Oak in mixtures and monocultures - results from the Snogeholm study area in southern Sweden

Dmitry Loginov
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SLU

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Examiner: Per-Magnus Ekö

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Abstract

Oak is a tree specie with fine, high valued wood and thereby timber of oak has high economical value. One drawback of growing oak is the expensive establishment cost due to high seedlings price. Establishing and growing oak in mixed stands could be a solution for this problem. Another problem with oak management is a quality of oak trees as it could be easily reduced due to e.g. crooks, epicormic branches, forks (double stems). Different mixtures will influence the possibilities to get oak trees with high quality. This study was carried out in the 16 years old plantations in Snogeholm study area in southern Sweden. Oak is growing in monoculture and in mixture with different tree species in this area. The oak specie is Pedunculate oak (*Quercus Robur*) for all stands except one monoculture plantation with Sessile oak (*Quercus Petraea*). There were studied 10 different planting methods where oak was growing together with spruce in different arrangements, beech, lime and birch. It was found that it worth to plant oaks in mixture with conifers, the best solution is to plant oak in mixture with spruce in groups. Mixtures will provide higher total volume than in monoculture and better crop oaks quality. Mixture of oak with beech gave the lowest quality for oak.

Keywords: oak, potential crop oak, spruce, oak with spruce, quality, mixture, monoculture.

Contents

1. Introduction

1.1 Oak - general characteristic

Quercus genus contains about 600 species. The genus is native to the northern hemisphere. There are 27 European species of oak (Savill, 1991). Pedunculate oak *Quercus Robur* and Sessile oak *Q. Petraea* (Figure 1) are the most common oak species in Europe. Figures 2a and b show the natural distribution of *Q. Robur* and *Q. Petraea*. Usually *Q. Robur* and *Q. Petraea* are not distinguished in practical forest management because of similarity in growth rates, management and timber properties.

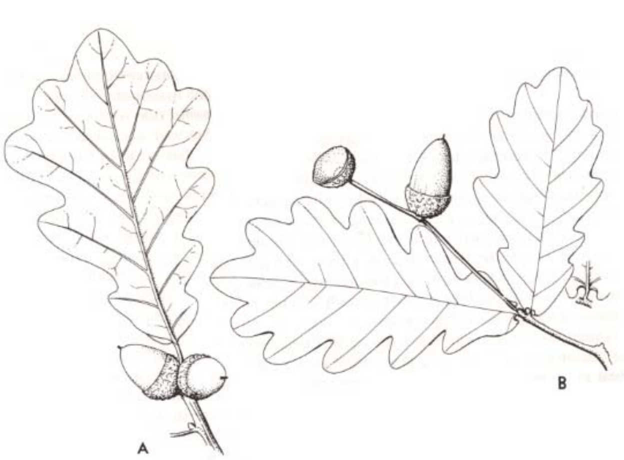

Figure 1. A) Sessile oak, *Q. Petraea*,
B) Pedunculate oak, *Q. Robur*.
Source: Savill, 1991

Figure 2a. Natural distribution of *Q. Robur*.
Source: Evans ,1984

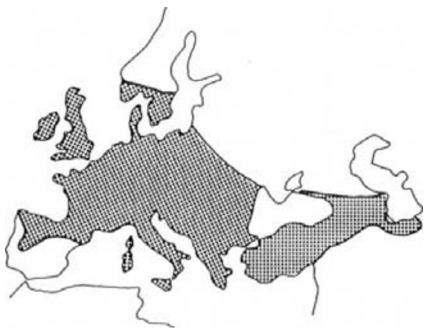

Figure 2b. Natural distribution of *Q. Petraea*
Source: Evans, 1984

Growing oak should be avoided on exposed sites and frost hollows. Oaks grow on a very wide range of soils. *Q. Robur* prefers moist and heavy, calcareous, rich in mineral soils, able to tolerate flooding while *Q. Petraea* intolerant of flooding and prefers acid soils (Savill, 1991). Both species are shade intolerant.

Oak species shows slow initial height increment equal to 10-20 cm per year during first 5 – 8 years. Weed competition is very significant during this period, when seedlings overgrow ground vegetation they began to grow much faster. Between the ages of 10 and 25 years annual growth attains 50 cm (Evans, 1984). Maximum annual yield is 6 m3/ha in Sweden (Carbonnier, 1975) but in most cases, even on better sites the yield is not higher that 3 – 5 m3/ha.

Oak trees begin to produce acorns when they reach the age of 35 – 40 years. Sometimes oaks produce large amount of seeds, those occasions happens every 3 – 5 years and called a mast years (Evans, 1984).

1.2 Broadleaves in Sweden

For centuries broadleaved forests and particularly such species as oak and beech were harvested in a great scale in Europe. This accelerated during 17th, 18th and 19th centuries. Old stands were cut down and replaced with a fast growing species like spruce. Spruce has also been planted on former agricultural lands.

In Sweden many broadleaves stands were replanted with spruce in order to satisfy rising demand in timber until the year 1984 when Forest Act prevented it. In southern Sweden biggest part of the temperate broadleaved forest have been transformed into conifer monocultures (Löf, 2008). The share of oak stands in Sweden is rather low (Figure 3). Spruce is preferable to other species because of the simple management. Forest owners and organizations have a wide knowledge about spruce. And together with simple management other benefits like a short rotation period and high wood production leads to good economy results.

The importance of broadleaved forests is obvious. Rich biodiversity is impossible without broadleaves species as many threatened species are dependent on large dead or growing trees (Nilsson et al, 2001). Recreational value should also be considered. Löf, (2008) writes that there were made different efforts such as governmental subsidies and informational assistance directed to broadleaves restoration.

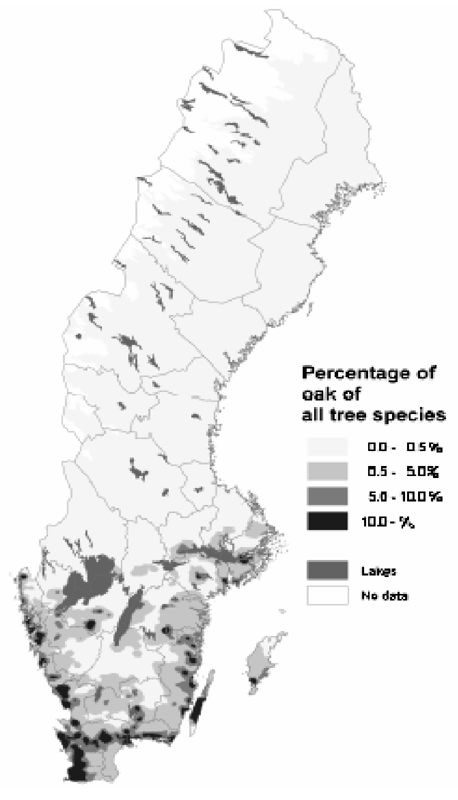

Figure 3. Oak stands distribution in Sweden (NFI, 2003).

1.3 Growing mixtures

1.3.1 General information.

Johansson, (2003) describes mixed forest as “a type of stand in which the total percentage of broadleaved species is 30-70 % of the growing stock”. It is evidenced e.g. by Johansson, (2003) that interest in growing mixed stands is increasing nowadays. On the other hand, Agestam et al, (2005) are trying to say that much of mixed stands benefits – are just thoughts; there are few evidences that they are better than monocultures.

Scientists claim that mixed stands will provide more niches for biodiversity. It is widely thought, but seldom and only in few examples proved that mixed stands will make the trees less susceptible to wind throws, protect them from pests and diseases, e.g. root rot appearance (Agestam et al, 2005). Jose et al, (2006) wrote that nutrient balance is better in mixed stands because roots are located on different levels. This can lower competition between trees in the stand level. From the other side, using fast growing species like spruce or larch as admixture will provide shelter and increase competition, but this may serve foresters well because there is a possibility that shelter will help to decrease number of new branches and will lower frequency of stem defects. Apparently the most significant effect of mixed stands is the economical aspect.

1.3.2 Mixtures with oak

Most broadleaves and especially species like oak has high costs for regeneration (up to €7000 per ha) (Madsen and Löf, 2005). Rotation period for oak is almost two times longer than for spruce. If we are speaking about oak and spruce, the cheapest way of regeneration will be a monoculture stand. Mixed stand of oak with spruce will be more expensive and much more complicated but still, it will be cheaper to establish a mixed stand than an oak monoculture stand (not in case if forest owner receive state subsidies for oak monoculture regeneration). The reasons are mainly because of high price for oak seedlings compared to spruce seedlings and high number of oak seedlings used per ha compared to spruce.

Monoculture stand has many benefits considering tending operations and clear-cutting. Growing monocultures of such species as spruce and oak is well explored. And serious drawback of growing mixed stands is a lack of knowledge in this area. Tending operations are more expensive in mixed stands because of difficulties in implementation. Admixture should be cut down at particular age otherwise it will be competing with crop trees. This “admixture cutting” age is difficult to determine. Problems with harvesting operation and thinning arrangement also makes mixture stands less attractive.

Fast growing admixture like spruce could give additional production and earlier incomes from thinnings. But mixtures silviculture still is not studied enough. Burkhart and Tham, (1992) says that the most important problem is a possibility of negative influence between species.

1.4 Oak timber quality

Premium oak timber has a high value but there are many factors affecting its quality and reducing the price. Among them are knot dimensions and numbers, epicormic branches, heart rot, shakes inside of stem, wood density etc.

Oak timber has a great strength and hardness, it contains high amount of tannin and therefore it has considerable resistance against fungus and insects. The average oak wood density is about 700 kg/m^3 (at 15 percent moisture content). Savill (1991) claims that the faster oak is grown, the stronger it is. If it grows fast – proportion of "latewood" increase, early wood is constant. Oak wood receives its strength from the latewood.

There are some essential problems growing oak. Epicormic branches are one of them. If epicormic left without attention for one year and light conditions are favorable an epicormic branch can continue to grow and it will form a knot. Such knots are not allowed for high quality timber. It's considered that *Q. Petraea* has less problems with epicormic branches growth that *Q. Robur* (Jensen, 2000).

Shake formation in timber is also a vital problem. Shake is a serious defect and it is impossible to predict when they will occur. It is widely thought that shakes creation depends on soil properties. Henman (1984) propose to avoid planting oaks on drought-prone sites. Shakes in the timber are most common on such soils because of stress caused by water deficit.

1.5 Oak timber value

Oak wood is widely used for furniture and veneer production, used in flooring and paneling. Oaks of big dimensions (bigger than 60 cm) could be used for veneer production, but timber must satisfy strong quality requirements (no shake, knots or rot occurrence, grain is straight). In this case price for superior veneer logs could achieve very high level. Oaks from pre- and commercial thinnings could be used as firewood because of high wood density. High density also allows using oak in constructions of different types. In Europe oaks were used in shipbuilding.

Because of above-mentioned features oak has always been the most popular wood for shipbuilding in Europe. More than a thousand oak logs had been used to build one ship. The oak logs had a diameter of at least 60 centimeters at breast height and a usable length of at least six meters. It takes between 150 and 200 years for an oak to grow to the dimensions required for shipbuilding. In the 18^{th} century according to the law at the time, all thick oaks in Sweden were the property of the Crown, in order to ensure the supply of oaks for building war ships (Soic, 2010).

Color of oak heartwood is dark brown. Oak has very good-looking wood structure, grain markings looks especially attractive if wood has been quarter-sawn. Oak timber is a valuable ornamental material; furniture made from oak wood is valuable for reach appearance.

1.6 Aim of the study

The aim was to study development of oak in different mixtures with focus on the following questions:

1. How different mixtures effect the possibilities to grow oaks with good wood quality?
2. How the methods of planting oak in mixtures will affect potential in economy?
3. What other problems could emerge?

2. Material and Methods

2.1 Snogeholm study area description

Material for the study was collected in the Snogeholm study area (Figure 1.) which is situated in Southern Sweden, approximately 45 km east of Malmö (latitude: 55°35'N, longitude 13°40'E).

The Snogeholm study area was established as a co-operation between two departments at SLU in Alnarp: department of Landscape architecture and Southern Swedish Forest Research Centre. The work was funded by the "region Skåne" with the purpose of getting experience of changing land use from agriculture to forestry and also to give examples of different tree species in monoculture stands and in mixed stands. This area serves well as a base for discussions and for identification of different problems and possibilities in silviculture.

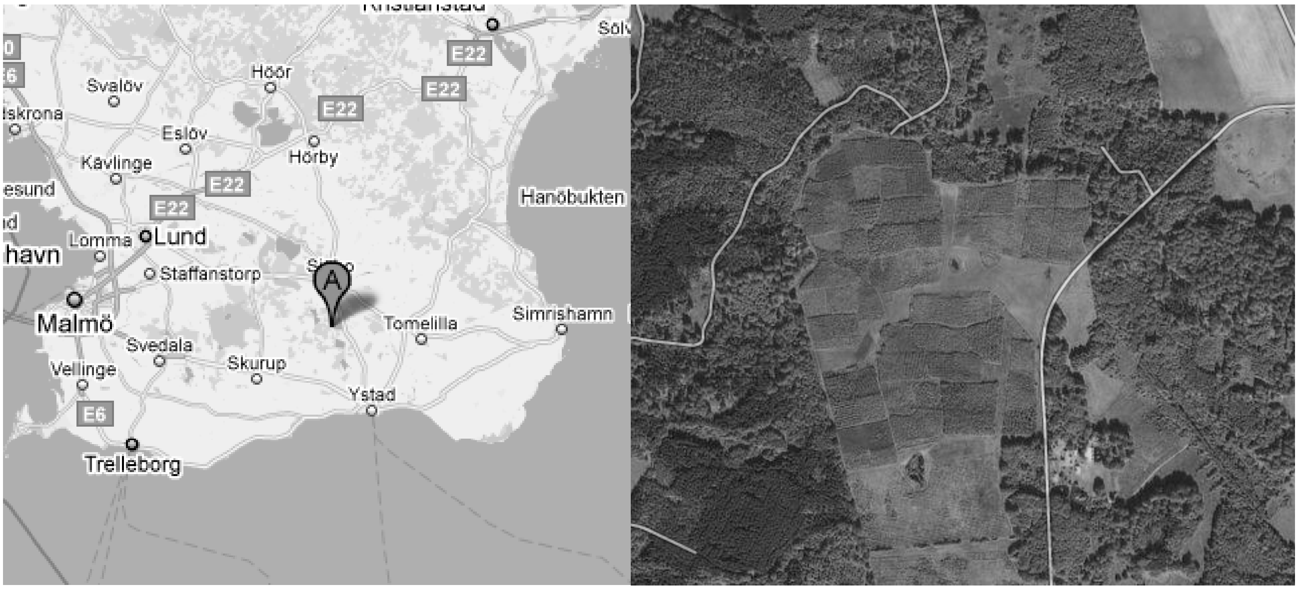

Figure 4. Experimental plot location and the Snogeholm study area, air photo, Skåne (Sweden). Source: google maps.

