Structural and demographic analysis of a multilayered forest in southern Sweden

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Master Thesis no. 231
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SLU

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Abstract

A structural and demographical analysis of a multilayered heterogeneously structured stand in southern Sweden has been conducted. The stand is characterized by an old pine overstorey where spruce and oak grow beneath out of natural regeneration. The purpose of the structural analysis was to identify differences regarding basal area, volume, tree species composition and diameter/height-distributions within two treatments, control and target diameter harvesting, which have been placed throughout the whole stand in three different blocks. In addition a development comparison between the last data collection in spring 2006 and spring 2014 was made. A later on derived future stand development was simulated to get a prediction on the future growing levels and stand composition after 50-years.

Based on the present structural analysis the diameter and height distributions inside the different treatments do not differ very much from each other. Spruce and pine clearly form the most dominant tree species in the stand, where the diameter is nearly consistent throughout all plots. Broadleaved tree species, especially oak, show higher diameters and highest increment in the target diameter harvesting treatment where the light conditions due to prior harvest interventions and wind throw seem to have the biggest influence on growth. In addition block 2 showed the largest increment for all tree species. Oak however can be found suppressed in the control, where spruce has a share of the tree species composition of 71%, and in block 3, due to high stand density. The height distribution shows a clear pattern where the pine forms the upper canopy, followed by spruce in the middle layer, followed by oak sharing the middle canopy with spruce in the target diameter harvesting plots, but forms the low canopy inside the control treatment. The derived development comparison between spring 2006 and beginning of 2014 showed an underestimation of the volume increment by 33% for the target diameter harvesting and 46% for the control treatment. The future development of the stand with Heureka showed a trend to a more even diameter distribution, which is less diverse in tree species and less structured. The original form of an uneven-aged and multilayered stand, the reversed J-shape, will almost get lost in both of the observed treatments.

An alternative that could be done to prevent this structural development is to perform a target diameter harvesting combined with a removal of some of the trees in the medium-range diameter sizes. This would grant a more diverse and multilayered structure, where also broadleaved tree species could profit, in order to enhance nature values and form a more stable stand for the future.

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1. Introduction and problem statement

1.1 Introduction

Continuous cover forestry (CCF) is a silvicultural term where the main focus lies on a stand treatment where not the whole tree population is cut at a certain tree age but in several interventions in order to create gaps and a certain vertical structure which should enhance nature values like biodiversity and natural regeneration. In addition it should also promote stability and still provide a positive financial outcome out of it. The harvesting costs are higher compared to even-aged monoculture plantations, but other advantages should not be underestimated like the better acceptance by the urban community, greater flexibility to changing markets, or simplified management in the long-term perspective (Dedrick et al. 2007). Most often the tree composition is showing multiple species which are able to interact and promote each other by just using their natural growth characteristics. These tree species compositions are e.g. oak-beech mixtures, or beech-spruce-fir mixtures in higher elevations in montane areas (Schütz 2001).

The CCF method is nowadays used in several European countries but is mainly established in Switzerland where today more than 8% of the total forest area is management under CCF and in Slovenia with 4.1% of the total forest area (Schütz 2001). CCF in Sweden has been more strongly discussed recently, but still the main management strategy here is described as a spruce or pine even-aged monoculture where the clear-cutting and the seed-tree methods are applied on 95% of the productive forest land to harvest mature stands (Anon 2002). However the societal expectations, especially close to urban areas, are changing rapidly, so that the advantages of uneven-aged multi-species ecosystems could be discussed superior to the even-aged monoculture plantations (Gadow et al. 2013). Especially in Southern Sweden and with consideration to the ongoing climate change effects, more CCF structures could be established and further analyzed especially in stands managed to enhance nature values (Andersson 2002).

One harvest method within CCF is target diameter harvesting where only those trees are cut which have reached a predefined diameter. In this way the vertical structure of a certain forest will become more diverse, because it forms gaps, and can form in the long-run multilayered structures and uneven-aged stands with a different diameter-age distribution compared to even-aged distributions. This is according to Sterba and Zingg (2001) one strategy to convert even-aged forests. The stand composition and the exposition however need to be taken into consideration when applying this form of management, especially in spruce monocultures on exposed sites, because storm damages are of a high risk to occur (Redde 2002).

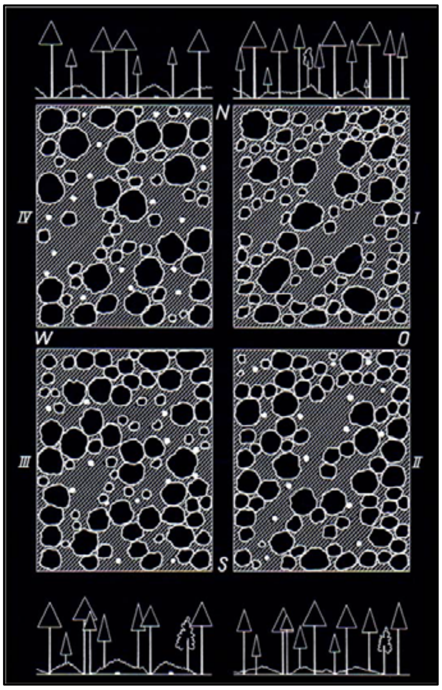
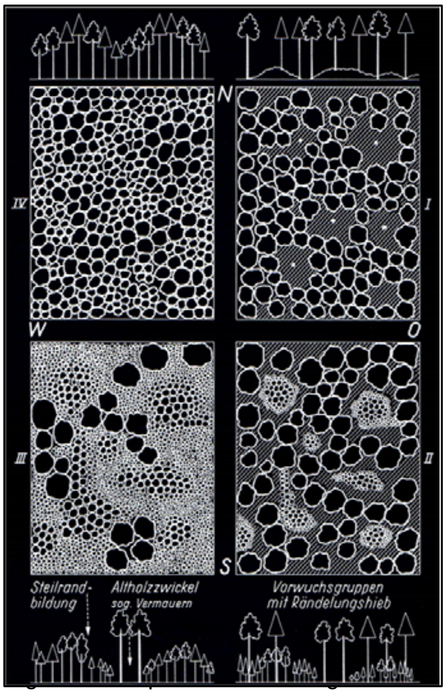


Figure 1: Sequence of a single-tree selection system. Source: Röhrig et al. (2006).

Today, the stands which are managed with the target diameter harvesting method result mainly in two different systems, the single-tree selection and shelterwood systems (Schütz 1997; Spellmann 1997). Single-tree selection systems such as a "Plenter Forest" are commonly used in Switzerland nowadays (Schütz 2001). The main advantages using this system are for example the reduced exposure of the soil, the minimization of the damage mitigated through snow and storm events, the potentially high value stem production and the different light conditions inside these stands which optimize the growing conditions especially for shade tolerant or intermediate tree species such as Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), or Silver fir (*Abies alba*) (Pommerening and Schütz 2013; Röhrig et al. 2006; Schütz 2001; Skovsgaard 2013). Figure 1 shows how such a system theoretically is designed and how tree sizes are distributed throughout different age stages (Röhrig et al. 2006). Commencing from "I" in the top right, going clockwise until "IV", the structure of the particular forest should not change much in the overall process. Trees in each diameter class will be removed in order to maintain the same equilibrium structure. Most important however is the ingrowth of the upcoming natural regeneration to be able to sustain the structure in the long term.



terwood system. (Source: Röhrig et al. (2006)

For shelterwood systems the main advantages are the flexibility to different scenarios, the enhanced volume growth, the value increase on the best trees and the use of the full site potential, mainly, after Skovsgaard (2013), the nutrient uptake (Skovsgaard 2013, pers. comm.). Figure 2 gives an overview on such a management system and its developmental stages. Beginning from the early stage in "I" in the top right a significant difference is visible going in clockwise direction until stage "IV". Selection and improvement thinnings are used here, which create an extended regeneration period which results in more diverse and heterogeneous structures in the long term. There is a high shelter effect given which promotes especially shade tolerant or intermediate species such as Silver fir and Douglas fir, mentioned in the single-tree selection system above.

1.2 Problem statement

This paper has the aim to give a present forest structure analysis of a multilayered uneven-aged pine-spruce-oak stand in Tönnersjöheden in southwest Sweden, called “Erikskööp”. The whole stand is owned by the Swedish forest company Sveaskog managed with different silvicultural treatments apart from common practice like clear-cutting or seed-tree method. The four main treatments are control, target diameter harvesting, target diameter harvesting with additional silvicultural interventions and target diameter harvesting with special consideration to nature values. The analysis focuses on two out of the four treatments, control and target diameter harvesting, since these two treatments are supposed to show the biggest difference in diameter distribution or tree species composition. In addition another interest was the development of oak in those treatments, because this tree species can substantially enhances nature values in the future and is therefore considered important (Ranius and Jansson 2000).

Furthermore a demographic analysis over the whole area will be done which shall simulate the upcoming 50 year development. The overall development of the area and especially in the two main focused treatments mentioned above will be hereby analyzed to indicate trends of forest development in order to provide forest owners with insights of how the development of similar stands could be influenced silviculturally. Also upcoming harvesting interventions will be simulated and discussed inside the target diameter harvesting treatment.

Three hypotheses were formulated for this paper:

1. There is an overall difference of 20% between measurement units in the diameter- and height distributions of the control and the target diameter harvesting treatment in 2014.

2. Based on the 50 year simulation, the future stand is characterized as more heterogeneous than today and still contains a multi-layered structure with a mixed tree species composition.

3. The simulation program Heureka gives a precise estimation of the development of the stand from 2006-2014 where the deviation from observed growth is under 10%.

2. Materials and methods

2.1 Stand description

Figure 3: Insight of the stand in Eriksköp.

The research area is located in the Tönnersjöheden experimental forest (56°42´02´´N, 13°7´56´´E, on 115 – 140 m a.s.l.) in Eriksköp in southern Sweden and is owned by the Swedish forest company Sveaskog. Characteristic for this area is the mean annual temperature of 6.7°C and the mean annual precipitation of 1050 mm which are usual values for the transition zone between the nemoral and boreal zone (Drössler et al. 2012). However, most of the area would be covered by natural broadleaf forest as the potential natural vegetation (Hickler et al. 2012). The current stand consists of a tree species composition mainly stocked with Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) where the mature *Pinus* most often forms the upper canopy, since it was planted as the first tree species on this former *Calluna* heath land in 1912. In addition other tree species such as pedunculate oak (*Quercus petraea*), European beech (*Fagus sylvatica*), silver birch (*Betula pendula*) and rowan (*Sorbus aucuparia*) are also part of the composition. The soil type is described as podzol, developed over sandy-fine sandy moraine which implies overall acid conditions and therefore suitable circumstances for the spruce. The rocky outcrop as seen in Figure 3 makes it more difficult for an establishment of natural regeneration. The site index for the stand is estimated by Hägglund (1973) as G32 which indicates 32 meters top height at a stand age of 100 years.

2.2 Stand treatments

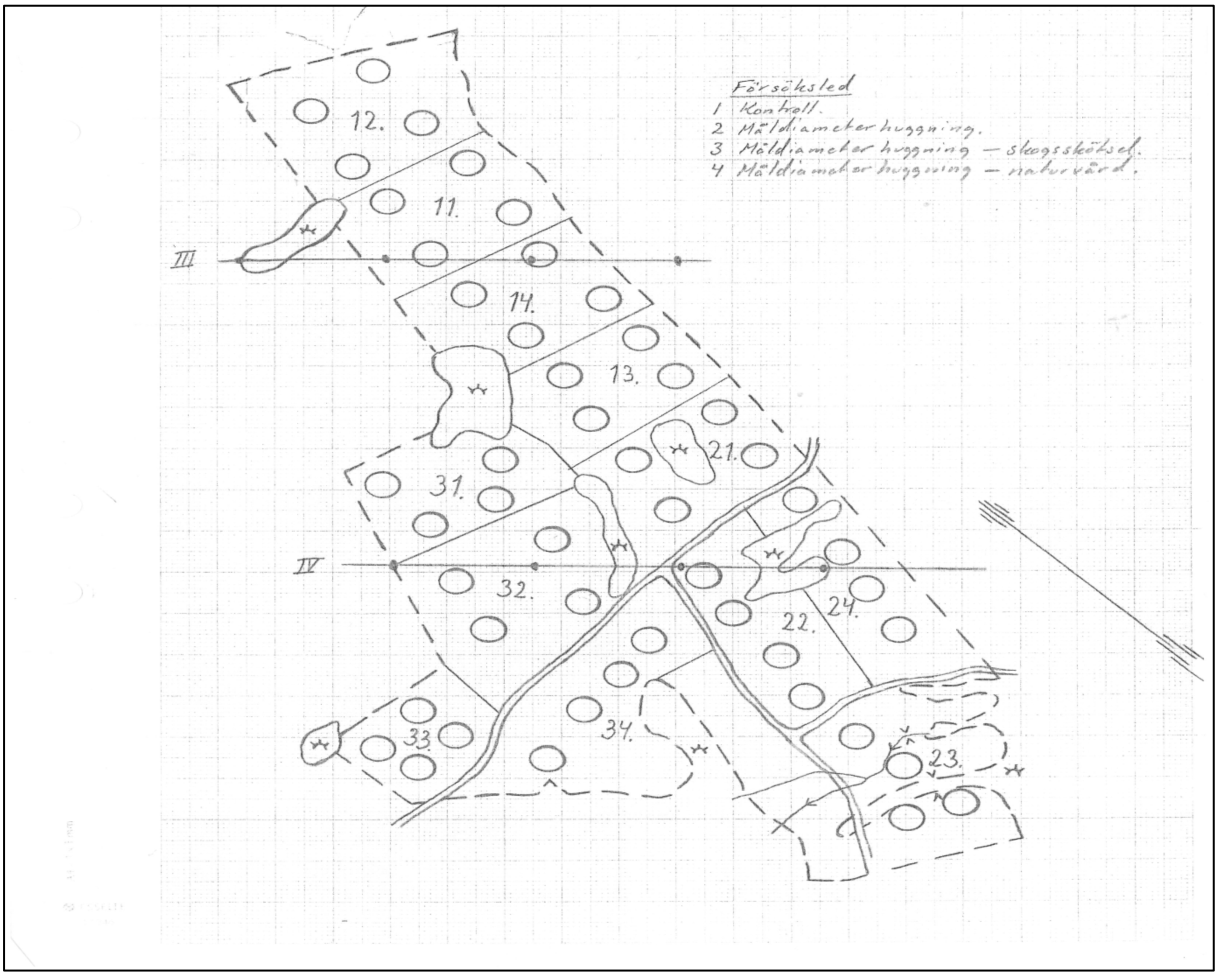


Figure 4: Drawing of the stand divided into three blocks (first digit) and four treatments (second digit; 1 – control, 2 – target diameter harvesting, 3 – Target diameter harvesting with additional silvicultural methods, 4 – Target diameter harvesting with special consideration to nature values).

The area of a total of 19 ha represents a study stand in the experimental forest where different silvicultural treatments are tested and observed in a long-term experiment (Figure 4). The stand is divided into three similar blocks with each four different treatments spread over the whole area. In each of these treatments four plots were established by using a systematic grid in order to get the whole variety of the stand structure. This gives a total of 12 plots per treatment which leads to a total number of 48 plots over the whole area (Figure 4). This gives a total of 1.51 ha of study area. The different treatments can be described as following:

1. **Control (C):** In every plot marked with “1” as the second digit the treatment was set to “no management”.
2. **Target diameter harvesting (TDH):** In every plot marked with a “2” as the second digit the trees are harvested where a specific diameter at breast height is reached. This differ from species to species (Table 1). The target diameter has been chosen with special consideration to economic criteria.
3. **Target diameter harvesting with additional silvicultural methods (TDHS):** In every plot marked with a “3” as the second digit, TDH was carried out, but additional to treatment 2 soil preparations for the new upcoming regeneration was carried out. The scarification process was done only in gaps and partly on skid trails. In addition tending of small trees can be carried out in the future. Special consideration for tending will lie on removal of wolf trees, and those with an abnormal stem form.
4. **Target diameter harvesting with special consideration to nature values (TDHN):** In every plot marked with a “4” as the second digit the diameter threshold of broadleaved species within the lower quality class (Table 1) was increased in order to enhance the nature values of the stand.

Table 1: Target diameter (in cm) of tree species according to treatment (TDH, TDHS and TDHN) and quality class q1 and q2 (class 2 describes trees with branches thicker than 6 cm, spike-knots or forks) (Source: Drössler et al, 2012).

	TDH and TDHS (cm)		**TDHN (cm)**
	q1	**q2**	
Pinus sylvestris	40	30	40
Picea abies	36	26	26
Betula pendula	30	20	30
Quercus petraea	60	30	60
Fagus sylvatica	50	30	50

2.3 Sampling methods

Each of the 48 plots was measured with a 10 m radius which gives a total of 1.51 ha as the sample size. In each plot, tree diameters from every tree thicker than 4 centimeter were taken, cross-callipered and then recorded. All plots have been pre-marked before so that the tree species and its tree number could be identified and the new diameter in 2014 was added to a spreadsheet and later on transferred to a database. Trees that have been thinned or died since the last data collection in 2006 were noticed and recorded as well. New ingrowth where the measured diameter was thicker or equal to four centimeter was recorded and added as new trees to the consecutively numbered plot. The measuring was performed mostly with a 50 cm caliper, but in case of thicker trees a measuring tape has been used.

