Stand structure and future development of a managed multi-layered forest in southern Sweden: Eriksköp - A case study

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Beståndsstruktur och framtida beståndsutveckling i ett flerskiktat bestånd i södra Sverige: Eriksköp - En fallstudie

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Abbreviations

BA – Basal area, grundyta
DBH – Stem diameter at breast height (1.3 m), diameter i brösthöjd (BHD)
ha – Hectare, hektar
MAI – Mean annual increment, årligt medeltillväxt
Volume – Total stem volume over bark, beståndsvolym inkl. topp och bark
(if not indicated differently as in the economic discussion)
SE – Standard error, standardfel
NPV – Net present value, nuvärd

Summary

A heterogeneously structured forest stand with pine overstory and naturally regenerated spruce and oak trees in different size classes was documented. The effect of target diameter cutting on stand structure and growth was analyzed as a case-study. Both, systematic sample plots and forest gaps were used to describe the stand structure after cutting. Target diameter cutting in different treatments reduced the standing volume from ca. 320 to 180 m³/ha. Forest canopy gaps were created on more than 15% of the stand area. The seedling number of advanced natural regeneration was low (less than 500-1000 individuals per ha).

Based on the advanced regeneration in gaps, three different scenarios for future ingrowth into the tree layer were defined. The extreme minimum ingrowth scenario assumed about 10 cm annual height growth and rather high mortality reported in literature from other experiments (resulting in one tree annually reaching 5 cm DBH during the next 50 years). Two other scenarios assumed 20 and 30 cm annual height growth. While no mortality was presumed within the latter scenario, moderate mortality rates (reported in literature) were chosen for the intermediate scenario. The maximum scenario postulates ten trees per year and ha reaching 5 cm DBH (equal to ingrowth reported from boreal single-tree selection forests). The moderate scenario assumes four new trees per year and he. Additional scenarios after soil preparation in gaps were used, defined on the base of shelterwood experiments.

To describe the future basal area growth and continued target diameter cutting in the next 50 years, a single-tree growth model was applied, using stand age-independent estimations of the age of single trees. Thereby, a mean annual increment of 0.53-0.64 m^2/ha was projected, similar to 5.6-6.8 m³/ha volume. Some errors to estimate the standing volume in multi-layered stands were detected during the simulation process. Compared to an even-aged spruce stand planted on the same site, the expected growth of the study stand during the next 50 years was one third lower. In average, about 120 m^3/ha standing volume was removed in 20-25 years-cutting cycles. To continue without longer harvest intervals after the 50 years-simulation period, soil preparation seems necessary to achieve a sustainable number of small trees. Beside timber production, profitability was also lower by selective cutting. But, the important advantage of target diameter cutting can be more equally distributed income over time, with investments costs that can be covered by profit from timber harvest at the same time. A regular income of 17000-28000 SEK per ha every 20-25 years seems possible from today´s perspective.

An additional treatment with alternative target diameters to promote particular tree species did not affect the amount of removals and the length of cutting intervals substantially. But simulations with 5 cm reduced target diameters caused very heavy removals and 35-40 years to reach 300 m³/ha standing volume again. The study includes discussions of tree species composition and development as well as a sensitivity analysis of the applied growth model.

Samfattning

Studien beskriver ett skogsbestånd med heterogen struktur (tall i det dominerande skiktet,, gran i alla skikt, och ek) och hur måldiameterhuggning påverkar beståndsstruktur och tillväxt. Inventering av beståndsstruktur efter huggning utfördes dels inom systematiskt utlagda provytor och dels som luckinventering. De testade behandlingar med måldiameterhuggning minskade beståndsvolymen från ca. 320 till 180 m^{3}sk/ha i medeltal. Luckorna i krontaket utgjorde 15% av beståndets totala yta. Antalet småträd i självföryngringen var lågt (färre än 500-1000 individer per ha med BHD mindre än 5 cm).

