ARBETSRAPPORT 1054-2020

Afforestation of abandoned agricultural land in Sweden

– EFFECTS OF TREE SPECIES ON BIOMASS PRODUCTION, CARBON BALANCE AND SOIL CHARACTERISTICS OVER LATITUDES

Beskogning av övergiven jordbruksmark i Sverige- Trädarters effekt på biomassa-produktion, kolbalans och markegenskaper på olika breddgrader




FOTO: LARS RYTTER & ROSE-MARIE RYTTER

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Contents

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Preface

This report describes research and results obtained from five tree species experiments established on abandoned agricultural land. The referred research work spans the period 2007 to 2020 when current financial support ends. The reason for a summary report is that many interesting results have been published to date and that the project will soon change project leaders. It is therefore appropriate to compile results and experiences collected so far. Funding for research on the experimental sites has mainly been obtained from the Swedish Energy Agency. There have been projects concerning tree crop biomass and nutrients as well as soil characteristics and carbon stocks. Table 1 shows the various projects over time and the funding received from the Swedish Energy Agency. In total, the agency has to this day financed projects with almost 5.5 million SEK over a 14-year period.

Table 1. Economic support from the Swedish Energy Agency to the five tree species experiments in Sweden.

Project	**Project number**	**Project period**	**Financing (SEK)**
Tree species trial with emphasis on biomass production	30658-1	2007–2010	1 000 000
Soil chemistry and C and N sequestration in plantations with fast-growing tree species	30659-1	2007–2010	500 000
Soil chemistry and C and N sequestration in plantations with fast-growing tree species – supplement	30659-2	2010	117 500
Tree species trial with emphasis on biomass production – supplementary application	30658-2	2011	241 000
Soil chemistry and C and N sequestration in plantations with fast-growing tree species – phase 2	30659-3	2012–2015	700 000
Tree species trial with emphasis on biomass production – phase 2	30358-3	2012–2014	849 000
Tree species trial with emphasis on biomass production – growth in the juvenile phase	30358-4	2016–2018	1 326 000
Environmental effects of biofuel production in fast-growing plantations on abandoned arable land	30359-4	2018–2020	764 300
		Total	**5 497 800**

The authors hereby wish to thank the Swedish Energy Agency for the support these research activities has received and at the same time thank all colleagues who, over the years, have been involved in the projects, from experiment layout to completion of scientific articles and their dissemination.

It should also be added that E.ON gave financial support for establishment of the two northerly experimental sites.

Ekebo, Svalöv June, 2020
Lars Rytter and Rose-Marie Rytter

Summary

Fast-growing tree species will be an important contribution to the future supply of renewables, in substituting non-renewable fossil energy sources and capturing carbon (C). Sweden has large areas of abandoned farmland usable for biomass production and carbon sequestration, but knowledge of growth performance of different tree species is insufficient. Changing land use from agriculture to forestry affects global C balances. In addition to reduce the use of fossil fuels, climatic benefits may be reached by increasing forested areas where appropriate. At present, there is limited data concerning whether differences in C sequestration rates occur among tree species. Land-use changes from arable land to forests will also affect soil chemical parameters. It is therefore important to follow the development of soil characteristics in forest cultivation systems with short rotation times and biomass removal to be able to make soil amendments and improvements in time. Whether there is an effect of tree species on soil properties has long been discussed and there is a need for more studies concerning the influence of tree species on sizes and distribution of nutrient pools in the soil.

An experiment was initiated where the growth rates of six potentially high-producing tree species were compared over the country. The best available plant material for each species was used on five sites from latitude 56 to 64°N. The six tree species were Norway spruce (*Picea abies* (L.) Karst), hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.), larch (Siberian larch, *Larix sukaczewii* Dylis, on the two northerly sites and hybrid larch, *L. ×eurolepis* Henry, on the three southern sites), poplar (*Populus* spp., species and hybrids mainly from section Tacamahaca, i.e. balsam poplars), willow (*Salix dasyclados* Wimm., clone 'Gudrun' on the two northern sites and *S. schwerinii* Wolf × *S. viminalis* L., clone 'Tora' in the south) and silver birch (*Betula pendula* Roth).

In the experiment we also evaluated the effects of various species on C sequestration and soil parameters at the early stage of afforestation. Total C stocks, i.e. C in biomass, litter and soil, were compiled for the tree species. Soil, litter and plant biomass were sampled repeatedly, except for root biomass which was calculated from functions found in the literature. The development of different soil parameters was followed in the mineral soil down to 30 cm depth, divided into two depth levels, 0–10 and 10–30 cm, for analyses. The first soil sampling was performed before planting to obtain initial values showing the pre-planting conditions. Soil bulk density was estimated, nutrient concentrations were analysed and sizes of nutrient pools were calculated. Litter samples were collected in connection to the soil samplings. Results from the first 8–9 years are reported.

Short rotation coppice (SRC) willow had the fastest initial growth and production of biomass in southern Sweden. Hybrid aspen and poplar, grown as short rotation forest (SRF) like the remaining species, grew well over all sites and showed a comparably high productivity at the two northern sites. Hybrid larch displayed a high potential at the two most southerly sites, while silver birch was so far a medium-producing species at all sites. Norway spruce started slowly, and Siberian larch produced poorly at the two northern sites in the initial stage. All tree species followed reported height development curves for respective species on a high site quality level.

There were no differences among species in C stocks after 8–9 years growth, except for SRC willows that reached a high production early due to a higher stand density compared to species managed with SRF. Total C sequestration rates over sites varied from zero to 4.9 Mg C ha^{-1} yr^{-1}. There were, however, no effects of species on soil organic carbon (SOC), but significant decreases were noted for sites with high initial amounts, while SOC was unchanged or increased on sites with lower initial amounts. Mean SOC sequestration rates for sites ranged from -3.0 to 0.78 Mg C ha^{-1} yr^{-1}. There were few differences between species in litter C in these young stands.

There were also few differences among tree species in their impact on mineral soil characteristics. Decreases in SOC and total nitrogen (N) occurred in the lower soil layer for most species at the end of the 8^{th}–9^{th} growing seasons. Those pools were reduced with 12–18 percent and 13–15 percent, respectively, from the initial amounts. The CN ratios were generally unchanged compared to the pre-planting conditions. The only exception was under Norway spruce where a slight decrease could be seen. Plant-available phosphorus (P) decreased under all species. The plant-available concentrations and pools of the base cations potassium (K), magnesium (Mg) and calcium (Ca), showed various development. While Ca decreased in both soil levels, K and Mg increased in the upper soil and decreased or was unchanged in the lower soil layer. This implies that K and Mg were redistributed from deeper to shallower soil levels by plant uptake and recycling through decomposition of litter. Decreases in pH with 2 percent on average were observed for all tree species.

The study showed a high growth potential for most tested species on former agricultural lands. We conclude that increased tree productivity had a positive effect on total C sequestration at this early stage of afforestation. It is crucial to include C in both biomass and soil when discussing C capture at land use change. There were few tree species-specific effects on the investigated soil parameters. Nearly a decade of afforestation of the former arable sites resulted mainly in general soil effects associated with the cessation of earlier annual management measures, enhanced litter production from trees and ground vegetation, and probably also with altered soil physical conditions, for example humidity and temperature, in the growing plantations. The time factor is important and experiments like this should therefore be followed for an extended time to achieve best possible information.

Sammanfattning

Snabbväxande trädslag utgör ett viktigt bidrag till framtida förnybara energikällor. De kan ersätta fossila energikällor och binda kol. Sverige har stora områden med övergiven jordbruksmark som kan användas för biomassaproduktion och kolbindning, men kunskapen om olika trädslags potential för detta är inte tillräckligt känd. Ändrad markanvändning från jordbruk till skogsbruk påverkar den globala koldioxidbalansen. Förutom att minska användningen av fossila bränslen kan klimatfördelar uppnås genom att öka andelen skogsmark. För närvarande finns det begränsad kunskap om skillnader i kolbindning mellan olika trädslag. Ändrad markanvändning från åker till skog kommer också att påverka markens kemiska förhållanden. Det är därför viktigt att följa utvecklingen av markegenskaper i intensiva skogsodlingssystem med kort omloppstid och skörd av biomassa för att kunna göra markförbättrande åtgärder i tid. Huruvida det finns en effekt av trädslag på markegenskaperna har länge diskuterats och det finns behov av fler studier om olika trädslags påverkan på näringsmängder och näringens fördelning i markprofilen.

För att studera olika trädslags tillväxtpotential över landet, uttryckt som produktion av ovanjordisk biomassa per arealenhet, anlades ett experiment där sex potentiellt högproducerande trädslag inkluderades. Det bästa tillgängliga växtmaterialet för varje trädslag användes på fem försökslokaler från latitud 56 till 64°N. De sex trädslagen var gran (*Picea abies* (L.) Karst), hybridasp (*Populus tremula* L. × *P. tremuloides* Michx.), lärk (sibirisk lärk, *Larix sukaczewii* Dylis, på de två norra lokalerna och hybridlärk, *L. ×eurolepis* Henry, på de tre södra lokalerna), poppel (*Populus* spp., arter och hybrider främst från sektion Tacamahaca, dvs. balsampopplar), pil (*Salix dasyclados* Wimm., klon "Gudrun" på de två nordliga lokalerna och *S schwerinii* Wolf × *S. viminalis* L., klon 'Tora' i söder) samt vårtbjörk (*Betula pendula* Roth).

I experimentet undersöktes även effekterna av de olika trädslagen på kolinlagring, på näringsämnen i marken och på andra markparametrar i ett tidigt skede av omloppstiden. Totala kolförråd, dvs kol i biomassa, förna och mark, sammanställdes för respektive trädslag. Provtagning av mark, förna och trädslagens ovanjordiska vedbiomassa utfördes upprepade gånger. Rotbiomassan beräknades med hjälp av funktioner hämtade från litteraturen. Utvecklingen av olika markegenskaper följdes genom provtagning av mineraljorden ned till 30 cm djup uppdelat i två djupnivåer, 0–10 och 10–30 cm. Den första markprovtagningen gjordes före plantering för att erhålla initiala värden. Jordens volymvikt bestämdes, näringskoncentrationer analyserades och storlek på näringspooler beräknades. Förnaprover samlades in samtidigt med markprovtagningen. Resultat från de första 8–9 åren efter plantering avrapporteras.

Skottskogsbruk med *Salix* med kort omloppstid uppvisade den högsta initiala produktionen i södra Sverige. Hybridasp och poppel, odlade som konventionellt skogsbruk med kort omloppstid liksom övriga trädslag, växte bra på samtliga lokaler och hade en jämförelsevis hög tillväxt på de två nordliga lokalerna. Hybridlärk uppvisade en hög potential på de två sydligaste lokalerna, medan vårtbjörk hittills varit ett medelproduktivt trädslag. Granen har startat långsamt och sibirisk lärk har haft en svag inledande tillväxt på de två nordliga lokalerna. Alla trädslag har följt de höjdutvecklingskurvor som finns tillgängliga för respektive art på en hög nivå av ståndortsindex.