For each of the tree species pedunculate oak, silver birch, Scots pine and Norway spruce 30 heights, distributed throughout all age classes, have been measured. A later derived logarithmic height regression for each of those species was done to complete the missing estimated height values. The aim was to create a single height curve per species for the whole stand. The amount of beech and rowan in the treatments was low enough to measure each of the individuals by hand on site. The heights were derived with a Vertex III which has been calibrated each day to make sure to receive as precise estimates as possible.

Regarding the different main tree species spruce, oak and pine in the area the specific height curve regressions (Figures 5 to 7) show a precise value, especially for spruce with R^2=0.92. Figure 5 shows the height regression of spruce, where 30 trees systematically measured throughout all diameter classes were taken to perform a logarithmic height regression. It can be seen that the spruce grows almost in a linear way despite in the lower DBH where it grows faster compared to higher ones. The variance of spruce can therefore be seen as low. The mean height of spruce is 15.3 m.

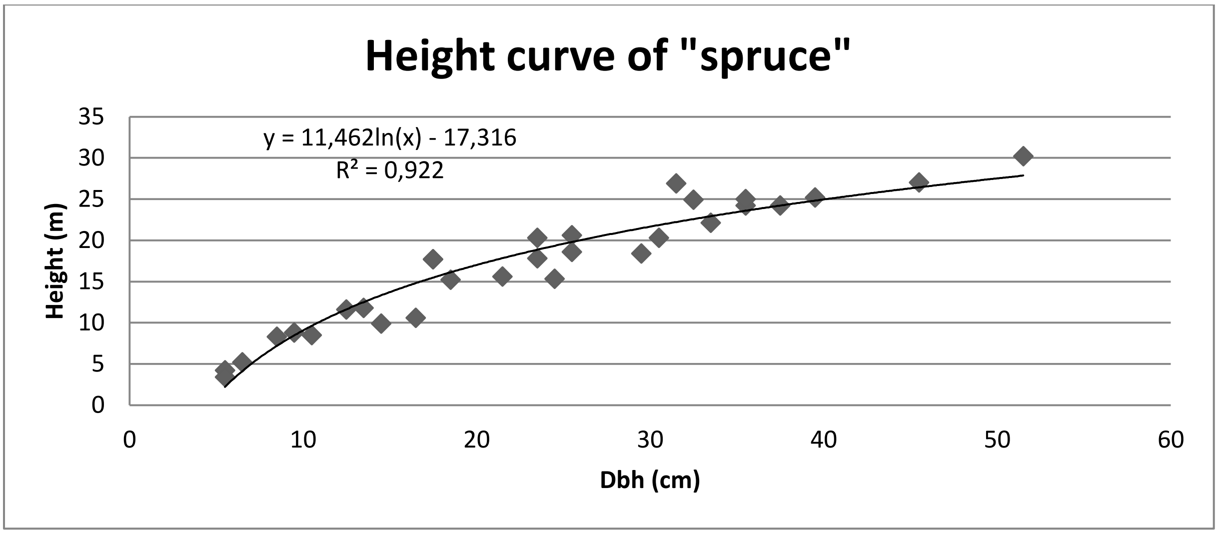


Figure 5: Height curve “spruce”.

A bit different are the circumstances with pine, where no young upcoming regeneration could be found in order to perform a more precise estimation of its height behavior. Yet the regression presented in Figure 6 resulted in estimation of R^2=0.83. The growth behavior however is not very different from the spruce, since the pine follows similar growth characteristics resulting in a slower growth above 35 cm in diameter. The mean height for pine is 22.1 m.

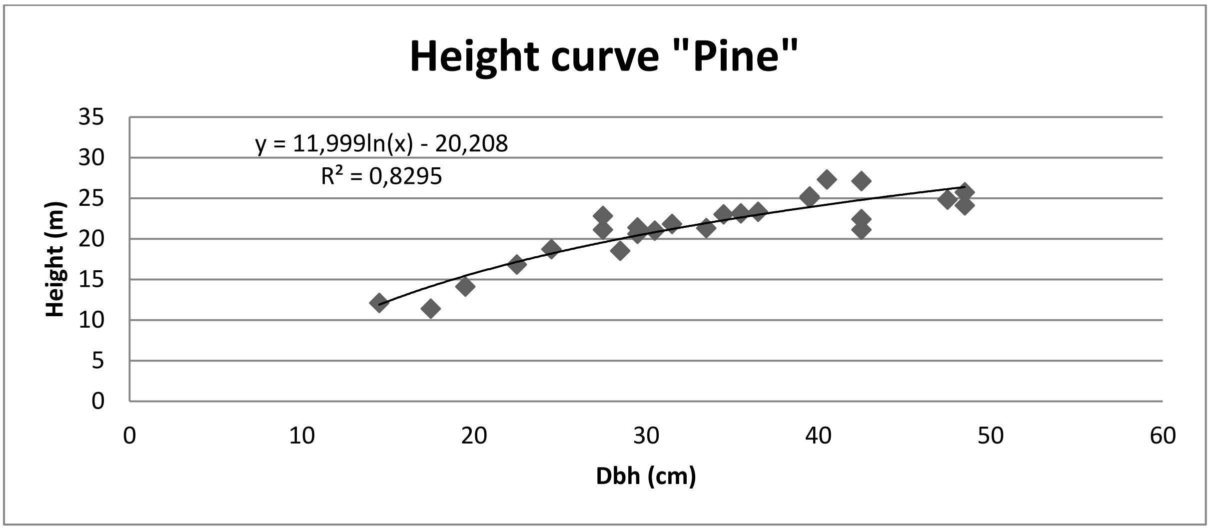


Figure 6: Height curve „pine“.

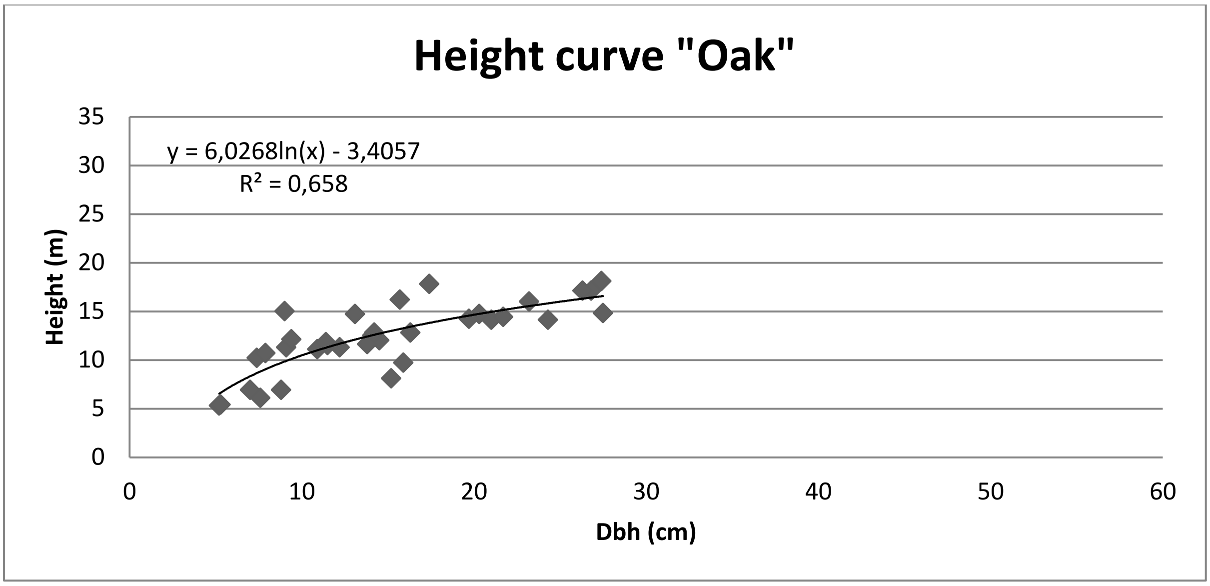


Figure 7: Height curve „oak“.

The height curve for oak has to be considered different, because it shows by far the lowest R^2-value with 0.66. Therefore the DBH-Height-ratio presented in Figure 7 does not always follow a clear pattern likewise the other species. There is a higher variance compared to the other two species visual here, which is especially true for the lower DBH values around 10 and 15 cm. The mean height of oak is 12.0 m where the highest oak is 17.3 m and the lowest oak has a height of 6.3 m. There is a large difference compared to the spruce and pine visual where the highest spruce has a height of 27.1m (32.0 m is represented by the outlier) and the highest pine shows a height of 26.6 m.

In total 1317 trees were calipered which represents 7.9% of the total area sampled in the data collection in January 2014. Kleinn et al (2011) suggests that at least 5% of the total population has to be sampled in order to lower the standard error and increase the estimated precision which therefore is given in this stand analysis.

The database derived from 2006 is available for this thesis and build the basis for the single tree increment from 2006 to 2014. Furthermore it will be used to establish height and diameter differences for the different blocks and treatments compared to 2014. The sampling methods in 2006 were equal to 2014 except the threshold for ingrowth which was 4.5 centimeter. The trees were recorded according to the tree sampling protocol of the unit of field-based research at the Southern Swedish Forest Research Center (SLU) and carried out by the professional stuff of the experimental forest in Tönnersjöheden.

2.4 Analytical methods, simulation and software

For the general stand characteristic of the observed area several key figures such as basal area in different treatments compared to the overall basal area or the diameter/height distribution in the mentioned treatments as part of the stand structure analysis are needed and will be analyzed. The development of oak trees will be analyzed within these treatments. The observed single tree growth will be calculated with the help of the database from spring 2006 and expressed by the basal area development. For the analysis and graphical presentation, MS Excel and R will be used.

The demographic development of the stand will be analyzed with the program “Heureka” developed by the Swedish University of Agricultural Sciences (SLU) (Wikström et al. 2011), where the data was imported plot-wise . Since Heureka can only show 5 year steps the calculated results will be multiplied with 8 and divided by 5 to compare simulated results with the observed growth. The chosen simulation period covers 50 years, although most reliable results can be expected for the first 20 years and without harvesting intervention (Drössler et al. 2013). It will be interesting to look especially at the increment in the control and the target diameter harvesting treatments, the development of the diameter distribution, the basal area development, volume development and the development of stems per ha. This is important to assess if there is a demographic continuity in the stand or not.

In the TDH treatment two selective thinnings will be simulated which are responding to the thinning guidelines made by the Swedish Forest Agency. According to this, the Site index G32 for Eriksköp is given where one could perform a thinning when the basal area reaches around 30 m^2/ha. It was decided to perform the first thinning after 10 years, because of a suited basal area of 32 m^2/ha and a volume reduction of 88.8 m^3/ha. The second intervention will be done after 35 years, where there will be similar conditions with a basal area of 34.3 m^2/ha and a volume reduction of 95.2 m^3/ha. The decision when to harvest was made mainly out of economic reasons.

In Heureka, it is possible to conduct a target diameter cutting, while a tree species and wood quality adapted target diameter threshold was not possible with this software. In the selective cutting, under a usage of the thinning model “HuginOld”, a fixed diameter of 36 cm has been set in order simulate the most accurate values close to the normal target diameter harvesting. The fixed diameter of 36 cm was set, because it represents the lowest target diameter for a normal grown tree of the one of the three most important tree species, which in this case is spruce.

3. Results

3.1 Stand structure for control and TDH treatments in 2014

3.1.1 Stand characteristics inside treatment “control”

In total the treatment “control” represents 12 plots which all have been re-measured in 2014. Inside this treatment no interventions were executed. Table 2 shows the stand description according to the measurements. The volume of the control treatment is 397.5 m^3/ha, where the spruce shares more than half of the total volume with 227.1 m^3/ha whereas the oak with 36 m^3/ha has only 9% of the total volume. The basal area of 43.4 m^2/ha is higher compared to the overall estimate. Species-wise the basal area of spruce with 20.8 m^2/ha and pine with 16.4 m^2/ha is higher compared to the oak with 3.3 m^2/ha. It can be seen that the spruce has with 666 trees per ha by far the highest amount of individuals which is more than double the amount of oak with 265 trees per ha. Although the oak represents the second species number-wise, its basal area is less compared to the one of pine. The d_g and d inside the control treatment show overall higher values compared to the whole area, although it has a higher stand density and basal area.

Table 2: General stand description over 12 plots of treatment “control” in Eriksköp in year 2014 with regard on volume per ha [m^3/ha], basal area per ha [m^2/ha], trees per ha (*N/ha*), diameter of the Quadratic Mean (d_g) [mm] and arithmetic diameter (d) [mm].

Tree species	**Vol [m^3/ha]**	**BA [m^2/ha]**	**N/ha**	**d_g [mm]**	**d [mm]**
Spruce	227.1	20.8	666	199	178
Pine	179.1	16.4	167	354	349
Oak	36.0	3.3	265	125	116
Beech	7.6	0.7	21	209	200
Birch	25.1	2.3	40	269	249
Aspen	-	0	0	0	0
Rowan	-	0	0	0	0
Total / Mean	**397.5**	**43.4**	**1159**	**218**	**191**

3.1.1.1 Tree species composition in treatment "control"

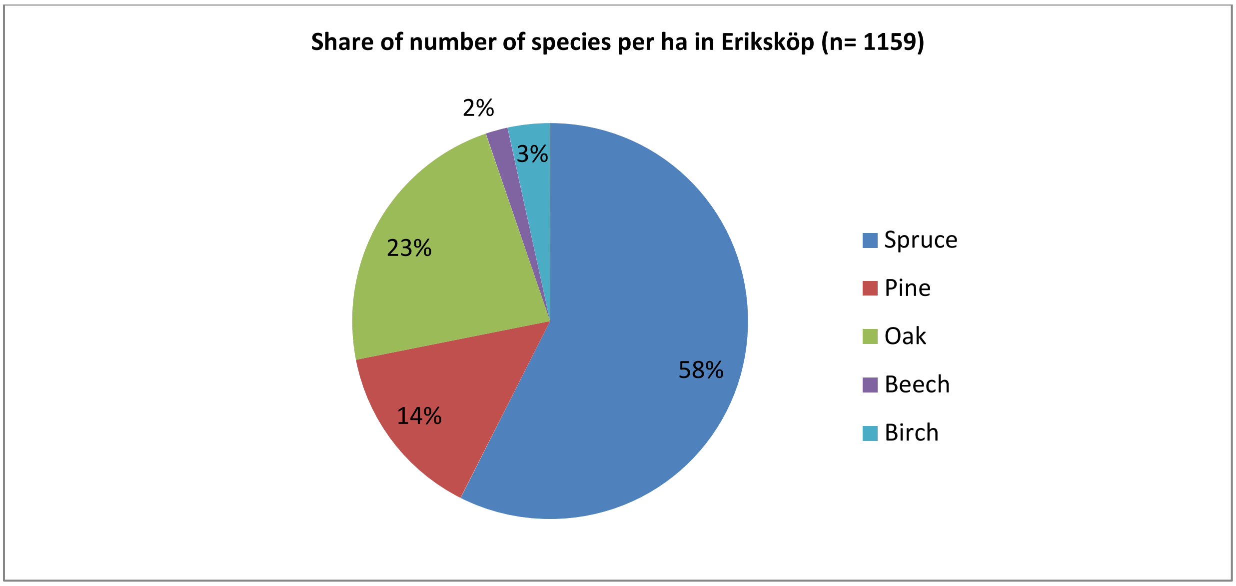


Figure 8: Tree species proportion per ha for treatment "control" in Erikskӧp.

Figure 8 shows the share of number of species per ha in Erikskӧp. The figure goes alongside together with Table 2 representing the spruce with 58% as the strongest tree species in the control treatments. The share of oak is with 23% the second highest, but regarding Figure 6 the basal area is only 7% which therefore means for a diameter distribution of oak in the lower diameter classes.

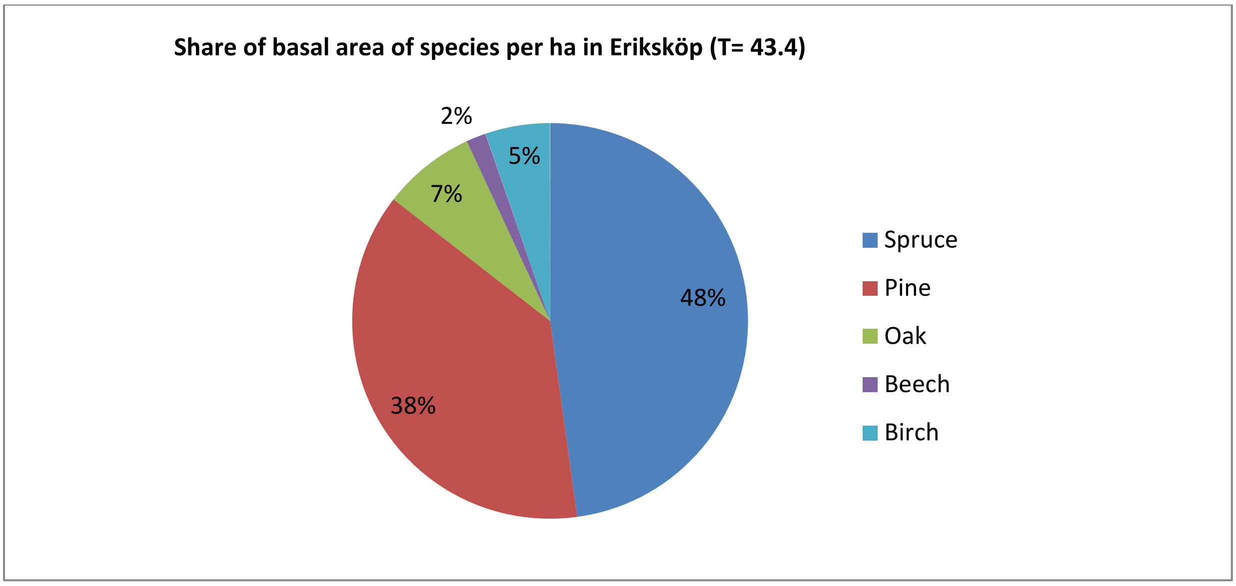


Figure 9: Basal area proportion per ha for treatment "control" in Erikskӧp.