Scenarier med tre olika nivåer förinväxning av självföryngring i luckor definierades: 1) låg nivå med ca. 10 cm årlig höjdtillväxt och hög mortalitet som resulterade i en inväxning av ett träd per år och ha i trädklass över 5 cm BHD, 2) medelnivåmed ca. 20 cm årlig höjdtillväxt och en inväxning av fyra träd per år och ha, 3) hög nivå utan mortalitet och en årlig höjdtillväxt på ca. 30 cm som resulterade i 10 nya träd per år och ha. Scenariot med hög nivå motsvarar observerad inväxning i boreal blädningsskog. Baserat på erfarenheter från flera skärmställningsförsök gjordes även olika antaganden angående markberedningens inverkan på inväxningen.

Tillväxten under 50 år med fortsatt måldiameterhuggning simulerades. . Under den simulerade perioden var den årliga grundytetillväxten 0,53-0,64 m^2/ha och volymtillväxten 5,6-6,8 m^{3}sk/ha i medeltal för den. Beräknad produktion i det studerade beståndet var en tredje del lägre än förväntad produktion i ett planterat likåldrigt granbestånd på samma ståndort. I medeltal var det möjligt att avverka omkring 120 m^{3}sk/ha varje 20-25 år. För att på längre sikt kunna bibehålla ett avverkningsintervall på 20-25 år och samtidigt trygga föryngringen, rekommenderas markberedning för att initiera föryngring som kan ersätter mogna träd på lång sikt. Även intäkterna var lägre vid måldiameterhuggning jämfört med trakthyggesbruk. Vid måldiameterhuggning var emellertid intäkterna mer jämt fördelade över tiden och det fodrades heller inga dyra inverteringar i föryngring. Netto intäkterna var ungefär 17000-28000 kronor per ha varje 20-25 år (förutsatt bibehållen prisbild).

En kompletterande behandling med alternativa måldiametrar för att gynnar specifika trädslag visade inga stora effekter på uttag och huggningsintervall. Simuleringar med 5 cm lägre måldiameter resulterade i ett stort uttag och det krävdes ett avverkningsintervall på 35-40 år för att åter nå upp till beståndsvolum på 300 m^{3}sk/ha innan nästa avverkning. I studien diskuteras även hur den framtida trädslagsfördelning i beståndet kommer att utvecklas. Dessutom diskuteras eventuella felkällor vid modelleringen av skogens utveckling. Skattningen av tillväxten i flerskiktad skog innebär i flera fall en extrapolering av tillämpade modeller med ökad osäkerhet som följd.

Introduction

Continuous cover forestry and other silvicultural systems in Sweden and northern Europe

The currently dominant method to harvest trees in mature forest is clear-cutting. In Sweden, clear-cutting and the seed-tree method are applied in ca. 95% for harvesting mature stands (Anon 2002). Other methods are shelterwood cutting (Holgen, 1996) and single-tree selection cutting (Lundqvist, 1989). However, the latter is accounted as thinning method in Sweden, not as harvest method (Anon 2002)!
Historically, dimension cutting was used in many parts of northern Sweden in the beginning of the 20^{th} century. After the removal of the largest trees in pristine forest areas, this type of cutting was repeated. Finally, target diameters were too small and caused forest depletion (Holmgren, 1959). The growth of the remaining trees and regeneration processes developed much slower than expected.
Crucial for sustainable target diameter cutting is the initial stand structure and the target diameter limit which determines harvest volume and cutting cycles. If the diameter threshold is too low, forest can be depleted. If the number of small trees is too low (and large trees are very regularly distributed in the stand), the cutting could open up forest canopy similar to shelterwood conditions (with more evenly distributed regeneration in the stand). Lundqvist (1989) provided a good reference to boreal single-tree selection stands under quasi-equilibrial conditions. A reference to natural stand structures in fully stocked boreal forests can be found in Shorohova et al. (2009).

Continuous cover forestry is currently under strong debate in Sweden (i.e. NSF, 2010). For some decades, silvicultural guidance for forest owners considering selective final felling as potential option was limited compared to treatments like clear-cutting, planting and thinning. More recently, the ecological value and recreational aspects after clear-cut were discussed more controversially (also due to the decreasing area of forest with continuous tree cover, changes of the perception in the society, and new insights into natural processes of the biocenosis; see i.e. Bengtsson & Rosell, 2010). Today, a certain potential for continuous cover forestry is recognized, especially close to urban areas or to protect species depending on continuous forest cover.
General overviews regarding continuous cover forestry in Sweden were given by Axelsson (2008), highlighting history and policy aspects, and Erefur (2010) with focus on regeneration issues. Saksa & Valkonen (2011), Laiho et al. (2011) and Kuulavainen et al. (2012) gave an overview on Finnish research about continuous cover forestry. Kuulavainen et al. (2012) and Pommerening & Murphy (2004) discussed the terminology to describe forms of continuous cover forestry. However, the term is to some extent still differently used in Finland, UK, or Sweden for instance. Another interesting approach in practice to continuous cover forestry is described by the Forestry Commission in UK (FC, 2004).