Det upptäcktes inga skillnader i kolförråd mellan trädslag efter 8–9 års tillväxt, med undantag för *Salix* som uppnådde en hög tidig produktion på grund av den betydligt högre stamtätheten jämfört med övriga trädslag. Den totala kolbindningen varierade från noll till 4,9 Mg C ha^{-1} $år^{-1}$ över försökslokalerna. Det fanns emellertid inga effekter av trädslag på organiskt markkol (SOC). En betydande minskning noterades på lokaler med hög initial mängd, medan SOC var oförändrat eller ökade på lokaler med lägre initial mängd. De genomsnittliga förändringarna av SOC varierade mellan -3,0 och 0,78 mg C ha^{-1} $år^{-1}$ över lokaler. Det fanns få skillnader mellan trädslag i förnans kolinnehåll.

Det noterades också få skillnader mellan trädslagen i deras påverkan på mineraljords-egenskaperna. Minskning av SOC och totalkväve (N) observerades i det lägre markdjupet för de flesta trädslag efter 8–9 år. Dessa förråd minskade med 12–18 procent respektive 13–15 procent från de initiala mängderna. CN-kvoten var i allmänhet oförändrad. Det enda undantaget var under gran där en liten minskning kunde ses. Växttillgänglig fosfor (P) minskade i marken för samtliga trädslag. De växttillgängliga koncentrationerna och förråden av baskatjonerna kalium (K), magnesium (Mg) och kalcium (Ca) visade olika utveckling. Medan Ca minskade i hela den undersökta markprofilen ökade K och Mg i det övre markskiktet och minskade eller var oförändrat i det nedre. Detta innebär att K och Mg omfördelades från djupare marknivåer till grundare genom trädens upptag och återföring via nedbrytning av förnan. En minskning av markens pH-nivå med i genomsnitt 2 procent observerades för alla trädslag.

Experimentet har visat på en hög tillväxtpotential för de flesta trädslag vid beskogning av tidigare jordbruksmark. Vi drar slutsatsen att en hög och ökande biomassaproduktion hos träd har en positiv effekt på den totala kolinlagringen i ett tidigt skede av omloppstiden. Det är av avgörande betydelse att inkludera kol i såväl biomassa, förna som mark när man diskuterar kolbindning vid ändrad markanvändning. Det syntes få trädslagsspecifika effekter på markegenskaperna. Nästan ett decennium efter skogsplantering av den tidigare åkermarken sågs huvudsakligen generella markeffekter vilka förknippades med upphörande av årlig markbearbetning, ökad förnaproduktion från träd och markväxter, och förmodligen också med förändrade fysiska förhållanden såsom fuktighet och temperatur, i de växande planteringarna. Tidsfaktorn är viktig och experiment som det här behöver därför följas under en lång tid för att ge bästa möjliga information.

Background

Land use change through deforestation, grass land cultivation, and increased pasture land area has reduced carbon (C) stored in soils and plants globally by approximately 180–200 Pg and caused one fourth of the anthropogenic C emission since the middle of the 19th century (DeFries et al. 1999, Hyvönen et al. 2007, Lal 2008). In the temperate and boreal zones of Europe, the total area with cereals has however decreased, resulting in large areas of abandoned agriculture land that could be used for other purposes (Rounsevell et al. 2005). These areas could be used, in addition to ceased fossil fuel combustion, to counteract the current climate change (IPCC 2014) and stabilize the atmospheric CO_2 levels by reforestation and afforestation that will sequester C (e.g. Ripple et al. 2019).

Recent estimates show that 1.8–2.6 million ha of abandoned agricultural land is available for afforestation in the Nordic and Baltic countries (Rytter et al. 2016). The figure for Sweden is 300 000–500 000 ha (Larsson et al. 2009). The area of available agricultural land is less than 5 percent of total productive forest land in this Nordic region (Rytter et al. 2016), but will still be of great importance as the production potential of agricultural soils is most often significantly higher than on forest land (Rytter et al. 2016, Mola-Yudego et al. 2017). If 5 percent of the available agricultural land in Nordic and Baltic countries were afforested, an additional 8.5 Mm^3 yr^{-1} of woody biomass could be produced according to Mola-Yudego et al. (2017), and Rytter (2012a) estimated that afforestation of 400, 000 ha in Sweden with willows and poplars could sequester 1.5 Tg C annually in woody biomass and 0.2 Tg C in the soil. In addition to high C storage capacity of forests and forest soils, wood products could offer long term storage or substitute fossil fuels with renewable energy.

Selection of the best performing species among different fast-growing tree species will be an important part in realization of the Nordic vision of a principally carbon neutral society by 2050 (IEA 2013). Rytter et al. (2011) showed that poplar and hybrid aspen (*Populus* species) have a large potential to contribute with increased biomass availability. Other broadleaved tree species like birch (*Betula*) and willow (*Salix*) also have high growth potentials in the Nordic region (Rytter et al. 2013, Tullus et al. 2013). Conifer species are not usually considered as being early biomass producers, but promising results (Johansson 2013a) have been reported for hybrid larch (*Larix ×eurolepis*). Norway spruce (*Picea abies*) is a common tree species in northern Europe, and it constitutes over 40 percent of the growing stock in Sweden (SUAS 2018). Spruce is productive on fertile soils (Johansson 1999a, Rytter et al. 2013), but the growth capacity is seen later during the rotation period.

There are currently limited data about differences in the C sequestration ability among different tree species. Some studies suggest that deciduous species have a higher potential to accumulate C in the soil than conifers (e.g. Morris et al. 2007, Laganière et al. 2010). Other studies found that conifers accumulate higher forest floor masses than deciduous species under similar climatic conditions (Vogt et al. 1986, Hansson et al. 2013). Litter from various tree species contains different levels of lignin, N, Mn and Ca which will affect the rate and degree of decomposition and give variations in C accumulation in the humus layer (Vesterdal & Raulund-Rasmussen 1998, Akselsson et al. 2005).

The effect of tree species on soil properties has been a subject of interest and the impact of different species on nutrient stock sizes, their distribution in the soil profile, and effects on CN ratio and pH has been studied (Alban 1982, Binkley 1995, Hagen-Thorn et al. 2004, Nordén 1994, Oostra et al. 2006). Specific species effects have been found at afforestation. For example, lime-tree stands had higher pH and base cation pools than Norway spruce on former arable soils (Hagen-Thorn et al. 2004), but Jug et al. (1999) and Rytter (2016) found no specific effects of species on soil properties in plantations with Salicaceae species on former arable land. Additional studies of the carbon sequestration and effects on soil properties of different tree species are desirable to improve our knowledge.

Using fast-growing tree species at afforestation has been widely proposed as they can deliver high biomass amounts and store C into the soil during a comparatively short time (Dimitriou et al. 2012, Don et al. 2012, Rytter et al. 2015, Georgiadis et al. 2017). However, there is a strong need of more field studies on biomass and C storage dynamics, as well as mineral nutrient pools, soil acidity and carbon:nitrogen (CN) ratios during afforestation of arable land. A review of changing land use to plantations and its effects on C dynamics noticed a lack of empirical studies and, in addition, both short- and long-term data sets are requested for validation of modelled data (Harris et al. 2015).

The aims of the tree trial experiments are multiple. A major aim is to evaluate the growth capacity of six different tree species: hybrid aspen, larch, Norway spruce, poplar, silver birch and willow when using the best available plant material, and compare them at five sites of different latitudes in Sweden at afforestation of agricultural land. Another major aim is to compile total C pools, i.e. C in above- and belowground biomass, litter and soil and compare the C sequestration rates of the different tree species. A third objective is to quantify effects on mineral nutrient pools, pH and CN ratios in the soil when planting the different tree species. In this report findings from the first decade after planting are presented.

Research layout and measurements on the study sites

THE EXPERIMENTAL SITES AND RESEARCH LAYOUT

The tree species experiment were established on five sites in Sweden and basic data of the sites are given in Table 1. The six different tree species mentioned above are represented by the best available plant material on each site (Table 2). The tree species were selected according to expected high growth rate and at the same time to be useful over large areas of the country.

Table 1. Basic data on the experimental sites. The mean length of the vegetation period is given as degree days above 5 °C. Climate data show 30-year-averages of temperature and precipitation (1961-1990 climate norms, SMHI 2015). SVA=Svalöv; LAN=Länghem; NYK=Nyköping; BJA=Bjästa; LOV=Lövånger.

Site	Lat.	Long.	Alt. (masl)	Top soil (0-30 cm)		Temperature mean (°C)		Precipitation mean (mm)		Length of veg. period	Previous land use
				Origin	Texture class	Jan	Jul	Jan	Jul	(5°C)	
SVA	55°56'N	13°12'E	100	Glacial	Silty clay	-0.8	16.5	51.3	75.0	210	Grain (–2004), fallow (2005–2008)
LAN	57°37'N	13°15'E	180	Glacial	Loam	-2.8	15.6	86.2	83.9	190	Grain, willow (–2008)
NYK	58°44'N	16°47'E	35	Glacial	Clay loam	-3.6	15.9	40.8	66.4	195	Grain (–2007), fallow (2008)
BJA	63°12'N	18°29'E	15	Postglacial	Silt loam	-8.8	15.0	48.5	70.4	160	Arable crops (–2003), abandoned (2004–2008)
LOV	64°20'N	21°14'E	20	Postglacial	Silt loam	-9.4	14.6	45.2	55.8	155	Grain (–1999), fallow (2000–2008)

The planting density is the same for respective tree species over the country. An initial review of the literature was carried out to choose the most relevant planting density for respective species (Rytter & Lundmark 2010). An important criterion in this work was that the merchantable wood share, except *Salix*, should reach 65 percent of the stem volume before self-thinning is initiated. The *Salix* plots were planted according to the standard at the time. A squared spacing was used for all species save for *Salix* (Table 2).

Four blocks were placed at each site (Figures 1–5), i.e. four repetitions. The block contained the six tree species with a random distribution. The species plot in the block was approximately 40 m × 40 m, but due to available space this form was sometimes slightly changed. Every tree species was thus represented by four plots per site.

The sites were prepared according to common practice to reduce mortal risks at establishment. They were ploughed, harrowed and treated with glyphosate against weeds before planting in spring and early summer of 2009. Nevertheless, planting of blanks was necessary during the next two years to keep survival high, i.e. preferably over 95 percent after 3 years. The reasons for the problem of survival was weed competition, drought and vole damage. The Nyköping (NYK) site was badly damaged by voles and had to be re-planted in 2012, except for the *Salix* plots.