As shown in Figure 9 the spruce and the pine represent the most dominant species with a basal area share of 48% for spruce and 38% for pine. This leaves the broadleaved species with 14% of the total basal area from where the oak shares 7% per ha. Regarding both figures the pine clearly represents the old mature trees in the control plots although it is only 14% of all trees per ha.

3.1.1.2 Diameter distribution in treatment “control”

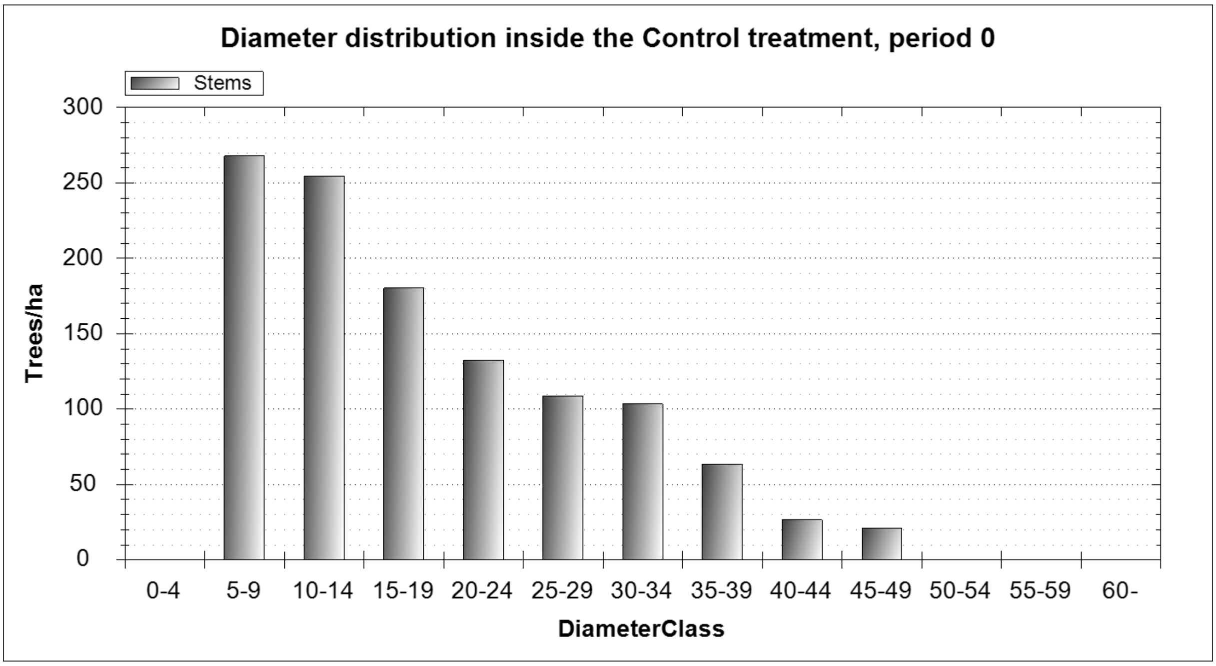


Figure 10: Diameter distribution in treatment “control” over all tree species per ha in Eriksköp in 2014.

Figure 10 shows the diameter distribution of the control treatment for all of the tree species in the 12 plots in Eriksköp. The distribution pattern here shows a stringent decrease with each diameter class, starting with the highest amount of trees in the first diameter class. Another fact is the flattened out decrease within the diameters between 20 and 35 cm. With 265 trees per ha the oak is the second strongest tree species after spruce, however its d_g of 12.5 cm is very low. This can also be seen in Figure 11, where the spruce, due to its high stem number, is representative over all diameter classes and even has more stems in the highest class compared to pine. It has a mean d_g of 19.9 cm where the main focus lies in a range between 10 and 22 cm. The oak forms the small diameters with the focus around 10 cm and the pine the large with the focus around 32 cm, where oak has its main d_g at 12.5 cm and pine at 35.4 cm.

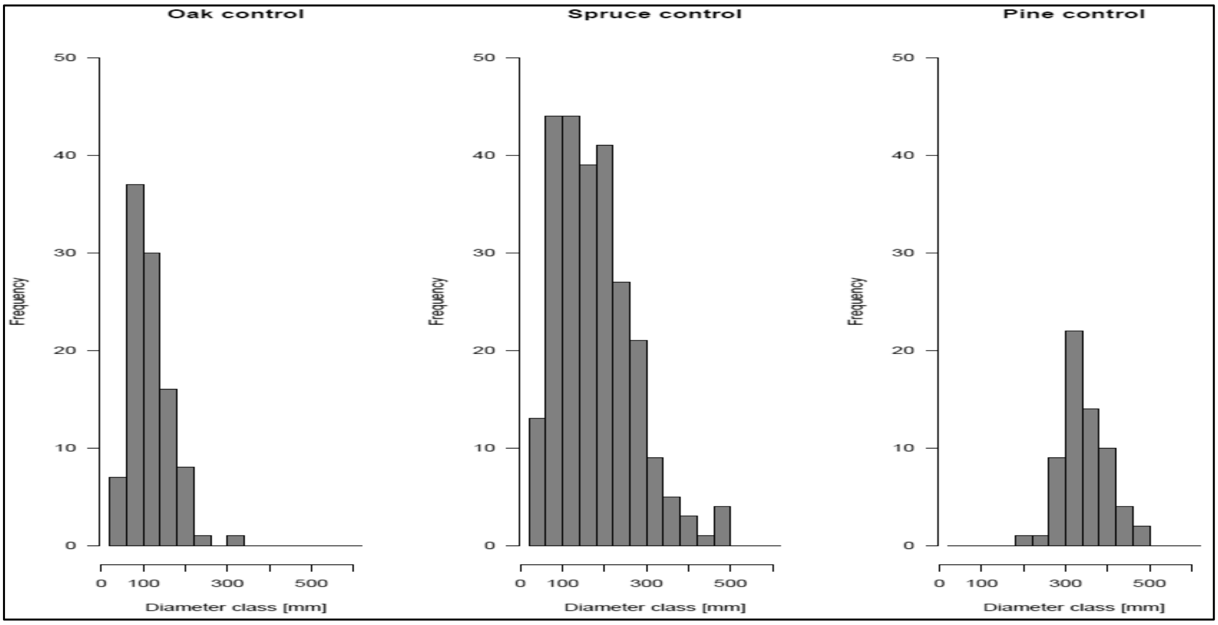


Figure 11: Specific diameter distribution in treatment “control” in Eriksköp 2014 in 4 cm classes.

3.1.1.3 Height distribution in treatment “control”

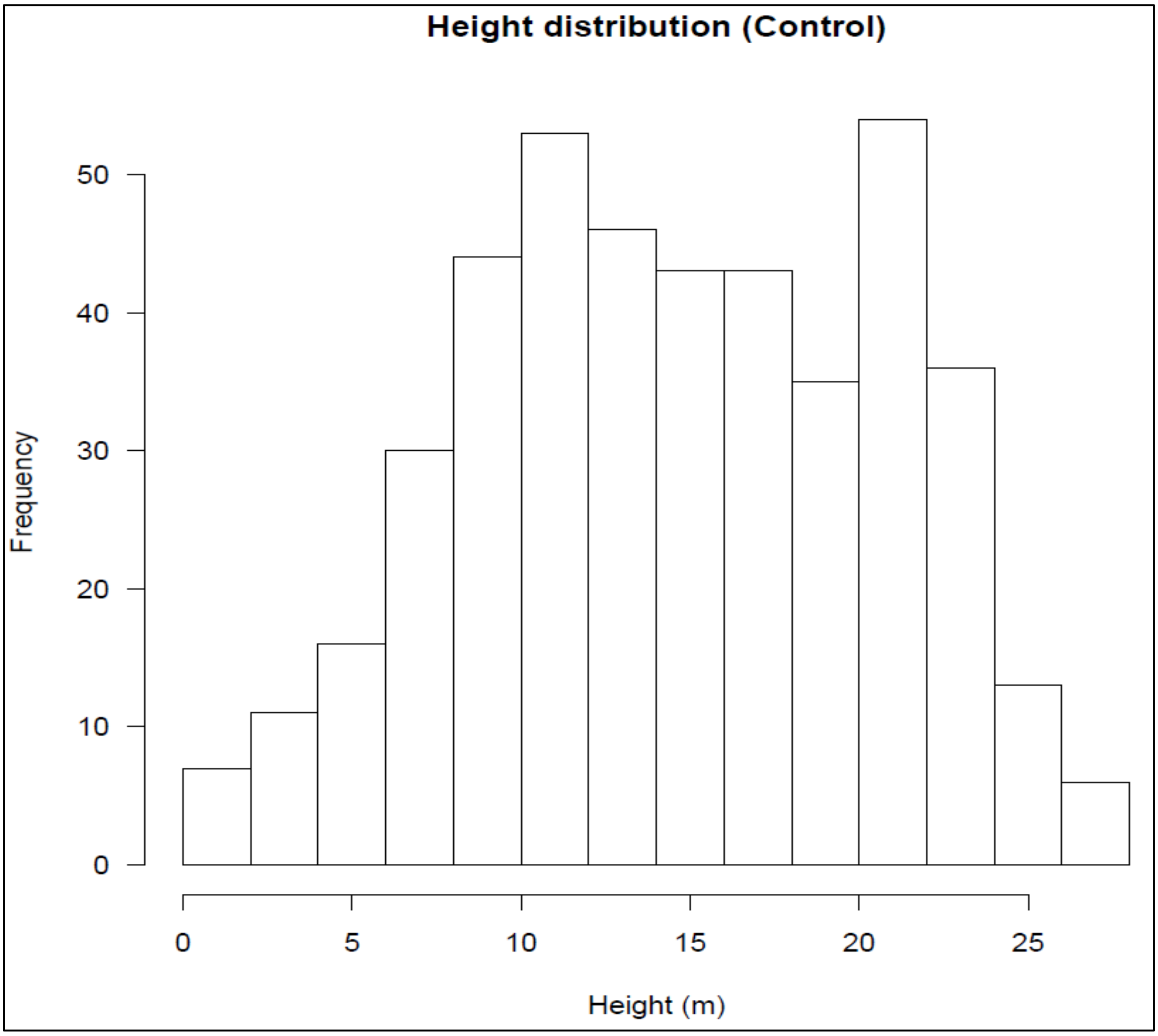


Figure 12: Histogram of the height distribution over all species in the treatment “control” in Eriksköp 2014.

The overall height distribution in the control plots in Eriksköp presented in Figure 12 shows diverse pattern, but can be compared to a normal distribution. There is a focus in taller trees, which are above 20 meters in height. The vertical structure in the control plots can be described as “diverse” since there are at least 30 observations in each height class in the range between 8 – 23 meters. This structure may vary in the different blocks though. By looking at the specific height distribution per species (Figure 13) there are considerably high differences visual. Hereby the oak represents the low canopy, with a mean height of 11.1 m. The pine forms with a mean height of 22.3 m the upper canopy together with spruce. The spruce is present over all height classes but mainly occurs in the middle canopy layer.

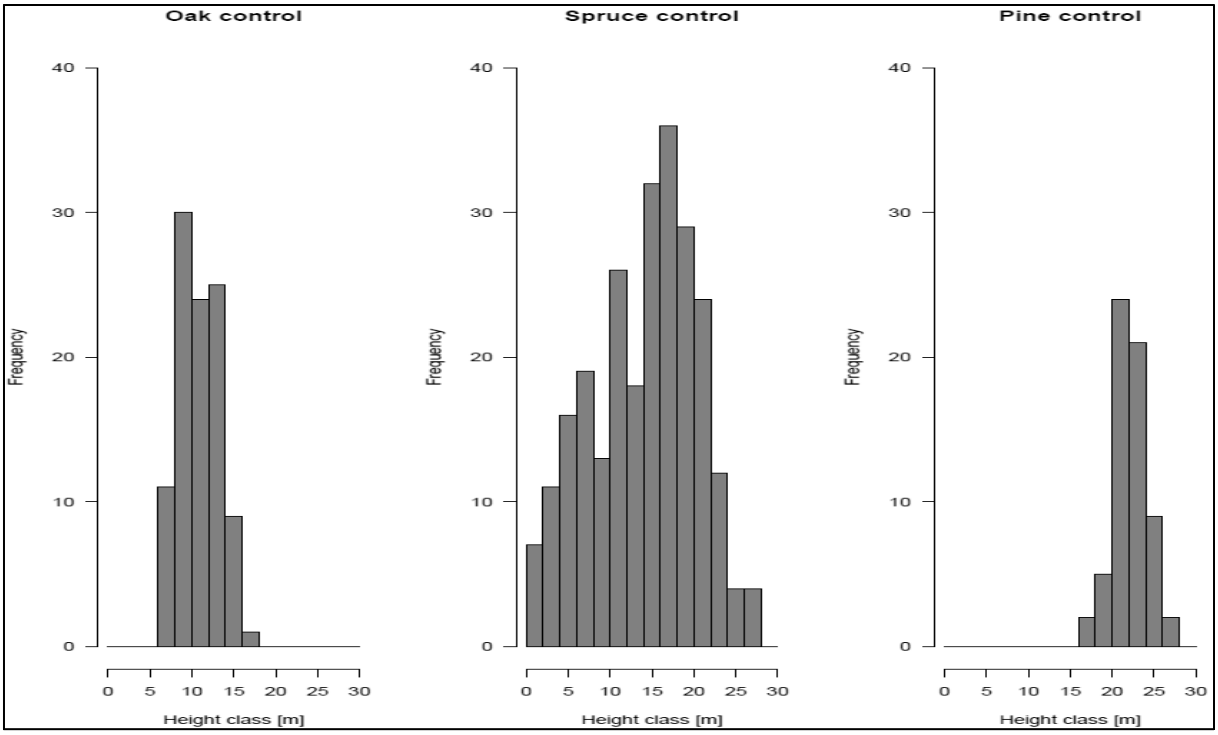


Figure 13: Specific height distribution in treatment “control” in Eriksköp 2014 in 2 m classes.

The spruce has a d_g of 19.9 cm and a mean height of 15.4 m which makes it an H/D-ratio of 77.4%. The H/D-ratio of oak with 88.8% (h= 11.1 m, d_g= 12.5 cm) is higher, but the stems are smaller with an increasing height compared to spruce. Pine in the upper canopy is often uncontested, because it is the remaining of the old stand. It can therefore increase its DBH and stop its height increment which leaves the H/D-ratio with 62.9% (h= 22.3 m, d_g= 35.4 cm).

3.2.1 Stand characteristics inside treatment "TDH"

In total the treatment "TDH" represents 12 plots which all have been re-measured in 2014. Table 3 shows the stand data derived from the field inventory in spring 2014. Comparing to the control stand characteristics (Table 2) the total basal area with 27.7 m^2/ha is considerably smaller compared to 43.4 m^2/ha overall. The oak however seems to grow in larger dimensions regarding basal area, number and diameter distribution. The oak shows a strong difference in basal area from 3.3 m^2/ha to 5.7 m^2/ha. Spruce has a lower basal area of 11.2 m^2/ha inside the TDH treatment compared to the control with 20.8 m^2/ha. The basal area of pine with 10.1 m^2/ha has also a lower value compared to the other treatments.

Also stem number and diameter differences are visual, which are about 2.5 cm in average per tree. Regarding the main tree species spruce, neither the quadratic nor the arithmetic diameters are showing large differences. The d_g is 0.6 cm smaller compared to the control treatment. The d_g of pine with 35.2 cm is 0.2 cm smaller compared to the control. The oak however has its highest d_g inside this treatment with 15.1 cm, which is even 2.6 cm higher compared to the control treatment. The mean d_g of 20.4 cm is the lowest of all the treatments, because of the other broadleaved tree species, beech and birch, which are showing considerably high difference. Beech is 3.6 cm smaller compared to the control. Birch shows by far the highest difference with even 14.9 cm difference compared to the control. The H_{100} as well as the D_{100} show slightly lower values compared to the "control" stands.

Table 3: General stand description over all 12 plots of treatment "TDH" in Eriksköp of 2014 with regard on volume per hectare [m^3/ha], basal area per hectare [m^2/ha], trees per hectare (*N/ha*), diameter of the Quadratic Mean (d_g) [mm] and arithmetic diameter (d) [mm].