The climate in the study area is influenced by the Baltic Sea. The mean annual temperature is 7,5°C. The mean temperature of July is 16°C, while January temperature is -1°C. The annual precipitation equal to 700 mm per year. The growing season, the number of days with a mean temperature above 5^{o}C, lasts for approximately 220 days in this region (National Atlas of Sweden 1996).

All stands were established on former agriculture land by planting in 1994. Totally 30 ha were planted with 29 species. Now the number of stands is 69. There are mixtures and monocultures of indigenous species included.

Field work collecting data describing the quality were done autumn 2009. The total age was 16 years, not including age of seedling.

2.2 Description of the stands

All study stands are situated inside of Snogeholm study area. Study was carried out in the stands with oak. There are 15 stands with oak in mixtures in the plantation (Table 1), and 3 stands with oak monoculture. 10 stands were selected for this study (other stands were repeating planting pattern of chosen stands either stand trees were not developed well):

- 2 stands with oak monoculture (*Q. Robur* and *Q. Petraea*),
- 4 stands representing oak planted with spruce – oak with spruce planted in groups, oak with spruce in rows and 2 stands of oak with spruce with admixture of another tree species ("Bubbetorp" and "Sillesas" models),
- Stand of oak planted with larch,
- 3 stands with oak planted with broadleaves - oak with lime, oak with beech and a model called "Sjöarps" (admixture of birch, hazel, ash etc.).

Stands description and stands characteristics could be found in Table 2 and Table 3. Stand data were gathered during the inventory made by SLU in the year 2008, (Övergaard, 2010). The stands were then 15 years old, not including age of seedlings.

Table 1. Overview of all stands with oak in the Snogeholm study area. Oak is pedunculate oak (*Q. Robur*) in all stands except the stand with sessile oak monoculture (*Q. Petraea*).

Mixture type	Size, ha	Admixture species	% of oak	Selected for this study
Oak/spruce groups	0,25	Spruce	20	Yes
Oak/spruce rows	0,28	Spruce	25	Yes
Bubbetorp model	0,3	Spruce, birch, hornbeam, hazel, lime	11	Yes
Sillesas model	0,33	Spruce, ash, hornbeam, beech, lime, birch, maple, cherry	30	Yes
Sessile oak *Q. Petraea*	0,31	None	100	Yes
Mixture	0,3	Spruce and beech	12,5	
Mixture	0,36	Larch and lime	56	
Oak/aspen	0,35	Aspen	20	
Oak/aspen	0,26	Aspen	38	
Oak/beech	0,28	Beech	20	Yes
Trolleholm model	0,43	Ash, hornbeam, lime, alder, cherry	30	
Mixture	0,3	Larch, sorbus species	35	
Oak/larch	0,29	Larch	25	Yes
Sjöarps model	0,26	Ash, hornbeam, cherry, birch, lime, hazel, apple, rowan	30	Yes
Oak seeded	0,33	None	100	
Pedunculate oak *Q. Robur*	0,29	None	100	Yes
Oak/lime	0,29	Lime	80	Yes
Oak. maple	0,36	Maple	28	

Table 2. Planting pattern used in the stands in the study

Stand characteristics	Mixture type									
	Oak with conifers					Oak monoculture		Oak with broadleaves		
	Oak/ spruce in groups	Oak/ spruce in rows	Oak/ spruce Bubbetorp	Oak/ spruce Sillesas	Oak/ larch	Oak *Q. Robur*	Oak *Q. Petraea*	Oak/ birch Sjöarps	Oak/ lime	Oak/ beech
% of oak in the stand	20	25	11	30	25	100	100	30	80	20
% of admixture in the stand	80	75	58	30	75	-	-	30	20	80
Oak origin	K lan	K lan	K lan	K lan	K lan	K lan	Nosk Agdor	K lan	K lan	K lan
Admixture origin	Maglehem	Maglehem	Maglehem	Maglehem	Maglehem	-	-	Asarum	Polish	Ramsasa
Spacing [m]	1,5 x 1,7	1,5 x 1,7	1,5 x 1,5	1,5 x 1,5	1,5 x 2,1	1,5 x 1,1	1,5 x 1,1	1,5 x 1,5	1,5 x 1,3	1,5 x 1,3
Number of seedlings 1000/ha	4 000	4 000	4 444	4 444	3200	6000	6000	4 440	5000	5 000
Number of oak seedlings in % of total seedlings n.	19	23	14	50	28	100	100	51	80	19
Expected number of trees in the final stand	50	50	50	50	50	50	50	50	50	50
Oak - planting pattern	Groups	One row	Groups	Groups	One row	-	-	Groups	Four oaks followed with one lime in rows	Groups
Admixture – planting pattern	Two rows surrounding oaks	Three rows	Two rows	Two rows	Three rows	-	-	Surrounding oaks		Two rows surrounding oak

Table 3. Stand characteristics at the age of 15 years. Measurements done by PhD Rolf Övergaard, SLU (Overgaard, 2010).

Stand characteristics	Mixture type									
	Oak with conifers					Oak monoculture		Oak with broadleaves		
	Oak/ spruce in groups	Oak/ spruce in rows	Oak/ spruce Bubbetorp	Oak/ spruce Sillesas	Oak/ larch	Oak *Q. Robur*	Oak *Q. Petraea*	Oak/ birch Sjöarps	Oak/ lime	Oak/ beech
Mean height of oak [dm]	72	66	71	72	84	87	80	75	74	75
Mean height of admixture [dm]	110	90	96	105	134	-	-	81 cherry	71	73
Mean diameter of oak [mm]	59	54	57	60	73	71	67	68	61	81
Mean diameter of admixture[mm]	138	103	101	137	161	-	-	91 cherry	65	73
Volume of oak [m3/ha]	3.3	2.7	1.4	4.8	4.5	30	27	7.3	15	4.4
Volume of admixture [m3/ha]	39	32	23	12	31	-	-	2.1 cherry	16	16
Total production of oak [m3/ha]	3.3	2.7	1.4	4.8	4.5	30	27	7.3	15	4.4
Total production of admixture [m3/ha]	39	32	24	15.5	31	-	-	3.6	16	16
Total volume production[m3/ha]	42	35	25	20	36	30	27	11	31	21

Oaks in all 10 stands were planted in rows or in groups with the only one exception in case of oak mixed with lime. In this case stand was formed from rows of trees containing 4 oaks followed with 1 lime. Planting maps shown on the next figure (Figure 5).

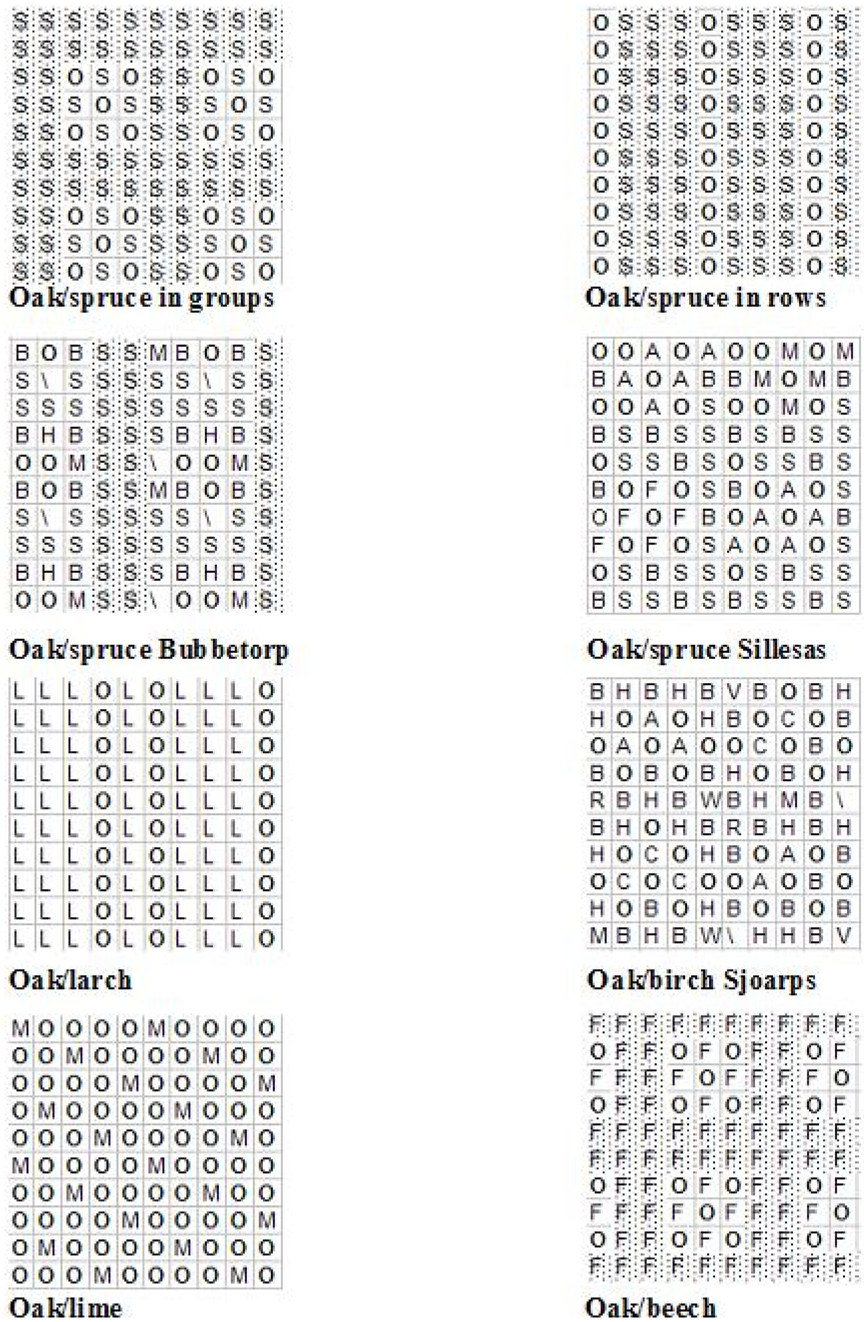

Figure 5. Planting patterns (Övergaard, 2010). Abbreviations: S – spruce, O - oak, \ - hornbeam, H - hazel, M – lime , B – birch, A – ash, F - beech, C - cherry, L – larch, V - viburnum, W - wild apple, R - rowan.

2.3 Data collecting

Data concerning potential crop oaks quality was gathered in autumn 2009. Data concerning oak development was collected autumn 2008 by PhD Rolf Övergaard, SLU (Overgaard, 2010). All the diameters were measured and some heights as well, this data were used to count total volumes per plots. Best looking oaks were marked in each stand during the investigations held by Rolf. Those oaks were considered as potential crop oaks and all quality measurements were conducted between those oaks.

Data concerning oak quality were collected in each stand according to next system. The central point of the stand was found. Then approximately 50 potential crop oaks previously marked by SLU (Overgaard, 2010) were found in a square with that point in center. Number of potential crop oaks was less than 50 in many stands, or was insignificantly higher. In those cases all the potential crop oaks were evaluated (Table 4.)

Table 4. Number of oaks measured in each stand.

	Mixture type									
	Oak with conifers					Oak monoculture		Oak with broadleaves		
	Oak/ spruce groups	Oak/ spruce rows	Oak/ spruce Bubbetorp	Oak/ spruce Sillesas	Oak/ larch	Oak *Q. Robur*	Oak *Q. Petraea*	Oak/ birch Sjöarps	Oak/ lime	Oak/ beech
All potential crop oaks measured	all	all	all	not all	all	not all	not all	all	not all	all
Number of measured oaks	36	63	55	58	46	50	52	46	50	15

The length of "potential log" was measured. As the trees were young and will develop further, this length is an approximate estimation. Height of severe defects, like double stems (forks) and large spike knots that in the future definitely will delimit the length of first log was recorded.

Scars left from previous pruning, presence of epicormic branches, forks occurrence and judgment of stem quality in general were recorded. Also crown development was studied – crown size and crown branches angle were recorded. All those parameters were estimated according to Table 5.

Table 5. Criteria for tree parameters judgment.

Parameter		Class	Parameter description
Tree position in the stand		1	Dominant tree with the top located above stand canopy or above crowns of surrounding same-species trees.
		2	Co-dominant tree - top is situated within the stand crown level, same as majority of tops in the stand.
		3	Dominated tree. Top is situated in a lower part of canopy level or slightly below it. Growth of those trees is limited; however there is a possibility to reach co-dominant level due to thinning operations.
		4	Suppressed tree - top of the tree is significantly below the stand canopy level. Tree has small dimension and slow growth. Thinning will not help to reach higher levels.
Scar left from the previous prunings		1	Number of scars is low, size is small – less than 3 cm. Most probably no effect on future quality.
		2	Insignificant number of scars with dimensions not bigger than 5 cm. Most probably no or small effect on future quality.
		3	Big amount of scars, presence of “chinese mustaches”. Judged to have significant effect on future quality.
Epicormic branches		1	No signs of dead or living epicormic branches.
		2	Some dead dried epicormic branches. Most probably no effect on future quality.
		3	Few living epicormic branches, insignificant amount. Most probably no or small effect on future quality.
		4	Number of epicormic branches. Judged to have significant effect on future wood quality. Judged to make it impossible for veneer production.
Crookedness		1	Stem has straight form, may be slightly crooked above 4 m. Most probably no effect on future quality or value.
		2	Tree is slightly crooked in the bottom (distance from straight line to bended part longer than ½ of tree diameter). Most probably no or just a small influence on future wood quality and value.
Fork occurrence		1	Tree has only one stem.
		2	Tree is forked in the upper part above 4 m height. Most probably no influence on value of bottom logs.
		3	Fork occurrence in the bottom. Judged to have significant influence on future wood value.
Stem quality in general		1	Well shaped stem without defects.
		2	Few defects like big scars, crookedness etc. Most probably no or small influence on future quality and value.
		3	Numerous defects, severe defects. Judged to have significant influence on future quality and value.
Crown properties	Crown size	1	Well-developed, wide crown.
		2	Tree has slightly suppressed crown from few sides.
		3	Crown is significantly suppressed, developed poorly.
	Crown branches angle	1	Branches has wide angle, more than 60 degrees.
		2	Branch angle is slightly narrow from 30 to 60 degrees.
		3	Very narrow branch angle, smaller than 30 degrees.

Table 5 (continuo) Criteria for tree parameters judgment.

Tree quality class	0	Tree of highest quality – takes dominant or co-dominant position, have few scars, doesn't have problems with epicormic branches, has straight stem of good quality.
	1	Normal quality. Tree could have few epicormic branches, may be slightly crooked. Few defects are allowed but stem shape should be nice.
	2	Low quality – dominated and suppressed trees, many scars, presence of forks and other defects. Problem with epicormics. Crown not developed well.
Consideration for future	1	Tree will be a crop oak in future if it will be no serious changes in quality.
	2	Tree will be removed through thinning operations due to competition with other oaks of better quality.
	3	Tree of low quality, will be removed.

2.4 Data analyzing

Analyzing of collected data can be divided into two parts: working with stands characteristics data and analyzing of data concerning oak quality. Also calculations of future volume yield and future incomes were made.