Table 2. Planted species on respective site, stand density and spacing. LOV=Lövånger; BJA=Bjästa; NYK=Nyköping; LAN=Länghem; SVA=Svalöv

Species		**Site**	**Stand density (stems ha^{-1})**	**Spacing (m)**
Hybrid aspen	*Populus tremula* L. × P. tremuloides Michx.	All	1,500	2.58 × 2.58
Poplar	*Populus spp.* (Tacamahaca)	All	1,500	2.58 × 2.58
Silver birch	*Betula pendula* Roth	All	1,600	2.50 × 2.50
Norway spruce	*Picea abies* (L.) Karst	All	2,000	2.24 × 2.24
Siberian larch	*Larix sukaczewii* Dylis	LOV, BJA	1,600	2.50 × 2.50
Hybrid larch	*L. ×eurolepis* Henry	NYK, LAN, SVA	1,600	2.50 × 2.50
Willow	*Salix dasyclados* Wimm., clone 'Gudrun' *S. schwerinii Wolf* × *S. viminalis* L., clone 'Tora'	LOV, BJA NYK, LAN, SVA	14,815 14,815	0.75/1.50 × 0.60 0.75/1.50 × 0.60

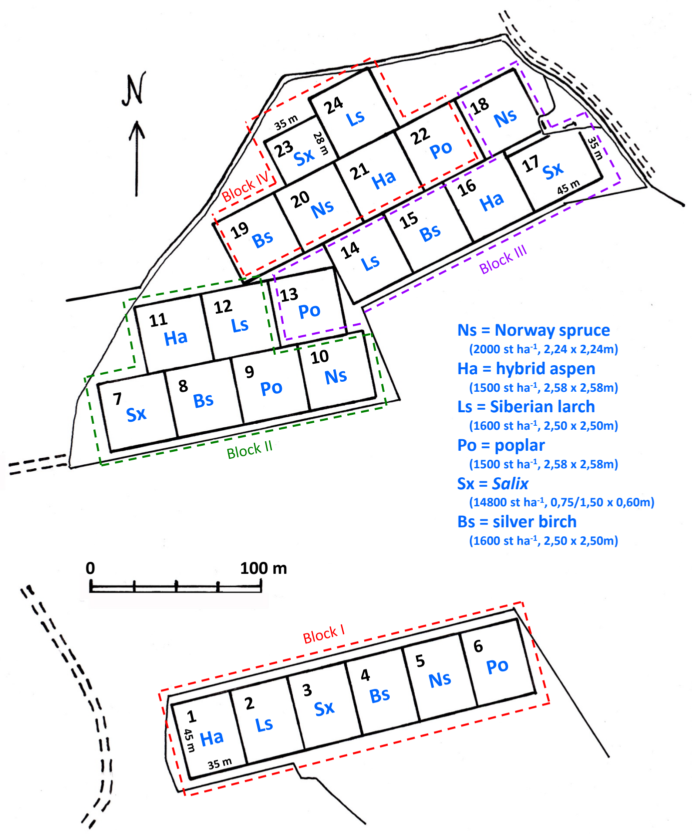
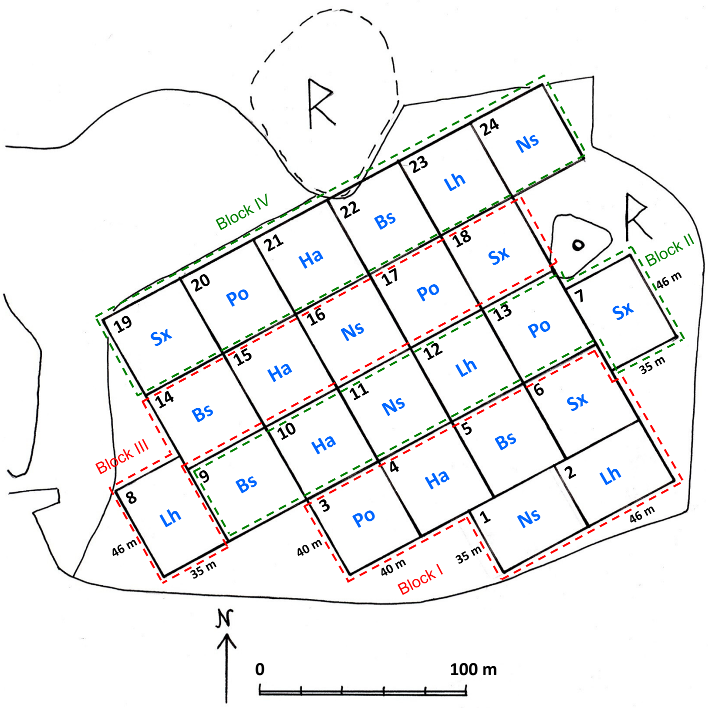


Figure 1. The Lövånger site is situated outside Västanbyn about 5 km SW of Lövånger. Block I is established on a different field about 200 m from the other three blocks. The land is owned by Erik Öhman.

Figure 2. The Bjästa site is found in Norrsvedje directly SW of the Bjästa municipality. Two drainage ditches are crossing through the experimental area. Odd Johansson is the landowner.

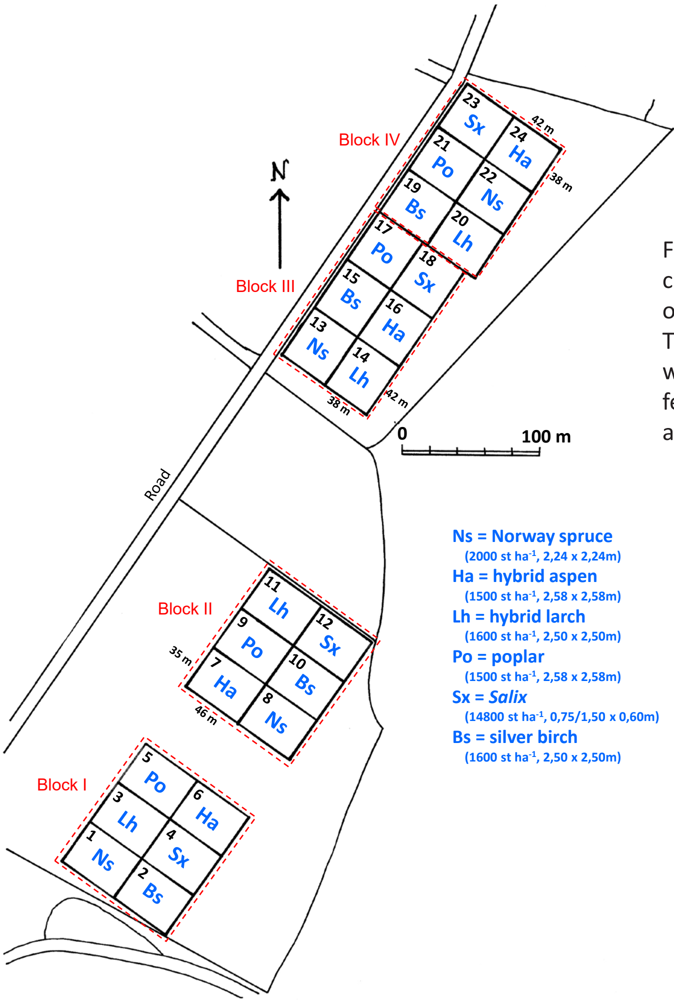
Ns = Norway spruce
(2000 st ha^{-1}, 2,24 x 2,24m)
Ha = hybrid aspen
(1500 st ha^{-1}, 2,58 x 2,58m)
Ls = Siberian larch
(1600 st ha^{-1}, 2,50 x 2,50m)
Po = poplar
(1500 st ha^{-1}, 2,58 x 2,58m)
Sx = *Salix*
(14800 st ha^{-1}, 0,75/1,50 x 0,60m)
Bs = silver birch
(1600 st ha^{-1}, 2,50 x 2,50m)



Ns = Norway spruce
(2000 st ha^{-1}, 2,24 x 2,24m)
Ha = hybrid aspen
(1500 st ha^{-1}, 2,58 x 2,58m)
Lh = hybrid larch
(1600 st ha^{-1}, 2,50 x 2,50m)

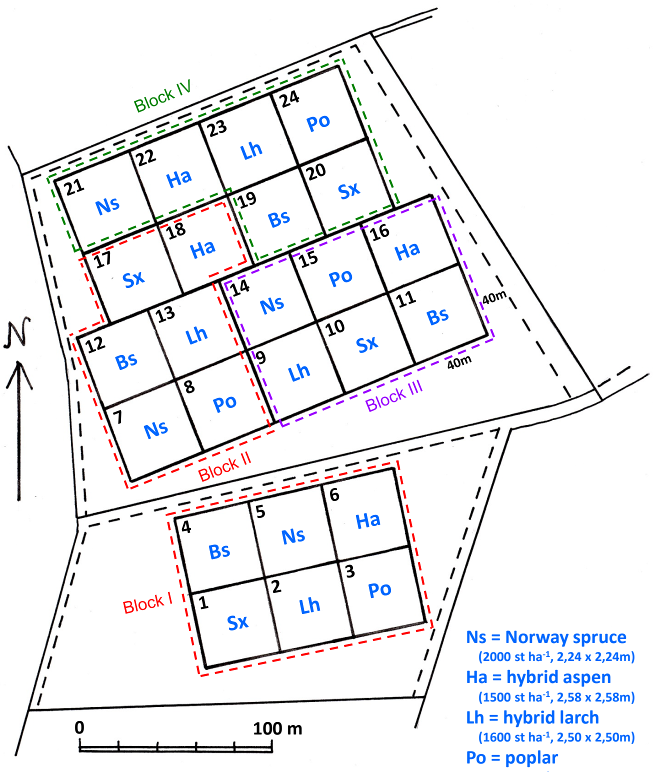
Po = poplar
(1500 st ha^{-1}, 2,58 x 2,58m)
Sx = *Salix*
(14800 st ha^{-1}, 0,75/1,50 x 0,60m)
Bs = silver birch
(1600 st ha^{-1}, 2,50 x 2,50m)

Figure 3. The Nyköping experimental site is established in Åkersta close to Jönåker, which is about 15 km W of Nyköping city. The area is surrounded by forest. The Diocese of Strängnäs is landowner.



Ns = Norway spruce
(2000 st ha^{-1}, 2,24 x 2,24m)
Ha = hybrid aspen
(1500 st ha^{-1}, 2,58 x 2,58m)
Lh = hybrid larch
(1600 st ha^{-1}, 2,50 x 2,50m)
Po = poplar
(1500 st ha^{-1}, 2,58 x 2,58m)
Sx = *Salix*
(14800 st ha^{-1}, 0,75/1,50 x 0,60m)
Bs = silver birch
(1600 st ha^{-1}, 2,50 x 2,50m)

Figure 4. The Länghem site is situated close to Rådde gård, an advice center of Hushållningssällskapet Sjuhärad. The trial is divided into two parts where block I-II is placed within one fenced area and block III-IV within another. Landowner is Rådde gård.



Ns = Norway spruce
(2000 st ha^{-1}, 2,24 x 2,24m)
Ha = hybrid aspen
(1500 st ha^{-1}, 2,58 x 2,58m)
Lh = hybrid larch
(1600 st ha^{-1}, 2,50 x 2,50m)
Po = poplar
(1500 st ha^{-1}, 2,58 x 2,58m)
Sx = *Salix*
(14800 st ha^{-1}, 0,75/1,50 x 0,60m)
Bs = silver birch
(1600 st ha^{-1}, 2,50 x 2,50m)

Figure 5. The Svalöv site is found about 6 km east of Svalöv municipality. Landowner is Trolleholms Gods AB.

PLANT MATERIAL AND PLANTING

The tree species were selected as representatives for fast growth and that they could be used over large areas in Sweden (Table 2). The best available plant material was used for all species for each latitude (Table 3; Rytter & Lundmark 2010). The plant material differed among latitudes as it is often inappropriate to move material far to the north or south (e.g. Stener & Karlsson 2005). In addition, the best establishment technique was used to produce the plants. The plant material used at respective site is given in Tables 2 and 3. The poplar for the Svalöv, Länghem and Nyköping sites was produced at Skogforsk research station in Ekebo. Hybrid aspen, silver birch and hybrid larch for these three sites were delivered from the Södra nursery in Falkenberg, who also delivered spruce for Svalöv and Länghem. Poplar, hybrid aspen, silver birch, Siberian larch and Norway spruce for the Lövånger and Bjästa sites were produced at Skogforsk's research station in Sävar as well as spruce for the Nyköping site. The *Salix* cuttings were produced by Lantmännen Agroenergi. At the replanting of the Nyköping site in 2012, the same material (Table 3) as in the initial planting was used. It was then delivered from Ramlösa plantskola and Södra (Norway spruce).