Tree species	Vol [m^3/ha]	BA [m^2/ha]	N/ha	d_g [mm]	d [mm]
Spruce	126.9	11.2	382	193	177
Pine	114.5	10.1	103	352	347
Oak	64.6	5.7	318	151	141
Beech	4.5	0.4	16	173	152
Birch	3.4	0.3	27	120	114
Aspen	-	0	0	0	0
Rowan	-	0.05	3	148	148
Total	**244.4**	**27.7**	**849**	**204**	**182**

3.2.1.1 Tree species composition in treatment “TDH”

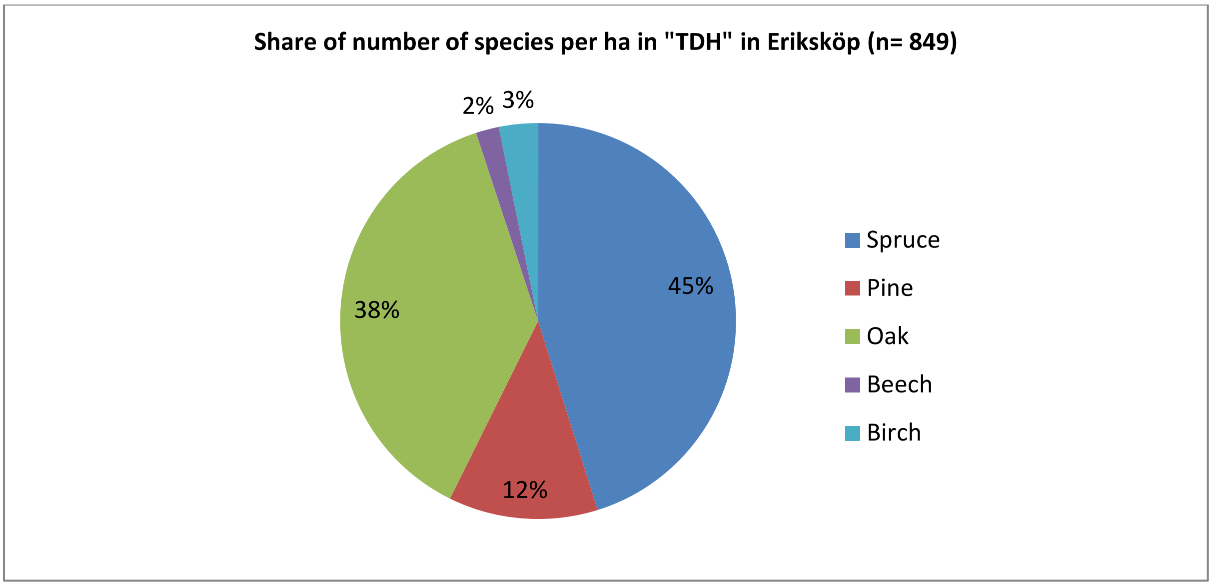


Figure 14: Tree species proportion per ha in “TDH” in Eriksköp (n= total number of observations).

In Figure 14 the proportion of tree species in stem number per ha is presented. Again, spruce is the most common tree species with a share of 45% of the total composition. This is however a smaller share compared to the control treatment where the oak is now more frequent. A similar result is also shown in Figure 15, where the basal area of oak shows a share of 21% of the total stand, which is three times more, compared to the control. The pine shows no considerable differences compared to the other treatments. Spruce loses some of its basal area share, but is still the tree species with the largest basal area inside the TDH treatment. The beech as well as the birch loses some of their share to the basal area compared to the treatments.

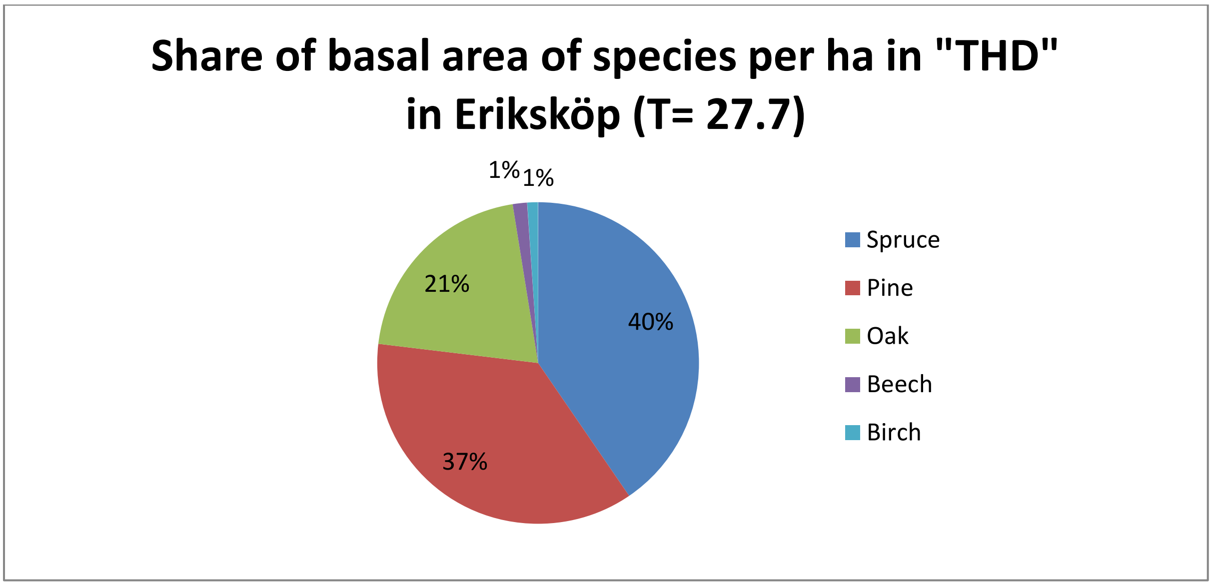


Figure 15: Basal area proportion of tree species per ha in “TDH” in Eriksköp (T= total basal area).

3.2.1.2 Diameter distribution in treatment “TDH”

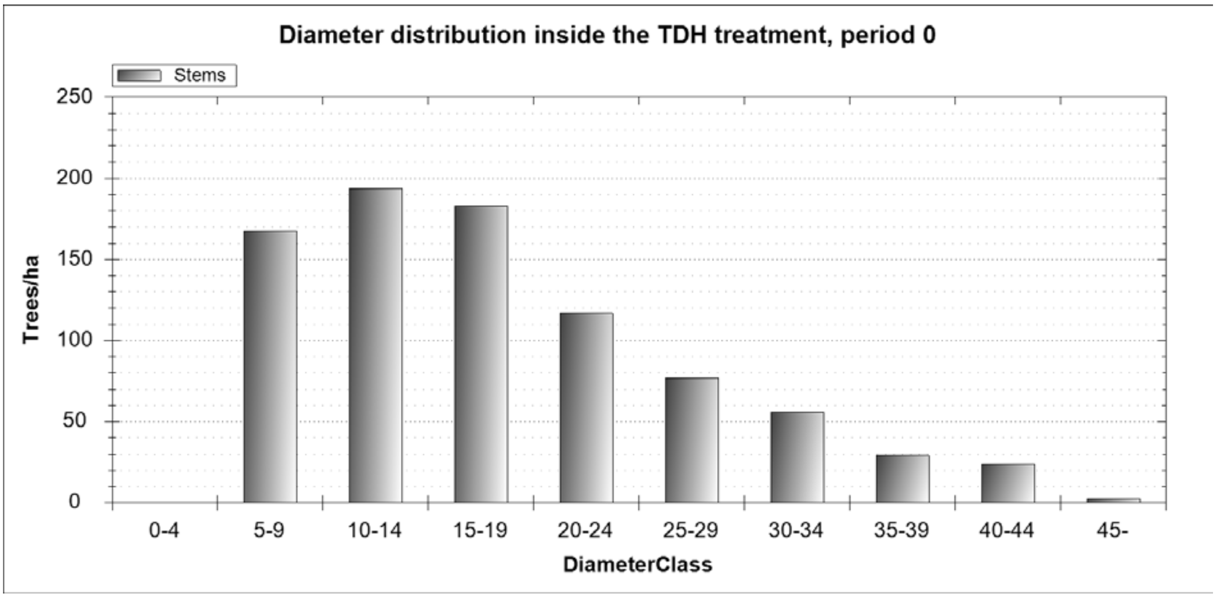


Figure 16: Histogram of the diameter distribution in treatment “TDH” over all tree species in Eriksköp 2014.

The diameter distribution for all species in the TDH treatment is very similar compared to the control diameter distribution (Figure 16). Most of the trees are present in the lower diameter classes but have the peak in the second class. From then on it consistently decreases in number into the next larger class. Additionally it can be seen that not all trees, which should be harvested according to the last thinning in 2008, have been cut, since the target diameter has already been reached. Again, like in the other treatment, the upper diameters are formed by the old pine trees as shown in Figure 17 with a mean d_g of 35.2 cm. One difference compared to the “control” treatment is that the oak reaches into the middle diameter classes with a d_g of 15.1 cm together with spruce with a d_g of 19.3 cm. Spruce however still reaches towards the larger diameter classes and is then replaced by pine.

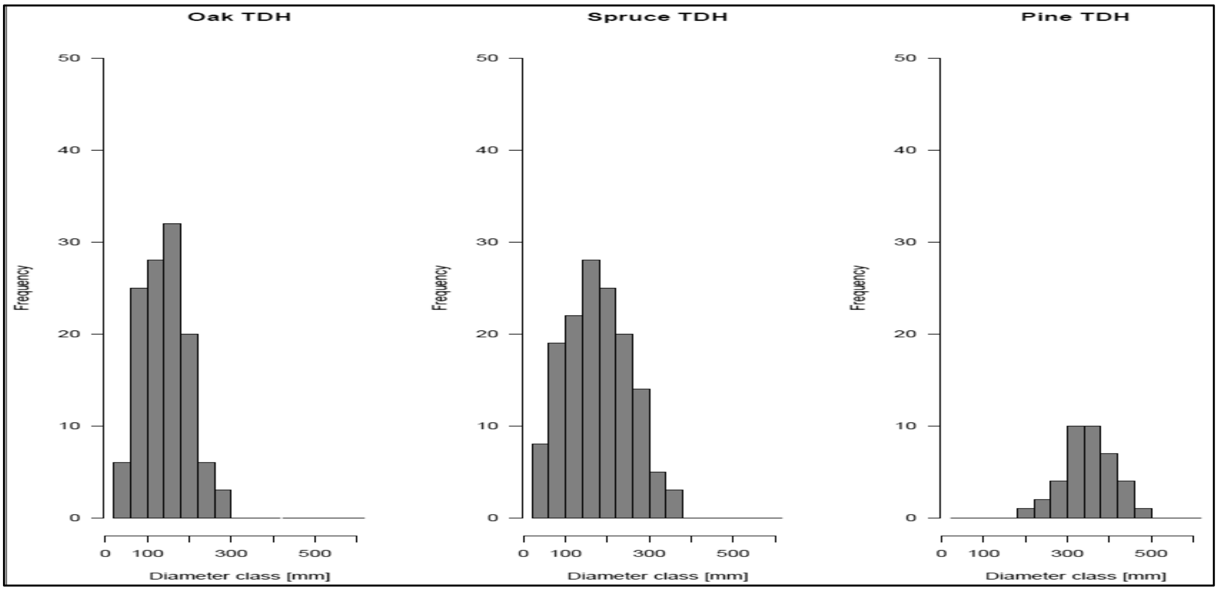


Figure 17: Specific diameter distribution in treatment “TDH” in Erikskӧp 2014 in 4 cm classes.

3.2.1.3 Height distribution in treatment “TDH”

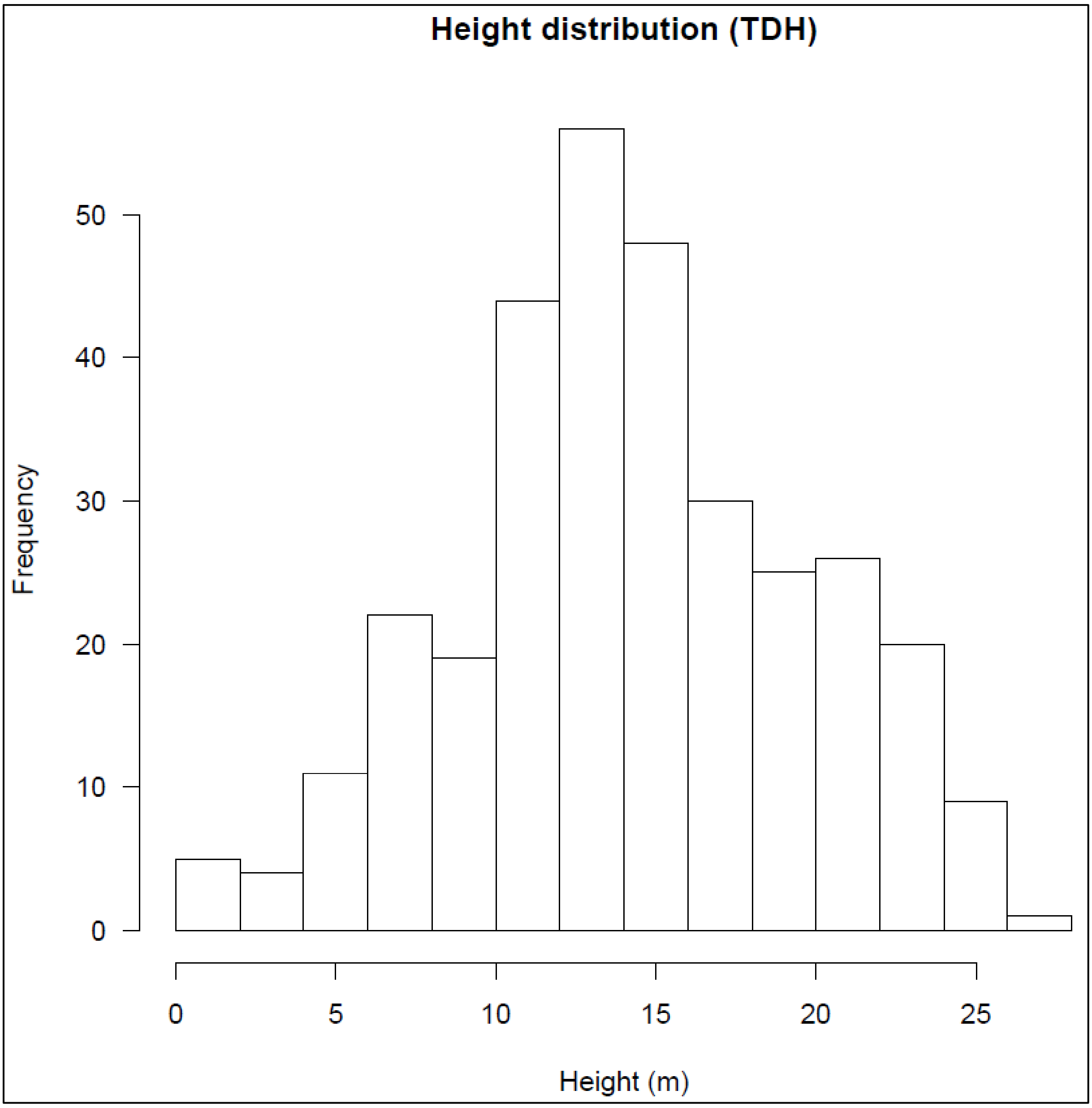


Figure 18: Histogram of the height distribution over all tree species in treatment “TDH” in Erikskӧp 2014.

The height distribution in the TDH treatment it is more even distributed compared to the other treatments (Figure 18). A clear focus here is on heights between 10 and 15 meters, whereas in the control treatment the height distributions are more uneven. Regarding the specific heights shown in Figure 19 the oak represents a dense distribution from 6.5 to 17.1 m, but with a clear focus and the peak at around 14 m. Spruce is again present throughout all height classes, but shares the middle canopy together with oak. The trees here are in general higher compared to the control treatment. The upper canopy is formed by pine and spruce where spruce is present in the lowest and upper height layers.

In the TDH treatment the spruce achieves a mean d_g of 19.3 cm and a mean height of 15.4 m, which results in an H/D-ratio of 79.7%. Furthermore the oak with its mean d_g of 15.1 cm and its mean height of 12.3 m forms an H/D-ratio of 81.5% and is higher compared to the control treatment. The H/D-ratio of pine is 63.4%.

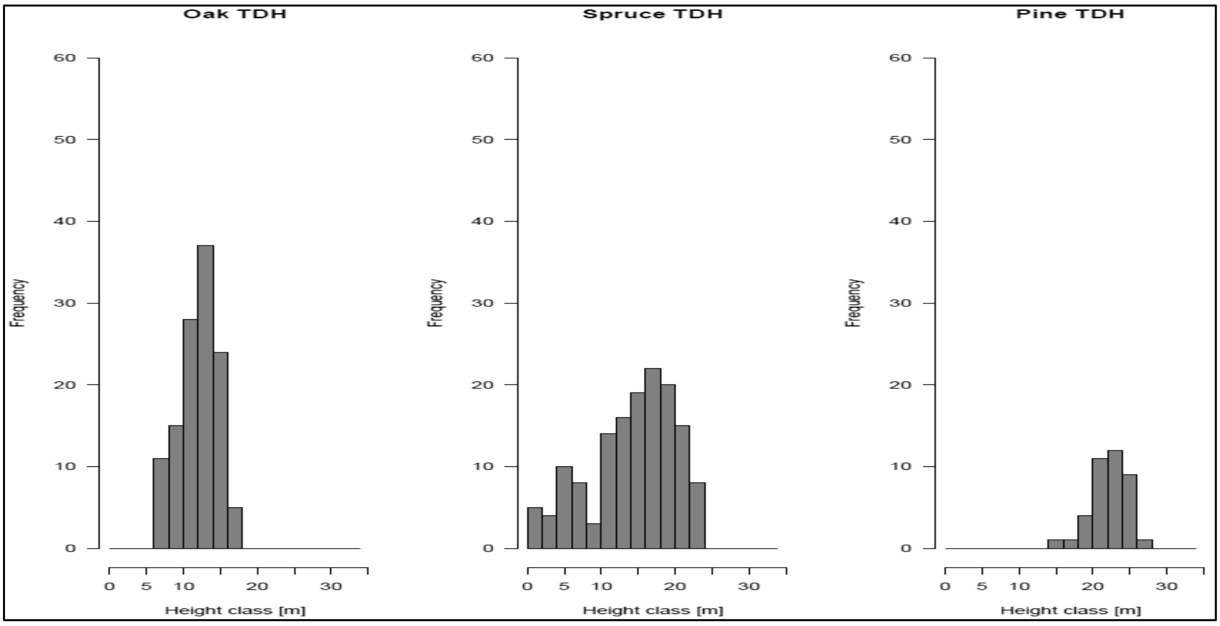


Figure 19: Specific height distribution in treatment “TDH” in Eriksköp 2014 in 2 m classes.