Comparison of different growth features was made in the first part. The stand volumes were calculated, mean diameters and heights of all trees were calculated.. Frequency of oaks in diameter - and height classes was calculated. Finally mixtures and monoculture stands where compared.

In the second part parameters describing oak timber quality, stem defects occurrence, crown properties, oak tree classes, were further analyzed.

There is a systematic way in data representing in tables and in the figures. The stands are divided into three groups – oak with conifers, oak monoculture and oak in mixture with broadleaves. In the figures the following order is used from left to right: oak with conifers, oak monoculture and oak in mixture with broadleaves. This arrangement gives better possibilities for comparison of shown properties between the groups.

MiniTab program was used for significance calculations that were made in ANOVA. There was made significance test between groups. Material was divided in 3 groups in testing – oak with conifers, oak monoculture and oak with broadleaves. Correlations were calculated for oak monoculture group and two other groups.

2.5 Calculations of future volume yield and incomes.

Calculations of future volume yield were made by using ProdMod simulation program based on growth and yield models by Ekö (1985). This program gives possibility to predict future volume production for stands of most tree species in Sweden. Growth and yield, standing and harvested volumes were calculated with steps of 5 years (the only possibility in this program). Rotation age for oaks was set at 120 years. All the conifers species (spruce and larch) were clear felled by the age of 40 years (all at the same age to simplify comparison between stands).

At first, basal area was calculated for oaks and admixture in each stand. Site index was estimated (Hägglund och Lundmark 1987) (site index is the predicted as height of 100 trees with largest diameters at the reference age of 100 years). Than all the data was inserted into ProdMod and simulation was made according to existing thinning guides for oak (Carbonnier, 1975). Almost after each 5-years period thinnings were arranged with required percentage of stems or basal area percentage removed. When simulation was finished, volume of thinned trees was calculated.

ProdMod have no functions for *Q. Petraea* so volume yield was counted with functions for *Q. Robur*. Neither ProdMod have functions for many other species. Larch has about the same MAI as a spruce but a shorter rotation, so spruce functions were used but rotation was 50 years. For other broadleaved species like lime and ash there were used functions for “other broadleaves”.

Costs for stands establishment, tending operations and logging were collected and compiled by SLU, Southern forest Research Centre (Ekö, 2009). Costs and prices for pulpwood and timber were used for southern Sweden (autumn 2009). All the volumes of thinned trees of different species, volumes from final-fellings were received from simulations in ProdMod.

The income from thinning and also cost for silviculture operations, except regeneration, comes at different ages. Therefore it was included in the calculations as a soil expectation value. Interest rate of 2,5% was used.

3. Results

3.1 Trees dimensions and volume

3.1.1 Heights for all trees

On average the highest oaks were growing in the Pedunculate oak monoculture stand (*Q. Robur*) (8,7 m), while the lowest oaks were in stand of oak/spruce growing in rows (6,6 m). Height of oaks in general did not differ much across the stands but the highest oaks were growing in the monoculture stands and in the oak/larch stand (Figure 6). Statistical analyze did not show significant difference neither between oak monocultures and oak/conifers group (p=0.149) or between oak monocultures and oak/broadleaves group (p=0.241).

The admixtured species were higher than the oaks in stands of oak with conifers. Biggest difference in heights between the admixture and the oak was found in the oak/larch stand. In stands of oak with broadleaves admixture trees were lower than oaks. But the difference was small.

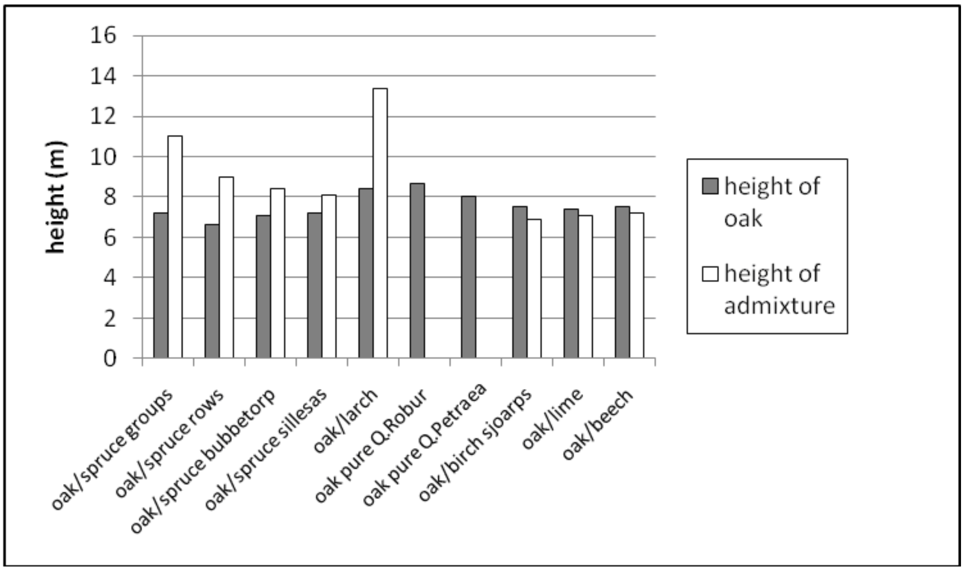

Figure 6. Mean hight of standing oaks and admixtured species.

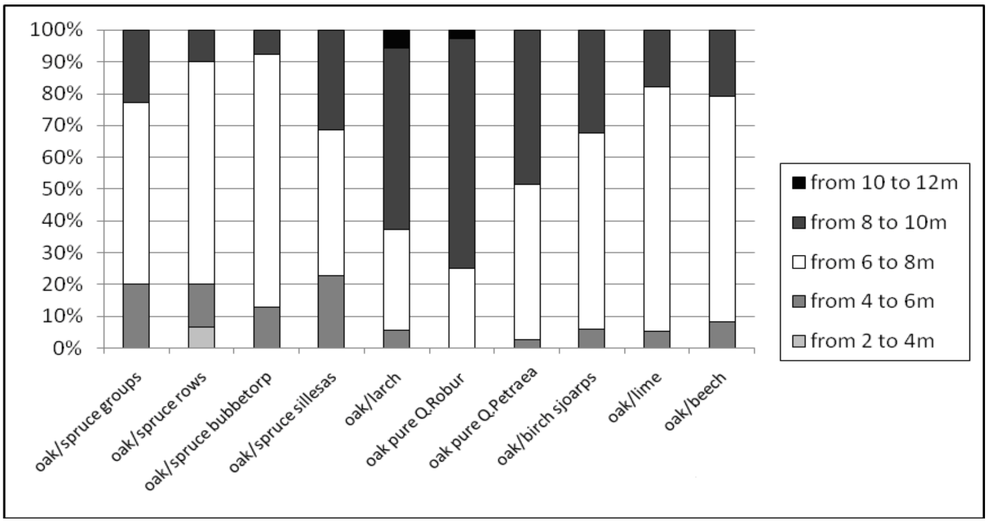

Figure 7. Frequency of all standing oaks in different height classes.

In oak monoculture stands and stand of oak with larch, most frequent heights were from 8 to 10 m (Figure 7). In mixtures with conifers and mixtures with broadleaves the proportion of trees with heights from 6 to 8 meters was bigger. Biggest amount of trees from heighest group was found in stands of oak *Q. Robur* and oak/larch. Lowest oaks were observed in stands of oak monocultures and oak growing with broadleaves.

Widest distribution of oak heights was observed in oak/spruce in rows stand while narrowest distribution was in *Q. Robur* monoculture (Figure 8). Top heights of oak trees varied much between the stands from 8,5 to 10,5 m.

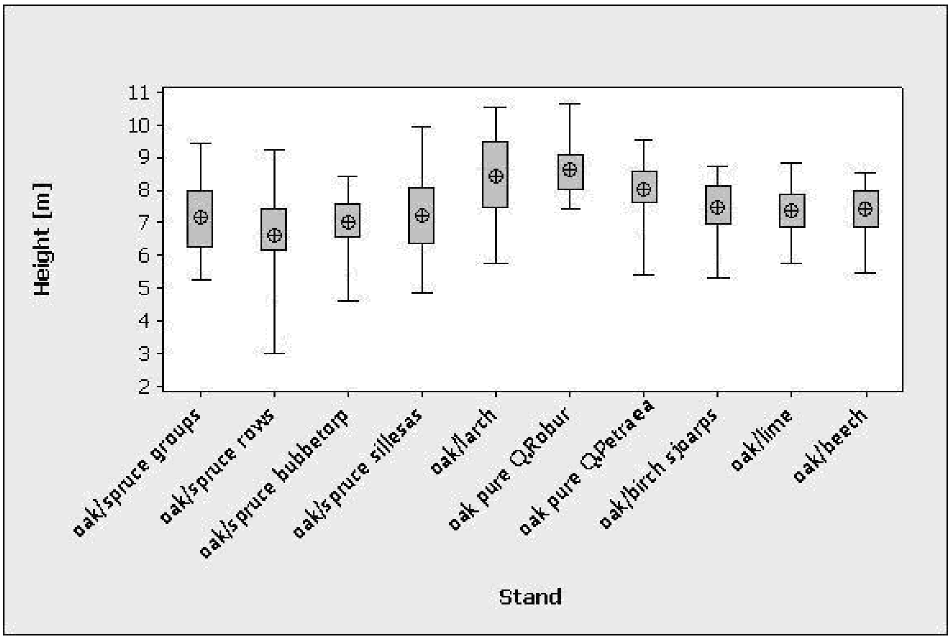

Figure 8. Height of standing oaks within the stand (+ mean, ☐ mean ± SD, I – min-max).

3.1.2 Diameters

3.1.2.1 Diameters for all trees

Largest oak diameters were observed in the oak monoculture stands and in the stand of oak growing with broadleaves. Diameters of oaks were smaller in stands of oak growing with spruces. Biggest average diameter was found in oak/beech stand (81 mm), smallest oak diameter was in oak/spruce in rows stand (54 mm). In mixtures with conifers, the diameters of the conifers were slightly bigger than the diameter of the oaks. In the stands with another broadleaves, oak and admixture diameters were almost the same (Figure 9).

Statistical difference was insignificant between all groups: p=0.093 in comparison with conifers group and p=0.887 between oak monocultures and mixture with broadleaves.

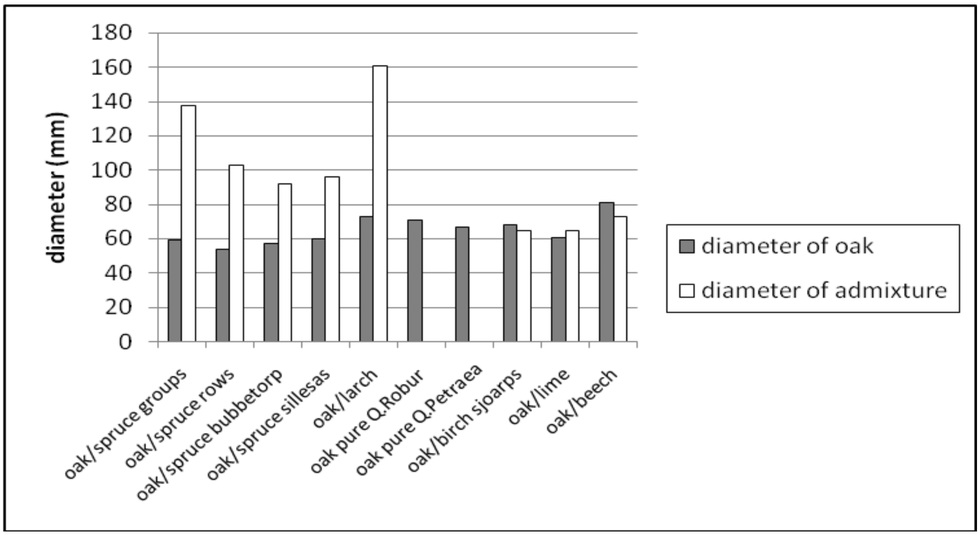

Figure 9. Mean diameter of oak and admixture.

Highest proportion of oaks with diameters from 3 to 6 cm was found in stands of oaks with spruces (Figure 10).

Oaks with biggest diameter (class from 12 to 15 cm) were noticed in stands of *Q. Robur* monoculture and oak/beech stand. Biggest diameter was changing significantly across the stands from 8 to 18 cm (Figure 11). Mean diameter was not dependant on mixtyre type.

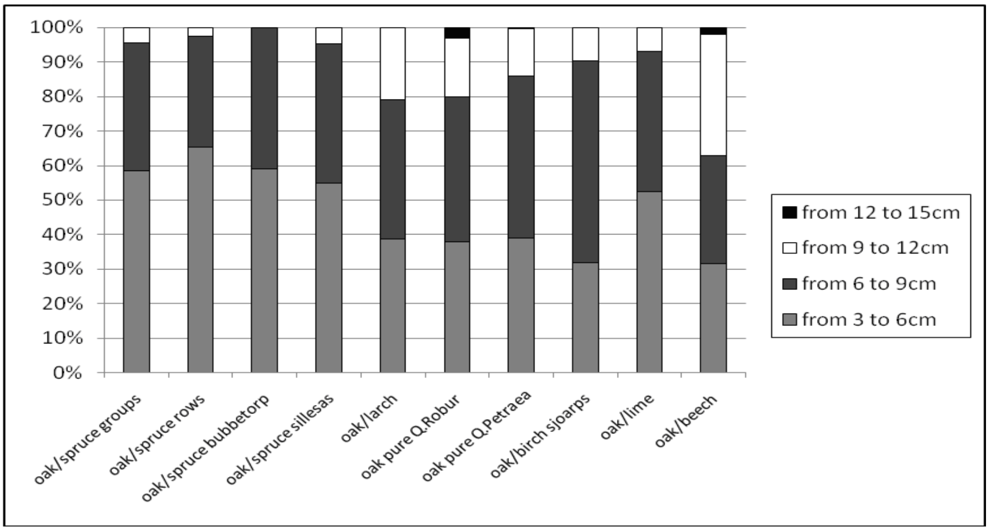

Figure 10. Frequency of oak in different diameter classes.

