversity. There were conflicts about the uncertainty in the outcome of these intensive practices, which it must be though the future can't be predicted to perfection. Anyhow, according to the research and evaluations made, the most likely outcome indicates that the climate change effects can be reduced because of change in energy sources and increased carbon storage (Hedwall et al. 2014).

Therefore, yes, these practices are sustainable in terms of production but also in terms of reducing climate change effects, in Sweden. Also, more intensive forest management practices can be applied in Swedish forestry and be sustainable, but regulations and certifications rules must be adjusted before this can happen, but there are possibilities.

In the SE US the forest management practiced can be much more intensive than currently done in Sweden. But these practices are discussed if they are sustainable for the soil and climate and many studies indicates that they are sustainable if additional nutrients are added to the sites. For example, Gresham (2002) showed with his study that intensive management is sustainable for two rotations in loblolly pine plantations in South Carolina, and that the sites accumulate nitrogen and phosphorous and it was a faster accumulation in the second rotation too. Eisenbies et al. (2009) discussed the sustainability of southern plantations as well, but looked at the possibilities of outtake of residues after harvests and still sustain the soil nutrients and productivity of growth. Their study showed it was possible to remove harvesting residues and still sustain the soil's nutrients. But, if too much residues are removed, there are risks to reduce the long-term productivity of the site. Anyhow, for the research available today, removal of residues seem not to have a negative effect on the long-term production as long as the forest floor keeps intact, particularly this is reliable on natural high fertile sites and fertilized sites.

Another realistic way to proceed was stated by Stanturf et al. (2003). They explain that one of the most important ways to keep the productivity of southern plantations sustainable in terms of climate change reduction and soil nutrients, is to focus on tree genetics and improvements to help increase production.

Sources of error

There can be error in data collection, but mainly I would address potential error in this master thesis to the modelling and coding in R. There can also be an error in the results due to type 1 error. And because the analysis was made with the α-level of 0.05, there is likely 5 % errors in the results.

Conclusion

Loblolly pine performed better than slash pine in terms of production of diameter, height, volume, and basal area across a range of installations, ages, management intensities and planting densities, showing that loblolly pine gives higher production and therefore higher economic yield than slash pine. The intensive treatment had largest impact of production of both the pines in terms of different stand-level measures, but due to high mortality when the intensive treatment was applied, the operational treatment will be as productive after 21 years when it comes to volume production for loblolly pine.

The planting density of 300 TPA had largest impact on the individual tree, such as diameter and height, but generated lower volumes than denser stands. The planting density of 1500 TPA had the opposite effect. Other studies showed consistent results with these results from this thesis.

More intensive management can be applied in Swedish forestry and can be sustainable and could increase carbon sequestration as well as the production. Also, the intensive management has shown to be sustainable in terms of production in the SE US, from a long-term perspective.

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Appendix

Appendix 1 - Conversion tables

Acre (ac) and Hectare (ha)

1 ac = 0.404 ha	10 ac = 4.04 ha
1 ha = 2.47 ac	10 ha = 24.7 ac

Trees per Acre (TPA) and Trees per Hectare (TPH)

300 TPA = 740 TPH	600 TPA = 1482 TPH
900 TPA = 2223 TPH	1200 TPA = 2964 TPH
1500 TPA = 3705 TPH	1800 TPA = 4446 TPH

Inches (in) and Centimeters (cm)

1 in = 2.54 cm	2 in = 5.08 cm
3 in = 7.62 cm	4 in = 10.16 cm
5 in = 12.7 cm	6 in =15.24cm
7 in = 17.78 cm	8 in =20.32 cm
9 in = 22.86 cm	10 in = 25.4 cm
11 in = 27.94 cm	12 in = 30.48 cm
20 in = 50.8 cm	23 in = 58.42 cm

1 cm = 0.39 in	5 cm = 1.97 in
10 cm = 3.94 in	20 cm = 7.87 in
30 cm = 11.8 in	50 cm = 19.68 in

Feet (ft.) and Meters (m)

1 ft = 0.304 m	10 ft = 3.048 m
20 ft = 6.09 m	30 ft = 9.14 m
40 ft = 12.19 m	50 ft = 15.24 m
60 ft = 18.28 m	70 ft = 21.33 m
80 ft = 24.38 m	100 ft = 30.5 m