3.3 Development comparison between treatments "control" and "TDH" since spring 2006

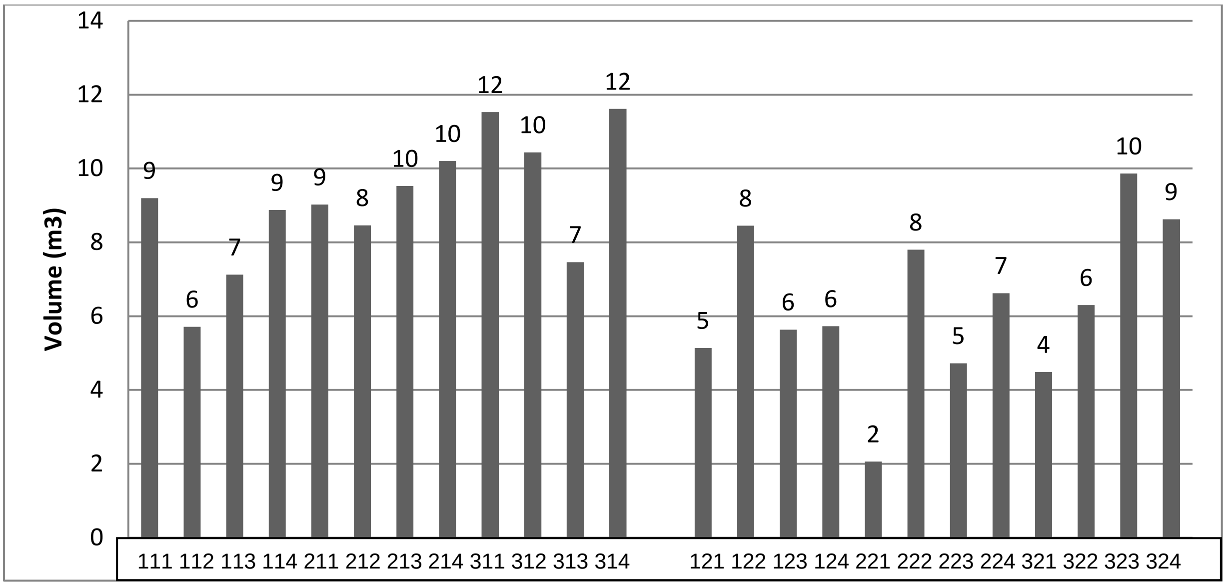


Figure 20: Volume increment per plot per year (blue: control; red: TDH) in m^3 from winter 2006 to 2014.

The mean observed volume increment was 9.5 m^3/ha and year for the control treatment. The volume development of the two observed treatments shows a different pattern (Figure 20). Overall the highest increment values for the control can be found in block 3 with 12 m^3 per year for plot 311 and plot 314, which represent the highest tree number, whereas plot 112 and 113 present the lowest volume increment with 6 m^3 and 7 m^3 equal to the lowest number of tree species, like oak and beech.

The mean observed volume increment for the TDH treatment was 8 m^3/ha and year. The highest volume increment numbers can also be found in block 3 with values of 10 m^3 for plot number 323 and 9 m^3 for plot number 324 which are also representing the largest tree number. What attracts attention however is the low volume increment of 2 m^3 for plot 221. Inside this plot the tree number of 12 trees is very low and where the mixture of tree species only consists of oak and spruce.

The predicted value for the MAI per year by Heureka, using a corrected value by a stand growth function, resulted in 5.3 m^3/ha and year for the TDH treatment and 5.1 m^3/ha and year for the control treatment. A deviation of 33% for the TDH and 46% for the control treatment is therefore given.

In order to make an adequate comparison between the two different treatments, control and TDH, in Eriksköp it is interesting to compare different increment values derived from the last data collection in spring 2006. Therefore, Table 4 shows the total increment within the two treatments, but also the increment per block to give an insight of different growing levels. Overall the mean increment per tree is higher in the TDH treatments compared to the control treatment. It can also be seen that block 2 has the highest increment with 3.4 cm per tree over all tree species, but also the highest regarding TDH (3.6 cm) and control (2.8 cm). Block 3 shows the lowest increment with per tree in average with 2.6 cm over all tree species and also the lowest in TDH (3.0 cm) and control (1.6 cm). Block 1 appears to have the closest increment to the average.

Table 4: Comparison between treatment control and TDH over basal area per ha [m^2/ha], trees per ha (N/ha) and the increment in total and in the three different blocks per tree [mm] between 2006 and 2014.

Treatment	**BA [m^2/ha]**	**N/ha**	***i*** Total mean	***i*** Block 1 [mm]	***i*** Block 2 [mm]	***i*** Block 3 [mm]
Control	43.4	1159	23	26	28	16
TDH	27.7	849	33	33	36	30
Total (4 treatments)	30.9	874	22	28	34	26

Furthermore it is important to see which of the main tree species has the highest increment and in which block each species shows the best result. Figure 21 shows the related results for the diameter increment of the different tree species in Eriksköp from spring 2006 – 2014.

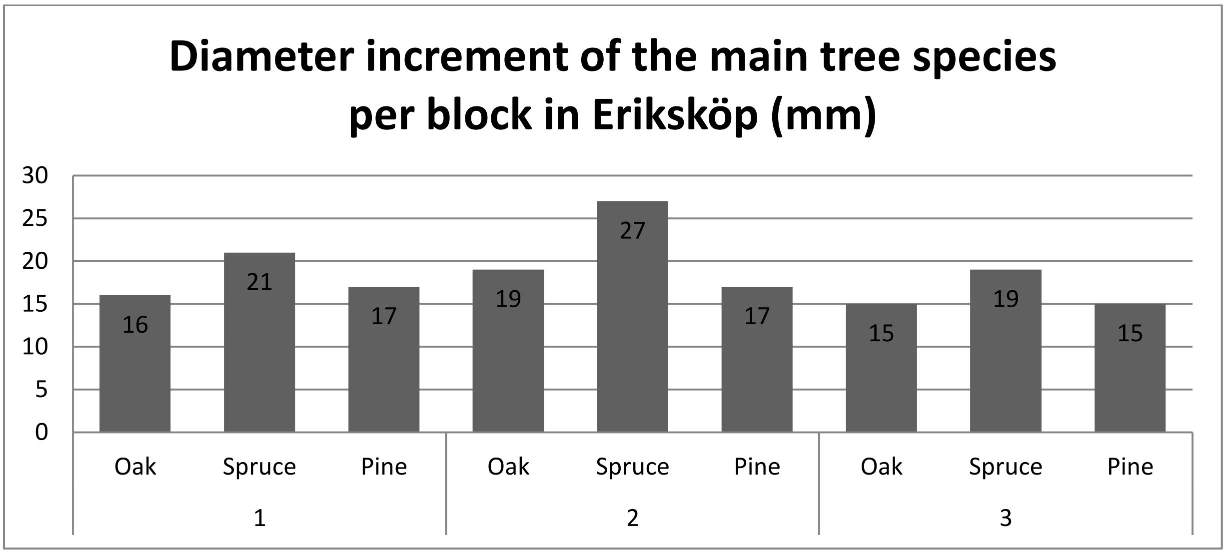


Figure 21: Diameter increment of the different main tree species in Eriksköp spring 2006 – 2014 divided by blocks.

As a result it can be said, that the oak has a similar diameter increment than pine. It is even slightly higher as the increment in block 2 with 1.9 cm compared to pine. The spruce shows the best result with a peak in block 2 of 2.7 cm within eight years. As the values of Table 4 already presume, the highest overall increment shows block 2 with 3.3 cm. These values can be seen a bit relative however, because block 2 has by far the lowest amount of measured trees with a total number of 395, whereas in block 1 the numbers are 493 and in block 3 are 429 measured trees. The overall lowest increment values are presented in block 3 with 2.4 cm diameter increment. Still the spruce is with 1.9 cm the tree species with the highest increment in block 3.

Regarding the increment of the single plots which can be seen in Figure 21 there are some considerably high differences visually. There are 24 values available for all of the plots in the control and the TDH treatment.

The control treatment is showing the lowest values of 1.1 cm, 1.2 cm and 1.7 cm which are all presented in block 3 inside the control treatment. Inside those plots with low values there is a high density and a high amount of spruce with a share of more than 90% over those plots. The broadleaved tree species inside those plots are showing the lowest diameter increment and only spruces in the medium to big diameter classes showing strong diameter increment. The plots with the highest diameter increment 2.7 cm, 2.9 cm and 3.4 cm are presented in Block 1 and Block 2, where the highest increments can be found only on spruce, which are in a diameter range between 16 and 26 cm. However, in Block 1 also oak and beech in the medium range diameters are showing good increment numbers.

In general the TDH treatment consists of higher diameter increment values compared to the control treatment. The differences of the plots are not considerably high compared to the control, but showing high differences between each other. The plots with the highest diameter increment can be found in block 2 and 3 with 4.3 cm, 4.2 cm and 3.3 cm. Here the highest increment values are mostly presented by spruce from a diameter of 25 cm onwards. In the plots with an average of 42 cm, represented in block 2, the highest increment values are from broadleaved tree species, especially oak, where the highest increment is found on medium range diameters above 20 cm. Apart from the highest diameter all other values are very similar to each other. In general the most growing tree species cannot be identified, since oak, beech and spruce showing almost the same pattern. Pine is the only tree species, which performs weakest overall. However, there is a tendency in increasing diameter increment for broadleaved tree species over spruce in block 1 and 2.

3.4 Future development of the stand

The forest management program Heureka can simulate the future development of a certain stand. The general stand characteristics like basal area, volume and stems per ha development are showing the biggest differences between the TDH and control treatment.

3.4.1 Basal area development

There are considerably high differences visual between the control and the TDH treatments regarding the basal area (Figure 23).

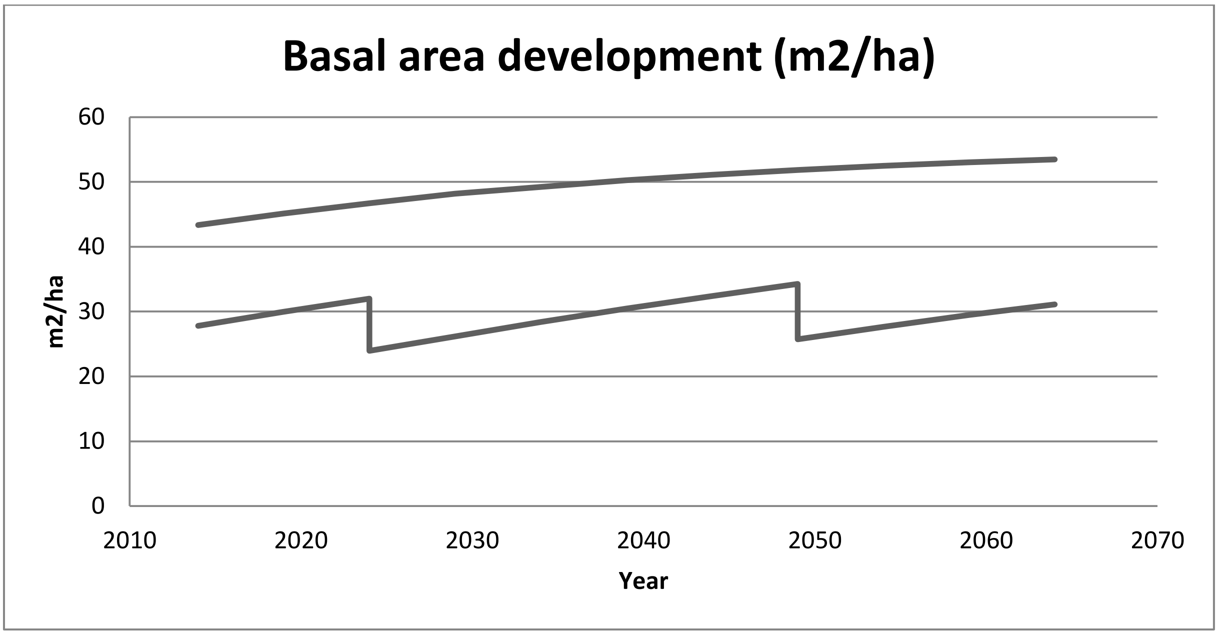


Figure 22: 50-year basal area development of the control (top) and the TDH treatment (bottom) in Erikskröp.

According to Heureka the development inside the control treatment is consistent. From a current basal area of 43.4 m^2/ha the development of the control goes gradually towards a basal area of 53.5 m^2/ha after 50 years.

The development after the TDH treatment performs another trend. Two selective thinning interventions were applied where the first one is after 10 years, removing the basal area from 32 m^2/ha to 24 m^2/ha and the second follows after another 25 years, where the basal area will be removed from 34.3 m^2/ha to 25.8 m^2/ha. Concluded, the basal area development does not differ much, starting from a current basal area of 27.8 m^2/ha and finishing at 31.1 m^2/ha after 50 years. If there would be no interventions taking place in the TDH treatment, the basal area development would also show, likewise the control, a steady increase to 44.2 m^2/ha after 50 years. Comparing with the control treatment the basal area inside the TDH treatment is 42% lower in the end.

Species-wise the basal area development shows a clear pattern. Spruce will increase its basal area starting from 11.2 m^2/ha in 2014 to 16.6 m^2/ha after 50 years. The basal area will rise strongest shortly after each thinning intervention. Oak also increases its basal area from 5.7 m^2/ha to 11.9 m^2/ha which does not drop after the thinnings. Pine however losses almost all of its basal area starting from 10.2 m^2/ha to 1.6 m^2/ha.

3.4.2 Volume development

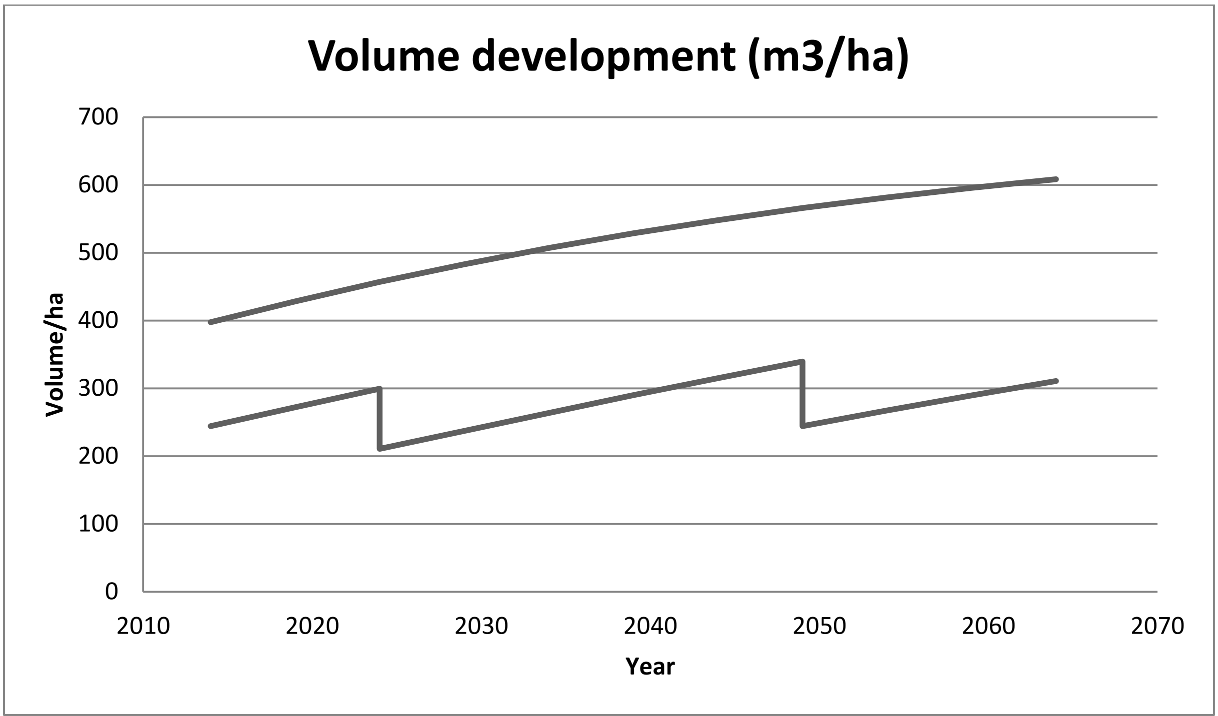


Figure 23: 50-year volume development of the control (top) and the TDH treatment (bottom) in Eriksköp.

The volume increment also shows a gradually and steady development inside the control treatment. With a current volume of 398 m^3/ha per ha the volume will continue to grow to 609 m^3/ha after the 50 year period as seen in Figure 24. This is an increase of 53.1%. The overall volume that will fall out due to mortality is 150 m^3/ha after 50 years. The upcoming ingrowth is, after Heureka, fully stocked by spruce. Regarding the mean annual increment (MAI) of the volume per species inside the control treatment the spruce has the highest mean value with 3 m^3/ha and year whereas the increment in the first 25 years is higher with 3.3 m^3/ha/year. The oak shows a MAI of 0.47 m^3/ha and year.