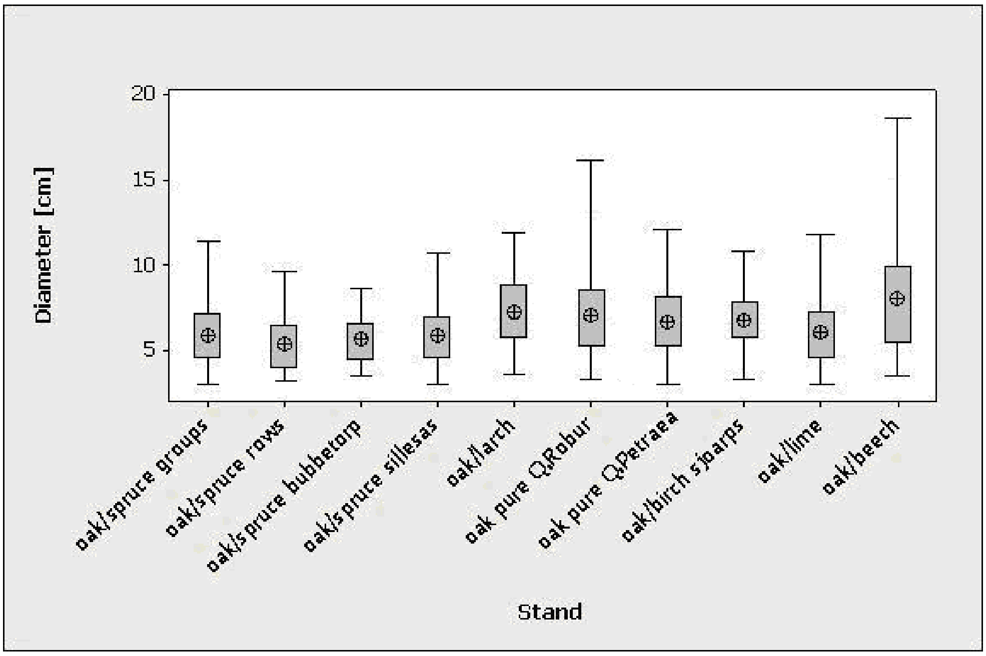

Figure 11. Diameter of oak within the stand (+ mean, ☐ mean ± SD, I – min-max).

3.1.2.2 Diameters of potential crop oaks

Diameter of the potential crop oaks were changing significantly from 68 mm (oak with spruce in rows, oak with spruce Bubbetorp) to 101 mm (*Q. Robur* monoculture). Potential crop oaks in conifer stands had smaller diameters than oaks in monoculture and oaks with broadleaves (Figure 12).

Difference was statistically significant between oak monocultures and oak with conifers (p=0.023). But there was no statistical difference between oak monocultures and oak with broadleaves (p=0.234).

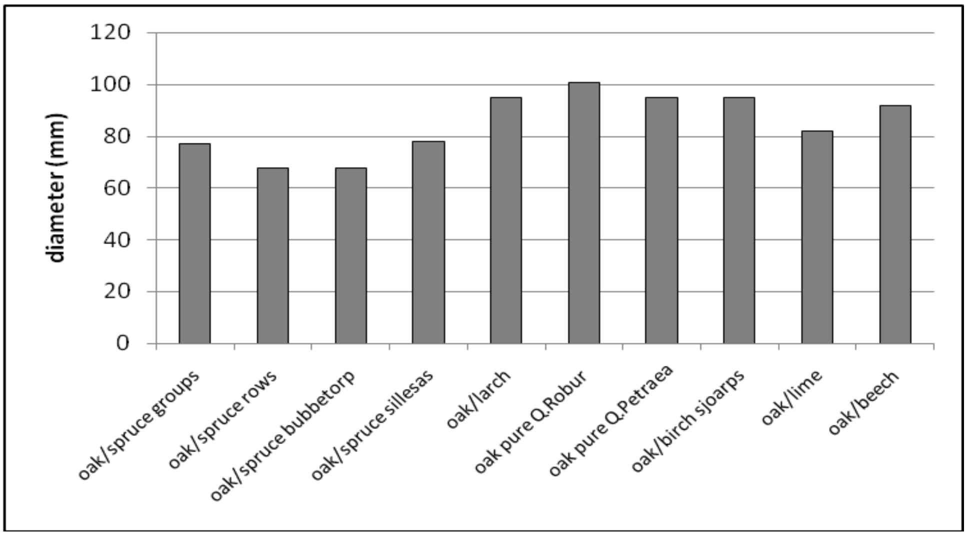

Figure 12. Mean diameter of potential crop oaks.

Diameters of potential crop oaks in stands with spruce were mostly in diameter class from 6 to 9 cm. Other stands (except oak with lime) had in average 10% of potential crop oaks growing in diameter class from 12 to 15 cm. Stand of *Q.Robur* monoculture had 20% of such potential crop oaks (Figure 13).

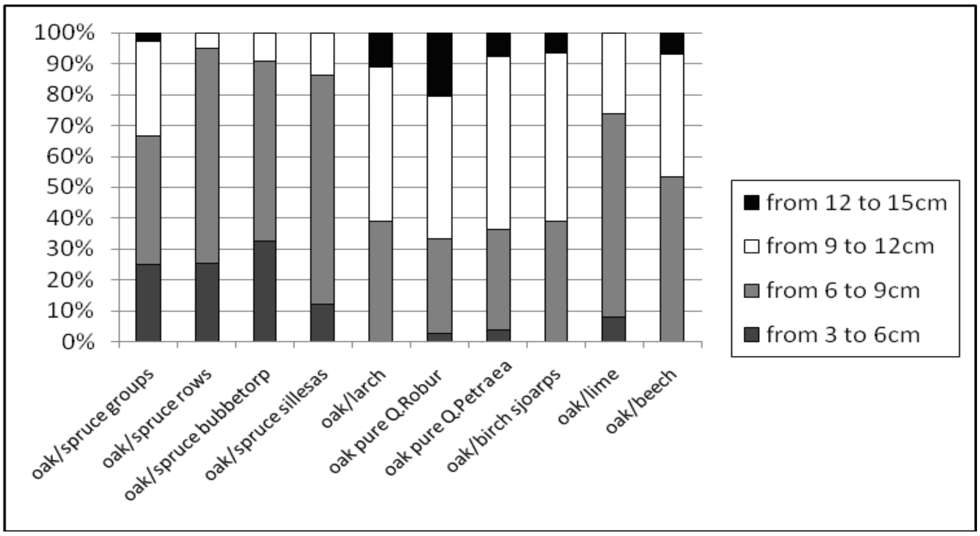

Figure 13. Frequency of potential crop oaks in different diameter classes.

The thickest potential crop oak was found in stand of *Q.Robur* (17 cm - individual), and the thinnest oak was in stands with spruce (3 cm – few individual values). Mean diameters differs from 6 to 8 cm (Figure 14).

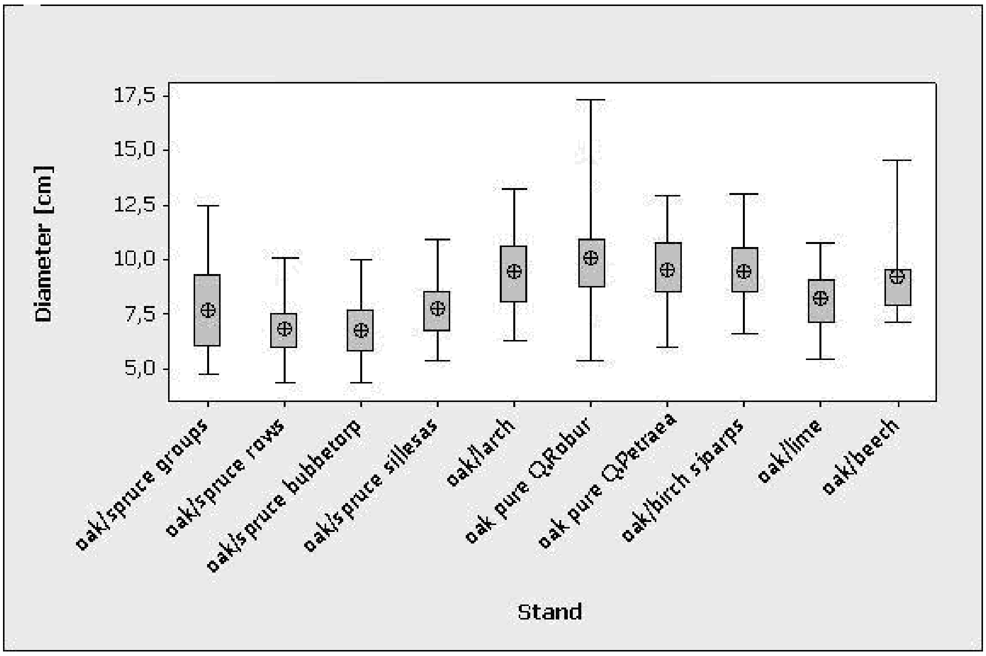

Figure 14. Potential crop oak diameter within the stand (+ mean, □ mean ± SD, I – min-max).

3.1.3 H/D ratio

Potential crop oaks had the same height/diameter ratio in almost all stands. It was equal to 1,2 (Figure 15). Only Sjöarps method and oak with beech stands were deviating. In the stand of oak with beech oaks had height/diameter ratio equal to 0,9.

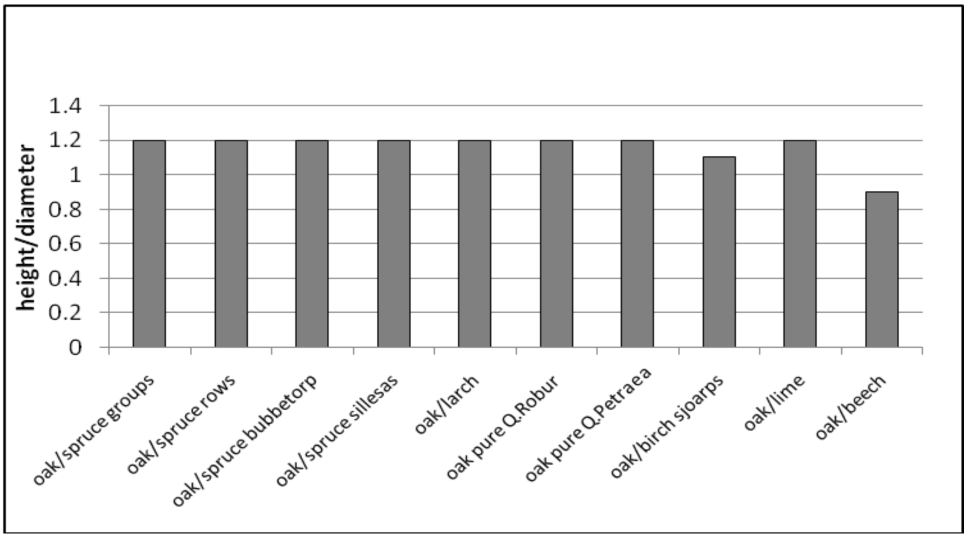

Figure 15. H/D ration of potential crop oaks.

3.1.4 Total volume

There was a large difference in total volume between stands. Highest yield was obtained in groups of oak with conifers stands. Lowest yield was observed in Sjöarps planting method, difference between those methods was equal to 31 m3/ha what was 3 times bigger than Sjöarps yield itself (Figure 16). Both groups of oak mixtures differ from oak monoculture stands, p=0,041 in comparison between monoculture with conifers mixtures and p=0.03 in between oak monoculture and mixture with broadleaves.

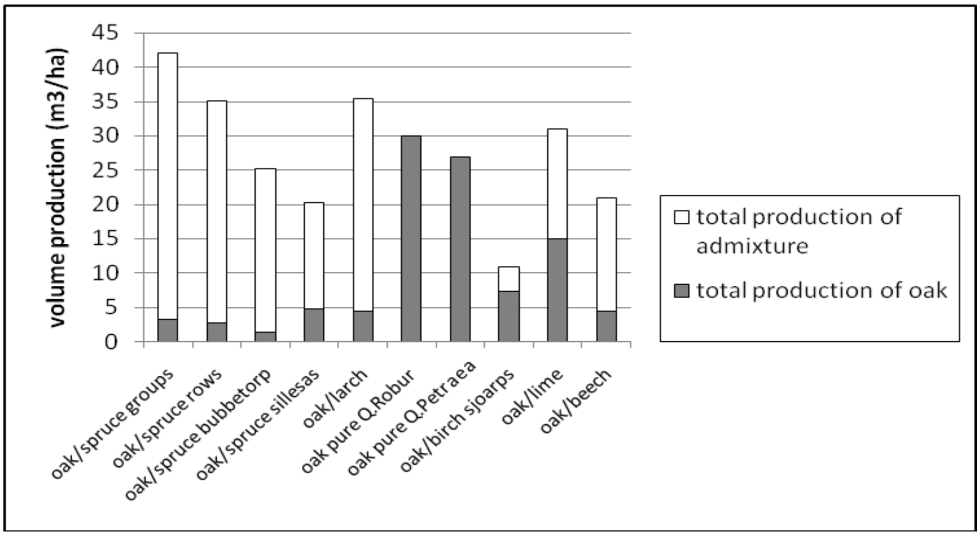

Figure 16. Total volume production until 2009, 16 years after planting.

Oak monocultures had produced much higher total volume of oak than mixtures (27 – 30 m^3/ha for oak monoculture). Oak growing with broadleaves gave higher production of oak than oak in mixtures with conifers. The lowest oak production was found in Bubbetorp method and was equal to 2 m^3/ha.

Average oak tree volume differed from 0,009 m^3/tree (oak with spruce in rows) to 0,022 m^3/ha (oak with beech). Highest average oaks volumes were found in oak/larch, *Q. Robur* monoculture and stands of oak with beech. Oaks with spruces had low average volume (Figure 17).

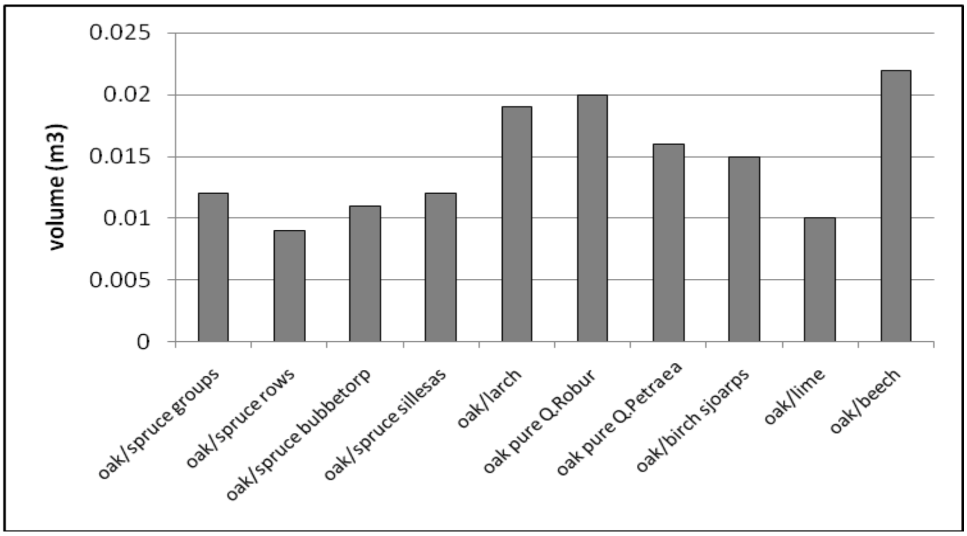

Figure 17. Average volume per tree of all standing oaks in the stand.

3.1.5 Tree classes

The largest proportion of dominant oaks among the potential crop oaks was observed in mixtures with broadleaves (in average 46% were dominant trees and rest were co-dominant oaks). Oaks monocultures had 22-30% of dominant oaks (Figure 18). Stands of oak growing with spruces had biggest amount of suppressed oaks among all stands (up to 10% in oak/spruce-groups stand). Biggest number of dominated crop oaks (among all stands) was found in mixtures with conifers.