Study goals and hypotheses

This case study aims at exploring diameter cutting as an option to manage heterogeneously structured forests in southern Sweden. The focus was set on the effects of target diameter cutting on stand structure and stand development per se. Additional silvicultural measures, like creating larger gaps or enrichment planting were not considered. The future stand development with continued target diameter cuttings was simulated with the empirical growth models that exist for Sweden. However, caution is warranted when interpreting the results, as the single-tree model was applied outside of its validation range (see discussion). The study stand represents a common forest type in Sweden, with pine-dominated overstory and shade-tolerant tree species below (Figure 1). The mixture of pine and spruce for instance, covers about 300.000 ha in Götaland, comprising a high proportion of mature stands (Drössler, 2010). Such a forest type can be considered as rather suitable for alternative silvicultural methods, because the risk of wind damage is lower than in a pure, single-layered spruce forest (Valinger & Fridman, 2011). The selected stand is more heterogeneously structured than the majority of Swedish forests.

The goal of the study was to estimate future stand growth and timber harvest over a 50 year period, and to test and discuss the effect of different ingrowth scenarios. Furthermore, the initial stand structure was documented for comparisons with other stands and for future re-measurements to validate the growth functions commonly used in forestry in Sweden.
The hypotheses of this study are: (1) Target diameter cutting can create an irregular pattern of gaps, different to uniform shelterwood. (2) For the next 50 years, forest production in the study stand, managed by target diameter cutting, is predicted to be similar to an even-aged spruce stand planted on the same site. (3) The projected growth will decrease significantly, if the target diameters applied are reduced by 5 cm. (4) Ingrowth will have a small impact on projected increment the first 50 years. (5) The tree species composition will change towards more shade tolerant species during the simulated development. (6) Replanting spruce after clearcut would result in a similar net present value compared to target diameter cutting (based on 2% interest rate).

Experiences from continuous cover forestry in Central Europe

In other parts of Europe, the largest proportion of uneven-aged managed forests can be found in Switzerland and Slovenia (ca. 10%), where single stands have been described and inventory methods were developed more than 100 years ago (Biolley, 1887). In France, Germany, Czech Republic, Austria and Slovakia, less than 2% of the forests are uneven-aged (Schütz, 1994). The typical uneven-aged forest are montane fir-spruce-beech stands, but on special places a management tradition can be found in subalpine pure spruce stands and submontane pure beech stands too (Indermühle, 1978; Erteld, Gerold, Mund, Schulze & Weller, 2005). Since 60 years, extensive research in fir-spruce-beech forests on stand structure and regeneration led to a better understanding of stand developmental pattern (Leibundgut, 1945; Mitscherlich, 1952; Kern, 1966).
Research in other heterogeneously structured forests with more light-demanding tree species is very limited. Schütz (2001) concludes that these stands often undergo a transition stage rather than approaching an equilibrium (regarding balanced inverse j-shaped diameter distributions). Under long shelter periods, the successful regeneration of light-demanding tree species is very difficult (Lüpke & Hauskeller-Bullerjahn, 1999).

Due to an increasing public interest in nature in the 1970's, the dominance of public forest owners in Germany, high population densities, and low contribution of the forestry sector to gross national products, the paradigm prior to timber production changed to a strong emphasis of other forest functions. After a general ban of the clearfelling system in Germany (which was applied in spruce and pine stands), shelterwood and target diameter cutting became the most common methods. In beech stands, shelterwood was already the dominant harvest method since 200 years (Hartig, 1791). Oak and many pine stands were also harvested by shelterwood cutting, but in short regeneration periods (ca. 10 years).