For the TDH treatment the standing volume develops from 244m^3/ha to 479 m^3/ha when no interventions would be conducted, which is an increase of 96.3%. As there will be two selective thinning interventions being conducted inside the TDH treatment the volume is changing. The total volume will change from 244 m^3/ha to 311 m^3/ha. By decreasing the basal area as seen in Figure 35 the volume will reduced by 89 m^3/ha from 299 to 211 m^3/ha in the first intervention and then, 30 years later, reduced by 95 m^3/ha from 340 to 245 m^3/ha. The MAI per tree species inside the TDH treatment shows a mean growth for spruce of 2.7 m^3/ha and year, for oak of 1.2 m^3/ha and year and for pine of 1.2 m^3/ha and year. The overall volume that will fall out due to mortality is 28 m^3/ha after 50 years.

The mean annual increment (MAI) inside both treatments however differs from each other. The net MAI for the control treatment decreases continuously from 6.2 m^3/ha per year to 4.2 m^3/ha per year, whereas inside the TDH treatment it decreases from 5.5 m^3/ha per year to 5.0 m^3/ha per year. It shows a higher production inside the TDH treatment compared to the control.

Financially, after Heureka, the total cost, including forwarding and harvesting of the TDH treatment accounts for 9'066 SEK for the first and 9'796 SEK for the second treatment. The net revenue however was indicated by 28'138 SEK for the first and 28'197 SEK for the second intervention.

3.4.3 Stem number development

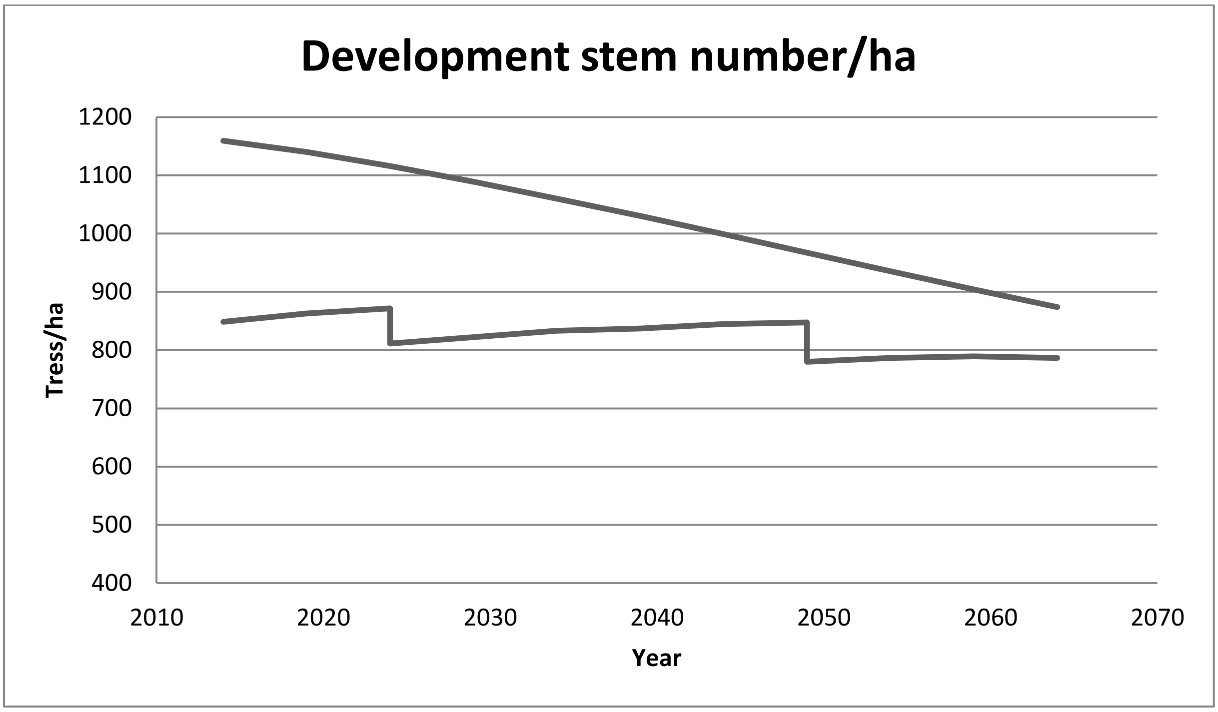


Figure 24: 50-year tree number development of the control (top) and the TDH treatment (bottom) in Erikskֶöp.

The development of the trees per ha inside the control and TDH treatments are decreasing due to mortality in the control treatment and due to mortality plus thinning interventions in the TDH treatment as seen in Figure 25.

For the control treatment the decline in trees due to mortality is 1159 to 874 trees per ha. The average mortality is 9 trees per ha per year which is equal to 3 m^3/ha and year whereas the amount of dead trees will slightly increase in the second half of the simulation period where there is a mortality average of 10 trees per ha and year compared to 8 trees per ha and year in the first 25 years. Species-wise oak has a mortality with ¼ (8 stems) of all stems that die after the first period and then continuously stay around the same value of 1 to 2 trees per ha and year. The mortality of spruce however shows a continuous increase from 5 stems per ha and year to 6 stems per ha and year after 50 years, which is half of all mortality. Pine and birch have rather low mortality with an average of 1 trees per ha and year that will fall out.

The development of the TDH treatment is more complex due to the two selective thinning interventions. The overall reduction of trees per ha accounts from 849 to 787 stems, from which an average of 19 trees per ha and period (187 stems total) is natural mortality and 129 stems result in losses due to the thinning interventions. The first conducted thinning intervention after 10 years will result in a stem removal of 61, from 872 to 811 stems. Over the upcoming 25 years the average tree ingrowth is predicted to be 1 to 2 trees per ha and year where the ingrowth is highest in the first 10 years after the first thinning with an average of almost 3 trees per ha and year. Likewise the control treatment, the ingrowth will mainly be formed by spruce. The second conducted thinning intervention after 35 years results in a stem removal of 68 stems, from 848 to 780. The stem number increase after this shows almost the same pattern, such as the last thinning, with a slow steady increase in stem number of 1 stem per ha and year again shortly after the thinning and after 50 years a slight decrease in stem number of 2 stem per ha and period from 789 to 787.

The natural mortality inside the TDH treatment is 3 to 4 stems per ha and year after 10 years up to 4 to 5 stems per ha and year after 50 years. The mortality decreases after each selective thinning intervention from 4 stems to 3 stems per ha and year for the first and stays at the same level of 4 stems per year and ha for the second intervention. The overall mortality of oak is smaller inside the TDH treatment compared to the control with an average of 8 trees per year per five-year period falling out before the first intervention. The mean mortality of oak between the two selective thinnings is 7 trees per ha per period and after the second one it stays at the same level at 7. The mortality of oak therefore results in a total loss in volume of 10.76 m^3/ha and a loss in basal area of 1.5 m^2/ha. The spruce shows a similar development in mortality likewise the control treatment where a small mortality with 5 stems per period and ha after the first five-year period and half of all mortality with 11 stems per period and ha out of 21 in total after 50 years was predicted. Therefore the total volume loss due to spruce accounts for 18.9 m^3/ha and a basal area loss of 1.9 m^2/ha. The natural mortality for pine and birch does not differ much with an average of 1 stems per period and ha falling out, where beech is with 3 stems over the whole 50-year period not a value to consider within the natural mortality.

3.4.4 Diameter distribution curve development

The diameter distribution for all tree species inside control and target diameter was simulated for the upcoming 50 years. The results for the final diameter distribution after the 50-year period can be found in Figure 26 for the control and 29 for the TDH.

3.4.4.1 Diameter distribution development inside "Control"

For the control treatment the change in the diameter distribution compared to the present stage of 2014 (cf. Figure 10) is big. As seen in Figure 26 the diameter classes after 50 years are more evenly distributed throughout the whole area, still with a peak in between 10 to 20 cm, but with less than 100 stems per ha compared to 2014 for the first diameter classes. The regeneration in the smallest diameter classes is 2.5 times less compared to 2014, where the stems in the larger diameter classes have more than double the amount of stems per ha. The stand is more homogeneous compared to the present stage in 2014 in general, but still follows pattern of the decreasing number of trees into the next larger diameter class. After Heureka the diameter distribution for the different tree species experienced the same increasing percentage of d_g-development, leaving the same distribution of tree species as mentioned in chapter 3.1.1.2.

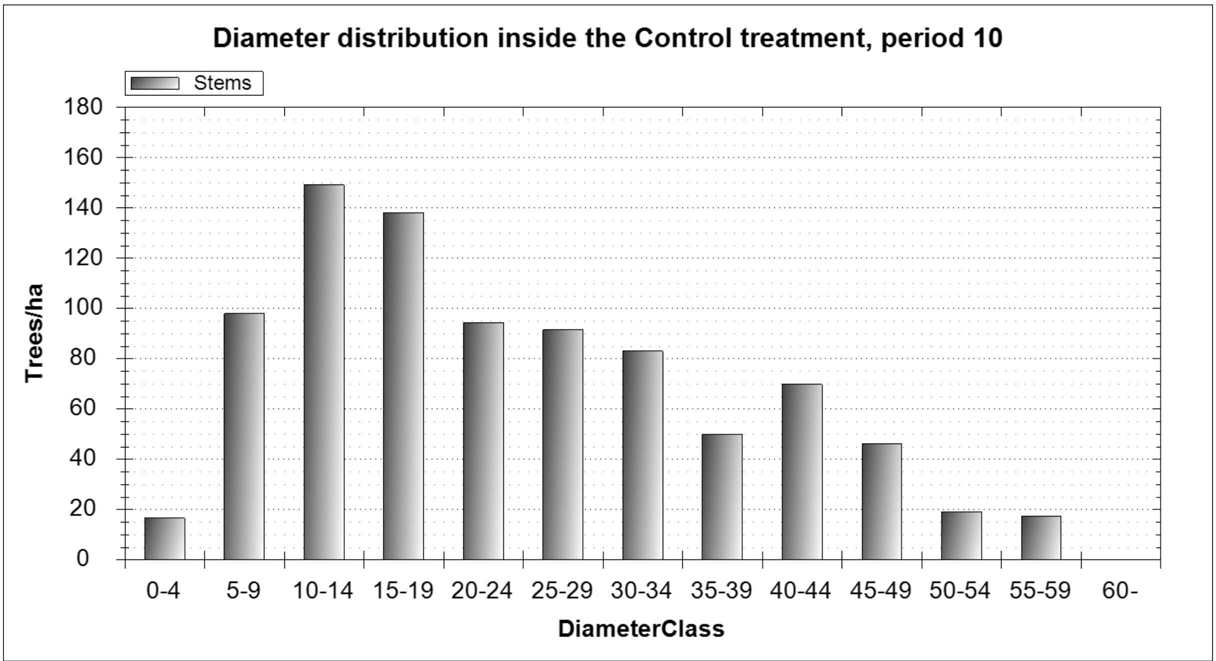


Figure 25: Diameter distribution in treatment "control" over all tree species per ha in Eriksköp after the 50-year period.

3.4.4.2 Diameter distribution development inside "TDH"

For the TDH treatment the diameter distribution can be shown in several steps to visualize the present status before each of the two selective thinning interventions. Figure 27 shows the diameter distribution for all trees right before the first conducted selective thinning after 10 years, where 88.8 m^3/ha from the upper diameter classes above 36 cm will be taken out. It can be seen that the amount of the lower diameter classes are still fairly even compared to the present status of 2014. The amount of trees above the target diameter of 36 cm will be completely harvested. As already mentioned in chapter 3.4.1 the decrease of the number of trees in the diameter classes is mainly due to the cutting of old pine and spruce, where especially pine loses most basal area. The d_g per species prior the first intervention shows are decrease of pine from 36.8 cm to 34.4 cm and a slight increase for oak (18.1 cm to 20 cm) and spruce (23.6 cm to 24.4 cm), which does not change much based on the analyzed diameter structure in chapter 3.2.1.2.

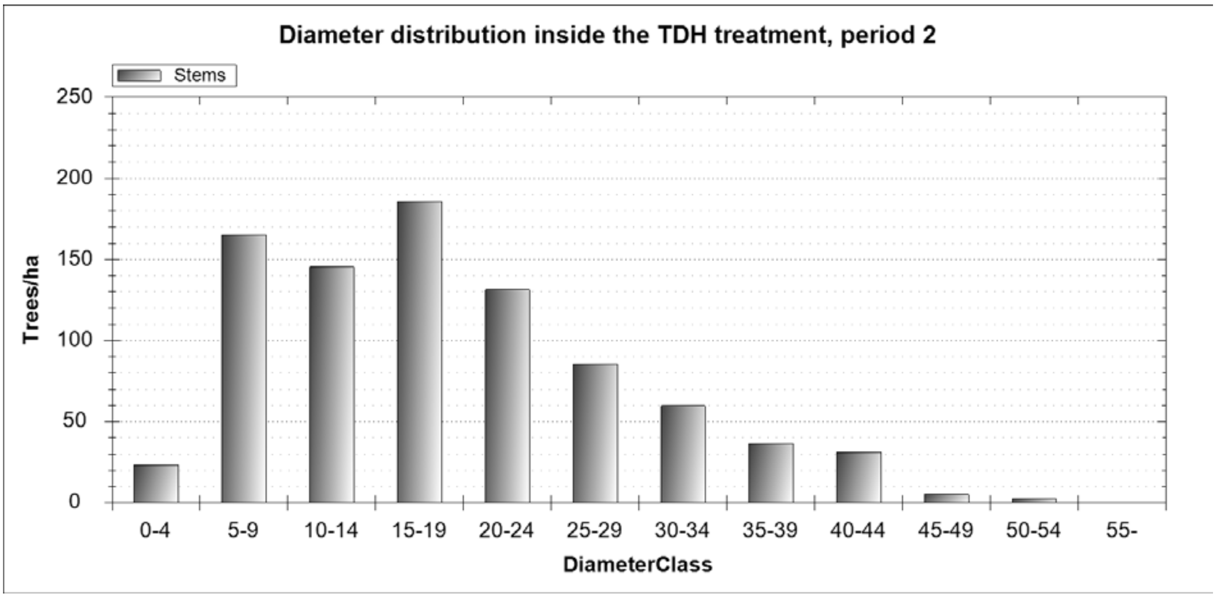


Figure 26: Diameter distribution in treatment “TDH” over all tree species per ha in Eriksköp before the first selective thinning intervention after 10 years.

One of the largest differences of the diameter distribution presented before the second selective thinning intervention after 35 years (Figure 28) compared to the first selective thinning intervention after 10 years is the slightly higher amount of ingrowth into the first diameter classes (188 trees per ha in classes from 0 to 9 cm after 10 years; 200 trees per ha in classes from 0 to 9 cm after 35 years), but furthermore also the lower stem numbers per ha in the upcoming diameter classes. The amount of stems for the largest diameters is due to the last target diameter setting diminishing and will be totally removed after this intervention. Species-wise the pine will still represent the highest diameters with a d_g of 35.5 cm shortly after the thinning, but regarding the low basal area of 1.34 m^2/ha those high diameters are now presented mainly by spruce with a d_g of 26.5 cm but also by oak with a strong increased d_g from 20 cm to 24.7 cm shortly after the second intervention. Since both of these species also show a gain in basal area as mentioned in chapter 3.4.1, the species diameter structure changed much compared to the present stage in 2014.

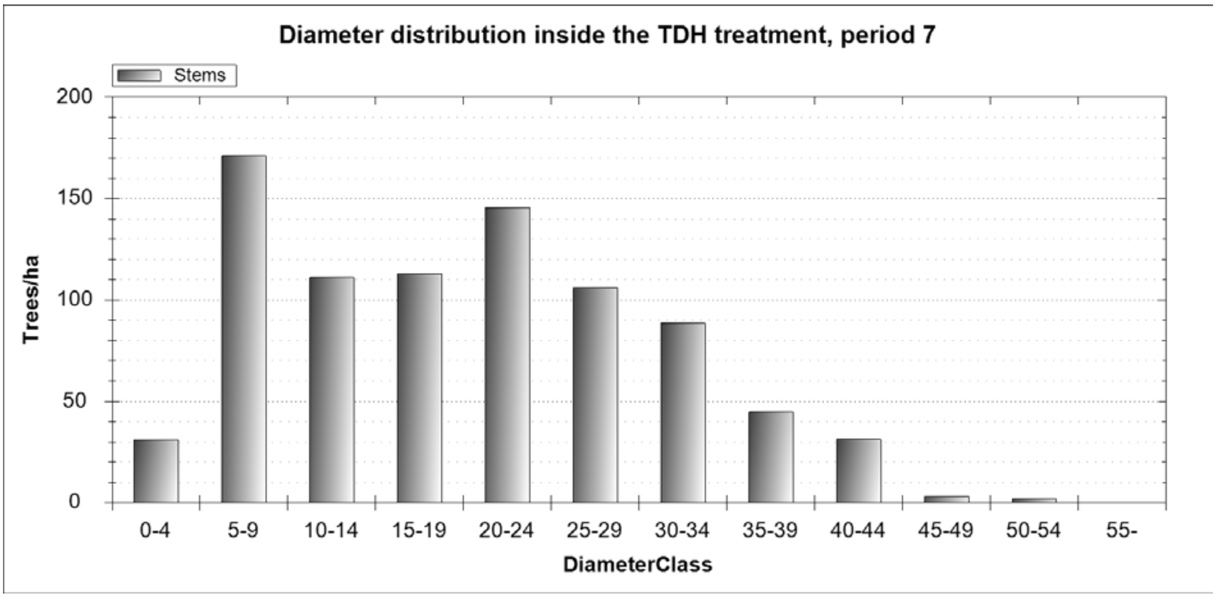


Figure 27: Diameter distribution in treatment "TDH" over all tree species per ha in Erikskِöp before the second selective thinning intervention after 35 years.