1 m = 3.28 ft	10 m = 32.8 ft
20 m = 65.6 ft	30 m = 98.4 ft

Square inches (in^2)/Square feet (ft^2) and Square centimeters (cm^2)/Square meter (m^2)

1 in^2 = 6.45 cm^2	
1 ft^2 = 0.09 m^2	10 ft^2 = 0.92 m^2
50 ft^2 = 4.64 m^2	100 ft^2 = 9.29 m^2
150 ft^2 = 13.9 m^2	200 ft^2 = 18.6 m^2

100 cm^2 = 15.5 in^2	
1m^2 = 10.76 ft^2	10 m^2 = 107.6 ft^2
15 m^2 = 161.4 ft^2	20 m^2 = 215.3 ft^2

Cubic feet (ft^3) and Cubic meter (m^3)

1 ft^3 = 0.028 m^3	100 ft^3 = 2.83 m^3
500 ft^3 = 14.15 m^3	1000 ft^3 = 28.3 m^3
2000 ft^3 = 56.6 m^3	3000 ft^3 = 84.95 m^3
4000 ft^3 = 113.26 m^3	5000 ft^3 = 141.58 m^3
6000 ft^3 = 169.9 m^3	7000 ft^3 = 198.2 m^3

1 m^3 = 35.3 ft^3	10m^3 = 353.14 ft^3
50 m^3 = 1765.7 ft^3	100 m^3 = 3531.4 ft^3
150 m^3 = 5297.2 ft^3	200 m^3 = 7062.9 ft^3

Pounds (lbs) and Kilograms (kg)

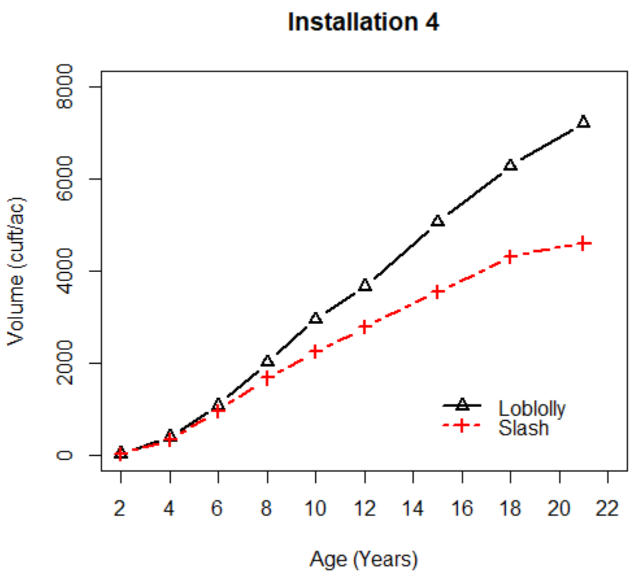
1 lbs = 0.454 kg	100 lbs = 45.4 kg
150 lbs = 68 kg	200 lbs = 90.7 kg