Today, most stands are managed by target diameter cutting which is applied in single-tree selection and shelterwood systems (Schütz, 1997; Spellmann, 1997). While target diameter cutting aims for equilibrium conditions in uneven-aged forests (Lundqvist, 1989; Schütz, 1997), it can be used to transform even-aged forest into more heterogeneously structured stands (Richter, 1995). In most cases, this means an extended regeneration period (ca. 40 years in even-aged beech stands) resulting in more heterogeneously structured natural regeneration (but still even-aged, e.g. Petritan et al., 2007). In the very long run, a transformation from even- to uneven-aged forest can be expected (Sterba & Zingg, 2001; Schütz, 2001, 2002; O'Hara, 2001; Kerr, Morgan, Blyth & Stokes, 2010). But, most authors pointed out that transformation of very homogeneously structured stands is difficult. In even-aged spruce forests for instance, the target diameter cutting caused considerable storm damage (Redde, 2002). Therefore, strip cutting is often recommended on labile sites.

Material & methods

Stand description and history

The study stand is located in southwest Sweden (56°42‘02‘‘N, 13°7‘56‘‘E, 115-140 m a.s.l.) at the Tönnersjöheden experimental forest, within the transition zone between nemoral and boreal forests (Ahti, Hämet-Ahti & Jalas, 1968; Bohn & Weber, 2000). Mean annual precipitation in the area is 1050 mm, mean annual air temperature is 6.7°C and the vegetation period lasts for 215 days (when mean daily air temp. > 5°C). The soil type is a podzol, developed over sandy-fine sandy moraine. The ground floor vegetation is mainly characterized by *Vaccinium myrtillus* and thin-leaved grasses on this mesic site. Regarding the site index according to Hägglund (1973), 32 m top height was estimated for a spruce stand at this site at the age of 100 years (based on observation in adjacent spruce plantations). The stand area was 19 ha (Figure 2).

Figure 1. Section of the stand Eriksköp.
Del av beståndet i Eriksköp.

Before stand establishment in 1912, the area was a *Calluna* heath land with some single trees (incl. *Picea abies* L. Karst) sparsely scattered across the landscape. The stand was established by seeding of pine (*Pinus silvestris* L.), supplemented by an abundant natural regeneration of birch (*Betula pendula* Roth.). The first cutting took place in 1947, releasing single pine trees in combination with a thinning from below on residual areas. In 1953 and 1958, thinnings from below were carried out. Thinnings were carried out in 1974 and 1991. During this development, additional trees like *Picea abies*, *Quercus petraea* Liebl., *Sorbus aucuparia* L. and *Fagus sylvatica* L. entered the stand. Single individuals of *Salix caprea* L., *Alnus glutinosa* L., *Populus tremula* L., *Juniperus communis* L. and *Malus silvestris* L. also established.

Figure 2. Montage of aerial photographs of the stand in summer 2008 immediately after the first target diameter cutting.

Flygfoto över beståndet tagna under sommar 2008, strax efter första måldiametershuggningen.

Stand treatments and target diameters

The stand was divided into three blocks, with four different experimental treatments repeated in each block (Figure 3):

1. Treatment **T** was defined by cutting according to target diameters. A tree was removed when the DBH was equal or larger than indicated in Table 1. These target diameters were chosen according to economic criteria and were similar to final tree diameters often used as production goal in even-aged stands.
2. Treatment **TS** was a target diameter cutting with soil preparation and tending of small trees as additional silvicultural measures. The soil scarification was applied in gaps. The cleaning removed some saplings with abnormal stem form, damages or spike-knots.
3. Treatment **TN** was a cutting with larger target diameters for broadleaves and pine. The target was to enhanced natural values and to promote other species on the expense of spruce (see Table 1).
4. The control treatment **C** was not managed.

In each of the three blocks, the single treatments were carried out on 1 ha. This area was sampled by four systematically distributed 10 m radius-plots (Figure 3). Each treatment was sampled by twelve plots on total stand area. Total plot number of the experiment was 48.

Some trees were left in the stand to increase the natural value, but none of these retention trees was selected on the plots. While 20 retention trees per ha were selected on the stand section managed according to treatment TN, ten trees per ha were chosen in other treatments.