Out of these results the final diameter distribution after the 50 year period could be derived and is presented in Figure 29. It can be seen that the diameters are slightly moved to the right, which can also be seen by observing the volume values, where the volume rises from 267.3 m^3/ha after the second selective cutting to 310.7 m^3/ha. Again, the largest diameter classes are almost not existing, but the diameters from 35 to 39 cm have almost double the amount of stems per ha. Pine has a final d_g of 38.7 cm and is present in the upper diameters. Oak and spruce both increased their d_g after the last thinning from 24.7 cm to 28.2 cm for oak and from 26.5 cm to 29.2 cm and now are both present equally distributed diameter-wise throughout the TDH treatment.

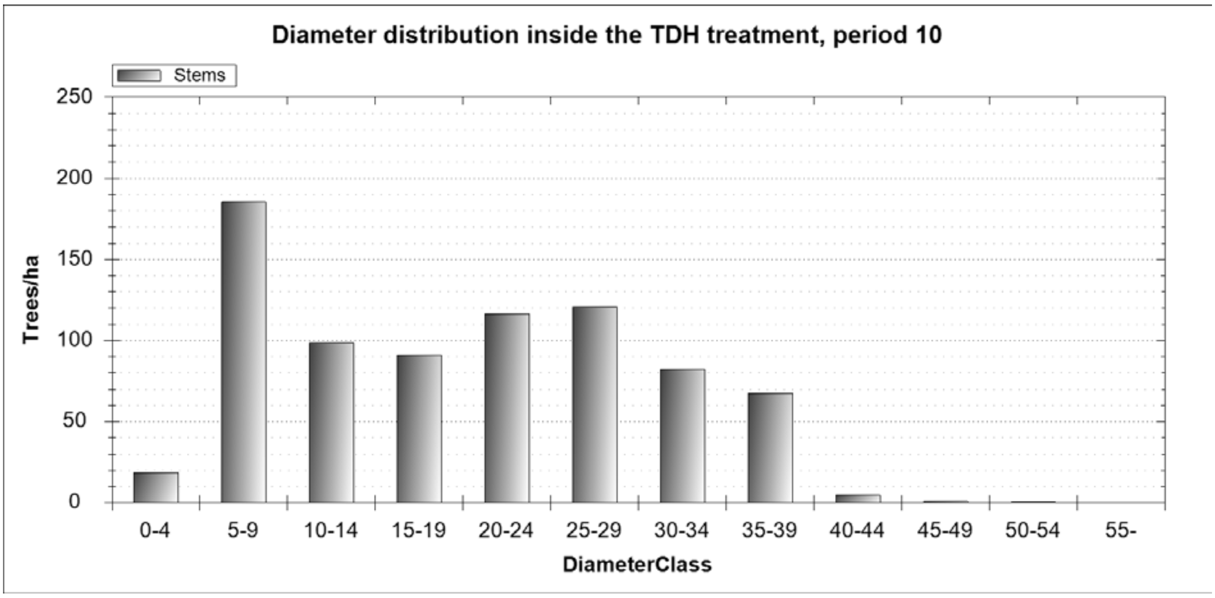


Figure 28: Diameter distribution in treatment "TDH" over all tree species per ha in Eriksköp after the 50 year period.

According to Heureka, the diameter development of the two different treatments will perform different trends. Inside the control the estimated number of upcoming new trees in the size class from 5 to 9 cm is almost half compared to the TDH treatment, where it is 98 stems per ha compared to 185 stems per ha after 50 years. The rest of the distribution however shows similar trends where there are almost equal conditions in all classes. For the larger diameter classes above 36 cm there are only some trees left inside the TDH treatment. Species-wise the trends between both treatments are similar, but pine will form the upper diameters, where the oak grows below them. The spruce is present and most dominant in all diameter classes.

4. Discussion

4.1 Diameter distribution analysis

4.1.1 Diameter distribution analysis treatment “Control”

The diameter distribution in 2014 inside the control treatment is not so different compared to the TDH treatment, since it almost shows the same decreasing pattern per diameter class. Because of more trees per ha (1159 stems compared to 874) and the fact that there is 48% spruce as basal area, the oak has problems growing in here. The light conditions inside this treatment are poorly, which leaves the oak with almost 3 cm less compared to the TDH treatment. Also mortality reduced the oak proportion in tree number and basal area. Due to this it is not surprising that the basal area is very low with 7% for oak, even though its proportion of tree species is 23% of the stem number, since there were no interventions being done and the number of trees per ha is extremely high.

4.1.2 Diameter distribution analysis treatment “TDH”

The diameter distribution inside the TDH treatment almost follows the same pattern likewise control, but starts with fewer trees in the first diameter class and has also fewer trees which are reaching into the upper canopy. Overall the trees inside the TDH treatment are 0.8 cm thinner compared to the control treatment, which is not true for the coniferous tree species. The reason why the d_g is smaller is beech and birch, where beech is 2.5 cm smaller compared to the other treatment and birch is 14 cm smaller compared to the control treatment, even though the amount of counted trees does not differ much with both species. In addition the oak performs better regarding the diameter which again strengthens the argument that with more light availability the diameter increment for oak is better, especially for oak regeneration in earlier stages (Schütz 2001). With lesser spruce inside the TDH treatment, which in the end results in a lower overall stem number, this treatment also seems to be more open and therefore provide better diameter growth conditions for oak. Pine and spruce have almost the same diameter distribution throughout all treatments, where the reason for pine is the early establishment in the stand, because it could grow nearly uncontested. The reason for spruce having higher diameter values is the fact that it is present over all diameter classes and therefore shows its presents in small clusters inside the TDH treatment. Another main reason is that all treatments are connected to each other and evenly distributed throughout the whole stand where similar growing conditions exist.

4.1.3 General diameter distribution analysis

Species-wise the diameter distribution looks different. The highest d_g and therefore the thickest trees are presented by pine, since these trees were first planted in the year 1912. Some of the trees were cut in the last intervention in winter 2008/09 and the rest nowadays provides shelter and competition for the upcoming spruce and oak over all treatments. The second most dominant species considering the diameter is spruce, which is present throughout all diameter classes, but mainly in a range from 10 to 14 cm. With its high number of 442 stems per ha spruce has a high impact on the stand structure, building the main tree species in every treatment and plot. This also makes the highest basal area share of 43% and the volume of 148.6 m^3/ha more obvious. The oak is tree species with thinnest trees and forms the lower diameter classes with a d_g of 14.4 cm. However there are differences in the diameter distribution visually, where oaks can be found with larger diameters when they grow in gaps and on edges and where its lower in diameter when found suppressed such as in the control treatment. This result can be converted to the other species as well and therefore the largest diameters can be found in block 2 (d_g=19.9 cm), since there was a small windthrow which created larger gaps to enhance the growing conditions with increasing the light conditions. Additionally not only the windthrow, but larger removal of pine trees created lighter conditions and were already there before the first cut. Also block-wise the diameter distributions per species can be distinguished from each other. What can be observed is the clear dominance of spruce in block 3, which therefore leaves the oak with a lower diameter compared to the other blocks. This competition by spruce is reduced to pine trees, since it grows in the upper canopy. It appears that the oak can compete better with the spruce in block 1 and 2, where these two tree species share the low to mid diameter classes, however with a slightly higher mean d_g for spruce.

The diameter differences are similar to each other, where the pine forms the biggest trees and the oak and spruce are sharing the low to mid diameter classes. Block 3 however shows, the clear dominance of spruce, where the oak has problems to grow under this competition due to the high stand density (Dobrowolska 2008).

4.2 Height distribution analysis

4.2.1 Height distribution analysis inside treatment “Control”

The height distribution inside the control treatment almost represents the circumstances likewise the TDH. The differences that can be observed however are the lower mean height of oak and the higher mean height of spruce, which, together with the results from the diameter analysis, leads to a suppressed circumstance for oak inside this treatment. The fact that there is an overall higher mean height inside the control treatment and especially considering spruce, leads to the assumption that is already been discussed by Drever and Lertzman (2001), where the trees start on height increment over diameter increment first. The H/D-ratio of spruce with 77 compared to the one of oak with 89 is also an index that the oak is smaller with increasing height which leads to an instability. Additionally the oaks that have been counted, especially inside this treatment, showed damages, mainly bending or crown damages, which will in the long-term lead to poorly developed tree crowns, or mortality, which is a result of leaking light (Dobrowolska 2008). The stand density inside the control treatment however is high enough to provide an optimum on stability.

4.2.2 Height distribution analysis inside treatment “TDH”

The height distribution inside the TDH treatment shows the tendency to be a bit more uniform compared to the other observations from the control. The distribution pattern however is nearly the same, apart from a smaller tree number in height class between 20 and 22 m. The oak reaches the mid layers up to 15 m in height more often compared to the control, which therefore is an index of more light availability combined with a high density of 849 stems per ha. The H/D-ratios of spruce (79.7) and oak (81.5) show almost the same values so that the stability of both species can be described as stable according to (Kramer and Akça 1995), whereas the oak is still a bit more slimmer.

4.2.3 General height distribution analysis

Due to a wide range of height values however, the precision for each species predicting the height can vary a bit. It therefore shows the highest precision for spruce R^2= 0.92, followed by pine R^2= 0.83. With these values good estimates can be derived to predict a good height simulation. The range in height of the oak however is very high, which therefore leaves the precision to R^2= 0.66. This low value is according to its growth characteristics which is light demanding like pine and spruce, but because of its slower growth in youth it is a more difficult scenario for oak to establish a good growth without sufficient light conditions. Therefore the estimates here might not respond true and can still vary a bit in the field, because of a large natural variation. It can be said, that there is a multilayered structure inside the plots which does not differ whether between the different blocks nor between the treatments. There are 2 peaks in the overall height distribution, 13 meter and 21 meter, where there are the main amounts of all trees. Species-wise the oak overall, but also per block, forms the lower canopy at about 12-14 meters together with spruce. This shows the dominance of spruce per block, which has its peak in the next height class, which for the oak seems to be like a barrier where it cannot grow into the upper canopy. However, Schirmer et. al (1999) could observe that the growth of pedunculate oak in mixed coniferous stands is not considerably lower with increasing stand density. The mid and upper canopy is then formed by spruce and pine, which is because of the early establishment of pine and also because of the good growing conditions for spruce on this podzol soil type. Most of the observed trees can be found in the range between 10 and 15 meters, which is preferable in the TDH treatment, since there will be enough ingrowth into the next diameter class which later form the mature stand.

4.3 Evaluation of the future development of the stand

The basal area development for the control is showing a clear and reasonable increasing pattern, which will result in 53.5 m^2/ha after 50 years. The stem number of 1159 stems per ha is very high. The estimated development of the basal area per species showed an increase in share from 7% to 9% in basal area for oak, which can be considered questionable, due to the heavy shelter effect for the young upcoming oak and because of the missing regeneration. Noack (2011) and Goris et al. (2007) however, showed that oak regeneration can do well under pine unless the canopy is not too closed. For Goris et al. (2007) a canopy disturbance had to happen in order to establish oak seedlings and Noack (2011) proved an increasing increment loss the greater the canopy cover of pine trees is. The proportion of pine and spruce stays on the same level, whereas the other broadleaves, birch and beech, almost completely fall out.

Regarding the final diameter distribution for the control treatment after the 50 years the development can be described as critical. The treatment seems to get more homogeneous over time, which leads to insufficient upcoming regeneration with fewer than 100 trees per ha ingrowth, compared to the TDH almost the double amount. Drössler et al. (2012) recommended a prior soil preparation to enhance the upcoming regeneration. In order to establish the oak furthermore it can be useful to create more gaps inside the TDH treatment and plant oak in groups in a mixture with spruce (Loginov 2012). This will, after Loginov (2012), result in a higher total volume compared to a planting with only oak, however with a constant requirement of silvicultural promotion. Another, more suited approach when oak is desired and should get a higher tree proportion has been made by Saha (2012), where oaks are planted in cluster plots without mixing other species to it. Hereby 20 to 30 seedlings will be planted in nests (dense spacing = 0.2 m between trees) or in groups (larger spacing = 1 m between trees). It has been shown that planting oaks in groups resulted in an equal or superior value for survival, growth and tree quality compared to a planting in rows (Saha 2012). Another factor is that, after Heureka, the ingrowth mainly consists of spruce which leads to an almost pure stand in the simulation, especially when the old pine trees starting to fall out over time. In reality however oak seedlings are plentiful available inside the stand, but they are under big pressure by browsing or intraspecific competition. The future tree species composition will after Heureka however still consist of broadleaved tree species.

The projected MAI by Heureka gave a mean of 5.3 m^3/ha and year for the TDH treatment and 5.1 m^3/ha and year for the control treatment for the next 50 years, where there is 10% more increment in the TDH in the first periods compared to the end. For the control treatment the increment is even 20% higher after the first five years. The results from Drössler et al. (2012) gave an almost similar increment prediction of 5.9 m^3/ha and year for the TDH, whereas the prediction for the control treatment was higher with 6.7 m^3/ha and year compared to the results of this simulation study. However Drössler et al. (2012) used only single-tree functions, while Heureka provides single-tree projections which are corrected by a stand growth function. The observed growth however between spring 2006 and spring 2014 was 9.5 m^3/ha and year for the control and 8 m^3/ha and year for the TDH from winter 2006 to early 2014. This shows a huge deviation by Heureka, estimating 33% less MAI for the TDH and 46% less for the control treatment. These values are even higher compared to the experiment by Elfving (2009) where an uneven-aged spruce stand in central Sweden, managed by single-tree selection system was used. He found an underestimation of 12.5 % for harvested plots and 4% for the control treatment (Elfving 2009). Despite this underestimation of Heureka there are some reasons behind why this error could occur. The first factor is that the stand stood untouched for three years after the first data collection in winter 2006/06, although it should have been harvested immediately which the first data simulation presumed. Because of this, more increment capacity was achieved. The second reason for the possible projection errors is that during the last thinning intervention 46 trees, which have been marked for felling, had not been cut, due to the terrain inaccessibility or due to overlooking of marked trees. These two reasons would be the main explanation for the higher observed MAI compared to the estimated one. In fact, Heureka delivers accurate projections, because the estimates vary from stand to stand and the derived database for it is big. The overall stock was higher and therefore more increment could be achieved. The deviation for the single tree diameter development can even reach values of 50% to 200% difference due to Drössler et al. (2013). However it can be described bigger for small trees and lesser for big trees, due to huge variations possible in the young ages per tree species (Drössler et al. 2013). The third hypothesis will be rejected, because the estimated values showed a big underestimation of the future volume development for both of the observed treatments.

Heureka can provide a good planning basis in forestry. However this system was mainly produced for even-aged stands. Although 10-20% deviation may be expected, this case-study showed that even larger errors may be involved. When applying, Heureka, it should be kept in mind that the models are not yet really validated on a sufficient base of multi-layered stands. Those errors however can be considered normal for a simulation program like this (Drössler et al. 2013).

Based on the future development of the stand however the present structure tend to get lost and regarding the natural regeneration of spruce the danger of a more homogeneous future tree species composition is given. All observations on a subjective impression by the author regarding the new upcoming regeneration showed only some new seedlings of oak and beech in more open areas, which are threatened by browsing, damaged or suppressed by the shelter effect. These tree species like oak and beech are not only good for the structural diversity of the stand, but also help to improve biodiversity and other ecological factors (Gadow et. al 2013).

The future treatment simulation of the heights will also show a development which end in a more even structure. For the TDH treatment Heureka predicts a strong mean height increment for every tree species, especially for spruce (18.3 m to 24 m after 50 years), which then forms the upper canopy almost solitary, because pine (24.3 m after the 50 years) is not present too much anymore due to its high basal area loss. Also oak may experience a high mean height increment from 13.7 m to 18 m after 50 years and therefore dominates the middle layers of the stand. However these developments in mean height show are trend into taller trees, where the younger generation will not have a sufficient amount of trees, which can already be realized regarding the future diameter distribution. With the future height development, the trend for the stand of becoming more even-aged will be even more visually.

The regeneration inside the control and TDH treatments and overall can be seen as low. It already was quite low in the first data collection in winter 2006/06 where a soil preparation was recommended to receive a sufficient young ingrowth for the upcoming years (Drössler et al. 2012). Various authors describe for Swedish plenter forests a seedling establishment of 1000 to 50000 plants per ha after 5 to 10 years after a shelterwood cutting to be a variable and safe tree number (Holgén & Hånell (2000); Örlander & Karlsson (2000); Nilsson et al. (2002)). As Schütz (2001) already claimed, there will be less survivable regeneration under a high shelter effect, compared to more open areas.

It is not only the quantity of new upcoming regeneration that secures a successful ingrowth, which is definitely needed inside a multilayered stand like this, but it is also the height increment and growth. In the shelterwood experiment by Örlander & Karlsson (2000) the authors could reveal annual height increment of less than 5 cm for seedlings smaller than 1 m, if the stand density is higher than 320 tress per ha. Regarding the fact that there are more than double the amount of trees inside every treatment and even more than three times the amount of 1159 trees per ha inside the control treatment the density can be described as very high and therefore the effect on the upcoming regeneration is negative. The shelter effect under pine however does not seem to decrease the height growth of oak according to Schirmer et. al (1999). The authors found no considerably high differences for oak and beech growth inside a stand primarily stocked with Scots pine regarding the stand density. However, these results cannot be transferred towards the different treatments in Eriksköp, where the amount of spruce is too high. This additional shelter effect leaves the oak with lesser light availability compared to the research plots of Schirmer et. al (1999), which inherit its growth. Moreover, from 2006 to 2014 84 new small trees reached the threshold of 5 cm in the study area of 1.5 ha from where the spruce has a share of 57%.