Table 3. The improved plant material used at the different sites of the trial.

	Site, latitude				
Tree species	**1. Lövånger, 64**	**2. Bjästa, 63**	**3. Nyköping, 59**	**4. Länghem, 58**	**5. Svalöv, 56**
Hybrid aspen	The 7 best clones from the archive at the Sävar research station	The 7 best clones from the archive at the Sävar research station	15 clones selected at the Ekebo research station. KB-002 in the National List	15 clones selected at the Ekebo research station. KB-002 in the National List	15 clones selected at the Ekebo research station. KB-002 in the National List
Poplar	The 7 best clones from the archive at the Sävar research station	The 7 best clones from the archive at the Sävar research station	KB-003 in the National List. 15 clones selected at Ekebo	15 clones selected at Ekebo + the clone OP42	15 clones selected at Ekebo + the clone OP42
Silver birch	Finnish seed orchard, SV413	Finnish seed orchard, FP431	Seed orchard Ekebo-4	Seed orchard Ekebo-4	Seed orchard Ekebo-4
Norway spruce	Seed orchard FP-13 Hissjö	Seed orchard FP-66 Saleby	Seed orchard FP-66 Saleby	Seed orchard FP-501 Bredinge	Seed orchard FP-501 Bredinge
Larch	Siberian larch from the Sävar archive = seed orchard Östteg, origin from Raviola and Archangelsk	Siberian larch from the Sävar archive = seed orchard Östteg, origin from Raviola and Archangelsk	Hybrid larch from seed orchard FP-51 Maglehem	Hybrid larch from seed orchard FP-51 Maglehem	Hybrid larch from seed orchard FP-51 Maglehem
Salix	Clone Gudrun	Clone Gudrun	Clone Tora	Clone Tora	Clone Tora

Plantings were performed in 2009 during the following periods for the respective site: Lövånger 22–26 June; Bjästa 29 June–10 July; Nyköping 25–29 May; Länghem 8–12 June; Svalöv 15–20 May.

SOIL SAMPLING AND ANALYSES

Repeated sampling of the mineral soil down to 30 cm depth was done in 2009, 2013 and 2016/17 in all experiments. The first sampling was done on unplanted soil, after ploughing, harrowing (2008) and chemical weed control (2008, 2009). The successive samplings were performed at the end of the 5th and the 8th–9th growing seasons. All soil samples were collected in the central 30 m × 30 m of a plot to avoid edge effects. Twenty soil cores were sampled on each plot and divided into 0–10 cm and 10–30 cm fractions. The fractions were pooled to one sample per depth and plot prior to analyses. Earlier studies in forest stands have shown that soil chemical changes will initially be seen in the upper soil layer (Alriksson & Eriksson 1998. Vesterdal & Raulund-Rasmussen 1998, Hagen-Thorn et al. 2004). A soil auger with an outer diameter of 25 mm, an inner diameter of 20 mm and a length of 30 cm has been used on all occasions as has the procedure described.

All soil samples were sieved (hole size 2 mm) and dried at 70 °C to constant weight. Dry weight was recorded for the fractions fine earth (particle size <2 mm), gravel (2–20 mm), and coarse organic material (2–20 mm). The soil samples were analysed for total C, total N, plant available phosphorus (P) and base cations (K, Mg, Ca), and pH. All analyses were performed on the homogenized fine earth fraction (<2 mm). SOC and total N concentrations (mg g DW^{-1}) were analysed by dry combustion with an elemental analyser (Vario Max CN, Elementar Analysensysteme GmbH, Hanau, Germany). Plant available P and base cations (K, Mg, Ca) were extracted by the ammonium lactate method (Egnér et al. 1960) and concentrations in the soil were determined by plasma analysis (ICP-OES; Inductively Coupled Plasma with Optical Emission Spectrometry; Varian Inc. Model 735-ES, Palo Alto; CA, USA). pH was measured in 5 ml air dried soil suspended in deionised water by the proportions 1:5. The concentrations were further used in calculations of SOC and nutrient pools together with bulk densities of the fine earth, gravel volumes from the respective years and estimates of stoniness.

Three volume-defined samples were collected on each experimental plot for estimation of soil bulk density. The auger volume was 94.25 cm^3. Soil bulk density (g cm^{-3}) of the fine earth fraction <2 mm was calculated from the volume-defined samples by using the following formula:

$$\boldsymbol{\rho = \frac{M}{V} = \frac{M_b - M_{2-20mm}}{V_b - V_{2-20mm}} = \frac{M_b - M_{2-20mm}}{V_b - \frac{M_{2-20mm}}{\rho_{gr}}}}$$

where ρ = bulk density of the fine earth fraction <2 mm (g cm^{-3}), M = the weight of fine earth from the auger sample (g), V = volume of undisturbed fine earth (cm^3), M_b = the weight of auger sample including gravel (2–20 mm, g), V_b = auger volym (94.25 cm^3), $M_{2\text{-}20mm}$ = weight of gravel (2–20 mm, g), $V_{2\text{-}20mm}$ = volume of gravel (cm^3), and ρ_{gr} = mean density of granite (2.650 g cm^{-3}).

The method used for stone estimation was based on the so called “Viro”-method (Viro 1952). It uses a metal rod probed down to 30 cm with recording of hits on stones and blocks. To do this, a rod of 10 mm diameter and 130 cm length was used. The rod was knocked down in the soil by a sledgehammer. The average penetration depth was noted, and a reference function was developed by digging pits for determination of relative stone volume. More details on this investigation are found in Rytter (2012b). For further details of the soil sampling procedures see Rytter and Högbom (2010).

LITTER SAMPLING AND ANALYSES

Randomly distributed samples of aboveground litter from leaves or needles from trees and ground vegetation, i.e. grasses and herbs, were collected within the central 30 m × 30 m of each plot at the 5th and the 8th–9th growing seasons after the leaves were shed. A square frame with the internal dimension 20 cm × 20 cm was used. A sharp knife was used to cut along the inner edges of the frame and all litter within the frame was collected. The same procedure was repeated four times on each plot. The litter samples were dried to constant weight at 70°C and dry weights were determined. Analyses of C and N (mg gDW^{-1}) were performed after homogenization by dry combustion with an elemental analyser (LECO TruMac, LECO UK – Hazel Grove, Stockport).

TREE GROWTH MEASUREMENTS

Measurements for estimation of tree growth were carried out 4–5 years and 8–9 years after planting. All trees on the net plots, i.e. excluding the two outer rows of trees, were measured for diameter at 1.3 m (breast height) over bark. Height was recorded for about every 10th tree. An allometric function based on stem diameter was constructed for each tree species to estimate the height of remaining trees:

$$H = a \times D^b,$$

where H is tree height, D is diameter over bark at 1.3 m and a and b are constants. Dominant height (H_{dom}) was calculated in accordance with Swedish standard of average height of the 100 thickest trees ha^{-1}. This meant that on a 900 m^2 area, the height of the nine thickest trees was used.

Samples of stem and branch dry weights were collected on the same occasions as the height and diameter measurements at age 8–9 years. Stem discs were collected from the sample trees at every second metre and transported to the laboratory for further processing. The branches were collected from the sample trees and fresh weight was recorded in the field.

In the laboratory the stem discs were measured for diameter, fresh and dry weight and fresh volume using the water displacement method (Olesen 1971). Dry weight was recorded after drying the discs at 85°C to constant weight. Stem volume of a sample tree was calculated by summing the 2 m sections of the stem using the formulas for the frustum of a cone ($V = (\pi H_s/3)(R^2+Rr+r^2)$) and a circular cone for the top part ($V = (\pi R^2 H_s)/3$), where V is volume, H_s is length of the stem section, R is lower disc radius and r is upper disc radius. Stem biomass was estimated by using the densities from each stem section from the water displacement recordings. Branch dry weight was estimated by using the dry weight percentage from the one to two uppermost stem discs of the sample tree. Relations between stem diameter and tree height, and biomass were constructed by the formula

$$W = c(D^2H)^d,$$

where W is stem or branch dry weight, D is stem diameter at 1.3 m, H is tree height and c and d are constants related to stem or branch and tree species.

The estimates of the individual trees were then summarized for respective net plot to get area based figures. More details about measurements and the statistical treatments are given in Rytter and Lutter (2019).

ESTIMATION OF CARBON POOLS

In order to estimate the total C pools, the samples of litter and soil were collected at the start of the experiment, after 5 and after 8–9 years. Above-ground C in woody biomass was taken from the growth measurements presented above and the standing root biomass was calculated with functions given by Cairns et al. (1997), which are based on above-ground biomass and latitudinal zone. The translation of biomass into C was done with the factors 0.48 for the broad-leaved trees and 0.51 for the conifers, figures given by Lamlom and Savidge (2003) and suggested by IPCC (2006) for the temperate and boreal regions. Litter was collected on the two later sampling occasions and was performed after the leaves were shed. The litter consisted primarily of ground vegetation, i.e. grasses and herbs after 5 years, and a mix of leaves or needles from the tree species and ground vegetation after 8–9 years.

Results and discussion of studies performed within the project

INITIAL SOIL CONDITIONS

The initial soil conditions varied among the experimental sites (Table 4). Stones were most frequently found at the two southernmost sites while there were few at the northern two sites. The same pattern was seen for gravel content. Bulk density of the fine earth was around 1 g cm^{-3} for all sites. There were considerably more C and N per unit area in Lövånger and Bjästa compared to the southern sites. The conclusion from the study of soil physical conditions including stones (Rytter 2012b) was that although arable soils are commonly regarded as composed mainly of fine earth, the content of rock fragments cannot be neglected when nutrient stocks are estimated on an area basis. The study showed that exclusion of the relative volumes of gravel and stones overestimated C and N stocks by 8–9 percent. Inclusion of stones and gravel is important when comparing nutrient stocks of different sites and when effects of land use changes are scaled up to regional or global levels.

Table 4. Soil properties of the experimental sites. Means with different letters in the column are significantly separated. C and N content to 30 cm depth is given with stone and gravel volumes included. Table reworked from Rytter (2012b).

Site	**Stoniness** (%)	**Gravel volume** (%)	**Bulk density of fine earth** (g cm^{-3})	**C content** (Mg ha^{-1})	**N content** (Mg ha^{-1})
Lövånger	0.44^{d}	0.07^{d}	0.91^{b}	147^{a}	9.5^{a}
Bjästa	0.10^{d}	0.01^{d}	1.10^{a}	102^{b}	6.5^{b}
Nyköping	1.82^{c}	1.58^{c}	1.05^{a}	58^{d}	5.1^{c}
Länghem	4.42^{a}	3.26^{a}	0.88^{b}	55^{d}	3.9^{c}
Svalöv	3.60^{b}	2.56^{b}	0.85^{b}	84^{c}	7.0^{b}

Concerning plant-available nutrients the average levels for Swedish agricultural soils have been reported by Eriksson et al. (2010). When comparing the nutrient levels found at the experimental sites (Table 5), they were both lower and higher than the values presented by Eriksson et al. (2010). The P content found over the sites was 56–201 mg kg^{-1} of dry soil. Plant-available K was 56–142 mg kg^{-1}, Ca 736–1,480 mg kg^{-1} and Mg 24–131 mg kg^{-1}. The P content was substantially higher in Lövånger than at the rest of the sites, Nyköping had a higher Mg content than the other sites and Bjästa had significantly less Ca (Table 5).