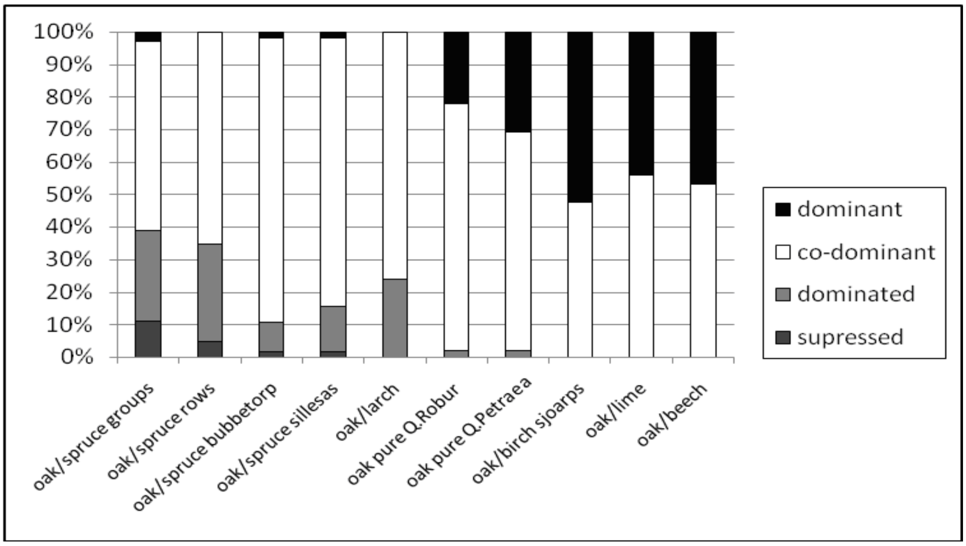

Figure 18. Frequency of potential crop oaks in tree classes.

3.2 Quality of potential crop oaks

3.2.1 Potential log length today

Longest potential logs were found in oak monoculture stands, in mixtures with broadleaves (except oak with beech) and in stand of oak with larch (Figure 19). In those stands in average 60% of the oaks had severe defects (like double top or fork) limiting the log lengths (Figure 20). Stands with biggest proportion of low trees (oaks with spruces) had up to 84% of oaks without growth limiting defects.

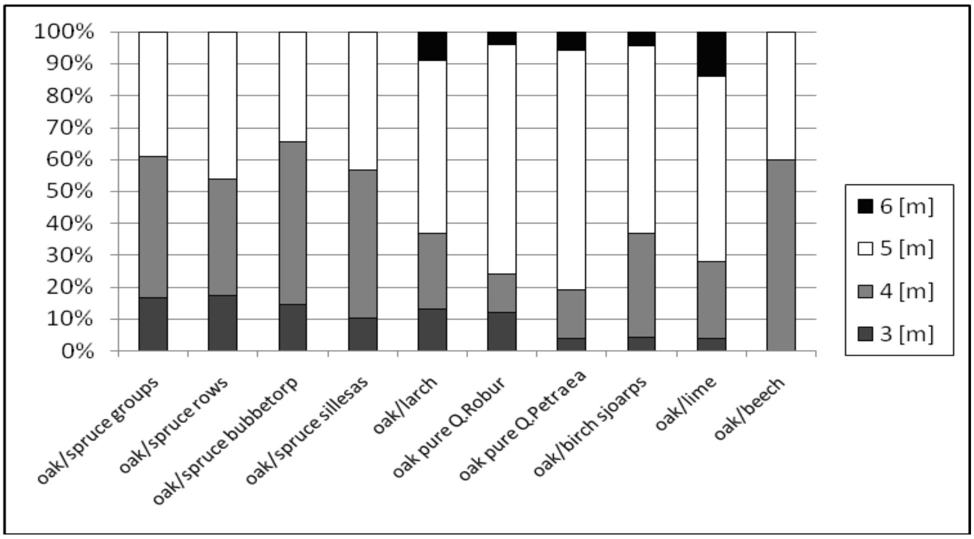

Figure 19. Frequency of potential log length today (might be longer in future); potential crop oaks. Classes**:** 3[m]=2,5-3,4m, 4[m]=3,5-4,4m, 5[m]=4,5-5,4m, 6[m]=5,5-6,4m.

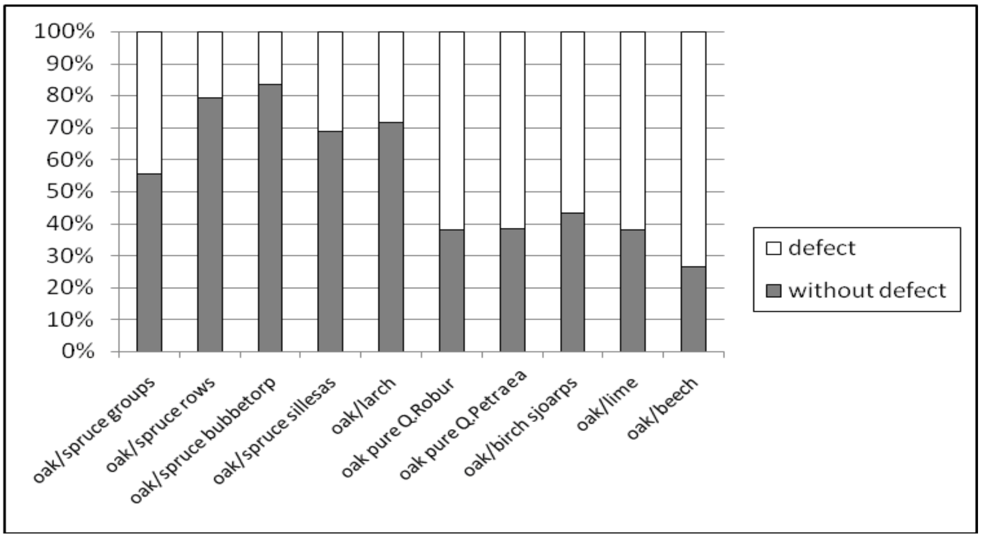

Figure 20. Log length limitation by severe defect.

Lowest oak log of 4,2 – 4,3 m was found in mixtures with spruce. Highest log height of 4,6 – 4,8 was found in monoculture stands, in the stand of oak with larch and stands mixed with broadleaves (Figure 21).

There was a significant difference in potential log length between control group and group with conifers (p=0.008) while there was no difference found in between oak monoculture groups and oak with broadleaves groups (p=0.355).

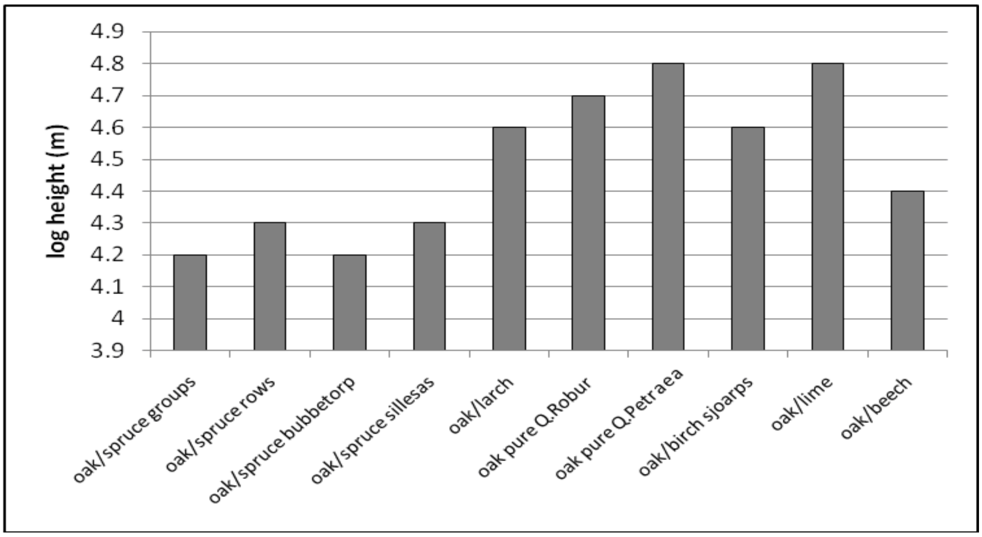

Figure 21. Potential log length today (might be longer in future); average for potential crop oaks.

3.2.2 Scars left from pruning

The Sjöarps model had lowest frequency of trees with scars - 78% of trees with few scars and no trees with large amount of scars. A low frequency of trees with scars was also found in oak/spruce stands and oak/larch stand – 60% of trees with few scars in average. Oak/beech stand had the biggest amount of scars - 27% of trees with significant amount of scars (Figure 22).

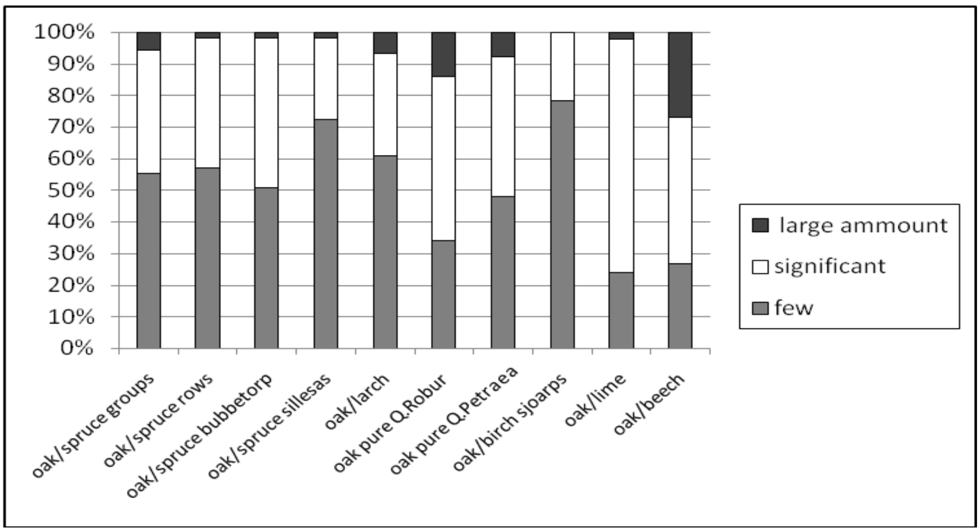

Figure 22. Scars left from pruning; potential crop oaks.

3.2.3 Epicormic branches

Biggest amount of living epicormic branches was found in the oak/larch stand and in the stand of *Q. Robur* monoculture. In those stands problem of epicormic branching was most vital. The Oak/lime stand and the Bubbetorp model had almost 90% of potential crop oaks with no signs of epicormics at all (Figure 23). All other stands had in average 75 % of oaks without epicormic branches.

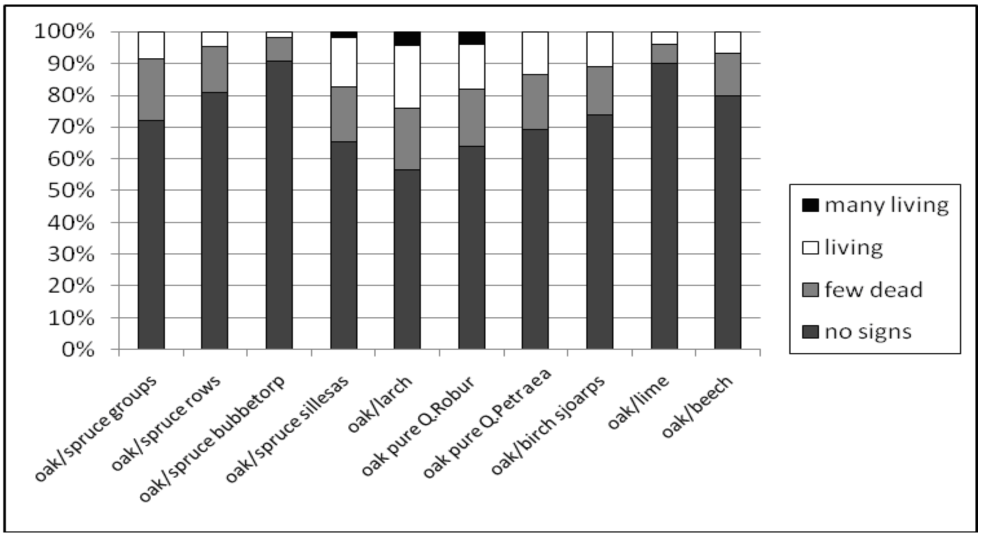

Figure 23. Epicormic branches occurrence; potential crop oaks.

3.2.4 Crookedness

98% of potential crop oaks had straight stems in the Sillesas model. Highest frequency of crooked stems was found in the oak/larch stand. About 80% of potential crop oaks stems were crooked there (Figure 24).

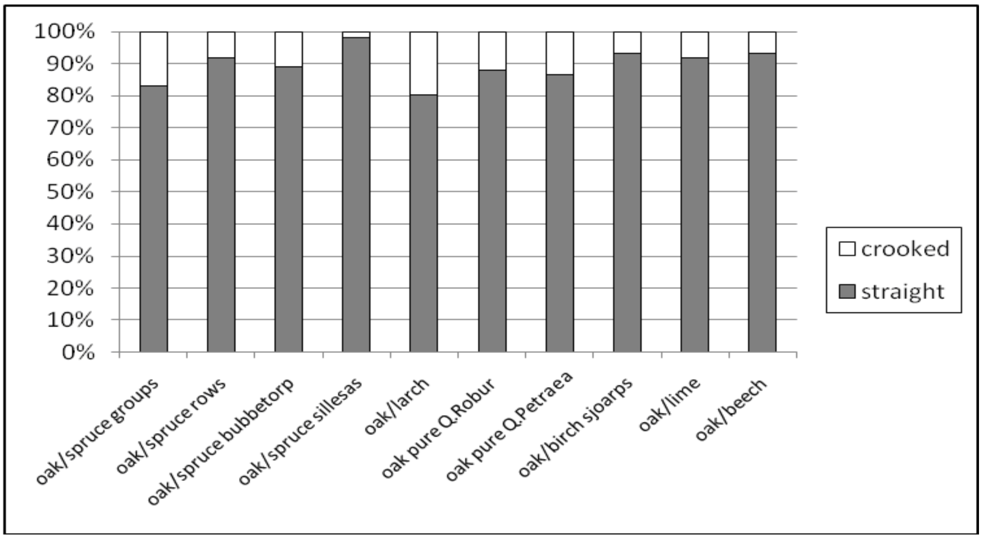

Figure 24. Frequency of crookedness; potential crop oaks.

3.2.5 Tree shape and stem defects

Lowest proportion of forked trees was found in stands with conifers – 77% of trees without fork. In the stand of oak/spruce-rows there were growing almost 10% of oaks forked below 4m. Potential crop oaks from monoculture stands and from stands with broadleaves were not forked in 56% of cases. The oak/beech stand had biggest proportion of forked trees equal to 60% (Figure 25).