One aspect for the future needs to be the discussed upcoming ingrowth for the stand. The crucial factors are that the upcoming regeneration in the smallest size class needs to form the highest amount of tree species in order to maintain the specific diameter distribution in the long term and that there are sufficient trees inside the medium-range classes (Pommerening and Schütz 2013). As seen for this stand, there are and will be enough trees in the medium-range diameter classes. One additional measure to the normal target diameter cutting could be a removal of stems inside these medium diameter classes in order to enhance the development of oak, by opening of the canopy, and additionally form a better stand structure towards a more reversed J-shape pattern. On top of that the young ingrowth could be enhanced too to provide more stem number in the smallest diameter classes as recommended by Pommerening and Schütz (2013). Additionally a promotion of oak, or the other broadleaved tree species like beech could be considered, to make the stand more diverse regarding the tree species composition. This could be achieved by creating more sufficient gap sizes for the oaks and creating more shelterwood for the upcoming beech regeneration.

Mixed stands provide a good nutrient distribution of the soil which makes them more stable, vital and trees can establish a good root anchorage inside them (Gardiner et al. 2000). Through stabilizing climate tolerant species the diversity and therefore the adaptation for stands is increased (Brosinger and Tretter 2007). Brosinger and Tretter (2007) advises foresters to establish more stands with broad-leaved species like beech (*Fagus sylvatica*), oak (*Quercus robur* and *Quercus petraea*), or other noble deciduous species, because such trees are already more adapted to climate change effects as drought or heat which stabilizes the stand and furthermore the risk against upcoming storm events are minimized.

Schütz (1999) developed a model that needs to be considered to establish and stabilize stable forest stands (Figure 30). There needs to be a focus on all of the three different dimensions, structural diversity, naturalness and hemeroby simultaneously, because they are not necessarily convergent (Schütz 1999). That means that if the focus only lies on naturalness, the focus for a certain structure cannot be achieved, if it lies purely on silvicultural intervention, the costs of controlling would be too high (Schütz 1999). Only through a realistic and an opportunistic multifunctional silviculture the best combination of these three axes will be realized which by Schütz (1999) is called a “polyvalent” silviculture.

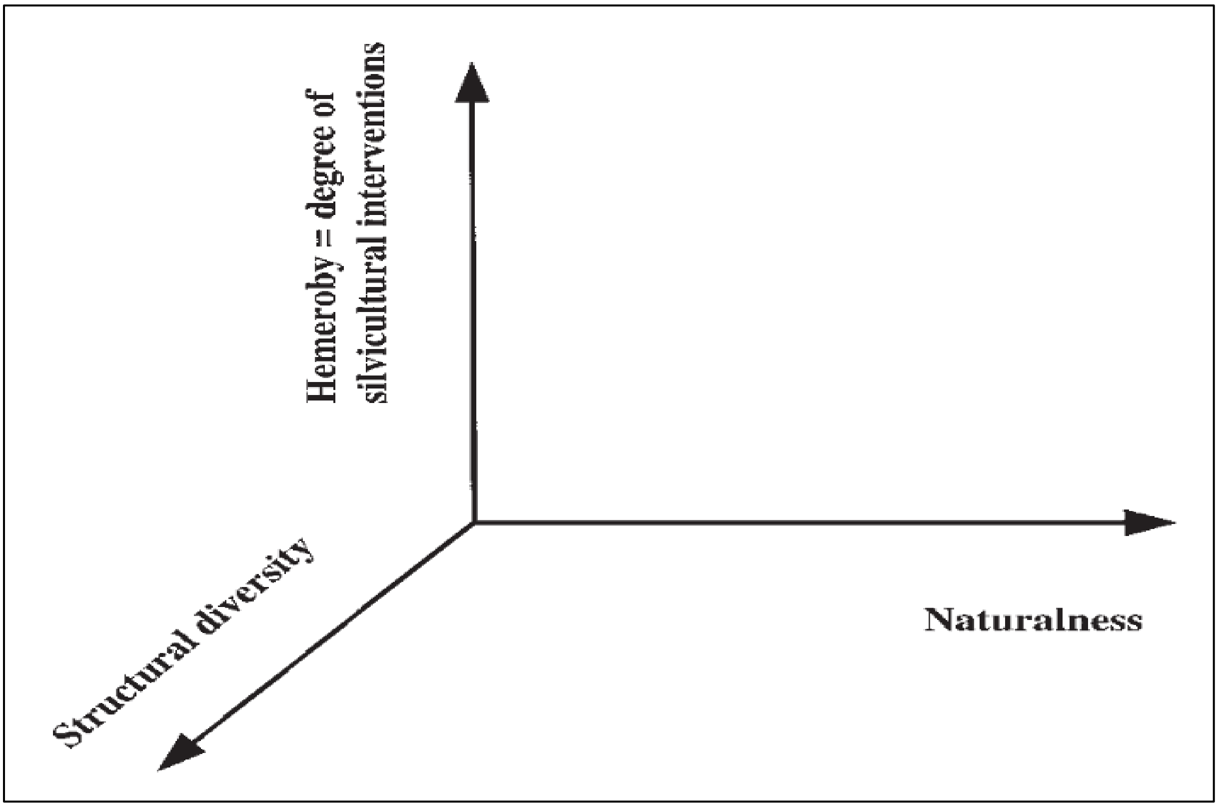


Figure 29: Three dimensions defining a polyvalent silviculture. Source: Schütz (1999)

5. Conclusions

Concluding, the height differences per block and per treatment are not considerably high, since the differences in the d_g show only a difference of 4%. There are differences visually showing that all the three main tree species have a different peak in height, leaving the oak in the low to mid canopy, the spruce forms the mid to upper canopy and the pine clearly forms the upper canopy. Species-wise the differences are clearly visual due to the stated facts above, considering the overall result. The diameter distributions for the different observed treatments did not differ much from each other, showing only 6.9% difference in the present stage in 2014. The present status even looks kind of similar comparing the TDH and the control treatment due to the reasons mentioned above. Therefore the first hypothesis will be rejected.

Also the second hypothesis cannot be accepted completely, because the future stand is unlikely to result in a more heterogeneous structure which is already indicated by the future diameter distributions (Figures: 26 to 29) and furthermore by considering the future height development. Without conducting a clearing and soil preparation the threat of creating a monoculture in the long-term might occur. A monoculture with spruce does not represent the prior aim for this stand and would be an inappropriate approach to achieve. By maintenance of the present stand structure by using the target diameter cutting, the stand could, with strict focus, become even more uneven, which can lead to a single tree selection system in the long term, which should be focused on as the main aim for this stand. The multi-layered structure however will be given, since the diameters as well as the heights are almost evenly distributed over all classes. The dominance of spruce is inevitable at this point, unless there will be some extra preparation cutting inside the different treatments, even though the oak will have some great basal area and volume development. It should be kept in mind however, that these points are only small hints, which could result in a more homogeneous structure, but the certainty is not absolute.

The future goals for this stand should be laid on maintaining the present structure of the stand, especially inside the TDH treatment. Additionally, in the next harvest intervention there should be a removal of some trees in the medium-range diameter classes in with the aim of forming a better diameter distribution with the future goal of creating an equilibrium stage in the diameter distribution. With this, the stand might result in a single-tree selection system in the very long term, where all of the discussed recommendations could profit from. In order to make this work for the oak however, a lot of other management will be needed additionally, like planting oak inside large gaps, or in groups (Saha 2012), or single tree protection for oak. Intensive silvicultural promotion every 5 to 10 years to release it from competing spruce would be further conflict to solve in the future.

6. Resources

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Appendices

Figure 30: Insight into a TDH plot.

Figure 31: Upcoming regeneration of spruce and beech.

Figure 32: Height measurements inside a TDH plot.

Figure 33: Insight into the control treatment.

Result type	Variable	Unit	year 2014	year 2019	year 2024	year 2029	year 2034	year 2039	year 2044	year 2049	year 2054	year 2059	year 2064
Data per Species	Basal Area After Oak	m2/ha	5.719	6.256	6.777	7.512	8.275	9.002	9.691	9.619	10.373	11.142	11.874
Data per Species	Basal Area After Pine	m2/ha	10.203	10.812	4.216	4.527	4.839	5.133	5.408	1.342	1.426	1.508	1.584
Data per Species	Basal Area After Spruce	m2/ha	11.159	12.102	12.128	13.232	14.29	15.267	16.176	13.905	14.896	15.804	16.62
Forest Data	Basal area (incl overstorey) After	m2/ha	27.8	29.95	23.96	26.18	28.39	30.46	32.39	25.75	27.64	29.46	31.13
Forest Data	Basal area (incl overstorey) Before	m2/ha	27.8	29.95	32	26.18	28.39	30.46	32.39	34.29	27.64	29.46	31.13
Forest Data	Dgv After	cm	27.2	28.1	24.8	25.8	26.9	27.8	28.7	26	27	28	29
Forest Data	DominantHeight After	m	17.54	18.52	18.51	19.39	19.84	19.82	20.54	20.62	21.3	21.61	22.23
Forest Data	Hgv After	m	19	19.7	18.8	19.4	20	20.6	21.1	20.3	20.7	21.2	21.6
Forest Data	Regeneration Species After	species	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce
Forest Data	Stems After	Trees/ha	848.8	862.9	811	822.4	833.2	837.1	844.5	780.2	786.5	789.3	786.7
Forest Data	Volume (incl overstorey) After	m3sk/ha	244.4	272.1	210.6	237	263.8	289.8	314.9	244.5	267.3	289.5	310.7
Forest Data	Volume (incl overstorey) Before	m3sk/ha	244.4	272.1	299.4	237	263.8	289.8	314.9	339.7	267.3	289.5	310.7
Growth	MAI Gross (All species)	m3sk/ha,yr		6.119	6.138	6.019	5.996	5.971	5.94	5.929	5.849	5.786	5.723
Growth	MAI Net (All species)	m3sk/ha,yr		5.54	5.5	5.43	5.41	5.37	5.31	5.26	5.17	5.09	5.01
Growth	MAI Net Oak	m3sk/ha,yr		1.03	1.03	1.14	1.21	1.25	1.27	1.29	1.31	1.34	1.35
Growth	MAI Net Pine	m3sk/ha,yr		1.74	1.7	1.4	1.26	1.16	1.09	1.04	0.94	0.86	0.79
Growth	MAI Net Spruce	m3sk/ha,yr		2.64	2.63	2.74	2.79	2.8	2.79	2.78	2.77	2.75	2.71
Mortality	Mortality Stems	trees/ha,	0	16.377	18.131	15.949	17.074	18.219	19.185	20.897	19.236	20.406	21.336
Mortality	Mortality Stems Beech	trees/ha,	0	0.292	0.292	0.289	0.285	0.285	0.285	0.285	0.233	0.233	0.233
Mortality	Mortality Stems Birch	trees/ha,	0	1.354	1.549	1.688	1.928	2.121	2.258	2.34	2.387	2.528	2.607
Mortality	Mortality Stems Oak	trees/ha,	0	8.06	8.322	7.352	7.415	7.477	7.577	7.69	7.14	7.168	7.182
Mortality	Mortality Stems Pine	trees/ha,	0	1.067	1.275	0.471	0.533	0.552	0.56	0.597	0.17	0.179	0.185
Mortality	Mortality Stems Spruce	trees/ha,	0	5.552	6.585	6.01	6.708	7.524	8.203	9.642	8.94	9.884	10.672
Mortality	Mortality Volume	m3sk/ha,	0	2.89	3.483	2.499	2.902	3.341	3.817	4.478	3.68	4.165	4.628
Mortality	Mortality Volume Beech	m3sk/ha,	0	0.045	0.051	0.057	0.064	0.072	0.08	0.088	0.046	0.051	0.057
Mortality	Mortality Volume Birch	m3sk/ha,	0	0.071	0.081	0.09	0.102	0.113	0.124	0.134	0.143	0.152	0.161
Mortality	Mortality Volume Oak	m3sk/ha,	0	0.683	0.805	0.787	0.899	1.02	1.144	1.274	1.257	1.381	1.512
Mortality	Mortality Volume Pine	m3sk/ha,	0	0.972	1.153	0.302	0.333	0.368	0.411	0.465	0.101	0.11	0.122
Mortality	Mortality Volume Spruce	m3sk/ha,	0	1.115	1.388	1.257	1.497	1.759	2.048	2.505	2.121	2.455	2.759
Structural Diversity	Even-aged Class After		UnevenAged	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAged
Structural Diversity	Tree Size Diversity (Gini Coefficient) After		0.504	0.509	0.473	0.478	0.483	0.487	0.493	0.473	0.48	0.486	0.49
Structural Diversity	Tree Size Diversity Class (Hugin def.) After		InverseJShape	InverseJSh	Homogen	Homogen	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJShaped

Figure 34: Simulation result for the TDH treatment

Result type	Variable	Unit	Period 0	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10
Result type	Variable	Unit	year 2014	year 2019	year 2024	year 2029	year 2034	year 2039	year 2044	year 2049	year 2054	year 2059	year 2064
Data per Species	Basal Area After Oak	m2/ha	3.241	3.464	3.677	3.879	4.073	4.259	4.437	4.609	4.776	4.938	5.097
Data per Species	Basal Area After Pine	m2/ha	16.404	16.967	17.452	17.864	18.21	18.497	18.733	18.925	19.079	19.202	19.299
Data per Species	Basal Area After Spruce	m2/ha	20.723	21.716	22.587	23.342	23.991	24.546	25.016	25.404	25.729	25.999	26.22
Forest Data	Basal area (incl overstorey) After	m2/ha	43.35	45.13	46.7	48.07	49.24	50.26	51.12	51.85	52.48	53.01	53.46
Forest Data	Dgv After	cm	29.9	30.7	31.5	32.3	33.1	33.8	34.6	35.3	36.1	36.8	37.5
Forest Data	DominantHeight After	m	21.7	22.7	23.62	24.48	25.27	25.95	26.63	27.27	27.64	28.16	28.59
Forest Data	Hgv After	m	20.2	21	21.7	22.3	22.9	23.4	23.9	24.4	24.9	25.3	25.6
Forest Data	Regeneration Species After	species	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce	Spruce
Forest Data	Stems After	Trees/ha	1159.2	1139.5	1115.9	1089.1	1060	1029.8	998.7	966.9	935.4	904.4	874.1
Forest Data	Volume (incl overstorey) After	m3sk/ha	397.5	428.2	456.8	483	506.9	528.6	548.2	565.8	581.6	595.8	608.5
Growth	MAI Gross (All species)	m3sk/ha,yr		8.108	8.028	7.939	7.844	7.745	7.644	7.54	7.436	7.331	7.228
Growth	MAI Net (All species)	m3sk/ha,yr		6.15	5.93	5.7	5.47	5.25	5.03	4.81	4.6	4.41	4.22
Growth	MAI Net Oak	m3sk/ha,yr		0.49	0.48	0.48	0.47	0.47	0.46	0.46	0.45	0.45	0.45
Growth	MAI Net Pine	m3sk/ha,yr		1.99	1.88	1.78	1.68	1.58	1.49	1.41	1.33	1.25	1.19
Growth	MAI Net Spruce	m3sk/ha,yr		3.53	3.42	3.31	3.19	3.08	2.96	2.84	2.73	2.62	2.51
Mortality	Mortality Stems	trees/ha,	0	40.212	42.199	43.711	44.694	45.089	45.031	44.885	43.979	42.867	41.61
Mortality	Mortality Stems Beech	trees/ha,	0	0.714	0.76	0.761	0.778	0.776	0.759	0.725	0.692	0.655	0.618
Mortality	Mortality Stems Birch	trees/ha,	0	2.605	2.564	2.446	2.301	2.155	2.02	1.897	1.781	1.668	1.563
Mortality	Mortality Stems Oak	trees/ha,	0	8.737	8.907	8.997	9.021	8.979	8.891	8.701	8.472	8.216	7.918
Mortality	Mortality Stems Pine	trees/ha,	0	4.532	4.655	4.727	4.751	4.726	4.659	4.555	4.419	4.265	4.1
Mortality	Mortality Stems Spruce	trees/ha,	0	23.624	25.29	26.733	27.775	28.363	28.592	28.881	28.472	27.905	27.241
Mortality	Mortality Volume	m3sk/ha,	0	9.779	11.187	12.582	13.882	15.044	16.056	17.012	17.712	18.286	18.749
Mortality	Mortality Volume Beech	m3sk/ha,	0	0.107	0.129	0.156	0.181	0.204	0.226	0.248	0.264	0.279	0.292
Mortality	Mortality Volume Birch	m3sk/ha,	0	0.961	0.955	0.943	0.928	0.911	0.892	0.872	0.851	0.831	0.811
Mortality	Mortality Volume Oak	m3sk/ha,	0	0.505	0.592	0.681	0.769	0.852	0.93	1.002	1.069	1.131	1.189
Mortality	Mortality Volume Pine	m3sk/ha,	0	3.925	4.467	4.987	5.46	5.872	6.218	6.497	6.708	6.863	6.968
Mortality	Mortality Volume Spruce	m3sk/ha,	0	4.281	5.045	5.815	6.544	7.204	7.79	8.392	8.817	9.179	9.486
Structural Diversity	Even-aged Class After		UnevenAged	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAg	UnevenAged
Structural Diversity	Tree Size Diversity (Gini Coefficient) After		0.534	0.534	0.533	0.532	0.531	0.53	0.529	0.527	0.526	0.524	0.523
Structural Diversity	Tree Size Diversity Class (Hugin def.) After		InverseJShape	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJSh	InverseJShaped

Figure 35: Simulation result for the control treatment