Table 5. Plant-available concentrations of macro nutrients (mg kg^{-1} of dry soil) in the fine earth fraction of the soils of the experimental sites. The figures were derived by extracting the samples with ammonia lactate. Different letter indicates significant differences for a specific element among the sites. Data taken from Rytter and Högbom (2010).

Site	**Soil depth** (cm)	**P**	**K**	**Ca**	**Mg**
Lövånger	0–30	201^{a}	73.6^{b}	1,480^{a}	53.6^{b}
Bjästa	0–30	61.9^{c}	56.4^{c}	736^{d}	24.2^{d}
Nyköping	0–30	62.8^{c}	123^{a}	1,200^{b}	131^{a}
Länghem	0–10	83.8^{b}	114^{a}	1,250^{b}	48.0^{bc}
Länghem	10–30	71.6^{bc}	65.1^{bc}	1,180^{bc}	39.0^{bcd}
Svalöv	0–30	55.9^{c}	71.7^{b}	1,020^{c}	29.7^{cd}

ESTABLISHMENT PERFORMANCE

The goal for receiving even future stands was to have ~95 percent survival rate on each plot during the first years. This meant that supplementary planting had to be performed on a number of plots. In the autumn of 2009 and 2010, inventories of the survival of each trial site were carried out to determine the need for supplementary planting (Table 6). In the summer and autumn of 2009, some planting of blanks was carried out at certain plots, which is why the results of the early inventories at each site not accurately showed the survival of the originally planted plants. The results from the inventories generally showed a good survival rate. An exception was that larch had poor survival on some plots. In addition, the survival rate for hybrid aspen and poplar was slightly lower than the set target, so supplementary planting was considered needed. Initially, spruce, silver birch and *Salix* survived well on all sites.

Table 6. Survival (percent of planting spots) of the different tree species on the five experimental sites after the 2010 growing season. The figures include a supplementary planting performed during 2010 and thus do not show survival of the originally planting. The table is an abbreviated version from Rytter and Lundmark (2010). Blue colour denotes a survival level below target (95 percent), while orange colour shows a critically low survival level. nm = not measured. Note that an additional supplementary planting was done in 2011.

Tree species	**Block**	**Experimental site**				
		Lövånger	**Bjästa**	**Nyköping**	**Länghem**	**Svalöv**
Hybrid aspen	I	94.0	96.0	94.2	85.5	89.6
	II	98.0	85.0	92.1	83.7	94.6
	III	98.0	97.0	94.2	87.1	95.8
	IV	98.0	94.0	97.9	94.6	94.5
	Average	97.0	93.0	94.6	87.8	93.6
Poplar	I	99.0	99.0	95.0	64.3	87.5
	II	89.0	99.0	88.8	64.3	85.8
	III	89.0	98.0	95.4	89.7	92.9
	IV	95.0	97.0	92.9	82.1	88.0
	Average	93.2	98.3	93.0	75.2	88.5
Silver birch	I	99.0	96.0	99.2	84.5	98.4
	II	93.0	98.0	96.1	86.5	97.6
	III	96.0	94.0	97.3	97.5	99.6
	IV	90.0	91.0	99.6	97.1	98.8
	Average	94.4	95.1	98.0	91.3	98.6
Norway spruce	I	98.0	98.0	99.7	95.0	96.7
	II	86.0	97.0	99.1	97.0	96.8
	III	97.0	89.0	100	93.8	91.7
	IV	99.0	96.0	97.8	98.7	96.1
	Average	95.1	94.9	99.1	96.1	95.3
Larch	I	98.0	100	92.2	65.9	97.4
	II	90.0	91.0	88.4	58.3	93.8
	III	97.0	85.0	64.5	61.7	97.3
	IV	93.0	94.0	93.4	71.7	95.4
	Average	94.6	92.7	84.6	64.3	96.0
Willow	I	98.0	99.0	98.6	nm	95.2
	II	94.0	94.0	92.8	nm	93.1
	III	97.0	100	94.9	nm	89.9
	IV	97.0	100	97.6	nm	93.1
	Average	96.7	98.9	96.0	-	92.9

After supplementary plantings survival was generally at a satisfyingly high level at the end of the 2010 growing season. However, voles almost completely damaged the Nyköping experimental site during the winter 2010/2011, and this site was replanted with the original layout and plant material in the spring 2012. Only the willow remained in good condition at this site and was not replanted. Survival was later recorded on the ordinary sampling occasions in 2012–2013 and 2016–2017. After 4–5 years (2012–2013) survival was acceptable (>80 percent) for all sites and species save for the larch plots at Nyköping (Figure 6a). After this date, the willows at Lövånger and Bjästa (clone Gudrun) were heavily attacked by *Melampsora* and did not recover after harvest. Thus, we lost the possibility to follow the development of willow at the two northernmost sites. On the next sampling occasion at age 8–9 years, survival had dropped at the Lövånger site, while it was still at an acceptable level at the other sites (Figure 6b).

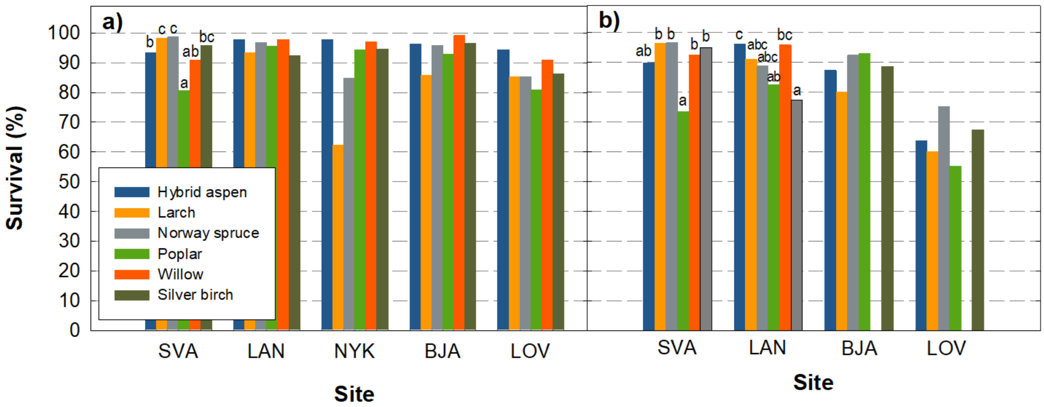


Figure 6. Plant survival for tree species and sites. a) Survival after 4–5 years; b) survival after 8–9 years. Since the Nyköping site was replanted in 2012, only data after 5 years were available. Figures for willow are given for stool age as these plots were harvested after 4 or 5 years. Different letters indicate significant differences among the tree species for the site on the measurement occasion when tested with logit-transformation. SVA = Svalöv; LAN = Länghem; NYK = Nyköping; BJA = Bjästa and LOV = Lövånger. Figure redrawn from Rytter and Lutter (2019).

GROWTH OF THE TREE SPECIES

The growth measurements showed that an initial high productivity can be expected when planting trees on abandoned farmland. The short rotation coppice (SRC), applied to willow, showed the fastest growth during the initial 8–9 years (Figure 7). With a dense spacing of 14,800 cuttings ha^{-1} willow was extremely productive on the Svalöv site where mean annual increment (MAI) exceeded 18 Mg DM ha^{-1} yr^{-1} (Figure 8). This high level has rarely been reported before and only with intensive fertilization (Christersson 1987, Mola-Yudego & Aronsson 2008). Productivity of willows on research sites showed an average level of 7.7 Mg DM ha^{-1} according to Dimitriou and Mola-Yudego (2017), while commercial willow plantations only produced 4.2 Mg DM ha^{-1} (Mola-Yudego et al. 2015). A combination of a well-adapted clone and a fertile soil with good water supply was considered the reasons for the high productivity (Rytter & Lutter 2019).

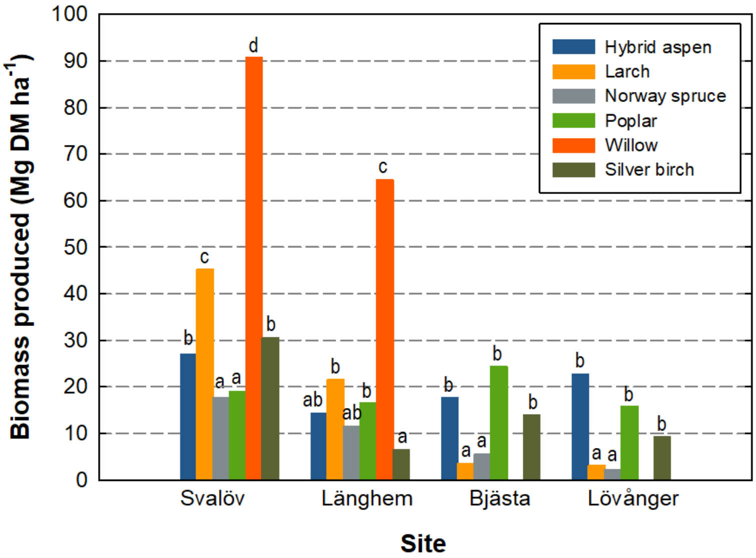


Figure 7. Total biomass production during the initial 8–9 years of the experiment. The Nyköping site was replanted in 2012 and only data efter 5 years were available. The willow in the north was mortally attacked by *Melampsora* fungi after 5 years and could not be followed afterwards. Different letters indicate significant differences among the tree species for a specific site. Figure redrawn from Rytter and Lutter (2019).

Another strategy of producing renewable biomass was represented by the remaining five tree species. The short rotation forestry (SRF), planted with a conventional spacing, could combine biomass for energy with wood production of other assortments. This strategy is more flexible to market situations but can generally not compete in productivity with SRC in the early phase. Of the SRF species, hybrid aspen and poplar generally grew well with a MAI of 1.8–3.4 Mg DM ha^{-1} yr^{-1} with no drop along latitude after 8–9 years. Silver birch produced 1.6–3.8 Mg DM ha^{-1} yr^{-1}, which is within the range reported for other planted birch stands on abandoned farmland (Johansson 1999b, Eriksson & Johansson 2006). Hybrid larch showed a varying growth rate over the three southern sites. It was high at the Svalöv site (Figure 7) but much lower at the Nyköping site (not shown). The conclusion was that hybrid larch has a high growth potential but is sensitive to both dry and moist conditions. The few studies performed show that a productivity of 5.5–6.3 Mg DM ha^{-1} yr^{-1} can be expected for hybrid larch in the southern part of Sweden (Ekö et al. 2004, Johansson 2013a). Siberian larch had a low initial growth and could so far from this experiment not be recommended to be included among fast-growing species for bioenergy production. Norway spruce showed, as expected, a slow start in productivity. However, the growth level is expected to increase in the near future and a MAI of over 6 Mg DM ha^{-1} yr^{-1} could be expected on former agricultural land (Johansson 1999a).