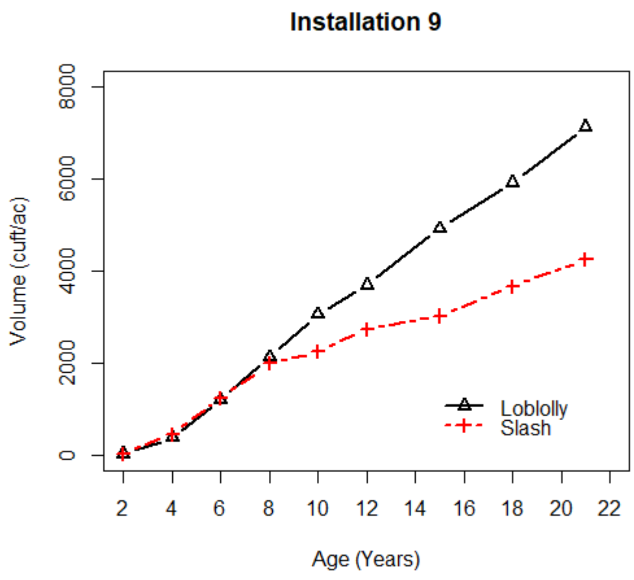
1 kg = 2.2 lbs	100 kg = 220 lbs

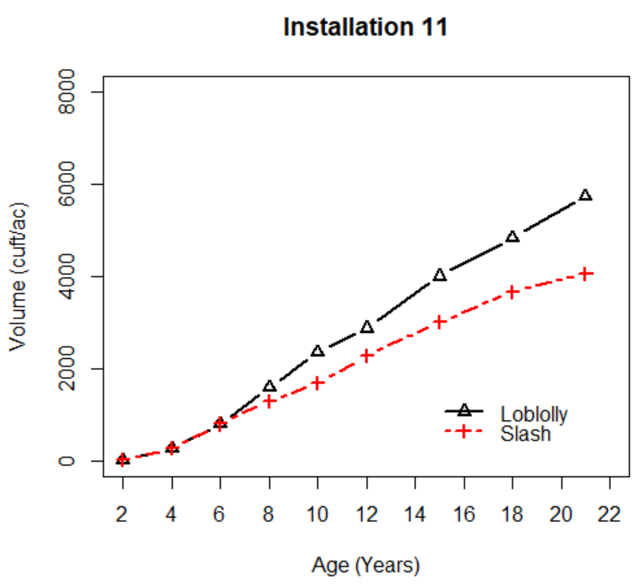
1 US ton = 0.9072 Metric ton
1 US ton = 2000 lbs

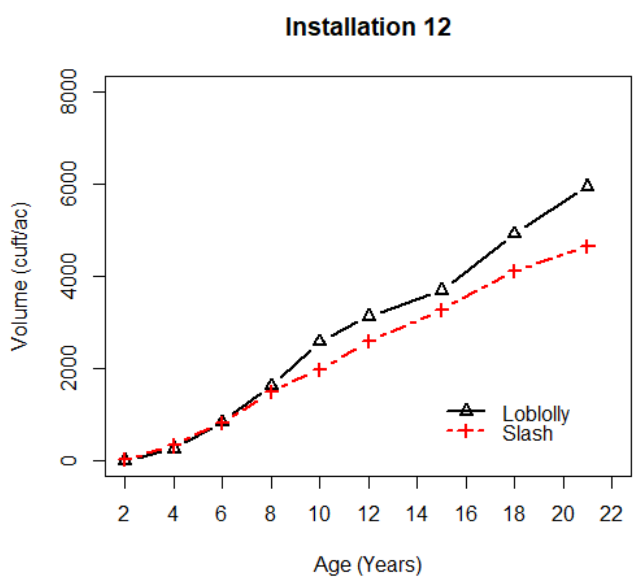
Appendix 2 - Graphs

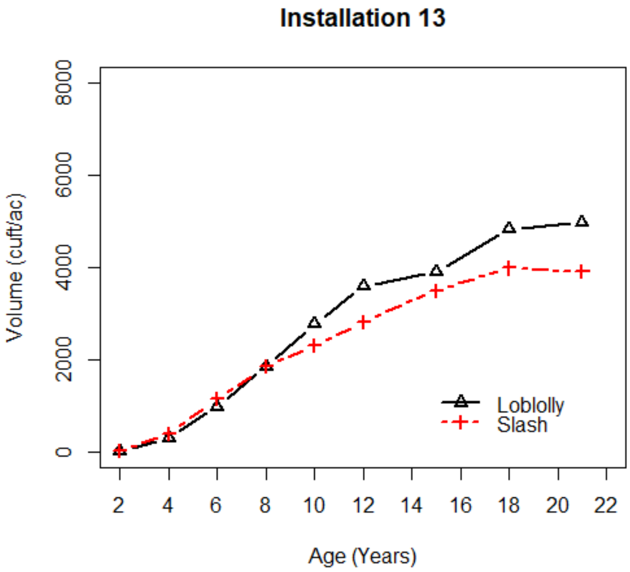
These graphs are showing the differences in growth between the six installations, expressed in terms of total volume outside bark and in DBH.