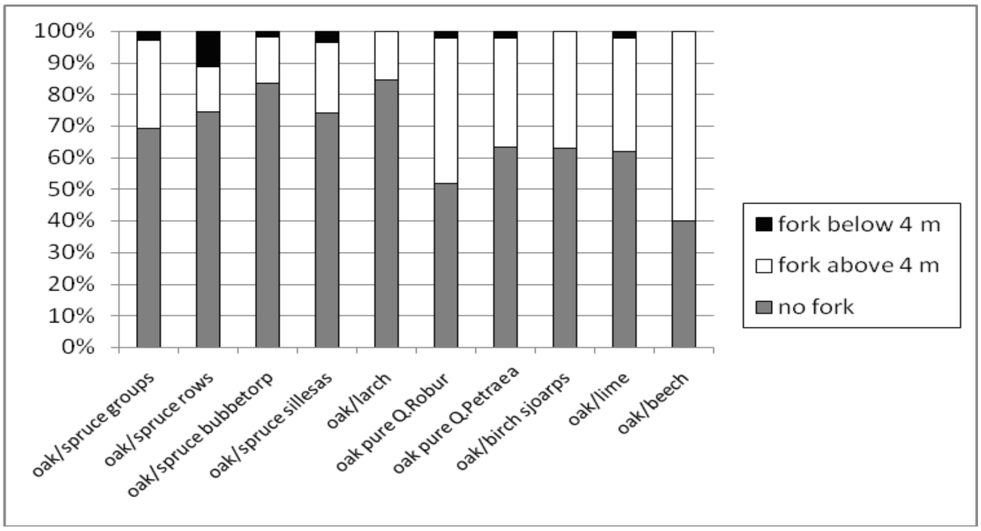

Figure 25. Frequency of forks; potential crop oaks.

There was only a small difference in frequency of trees without defects between the stands (Figure 26). *Q. Robur* monoculture stand had 4% of potential crop oaks with numerous stem defects. The Sillesas and the Sjöarps models and oak/spruce-rows stand had lowest amount of defected trees – less than 19%.

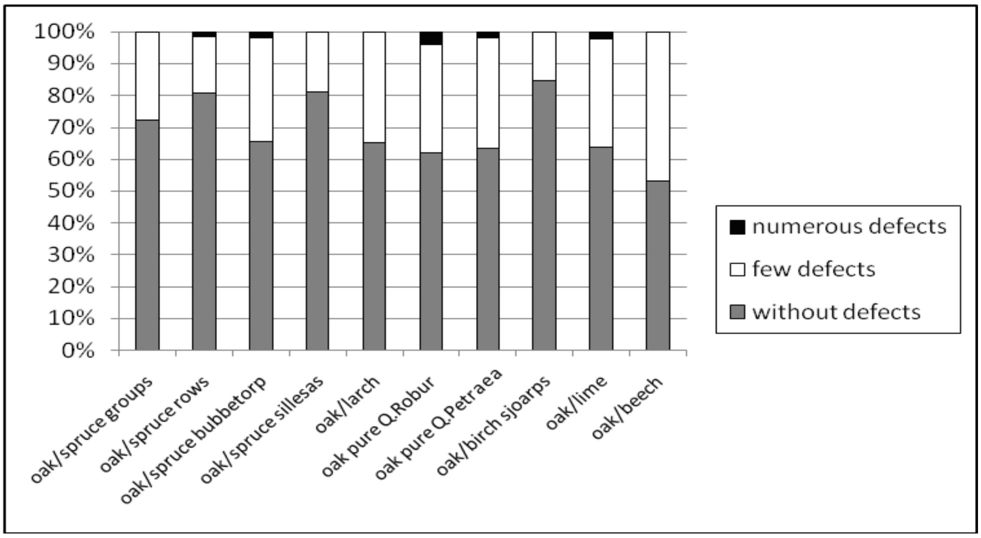

Figure 26. Stem quality; potential crop oaks.

3.2.6 Living crown properties

Highest proportion of potential crop oaks with well-developed crowns was found in the Bubbetorp method, in the oak/larch and in the *Q. Petraea* monoculture – 35% in average. Other methods gave 20% of oaks with well-developed crowns.

From 40 to 62% of crop oaks had “slightly suppressed” crowns. The oak/beech stand had highest proportion of suppressed potential crop oaks - 40% (Figure 27).

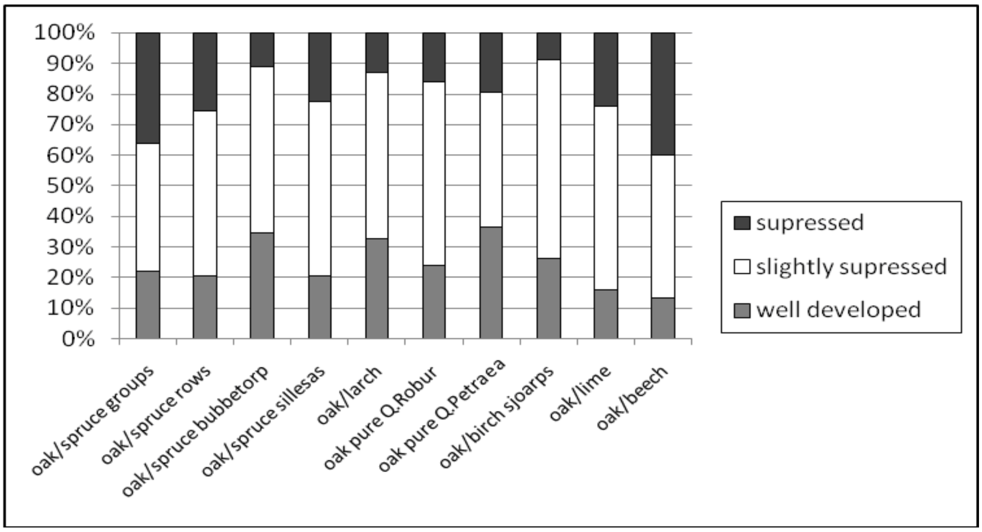

Figure 27. Crown development; potential crop oaks.

Potential crop oaks from oak/spruce in groups and rows stands had highest proportion of wide crowns (70% of wide branches on potential crop oaks) (Figure 28). Oak/spruce growing in rows and in groups had only 7% of very narrow branches. Oak/lime and oak/beech had narrowest angle of crown branches (34% of very narrow branches).

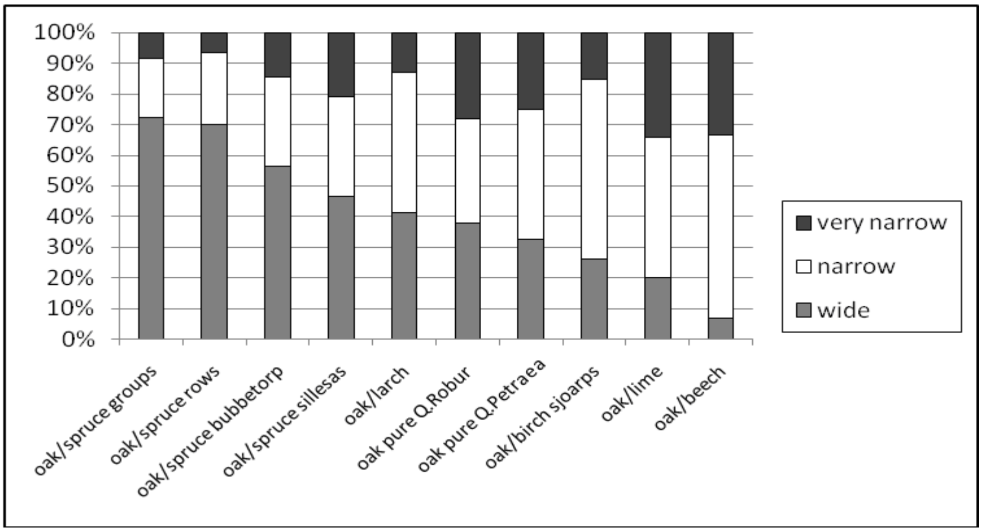

Figure 28. Crown branches angle; potential crop oaks.

3.2.7 Oaks quality classes

Highest frequency of potential crop oaks in highest quality class (class 0) was found in oak/spruce-groups and the Bubbetorp stands – 35 to 36% (Figure 29). Oak/lime and oak/beech stands had only 12% and 13% potential crop oaks of 0-class accordingly. Oak/spruce rows and groups stands, the Bubbetorp model, *Q. Robur* monoculture and oak/beech stand had 22% of 2-nd class potential crop oaks in average.

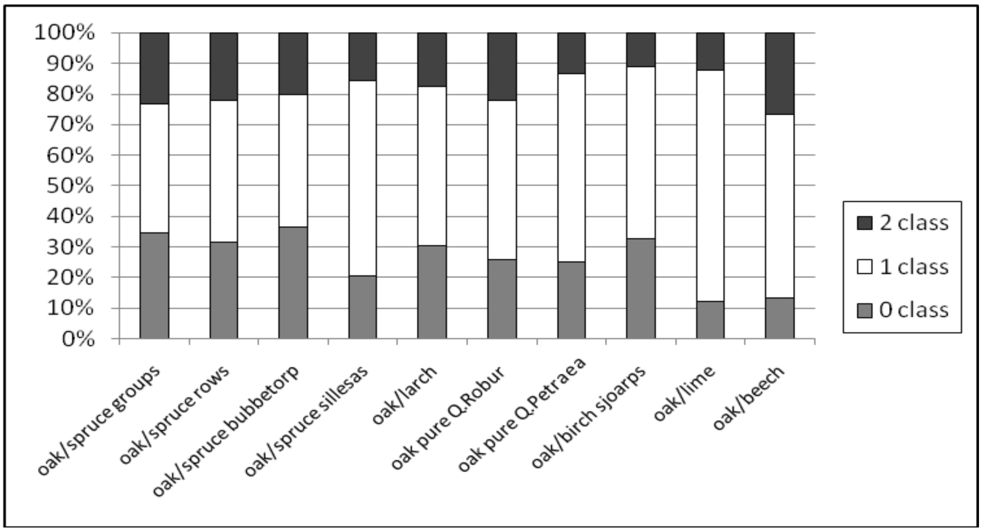

Figure 29. Frequency of potential crop oaks in quality classes
0= high quality, 1= normal quality, 2= low quality.

37% of the potential crop oaks in the stand oak/spruce in rows were judged to be of high quality in the future. In the stand oak/spruce in groups 68% of the potential crop oaks were judged to be of high quality in the future (Figure 30). Highest frequency, 12%, of potential oaks judged to be of poor quality was found in the Sillesas model and in the *Q.Robur* monoculture stand.

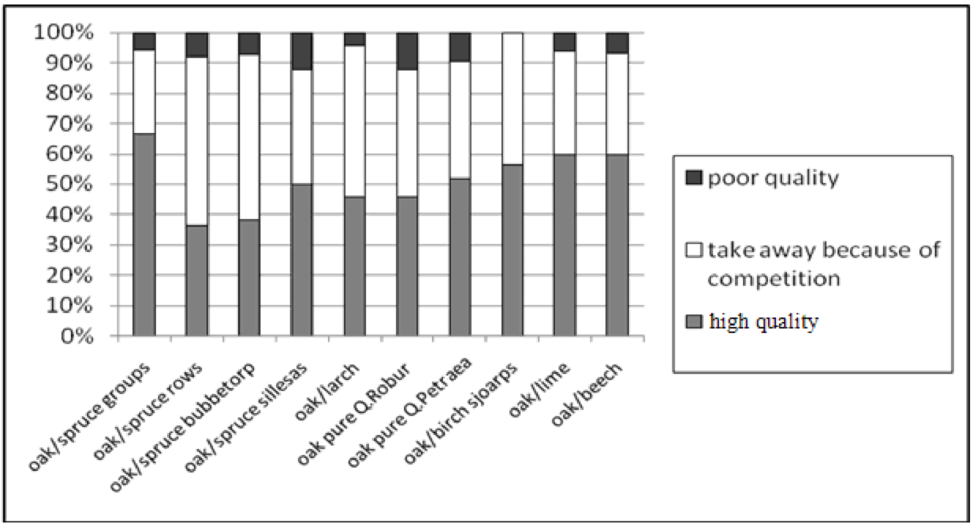

Figure 30. Potential crop oaks consideration for future.

3.3 Results of simulations of volume yield

Table 6 contains information about volumes that were simulated. Highest volume was obtained in the mixture of oak with larch – 878 m^3/ha and lowest volume was found in the Sjöarps model - 290 m^3/ha (Figure 31). Total volume was higher in mixtures with conifers than in monoculture, but oak production was highest in monoculture stand. The oak/larch stand had highest production of admixture.

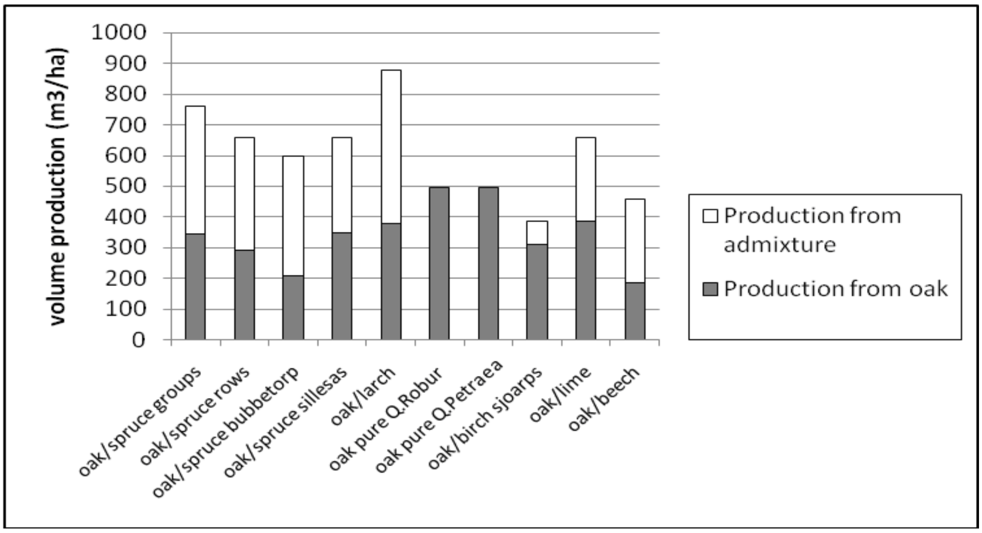

Figure 31. Simulated total volumes.

Table 6. Results of future volume growth simulations by the growth and yield model ProdMod, (Ekö 1985).