The MAI increased for all studied species from the first 4–5-year period to the second 4-year period (Figure 8). This is expected when stands approach canopy closure. The second rotation cycle for willow also showed a higher productivity than the first, which confirms the general knowledge of a difference between rotation cycles (Willebrand et al. 1993, Sleight et al. 2015). The acceleration of MAI of hybrid aspen and poplar has also been noticed before (Johansson & Karačić 2011, Rytter & Stener 2014) and supports the prediction of reaching a MAI of 25 m^3 of stem biomass ha^{-1} yr^{-1} for superior hybrid aspen clones on fertile sites after about 25 years (Stener & Karlsson 2004). Although being a pioneer species the development of silver birch is slower than for the *Populus* species (Rytter et al. 2013) and the full growth potential will be revealed at a later stage of the experiment.

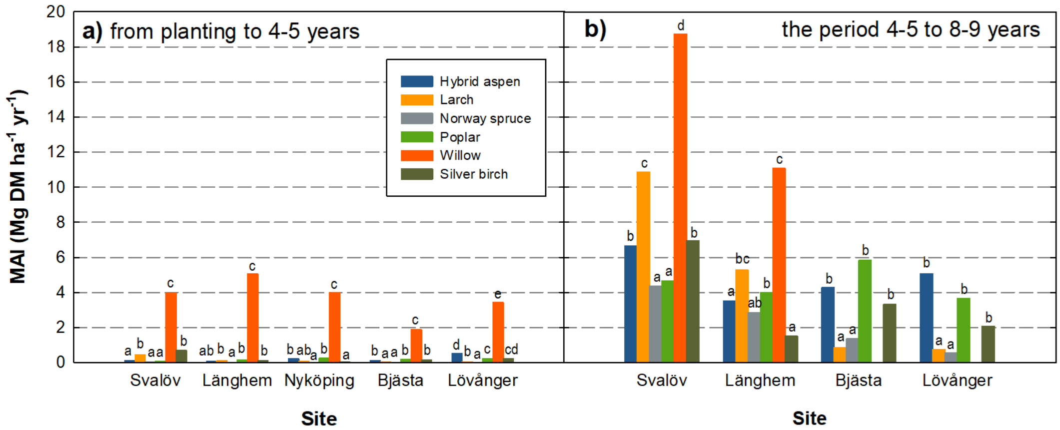


Figure 8. MAI under two periods, the first 4–5 years and the next 4 years, i.e. from 4–5 years to 8–9 years, in the tree trial experiments. Different letters indicate significant differences among the tree species for a specific site. Figure redrawn from Rytter and Lutter (2019).

The height growth (Figure 9), expressed as dominant height (H_{dom}), was generally on a similar level with existing height development curves on the best site classes for respective tree species (Johansson 1995, Eriksson et al. 1997, Johansson 2011, 2013b). The fast height development showed that the selection of the plant material was suitable for the different sites. For example, the fast-growing *Populus* material H_{dom} reached 10.9 m in poplar plots on the Svalöv site after 8 years and the hybrid aspen reached 11.5 m on the Lövånger site after 9 years.

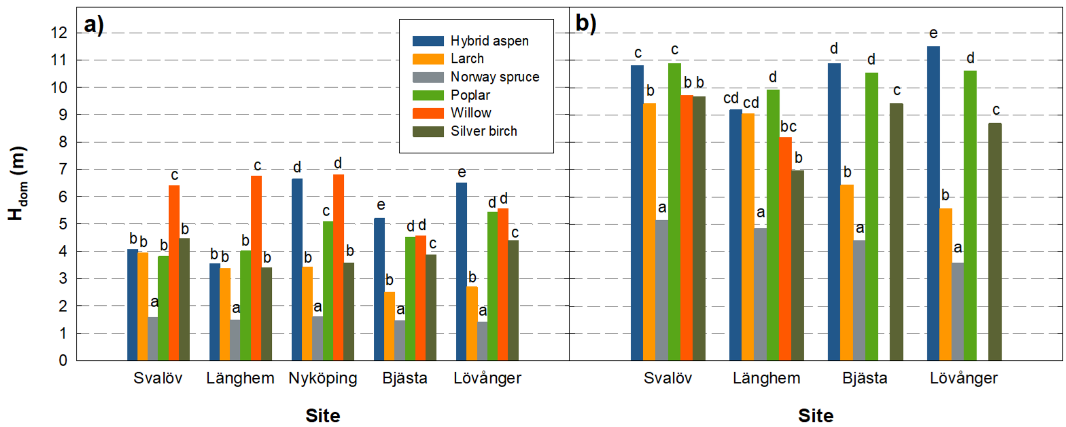


Figure 9. Dominant height as average values of plots for tree species and site after 4–5 years (a) and after 8–9 years (b). More details are given in Figure 7. Figure redrawn from Rytter and Lutter (2019).

EFFECTS OF AFFORESTATION ON SOIL CHARACTERISTICS

After nearly a decade of tree growth on the former arable sites there were few differences in soil characteristics found that could be related to tree species. The effects observed were mainly general soil effects associated with, for example, cessation of annual management measures, enhanced litter production by the growth of trees and ground vegetation, and changed soil temperature and increased shadowing of the ground by the growing plantations.

A comparison of the influence of different Salicaceae species on soil chemical parameters was performed at the end of the 5th growing season (Rytter 2016). At that time, the SOC pools under those species were generally unchanged compared to the pre-planting conditions. Total N pools in the mineral soil had increased in willow plantations and P pools had decreased in hybrid aspen and poplar plantations. Concentrations and pools of Ca were unchanged. Plant-available K and Mg had increased in the upper 0-10 cm soil and decreased in the lower 10-30 cm for all species. This implies a redistribution of those nutrients from deeper soil layer to shallower by plant uptake and recycling through decomposition of litter (e.g. Alban 1982).

The CN ratio was reduced by ca 10 percent for all Salicaceae species on all sites after 4–5 years (Figure 10). In general, an increased CN ratio may be expected upon afforestation since the supply of forest litter with higher CN ratios increases, as does the uptake of N, while N fertilization ends (e.g. Jug et al. 1999, Rosenqvist et al. 2010). The repeated soil investigation at the end of the 8th–9th seasons showed that the CN ratios for poplar and hybrid aspen had increased from the previous sampling at all sites (Figure 10, Rytter & Rytter, manuscript). The willow plots at the two northern sites suffered from *Melampsora* infection which in combination with frost damage caused the death of the major part of the plants 2012/13. Thus, willow was not included in the latter sampling. Earlier studies have found that mineral soil CN ratios did not differ significantly or tended to differ only slightly between species at afforestation (Ritter et al. 2003, Hagen-Thorn et al. 2004). This was also noted in the present experiment after 8–9 years growth where no differences were observed among most species (Table 8, willows not included). The only exception was a slight decrease under spruce.

The CN ratio in aboveground litter was ca 20 percent lower for willow than for hybrid aspen and poplar after five years growth (Rytter 2016). The relationship between litter CN ratios and CN ratios in the soil were negatively correlated among all Salicaceae species after five years growth. It has been suggested that the distribution of C in litter and mineral soil and the CN ratios may be important differences between species (e.g. Vesterdal et al. 2013). Analyses of litter CN at the latter sampling also revealed statistically significant differences in CN ratios among species (Rytter & Rytter, manuscript). For example, spruce had a higher CN ratio compared to the other species at one site. The statistical interaction that was found between species and sites regarding the litter CN ratios could imply that there are site specific conditions, like various climate and soil conditions, that influence both litter production and decomposition rates.

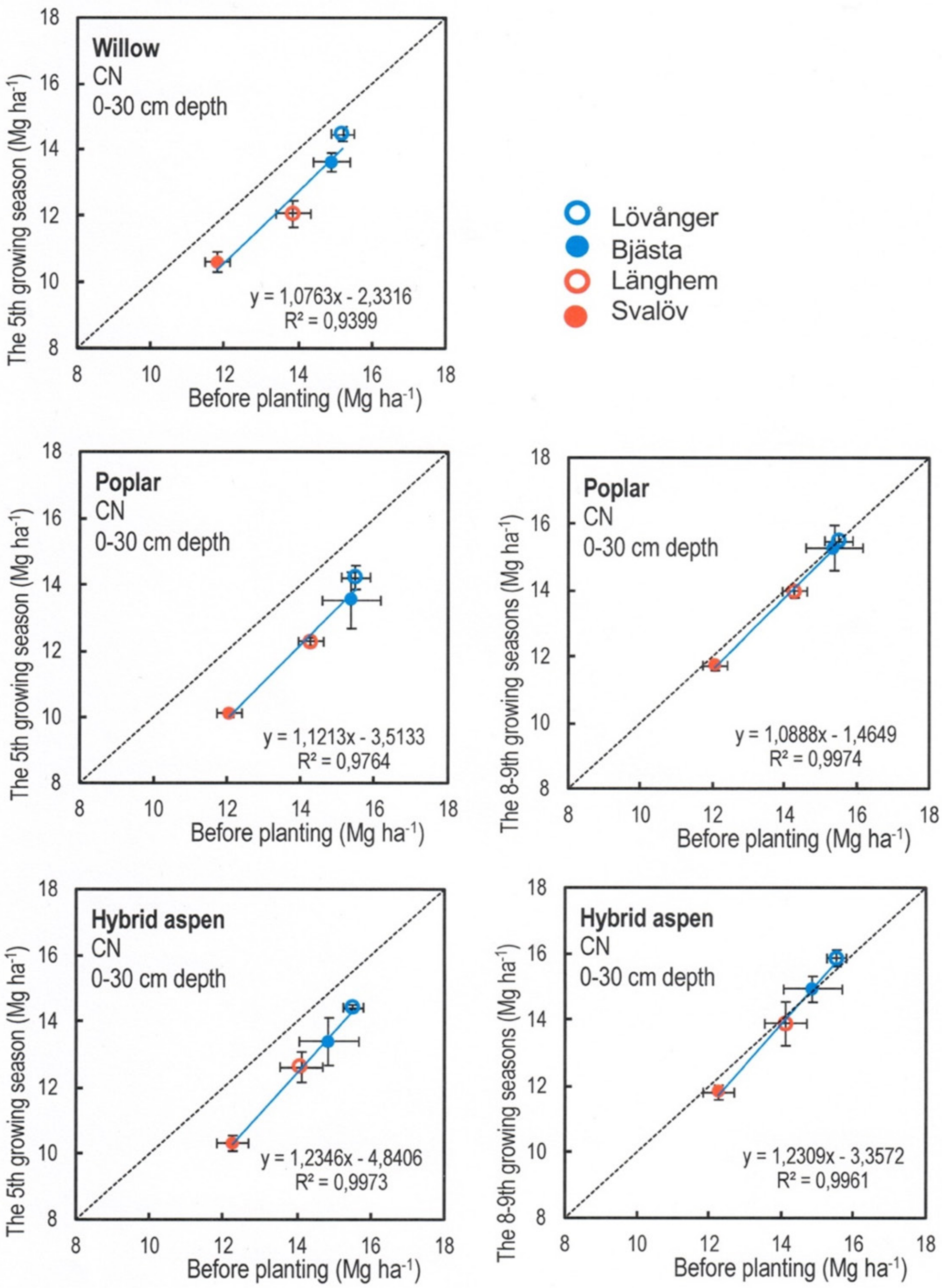


Figure 10. Mean CN ratios, based on amounts (Mg ha^{-1}), in the mineral soil to 30 cm depth on unplanted arable land after 5 years growth of tree species (to the left) and after 8–9 years growth (to the right). Standard error bars are shown (n=4, each n consisting of 20 subsamples). The dotted lines indicate no difference and solid lines show linear regressions over all site values.