The cutting was carried out in winter 2008/09. All removals were planned in order to be feasible by a harvester. Another target was to keep the harvesting costs low. Hence, no fixed skid road system was used for all treatments, given the responsibility to the harvester driver. However, mature trees were marked before harvest to maintain the experiment. In autumn 2010, soil scarification in treatment TS was carried out. No cleaning of dense regeneration was necessary.

Table 1. Target diameter (in cm) of tree species according to treatment (T, TS and TN) and quality class 1 and 2 (class 2 describes trees with branches thicker than 6 cm, spike-knots or forks). *Måldiameter (cm) för olika trädslag inom tre olika behandlingar och kvalitetsklass 1 och 2.*

	T/TS		TN
	1	2	
Pine	40	30	40
Spruce	36	26	26
Birch	30	20	30
Oak	60	30	60
Beech	50	30	50

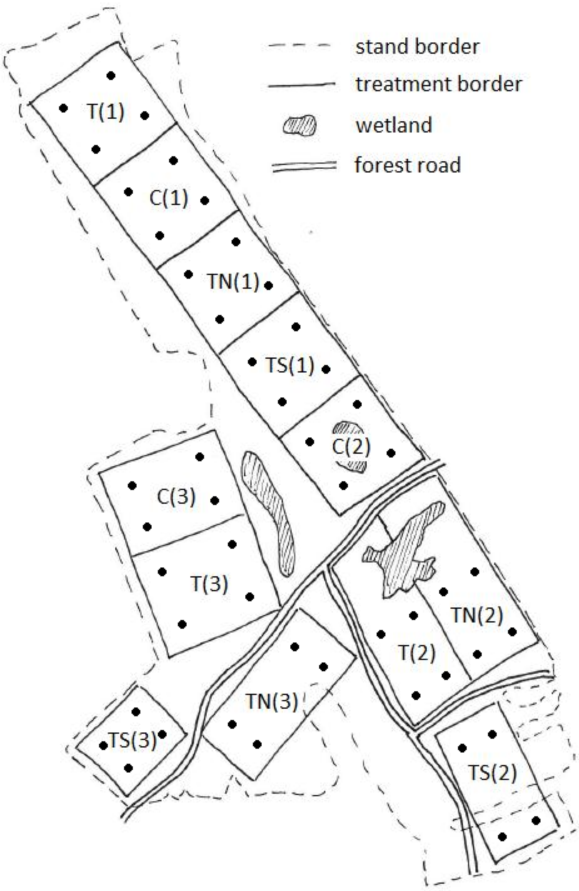


Figure 3. Stand map with the distribution of treatments and sample plots. C = control, T = target diameter cutting, TS = target diameter cutting with silvicultural measures, TN = target diameter cutting for natural values. Number of the three experimental blocks in brackets.
Beståndskarta med fördelning av behandlingar och provytor. C = kontroll, T = måldiameterhuggning, TS = måldiameterhuggning med skötselåtärder i kvarvarande bestånd, TN = måldiameterhuggning med naturhänsyn.

Sampling methods

Trees On the systematically distributed sample plots with 10 m radius, trees with DBH ≥ 4.5 cm were cross-callipered and the tree species was recorded. For every second tree, tree height was measured.
Smaller trees with DBH < 4.5 cm and height ≥ 10 cm (hereafter referred to regeneration) were counted on 192 circular 5 m^2-subplots, located on the 10 m radius-plots (5 m distant from its centre in the four cardinal directions). For each individual, tree species and height class were determined. Height classes were 10-19 cm, 20-49 cm, and 50 cm-height classes up to 299 cm. For trees with a height ≥ 3 m and DBH < 4.5 cm, height and DBH were recorded. For the largest individual of each species on a subplot, annual height shoot lengths of the last three years and damages by browsing or harvest were recorded. Dead shoots or shoots with unknown scars were neglected. (*Rhamnus frangula* L. was ignored in the regeneration survey.)