Stand	Rotation period for oak	Last admixture removed at age	Number of thinnings		Volume from thinnings, m3/ha		Volume from final-felling, m3/ha		Total yield	MAI for oak to age of 120, cm/year
			Oak	Admixture	Oak	Admixture	Oak	Admixture		
Oak/spruce groups	120	40	16	5	118	419	226	0	763	2.87
Oak/spruce rows	120	40	16	5	128	365	165	0	658	2.44
Oak/spruce Bubbetorp	120	40	9	5	29	391	179	0	599	1.73
Oak/spruce Sillesas	120	40	12	5	109	309	240	0	438	2.91
Oak/larch	120	40	15	4	150	500	228	0	878	3.15
Oak *Q. robur*	120	0	17	0	263	0	234	0	497	4.14
Oak/birch Sjöarps	120	120	13	10	84	13	226	64	387	2.58
Oak/lime	120	120	14	14	170	95	215	178	658	3.21
Oak/beech	120	120	8	14	12	144	175	127	458	1.56

3.4 Economical outcome

The stand of oak with larch had the biggest total revenue (income from thinning and final felling) - 360 600 SEK/ha (figure 32). This mixture showed 30% higher income than stands of oak with spruce. Mixture with beech had lowest income of 182 000 SEK/ha. Oak/beech stand gained two times less than monoculture. Highest profit from oak silviculture was obtained in oak monoculture stands.

Figure 33 shows regeneration costs for different planting methods. Highest costs were found in the monoculture stands (64 700 SEK/ha), lowest costs were in stands of oak with spruce (in rows and in groups) and in the stand of oak mixed with larch (40 000 SEK/ha).

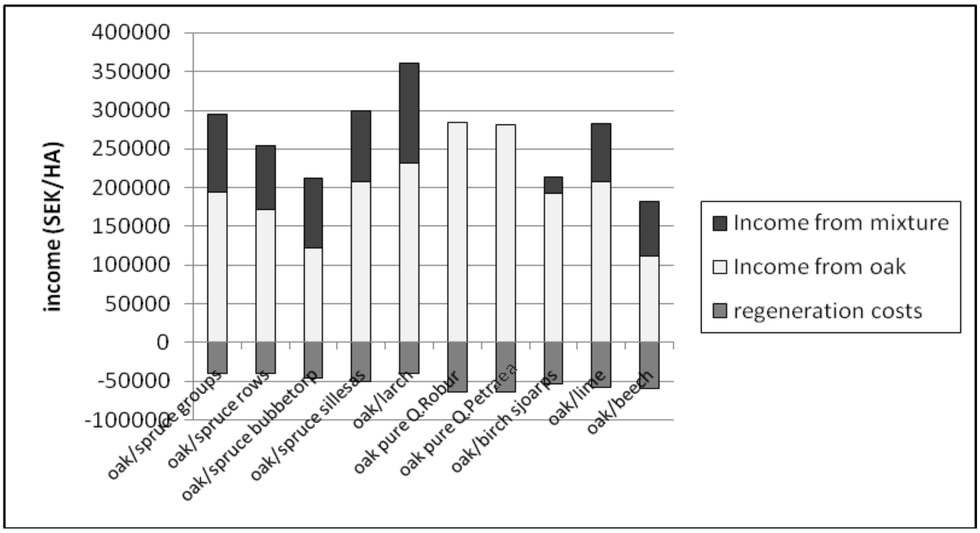

Figure 32. Costs and future incomes.

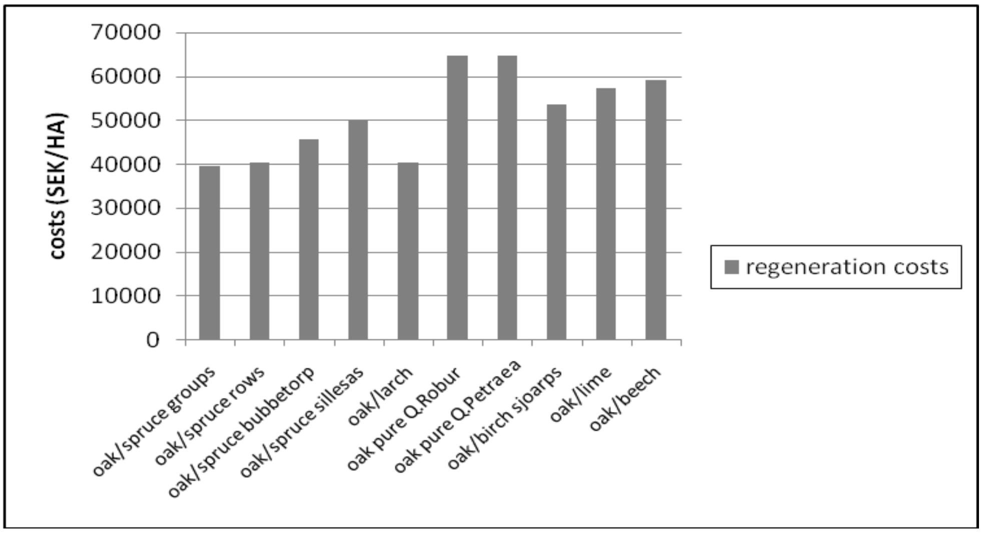

Figure 33. Regeneration costs.

Income from thinnings (Figure 34) of admixture trees gave highest revenues in the stand of oak/spruce planted in groups. Oak/spruce, the Bubbetorp and the Sillesas model, oak planted by the Sjöarps method gave lowest profit from admixture thinnings. Highest thinnings profit was gained in oak monoculture stand – 128 000 SEK/ha, while lowest was found in the oak/spruce - Bubbetorp model - 24 000 SEK/ha.

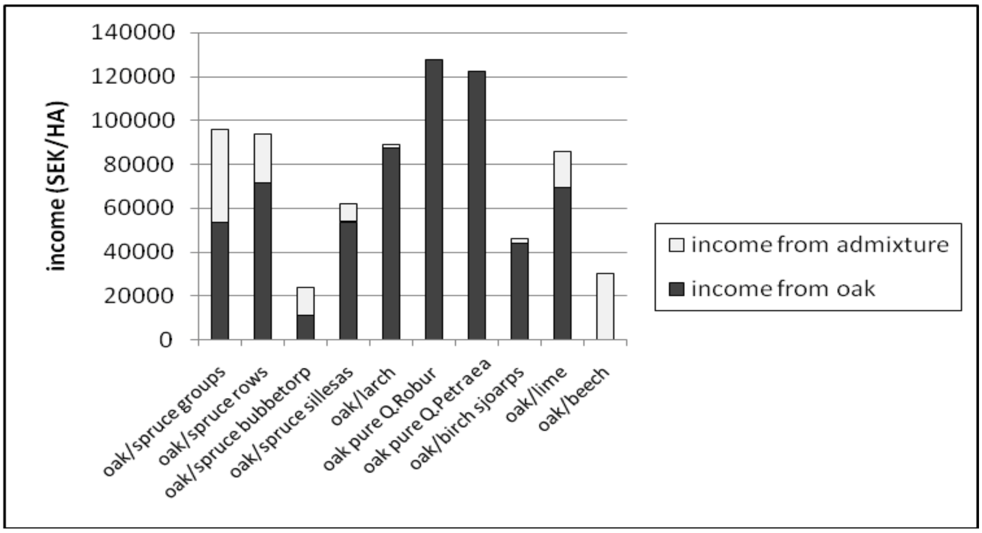

Figure 34. Income from thinnings.

Income from oak final felling varied from 97 000 SEK/ha in oak/spruce-rows stand to 160 000 SEK/ha in *Q. Petraea* monoculture stand (Figure 35). Lowest income from oak final cutting was gained in stands with admixture of spruce – planted in rows and the Bubbetorp, and the oak/beech stand. Highest total income from final felling was found in oak/larch stand (271 000 SEK/ha) and Sillesas stand (240 000 SEK/ha). Lowest revenues were gained in the oak/beech stand – 152 000 SEK/ha.

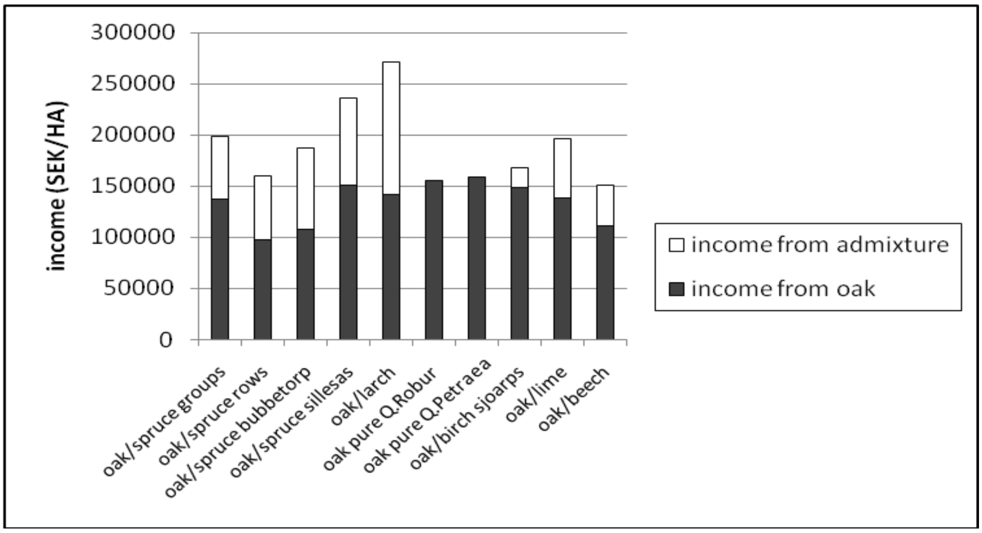

Figure 35. Income from final cutting.

Positive soil expectation values were found only in 3 stands – oak/larch; oak/spruce-groups and oak/spruce-rows (Figure 36). Maximum soil expectation value was obtained in oak/larch stand (24 011 SEK/ha). All other stands had negative values of this parameter with lowest value at oak/beech stand (-50 140 SEK/ha).

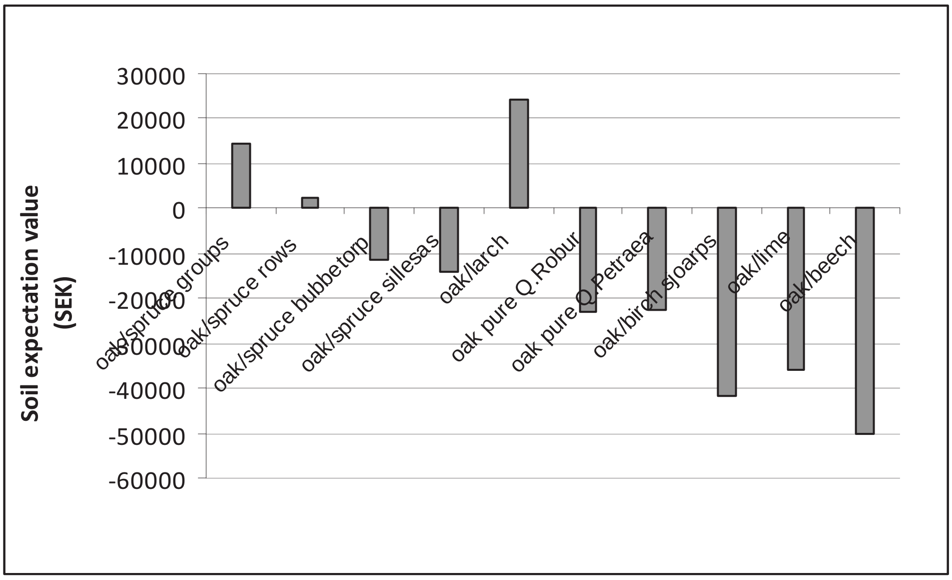

Figure 36. Soil expectation value calculated with interest rate 2,5%.

4. Discussion

4.1 Growth properties

4.1.1 Height

Average mean height for oak was 7,7 m in all stands (Figure 6). In the two monoculture stands oaks were a little bit higher. Oaks in stands with spruce had lowest height, probably due to competition.

This result is supported by Norback (1948) who mentioned that oak and spruce can grow together without significant reducing oak height growth. Mixtures of oak with broadleaves species have the same trend and it was supported by previous studies of Carbonnier (1951) who wrote that under storey of broadleaves will not negatively affect height growth for oak. Kelty (1989) also agreed with this hypothesis in his work. Biggest difference in heights was observed in comparison of height classes. Monoculture stands and stand of oak with larch had the highest proportion of potential crop oaks from 8 to 10 meters (Figure 7).

4.1.2 Diameter

Diameter will have impact on volume production and especially on the value of logs. Competition from spruces tended to decrease oaks diameter and this pattern was observed in this study (Figure 9). It was pointed in previous studies that shading species will affect negatively on diameter increment of shaded trees (Anon, 1946).

Oaks growing in monocultures and with mixture of broadleaves developed slightly better than those which were growing with conifers species. It is worth to mention that diameter today is not as important as it is 105 years until the end of rotation.

4.1.3 Volume yield

Admixture of broadleaves leads to a decrease in total production, especially in the case of the Sjöarps model. Stands with significant number of spruces and the stand of oak with larch gained the highest volume production (Figure 16). Explanation is most probably that the oaks were mixed with the fast growing conifer species which gave an additional volume production.

At an age of 15 years the highest volume yield for oak was obtained in monoculture stands. Total production was 5 times bigger in oak monoculture stands than in mixtures with conifers and stand with beech. But this information did not show the real differences in volume growth across different mixtures. We should compare stands with the same number of initially planted oaks in order to compare oaks productivity.

Average oak tree volume in monoculture was almost twice bigger than in stands with spruce (Figure 17). This could be explained by competition from spruces in mixed stands.

4.2 Quality properties

Quality properties were observed only for potential crop oaks chosen for the final felling. Almost all the properties were affected positively by planting oak with admixtures, especially with spruce. The most significant effect was noticed in the presence of defects limiting log length (best results in mixtures with spruce) and fork occurrence.

4.2.1 Epicormics problem

Epicormic branches development is considered to be a major problem of oak silviculture (Evans, 1984). Growth of old and appearance of new epicormics should be prevented by frequent pruning's. Results shows that any mixture will provide less epicormic branches than oak monoculture stand because of stem shading effect. Linden and Ekö (2002) wrote that Norway spruce would be more effective than oak in restricting the development of adventitious branches in oak.

The *Q. Robur* monoculture stand had considerable number of epicormic branches. The *Q. Petraea* monoculture stand had lower proportion of epicormics than the *Q. Robur* stand. And interesting is that stand of oak with larch had the highest amount of epicormic branches though larch was shading the oaks.

4.2.2 Crookedness

Stem data shows that mixture type did not affect on frequency of crooked oaks. In all the mixtures only about 10% of the potential crop oaks were crooked. Still, despite small differences between stands. Oak planted with broadleaves had less crooked potential crop oaks than any other stands. Oak monoculture stands had almost the same proportion of crooked potential crop oaks as in stands mixed with spruces. The oak/larch mixture had biggest number of crooked oaks – 20% of potential crop oaks. This example does not support theory that shading gives positive effect on stem properties, though it should be some explanation. From the other side in stands with big number of oaks (e.g. the oak monoculture stands) there were more oaks to use in selection and that gives a possibility to get better quality in future.