After the 8th–9th growing seasons a study of the influences of birch, hybrid aspen, larch, poplar and spruce on soil characteristics was performed (Rytter & Rytter, manuscript). The comparisons were done over sites. The site Nyköping was excluded since it was replanted in 2012. The mean pools of different soil parameters and CN ratios for the different sites at the three sampling occasions are shown in Table 7.

Table 7. Mean amounts (Mg ha^{-1}) down to 30 cm soil depth of the soil parameters total N (Tot N), plant-available base cations K, Ca, Mg, plant-available P and CN ratios for the different sites and sampling years (Year 0 = before planting). All species are included except willow.

Site	Year	Soil parameter					
		Tot N	CN ratio	K	Ca	Mg	P
Svalöv	0	7.61	12.00	0.19	2.60	0.08	0.14
	5	7.65	10.36	0.25	2.73	0.09	0.13
	8	7.61	11.72	0.36	2.76	0.13	0.11
Länghem	0	7.95	14.16	0.22	3.23	0.11	0.20
	5	8.45	12.35	0.24	3.08	0.11	0.18
	8	6.78	13.96	0.30	2.77	0.13	0.17
Bjästa	0	6.53	15.51	0.19	2.39	0.08	0.20
	5	7.56	13.65	0.17	2.45	0.07	0.15
	9	5.25	15.41	0.19	1.65	0.06	0.12
Lövånger	0	9.13	15.65	0.19	3.89	0.14	0.54
	5	9.66	14.27	0.21	3.87	0.14	0.50
	9	7.38	15.60	0.22	3.00	0.11	0.44

Significant changes in mean concentrations were observed for most soil variables after 8–9 years of tree growth (Table 8). However, there were still few effects on soil characteristics that could be related to tree species. Decreases in SOC and total N concentrations with 19 percent on average in the lower 10–30 cm soil layer were observed under all species (Table 8). Corresponding decreases for soil pools of SOC and total N (Mg ha^{-1}) were 12–18 percent and 13–15 percent, respectively (Rytter & Rytter, manuscript). Species related effects where SOC pools increased after afforestation with hardwoods, mostly eucalyptus, and decreased after afforestation with pine have been reported (Guo & Gifford 2002, Paul et al. 2002, Li et al. 2012). Decreases in total N stocks under all species in the present study indicate that N was taken up by the growing vegetation. The uptake of N is generally high in the phase of active tree growth before canopy closure. As SOC and N changes were related in relative size there were small changes in the CN ratios. Only for Norway spruce could a small decrease be observed.

Table 8. Significant changes of concentrations of soil parameters, CN ratio and pH from pre-planting conditions to after 8–9 years of tree growth. The changes with all species included are expressed as %. P-values from analyses when including all species are shown.

DEPTH	SPECIES	SIGNIFICANT CHANGES OF CONCENTRATIONS ($P \leq 0.05$)							
		SOC	Tot N	CN	P	K	Ca	Mg	pH
0-10	Birch					↑	↓	↑	
	Hybrid aspen				↓	↑	↓	↑	↓
	Larch					↑	↓	↑	↓
	Poplar				↓	↑	↓	↑	↓
	Spruce			↓	↓	↑	↓	↑	↓
10-30	Birch	↓	↓		↓		↓		↓
	Hybrid aspen	↓	↓		↓		↓	↓	↓
	Larch	↓	↓		↓		↓		↓
	Poplar	↓	↓		↓	↓	↓	↓	
	Spruce	↓	↓		↓	↓	↓	↓	↓
0-10	All			↓ 1.3 %	↓ 11 %	↑ 107 %	↓ 11 %	↑ 38 %	↓ 1.6 %
	p-value (year)	*0.20*	*0.46*	*0.0038*	*0.0007*	*<0,0001*	*<0.0001*	*<0.0001*	<0.0001
10-30	All	↓ 19 %	↓ 19 %		↓ 25 %		↓ 19 %	↓ 18%	↓ 1.5 %
	p-value (year)	*<0.0001*	*<0.0001*	*0.21*	*<0.0001*	*0.27*	*<0.0001*	*<0.0001*	0.0004

The current knowledge concerning the influence of various tree species on P dynamics and pools in the mineral soil is still limited and sometimes contradictory (e.g. Hagen-Thorn 2004, Deng et al. 2017). In the present study decreases were seen in the plant available P concentrations for both depth levels, but no significant effects of species could be observed (Table 8). It has been suggested that afforestation will enhance mineralization of soil organic matter and thus recycle P efficiently (Chen et al. 2008). However, a meta-analysis on P dynamics found that available P tended to decrease on crop land (Deng et al. 2017). The decreases observed in the present study were probably an effect of ceased P fertilization after abandonment of the arable sites in combination with an increased uptake by the growing plantations. The redistribution of plant available K and Mg that was seen after five years of afforestation (Rytter 2016) continued and increases with 107 percent and 38 percent, respectively, could be seen in the upper 0-10 cm soil after 8–9 years. Species-related effects on the K concentrations and pools were not observed but such differences have been found between lime and spruce earlier (Hagen-Thorn et al. 2004). Ca decreased in both depth levels for all species in the present study (Table 8). Decreases in Ca has been noted in different plantation types at afforestation (e.g. Berthrong et al. 2009).

Decreases in pH have been reported in earlier studies of afforestation (Alriksson & Olsson 1995, Jug et al. 1999, Ritter et al. 2003). In the present study, pH was measured after five years and decreases with 1.5–2.1 percent were seen for all species. This may have been the result of the replacement of base cations, taken up by plants or leached, by H^+ on the exchange sites of the soil particles (e.g. Berthrong et al. 2009). Differences in pH among various tree species which were planted on initially similar soils have been reported in the literature (Nordén 1994, Hagen-Thorn et al. 2004), but absence of differences have also been reported (Ritter et al. 2003). No species related differences were observed in the present study. The plantations were young and such differences may occur at a later stage of plantation development.

CARBON STOCK ESTIMATIONS

Afforestation of former agricultural land often results in a net increase of the soil organic C (SOC) pools (e.g. Cannell & Dewar 1995, Grigal & Berguson 1998, Laganière et al. 2010, Li et al. 2012, Bárcena et al. 2014, Georgiadis et al. 2017, Dimitriou & Mola-Yudego 2017), although the inverse has been found, sometimes followed by a recovery (e.g. Hansen 1993, Coleman et al. 2004, Dimitriou et al. 2012, Rytter et al. 2015). A decade is a short time span and will probably not mirror the long-term effects of afforestation on the study sites. However, the present experiments offer a unique opportunity to frequently follow the development of the C pools over latitudes with varying tree species from pre-planting conditions.

The results of the SOC pool evaluation did not reveal any tree species differences after 8–9 years (Rytter & Rytter 2020). Other studies have shown tree species differences in SOC sequestration at later stages of the rotation, especially between conifers and deciduous species. However, the pattern has not been consistent (e.g. Guo & Gifford 2002, Morris et al. 2007, Schulp et al. 2008, Laganière et al. 2010, Li et al. 2012, Gurmesa et al. 2013). A common pattern is that conifer stands have more C in the litter/humus layer, while stands with deciduous species have more C in the mineral soil (Vesterdal et al. 2008, Trum et al. 2011, Hansson et al. 2013). This has been partly explained by a higher abundance of earthworms in deciduous stands (e.g. Hansson et al. 2013). A change due to specific tree species is probably a process that takes time and could not be seen in the early stage of afforestation in this experiment. SOC varied among the experimental sites from 60–145 Mg C ha^{-1} at the experimental start to 66–115 Mg C ha^{-1} after 8–9 years. The SOC pools were found to change significantly at most sites but the direction varied. Significant decreases were noted for sites with high initial amounts, while SOC was unchanged or increased on sites with lower initial amounts.

The litter C pools showed no differences among the tree species within sites. The only exception was the larch at the Svalöv site, which had a significantly higher litter C pool than the other species (Table 9). C in biomass increased with time and especially from 4–5 years to 8–9 years. The C content in different pools is given in Table 9 and shows that the C in soil (SOC and coarse organic material) is the dominant fraction of the total C stock during the first decade of afforestation. However, the C in woody biomass of willow at the three southernmost sites has started to be of high significance. The total C stocks were 63–153 Mg C ha^{-1}, excluding willows in the north, at the experimental start and 75–166 Mg C ha^{-1} after 8–9 years.

Table 9. Carbon amount given per area unit (Mg C ha^{-1}) in different fractions for respective site, tree species and sampling occasion. Soil C includes SOC and coarse soil organic material C (2–20 mm). For willow harvested biomass is included (the Nyköping, Länghem and Svalöv sites). The Nyköping site was replanted in 2012, save for willow. Different letters indicate statistical differences among tree species on the sampling occasion within site. Tree species: B=silver birch, H=hybrid aspen, L=hybrid larch/Siberian larch, S=Norway spruce, P=poplar, W=willow. Table reworked from Rytter and Rytter (2020).

Site	Lövånger						Bjästa					
Tree species	B	H	L	S	P	W	B	H	L	S	P	W
2008												
Tree biomass	0	0	0	0	0	0	0	0	0	0	0	0
Litter	0	0	0	0	0	0	0	0	0	0	0	0
Soil	150	143	137	147	153	161	121	116	107	113	111	103
S+L	**150**	**143**	**137**	**147**	**153**	**161**	**121**	**116**	**107**	**113**	**111**	**103**
Total	**150**	**143**	**137**	**147**	**153**	**161**	**121**	**116**	**107**	**113**	**111**	**103**
2013												
Tree biomass	0.8	1.6	0.2	0.0	0.7	10.1	0.5	0.4	0.1	0.1	0.6	5.6
Litter	1.9	2.2	2.4	2.3	1.7	1.5	2.1	2.1	1.8	1.9	1.9	1.6
Soil	158	148	160	125	135	166	128	123	122	115	123	114
S+L	**160**	**150**	**163**	**127**	**137**	**168**	**130**	**125**	**124**	**117**	**125**	**116**
Total	**161[ab]**	**151[ab]**	**163[ab]**	**127[a]**	**138[ab]**	**178[b]**	**130**	**125**	**124**	**117**	**126**	**121**
2017												
Tree biomass	5.8	14.1	2.2	1.5	9.6		8.6	11.1	2.5	3.7	14.7	
Litter	2.9	2.7	3.2	3.3	2.2		3.0	2.0	2.6	2.5	2.7	
Soil	124	125	117	119	123		90	91	85	89	97	
S+L	**127**	**127**	**120**	**123**	**125**		**93**	**93**	**87**	**91**	**100**	
Total	**133**	**141**	**122**	**124**	**135**		**102[ab]**	**104[ab]**	**90[a]**	**95[ab]**	**114[b]**	