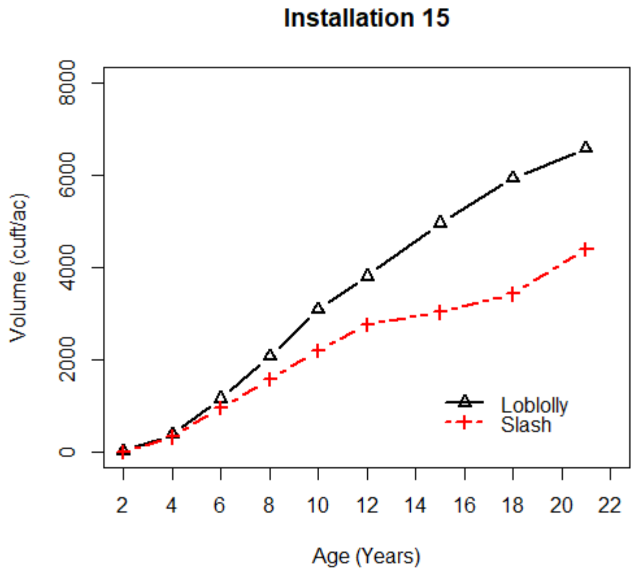


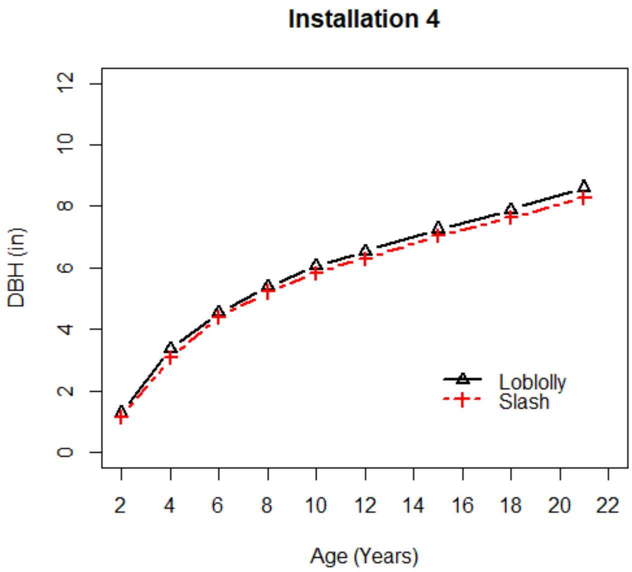


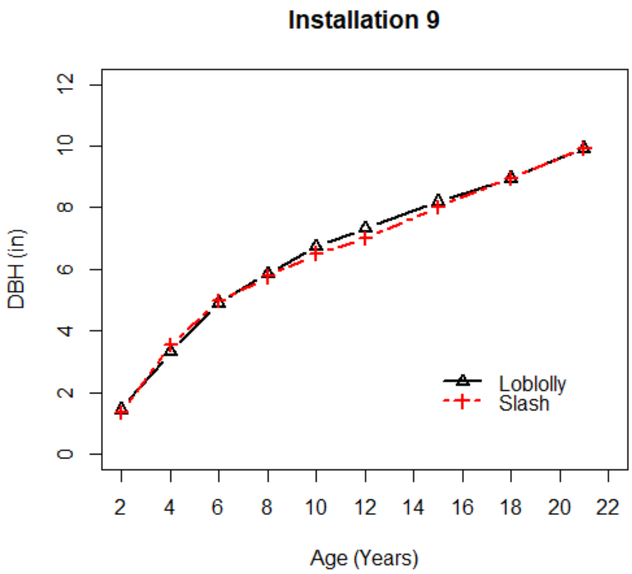




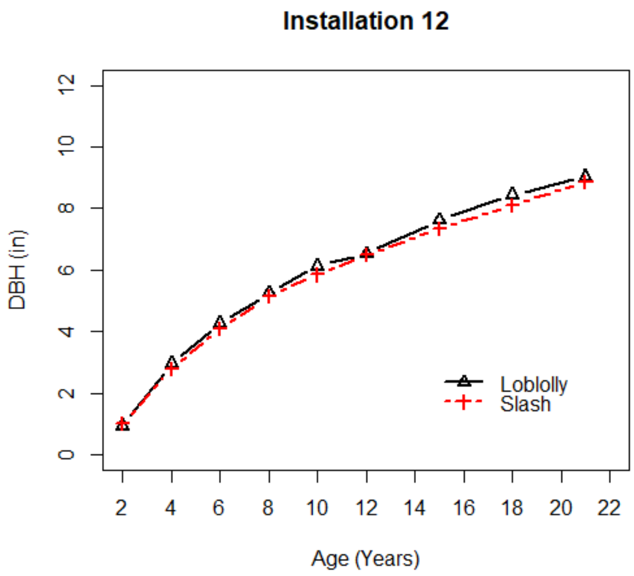

Installation 13
Volume (cuft/ac)
0 2000 4000 6000 8000
2 4 6 8 10 12 14 16 18 20 22
Age (Years)
Loblolly
Slash


Installation 15
Volume (cuft/ac)
0 2000 4000 6000 8000
2 4 6 8 10 12 14 16 18 20 22
Age (Years)
Loblolly
Slash

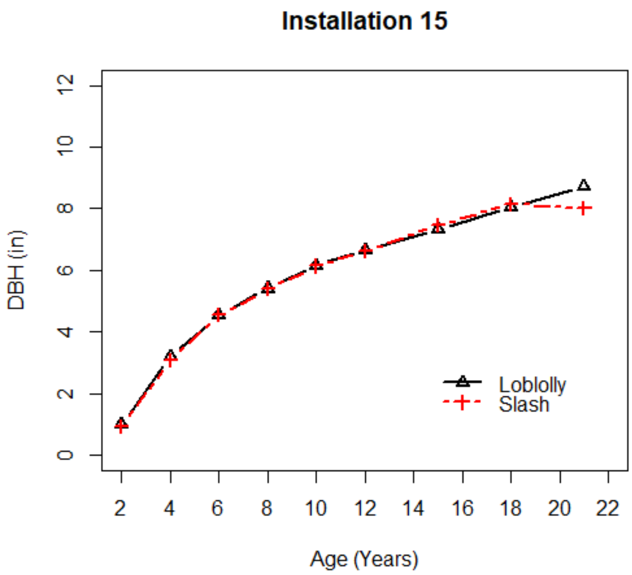

Installation 4
DBH (in)
0 2 4 6 8 10 12
2 4 6 8 10 12 14 16 18 20 22
Age (Years)
Loblolly
Slash


Installation 9
DBH (in)
0 2 4 6 8 10 12
2 4 6 8 10 12 14 16 18 20 22
Age (Years)
Loblolly
Slash


Installation 11
DBH (in)
Age (Years)
Loblolly
Slash


Installation 12
DBH (in)
Age (Years)
Loblolly
Slash


Installation 13
DBH (in)
Age (Years)
Loblolly
Slash


Installation 15
DBH (in)
Age (Years)
Loblolly
Slash

Appendix 3 - Code

difDBH = loblolly pine DBH – slash pine DBH
difHT, difCL, difCR, difSURVIVAL, difSDI, difVOL, and difBA follow the same format as difDBH
PLTPA = initial planting density (300, 900, 1500 trees per acre)
MAN = management intensity (intensive, operational)
INST = installation (4, 9, 11, 12, 13, 15)
AGE = age (2, 4, 6, 8, 10, 12, 15, 18, 21)
KEY = MAN-PLTPA-INST

```
model           <- lme(difDBH ~ PLTPA*MAN,
                 random = ~
INST+MAN:INST+PLTPA:MAN:INST+AGE:PLTPA*MAN|KEY,
                correlation = corAR1(form = ~AGE|KEY) ,data= dataset)


anova(model)



model2          <- lme(difDBH ~ MAN*PLTPA,
                random = ~ 1|INST,
                 data= dataset2, method="REML")


anova(model2)
emmeans(model2, ~ PLTPA+MAN, adjust="tukey",data = dataset2)
output1 <- emmeans(model2, ~ MAN, adjust="tukey",data = dataset2)
output2 <- emmeans(model2, ~ PLTPA, adjust="tukey",data = dataset2)
test(output1)
test(output2)
```