4.2.3 Stem shape and defects

Proper stem shape is essential if we are speaking about commercial timber usage. There were on average 20-30% of the potential crop oaks that had forked stems in the mixtures with conifers. All the other mixtures and monoculture stands had 40-60% of the potential crop oaks with forked stems. Presence of shading species like spruce or larch might have positive effect on oak trees stem shape. *Q. Petraea* had a better situation than *Q. Robur*. Oak with beech had 60% of forked oaks, what is absolutely inappropriate for potential crop oaks.

Situation with stem quality in general is the same: potential crop oaks with lowest results in the oak/beech stand, and best results for oaks in the mixtures with conifers. *Q. Robur* had 5% of potential crop oaks with significant number of stem defects - lower stem quality than in *Q. Petraea* monoculture stand.

4.2.4 Crown development

Crown development affects a large number of tree properties. It could be that tree will form lower number of epicormic branches if the crown is properly shaped. Highest frequency of well-formed crowns was in the monoculture stands, but those stands had medium number of trees with wide crowns, while the mixtures with spruce had biggest number of wide crowns. Mixtures of oak with another broadleaves species like lime or beech cause negative effect on potential crop oaks crown development. Oak with beech had the worst results across the stands.

In comparison with the *Q. Robur* monoculture stand, trees in the *Q. Petraea* monoculture stand had higher crown quality. Oaks mixed with larch had low number of suppressed and high number of well developed crowns. This means that larch is not shading specie, otherwise the number of suppressed crowns would be higher as it was in the stands with spruce. This also explains high proportion of trees with epicormic branches in the oak/larch stand.

4.2.5 Quality classes

All the mixtures had good results in the percentage of high quality trees – 30% of highest class (0-class) trees in average. Still, mixtures with conifers tend to increase number of highest class trees, while broadleaves admixtures decrease it. Two parameters are the most important here – the number of 0-class oaks, those oaks has a possibility to reach considerably high prices in future. Number of 2-nd class trees is also important. It shows if quality of oaks selected as crop oaks in the year 2008 has decreased by some reason.

Worst situation was observed in oak/beech stand as there were few top-class trees and significant number of bad quality oaks. This could most probably be explained with the whipping damage from the beech tops.

Mixture of conifers tends to cause positive influence on oak quality as it could be seen from the results. Possible explanation – shade from the fast growing species like spruce prevent occurrence of epicormic branches (but not in the case with larch admixture) and another stem defects.

Oak monocultures show a medium result. *Q. Petraea* monoculture had a better quality than *Q. Robur*, as there were significantly less of 2-nd class trees. This shows again that *Q. Petraea* had better quality than *Q. Robur*.

4.3 Estimations of volume yield and incomes.

The lowest total yield and also the lowest yield of oak were gained in the stand of oak planted by the Sjöarps model. Total volume yield for admixture was 20% of the total volume. On the other hand, in mixture of oak with larch admixture produced more than 55% of the total volume. This could easily be explained with the admixture specie type: in these two cases there were planted shrubs in one case and fast growing conifer species in another case. Stands with admixture of conifers accumulated highest total volumes. In all stands with conifers admixture gained at least 50% of the total volume, and it should not be set aside that all the conifers were removed already in the age at 40 years. Also it is clear that oak monoculture have stable and high oak productivity.

Regeneration costs were highest in the oak monoculture stands because of high price and the high number of oak seedlings planted per hectare. State subsidies for oak monoculture regeneration were not included. Seedlings of other broadleaves species are cheaper than oak but the price is still rather high, mixtures of oak with broadleaves had lower regeneration costs compared to oak monoculture.

The most economically beneficial solution is – to plant oak in mixture with conifers, results shows reduction of costs for almost 30% in this case. Ståål (1953) wrote that admixture would improve the economical results of growing oaks, because it will give incomes from spruce thinnings. Nordström (1956) claimed that regeneration costs will be reduced using smaller amount of expensive oak seedlings in mixtures. Both that theories were proved with economical simulations. Stands which gained less profit than monoculture stands after the final felling has less oak volume in a final stand. Explanation is that price for oak timber is high.

Lowest total revenues were gained in the stand of oak with beech. The Sjöarps model also showed rather low results, and even one stand of oak with spruce (the Bubbetorp model) was not as profitable as oak monoculture. This could be explained by the volume of oak in the stand. All the high mentioned planting methods (oak/beech, Sjöarps and Bubbetorp models) had less oak planted in the stand initially than other mixtures. The Bubbetorp model was unprofitable because there was lowest oak production in this stand (as low as in the oak/beech stand) and even profit from spruce did not change the situation.

Low income from admixture thinnings was found in stands planted by Bubbetorp, Sillesas and Sjöarps models. That is because of high percentage of admixtured broadleaved species in that stands, especially in stand of oak with admixture of broadleaved shrubs (Sjöarps model). Highest total income from thinnings was obtained in oak monoculture stands, in the oak/larch stand, the oak/lime and oak/spruce - in rows and in groups. Stands where the volume of planted oak was higher were more profitable.

Oak/spruce stands had significant profit from spruce thinnings. Income from final fellings of oak did not differ much across the stands as final number of oak trees is almost the same in each stand, except oak/spruce planted in rows and Bubbetorp model, where final number of oaks was slightly lower.

Highest total income from final felling was earned in the oak/larch stand, the oak/spruce Sillesas model and with oak planted in groups together with spruce. Final felling of admixture species in those stands gives additional profit which favors stands with conifers admixture. The stand of oak with beech admixture shows the lowest results across all the stands, income from oak cutting is low there, and there is not much profit from beech final felling.

4.4 Mixed stands management

Management in oak monocultures is generally intensive compared to spruce monocultures, requiring a greater number of thinnings and other tending operations (Linden, 2003). There are much more problems with thinnings in mixed stands, more problems with stand management. Thinnings should be arranged in proper time. Otherwise even more difficulties could arise if thinnings will be delayed or postponed.

During the field measurements the future thinning program was taken into consideration. Stands of oak mixtures with spruce had the biggest need of early thinning. As shown in this study, oaks in those mixtures had high percentage of suppressed crowns what points on necessity of thinning. The stands should be thinned at least every 5 years with big number of spruces removed. Few oaks shall be thinned as well to provide the better conditions for potential crop oaks growth. All the spruces should be removed before the age of 40 years. Otherwise strong competition from fast growing conifers will reduce volume increment in oaks. In the stand where oak is chosen as final stand trees this situation is unacceptable. In the age of 16 years, when the quality evaluation was done, stand of oak with spruce in groups had been already thinned twice. Strong necessity of thinning was mentioned in oak/spruce in rows stand. But it is clear that thinning operations arrangement is complicated in mixed stands. With dimensions increasing it become much more difficult and expensive to take away thinned trees. So that strip-roads arrangement should be elaborated. The same problem is inside of all the mixture stands.

Strip roads must be arranged in such a way to support growth of potential crop oaks. The strip roads shall not reduce the volume production and still give the possibility to carry out all the thinning operations. Each mixed stand is individual and many parameters such as trees quality, site features etc. should be taken into consideration. There were not made any considerations about strip roads in this thesis.

4.5 Total results

The overall comparison off different mixtures value is shown in Table 7. Features from each mixture were compared with the control stand of *Q. Robur* monoculture. If there were no difference in quality, mixture gained 0 points, if situation in mixture was better than in a control stand it gained 1 point and 2 points in case of significant quality improvement. And conversely, if mixture had worse quality than *Q. Robur* monoculture -1 point was taken off, and -2 points in case of severe quality reduction. Planting oak with admixture of spruce shows high results. These results completely support the idea that oaks quality is better in mixtures than in monoculture.

Mixtures with spruce planted in groups, in rows and Bubbetorp model show highest results across all the mixtures. Sillesas model and mixture of oak with larch also gives positive effects but not so significant. And all this is correct despite the fact that oak growth is slowed down due to competition in mixtures with spruce.

There were no problems like whipping damages on oaks from spruce tops. It is important that the monoculture stand of *Q. Petraea* gains few more points than *Q. Robur*. There were noticed less scars from pruning and less epicormic branches on *Q. Petraea*, as was claimed by Johnston (1956). Such a finding gives possibility to hypothesize that *Q. Petraea* has a better potential for commercial forestry. Mixture of oak with beech has unacceptable quality of the oaks.

Table 7. Overall comparison of different mixtures value (where 0= no difference for quality, += better, ++= significantly better, -= worse and --= significantly worse for quality).

Stand	Property										
	Diameter	Height	Stand volume	Limitin g defect presenc	Scars	Epicormi c branches	Crookednes s	Stem shape	Crown properties	Quality class	Total points
Oak/ spruce in groups	-	-	++	+	+	+	0	+	+	+	6
Oak/ spruce in rows	-	-	+	++	+	+	+	+	+	0	6
Oak/spruce Bubbetorp	-	-	0	++	+	++	0	+	+	+	6
Oak/spruce Sillesas	-	-	-	++	++	0	++	+	+	0	5
Oak/larch	0	0	++	++	+	-	-	+	+	0	5
Q. Robur	*Q. Robur*	*Q. Robur*	*Q. Robur*	*Q. Robur*	*Q. Robu r*	*Q. Robur*	*Q. Robur*	*Q. Robur*	*Q. Robur*	*Q. Robur*	*Q. Robur*
Q. Petraea	0	0	0	0	+	+	0	0	0	0	2
Oak/birch Sjöarps	0	0	--	0	++	0	+	+	0	+	3
Oak/lime	0	0	+	0	-	++	+	0	-	-	1
Oak/beech	+	0	-	0	-	+	+	-	-	-	-2

4.6 Benefits and drawbacks of planting mixtures

Within this study there was found a drawback of planting oak in mixtures - reducing of diameter and height growth in mixtures with spruce. This could be explained as spruce is a fast growing species and it strongly competes with young oaks.

All the mixtures, except oak with beech, show better quality than oaks growing as a monoculture stand. In case of oaks planted with another broadleaves results were not so good but still acceptable. Mixture with lime and admixture of broadleaved shrub layer in Sjöarps model gave results slightly better than in monoculture. Only oak planted with beech had poor quality, this was a worst stand observed.

4.7 Consideration for practical use

It could be told with a certainty: “Oaks should be planted in mixtures”. Planting in mixtures does not have big potential in oaks growth, but it does in stand value due to earlier incomes from spruce thinnings and higher total volume, in potential crop oaks quality. Oak growth does not play big role here, anyway total volume will be higher in the mixtures with spruce. And it should be noticed that oak height growth was not reduced significantly by spruce.

Many positive things that favor planting oak in mixtures were found from this study. The best solution is to plant it in groups with spruce. This will provide superior oaks quality; will give a possibility to receive early incomes from spruce thinning and will make planting costs cheaper. All this together will give higher total revenues than in the monocultures. Dependant on forest owner goals, oaks could be planted in mixtures with another broadleaves. The best way in this case is to plant oak with a shrub layer according to Sjöarps model, but this will work only for oaks quality, not for big total volume, revenues will be very low as well. If we are speaking about monocultures, it’s recommended to plant *Q. Petraea* as it had fewer problems with branches (including epicormics) than *Q. Robur*.

It is recommended that planting oak with beech should be avoided as it has very bad results in quality, in volumes and gained profit.

4.8 Further studies

All the results were received in the stands of only 16 years old. Estimations were done using simulations programs. It is better to make investigations through a longer period, at least for the half of rotation age. Potential crop oaks quality is at measured level today, but situation is changing with trees growing and quality level could change.

Results show that quality of potential crop oaks is better in the mixed oak-spruce stands (Table 7). From the other side competition is very high in those stands and the number of oaks is low while in oak monoculture stands there are much higher possibilities to favor good oaks. It is possible that in future situation will change and quality of potential crop oaks will be higher in oak monoculture stands.

Simulations of future incomes show that it is very profitable to plant oak with a mixture of fast growing larch. Oak quality is also high in such a mixture type. But such a hypothesis should be checked because it is not a good idea trusting only simulations. Worst situation in oak/beech stand could be also checked in a stand with few plots of such a mixture in order to receive confirmation or contradiction of received results.

Strip roads arrangement and realization of thinning operations should be investigated more carefully. This is a very important question in mixtures silviculture and it is not explored well enough yet.

4.9 Shortcomings

Snogeholm study area does not have any replications of different planting mixtures. This limit the possibilities for statistic analyze. The lack of replications is a problem as quality properties could be different in another stand planted nearby by the same planting pattern. Growth conditions are different across the study trial what also caused uncertainties.

The studied stands were young, 16 years (when crop oaks quality was evaluated) and very much can happen to quality before the time of final felling, quality can improve due to natural processes or vice versa some unpredictable damages can occur and it will affect quality negatively.

There were many problems in calculations of future volumes. Mixtures are not studied well enough and used models for growth and yield calculation works better for monoculture stands (interactions between species were not taken into account). There were no proper models for all the growing species and sometimes estimations were made approximately.

Counting incomes was based on simulated volumes. We cannot be totally sure in future trees dimensions or quality. And those factors are in a prime importance when we are calculating income from potential crop oaks, as price can vary in a great scale.

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6. Appendix

Photos taken in the Snogeholm object during the field work autumn 2009

6.1 Oak with admixture of spruce planted in groups

Photo. 1 Straight oak without branches

Photo. 2 Crown branches of wide angle

Photo. 3 Crooked stem

Photo. 4 Spike knot

6.2 Oak with admixture of spruce planted in rows

Photo. 5 Stand view

Photo. 6 Close rows of spruces and oak

Photo. 7 Crown shape

Photo. 8 Straight nice oak

6.3 Oak with admixture of spruce planted by Bubbetorp method

Photo. 9 Stand general view

Photo. 10 Crown coexistence

Photo. 11 Oak with numerous branches

Photo. 12 Straight oak stem

6.4 Oak with admixture of spruce planted by Sillesas method

Photo. 13 Stand view

Photo. 14 Oak decline signs

Photo. 15 Well developed oak

Photo. 16 Spike knot

6.5 Oak with admixture of larch

Photo. 17 Oak mixed with larch

Photo. 18 Large scar left from pruning

Photo. 19 Bark defect

Photo. 20 Numerous living epicormic branches

6.6 Oak monoculture (Q. robur)

Photo. 21 Wolf tree

Photo. 22 Significant number of epicormic branches

Photo. 23 Crown branches with wide angle

Photo. 24 Crown branches with narrow angle

6.7 Oak monoculture (Q. petraea)

Photo. 25 Q. petraea monoculture stand

Photo. 26 Perfect quality oak

Photo. 27 Oak decline

Photo. 28 Double top

6.8 Oak with admixture of broadleaves shrub species (Sjoarps method)

Photo. 29 View of oak with admixture

Photo. 30 Straight oak surrounded with admixture

Photo. 31 Oak growing with birch

Photo. 32 Good looking oak

6.9 Oak with admixture of lime

Photo. 33 Oak with lime admixture

Photo. 34 Numerous scars

Photo. 35 Crooked stem with a spike knot

Photo. 36 Significant number of branches

6.10 Oak with admixture of beech

Photo. 37 Mixture view

Photo. 38 Large scar

Photo. 39 Numerous stem defects

Photo. 40 Oak with epicormic branch and double top