Site	Nyköping						Länghem						Svalöv					
Tree species	B	H	L	S	P	W	B	H	L	S	P	W	B	H	L	S	P	W
2008																		
Tree biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Litter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soil	65	64	66	65	63	65	117	116	115	111	112	105	88	95	92	95	91	92
S+L	**65**	**64**	**66**	**65**	**63**	**65**	**117**	**116**	**115**	**111**	**112**	**105**	**88**	**95**	**92**	**95**	**91**	**92**
Total	**65**	**64**	**66**	**65**	**63**	**65**	**117**	**116**	**115**	**111**	**112**	**105**	**88**	**95**	**92**	**95**	**91**	**92**
2012						(2013)												
Tree biomass						11.8	0.3	0.2	0.3	0.1	0.4	12.5	1.8	0.3	1.3	0.1	0.2	9.8
Litter						1.3	1.1	1.5	1.2	1.2	2.0	1.0	1.9	1.7	1.7	1.5	1.6	1.6
Soil						72	121	125	118	113	124	115	85	93	90	82	86	88
S+L						**73**	**122**	**126**	**120**	**115**	126	**116**	**87**	**94**	**91**	**84**	**88**	**89**
Total						**85**	**122**	**126**	**120**	**115**	**126**	**129**	**89[ab]**	**95[ab]**	**93[ab]**	**84[a]**	**88[ab]**	**99[b]**
2016																		
Tree biomass	0.1	0.7	0.3	0.1	0.8	31.8	4.0	9.0	14.2	7.7	10.3	40.0	18.4	16.6	29.3	11.6	11.5	52.6
Litter	1.8	2.0	2.2	2.1	2.1	2.1	2.4	2.1	2.9	2.2	3.1	2.4	2.1	1.7	3.9	2.8	2.3	1.5
Soil	73	75	76	75	80	78	106	98	110	101	105	103	117	107	104	104	99	112
S+L	**75**	**77**	**79**	**77**	**82**	**80**	**108**	**100**	**112**	**103**	**108**	**106**	**119**	**109**	**108**	**107**	**101**	**114**
Total	**75[a]**	**78[a]**	**79[a]**	**78[a]**	**83[a]**	**112[b]**	**112[b]**	**109[a]**	**127[ab]**	**111[a]**	**118[a]**	**146[b]**	**138[a]**	**126[a]**	**137[a]**	**118[a]**	**113[a]**	**166[b]**

The development of the total C sequestration with time showed a significant increase at the Nyköping and Svalöv sites (Fig. 11). The general trend during this early stage of the rotation time was an increase at the three southern sites while the opposite was seen at the two northern sites. The mean C sequestration rates ranged from being no change over time to 4.9 Mg C ha-1 as site means after 8–9 years growth.

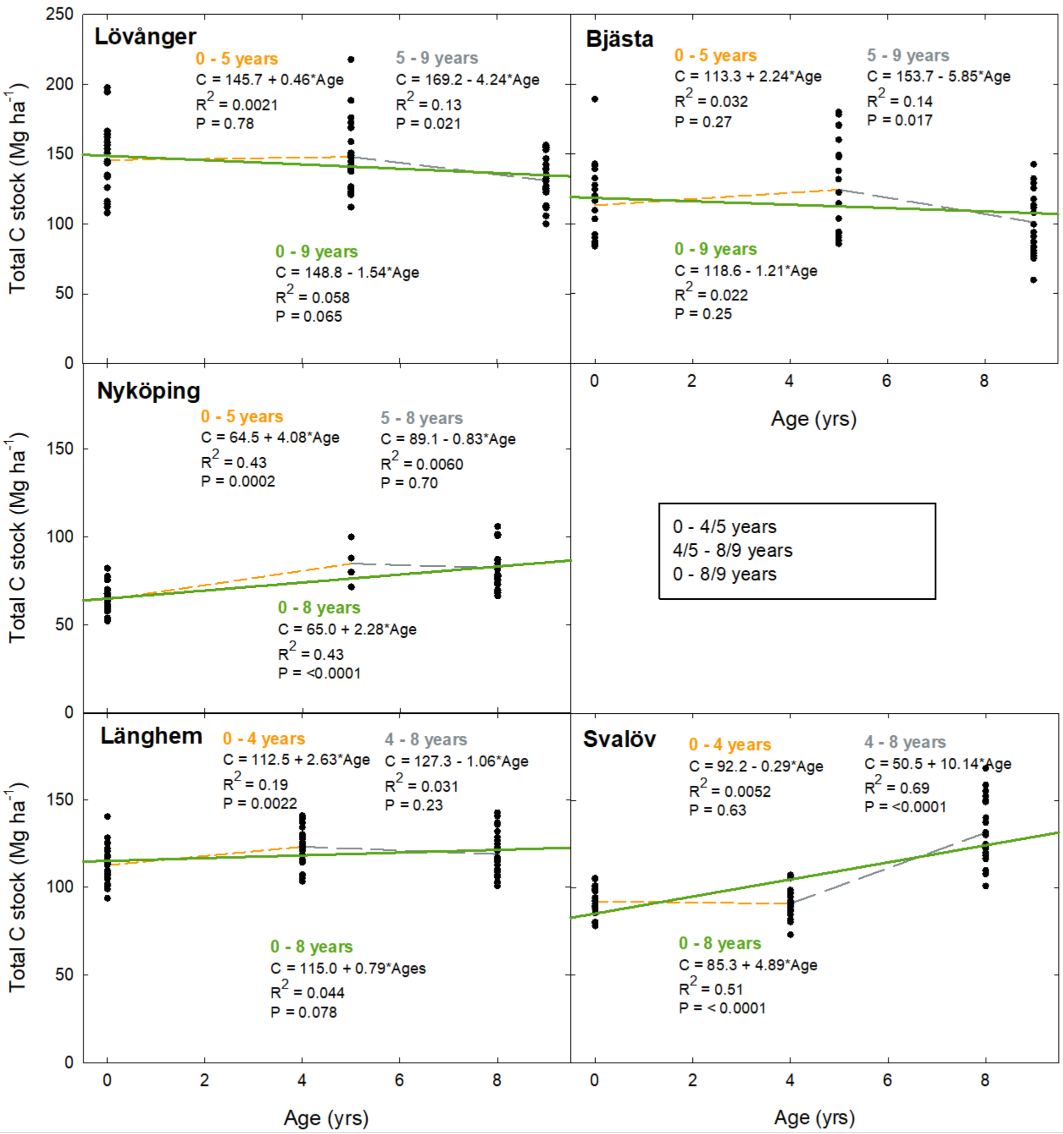


Figure 11. Total C sequestration on the five sites given for plots. Total C consists of SOC, coarse soil organic material C, litter C, and C in above- and belowground tree biomass. In Bjästa and Lövånger willow sites were excluded while in Svalöv, Länghem and Nyköping, C in harvested biomass of willow was included. Linear regressions were performed for respective sampling interval and for the total study period. Figure redrawn from Rytter and Rytter (2020).

The differences seen in the total C stocks for the tree species are so far dependent on the planting densities (Table 9). Short rotation coppice (SRC) with willows had reached a high productivity level, while the other species, managed with more conventional short rotation forestry (SRF), had yet not reached a high level. The growth rate of the perennial crop has a large impact on whether the total C sequestration will be initially positive or not and an increased productivity of the forest ecosystem will most probably increase the C sequestration (Hyvönen et al. 2007, Weslien et al. 2009). Differences among SRF species were only seen in Bjästa where poplar had a significantly higher C sequestration and growth than the Siberian larch (cf. Rytter & Lutter 2019).

The total C sequestration over all plots was positive for Svalöv and Nyköping after 8–9 years growth (Fig. 10). Although divergent trends were seen for the other sites no significant differences in total C sequestration were detected (Rytter & Rytter 2020). The reasons for the differences among sites are unclear but were most likely a combined effect of climate, altitude, initial SOC level, soil type, the intensity of former arable management and the length of the foregoing fallow. The different initial SOC stocks of our sites probably reflected former land use and the time of abandonment which are suggested as key factors when predicting early effects on SOC of afforestation (Paul et al. 2002, Laganière et al. 2010, Bárcena et al. 2014). We noticed that all sites except Svalöv had a tendency for increased C sequestration until 4–5 years (Fig. 10), but thereafter the trend was opposite, especially in the north. The declining trend in the north was attributed to a rapid loss of SOC during the last four years. It could be argued that the fertile southernmost Svalöv site had already passed this development in 4 years and that a positive C sequestration has started thereafter, which may happen also for the other four sites later on. This development pattern has been reported from other studies (Grigal & Berguson 1998, Jassal et al. 2013, Deng et al. 2014). The time factor is, thus, of great importance when evaluating C sequestration.

Conclusions

These experiments have indicated that different tree species with various management scenarios can be used for high biomass production on abandoned farmland. There are large areas of agricultural land available for other use than arable crops, at least temporarily, and if afforested they should be planted with best possible strategy using suitable tree species. The experiment showed that the early growth potential is high although production differences appeared between tree species at the different sites. Future tree species selection should also consider risks in the form of climatic and biological damage and use species that can adapt to the future climate.

The experiments have also shown that the productivity of the tree crop has a rapid and positive effect on total C sequestration on afforested agricultural sites. There were small differences in total C sequestered among species, save for SRC willows that reached a high production level earlier due to higher stand density compared to the SRF species. It is crucial to include all C pools when discussing the C capturing effect of a changing land use. The previous land use and time before afforestation are key factors that may lead to increase or decrease of the soil SOC at an early stage.

Effects on soil parameters could be seen at all sites after 8–9 years tree growth on the former arable soils. Those effects were similar among the tree species and may be associated with cessation of annual management measures, enhanced litter production and altered soil physical conditions, like humidity and temperature, under the trees. The influence of tree species on soil properties is probably a process that takes time.

This study was performed by repeated measurements on the same plots during the study period. By using methods like chronosequences and paired plots the uncertainty in estimates could increase since there may be an initial and continuing discrepancy due to the spatial heterogeneity of soil conditions, even in adjacent plots (Lal 2005). Despite the delay in obtaining results, repeated sampling on the same site during a long time period is probably the safest way of following C sequestration. However, since trends in climate may cause a time-dependent systematic bias the ideal design should include also a control site (Harris et al. 2015). For our study, comprising 8–9 years after afforestation, we noted that C and nutrient status under ongoing land use in agriculture have been stable during at least a decade according to an extensive Swedish study of arable soils across the country (Eriksson et al. 2010). Our opinion is that this and similar experiments in northern Europe will give useful data concerning both general and species-related effects of afforestation when followed repeatedly during a long time.

Publications generated from the project

The following publications are completely or partly based on data and results from the tree species experiments.

PEER-REVIEWED PUBLICATIONS IN SCIENTIFIC JOURNALS

Rytter, L. & Lutter, R. 2019. Early growth of different tree species on agricultural land along a latitudinal transect in Sweden. Forestry 93: 376-388. https://doi.org/10.1093/forestry/cpz064

Rytter, R.-M. 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. Biomass and Bioenergy 36: 86–95. https://doi.org/10.1016/j. biombioe.2011.10.012

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Rytter, R.-M. & Rytter, L. 2020. Carbon sequestration at land use conversion – Early changes in total carbon stocks for six tree species grown on former agricultural land. Forest Ecology and Management 466:118129, 11 p. https://doi.org/10.1016/j.foreco.2020.118129.

Rytter, R.-M. & Rytter, L. 2020. Changes in soil chemistry in an afforestation experiment with five tree species. (manuscript).

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Högbom, L. & Rytter, R-M. 2015. Markkemi och fastläggning av C och N i produktionsinriktade bestånd med snabbväxande trädslag – Etapp 2. Slutrapport till Energimyndigheten 2015. Skogforsk, Arbetsrapport nr 883, Uppsala, 19 s.

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Högbom, L. & Rytter, R-M. 2016. Snabbväxande trädslag på åkermark – markkemi och fastläggning av kol och kväve. Skogforsk, Webbartikel nr 37 2016, Uppsala, 3 s.

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