Forest gaps The gap survey was a complete stand inventory of forest canopy openings. Openings were defined as areas where the forest floor was not covered by the crown of

trees with DBH ≥ 4.5 cm. Minimum gap size was defined by 5 m gap length (app. 20 m² assuming a circular gap).
The length and width of a gap was measured from the edge of adjacent tree crowns at the four points indicated in Figure 4 using a crown projection prism. Gap area was calculated using gap length and width to calculate an ellipse according to Runkle (1992). If the shape of a gap was not similar to an ellipse, the gap area was measured by polygons. If single live trees with DBH ≥ 4.5 cm occurred in a gap, their crown cover was measured and subtracted from the gap area. GPS coordinates of the gap centre were also recorded.
In the gaps, stumps of harvested were counted if the diameter at the height of the cut was larger than 25 cm (assuming that the tree had reached the upper stand layer). Remnants of other *dead canopy trees* were counted if DBH was larger than 20 cm or the stump diameter on the ground was estimated to be larger than 25 cm. Four cases of mortality were identified: 1) Fresh stump, recently harvested by target diameter cutting. 2) Old stump (by former cuttings or breakage). 3) Recent wind-throw after target diameter cutting. 4) Old wind-throw before target diameter cutting.

Regeneration in gaps Two inventory concepts were applied to study forest regeneration: The systematic survey described above, and a complete inventory in gaps. Reasons for the second inventory was the low number of seedlings found on systematic plots and the hypothetical importance of gaps for future stand development. The minimum height to record seedlings in gaps was 20 cm. Height classes above 20 cm and tree measurements were identical with the survey on permanent plots. Only the highest individual of each species per gap was selected to record height shoots of the last three years and damages.

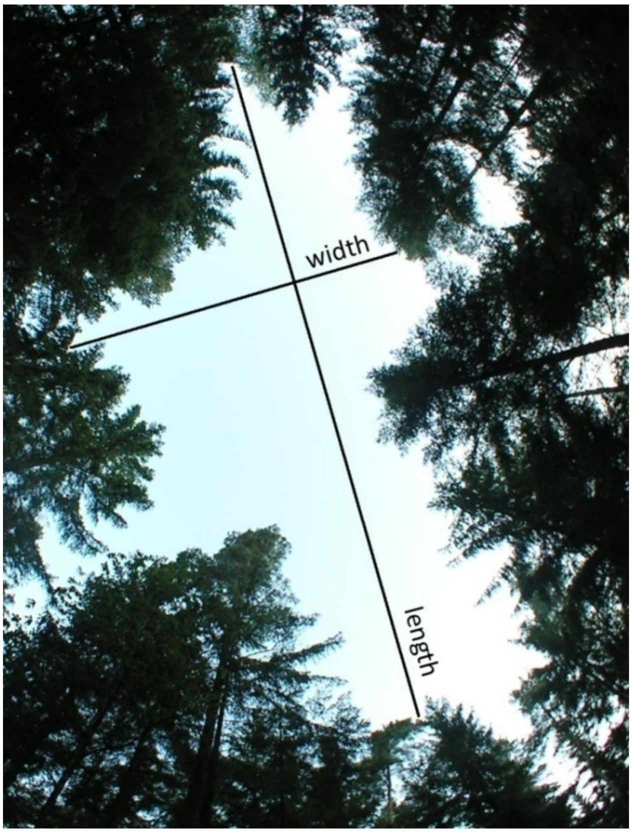


Figure 4. Fitting length and width to the canopy opening.
Mätning av luckornas längd och bredd i krontaket.

Light measurements To describe approximate light conditions in the stand and in gaps, the crown coverage was measured by a forest canopy densiometer (Lemmon, 1956). The mirror of this tool reflects a cone with an opening angle of 24 degree and allows a distinction of light and dark spots in a stand.
The measurements were taken in August, 1.5 m above the centre of the permanent regeneration sub-plots and in the centre of selected gaps, representing the range of gap sizes in the stand. The crown coverage was calibrated by the diffuse site factor (Wagner, 1994) which represented the whole range of light conditions in the stand. The diffuse site factor was determined by fish-eye photographs and analyzed according to Wagner (1994).

Ground vegetation was classified on the sample plots according to Hägglund & Lundmark (1994).

Analytical methods

For the *structural analysis*, the stand was divided into three height strata according to Leibundgut (1952). Stand height was determined as the regression height of the tree with a DBH equal to the arithmetic mean of the diameter distribution plus three times the standard deviation (Näslund, 1936), regardless tree species. In addition, logarithmic height curves were derived for pine, spruce, birch, oak and beech.
Söderberg's (1992) functions of height, form height and bark thickness were used to calculate initial stand volume. However, future volume was estimated by BA with volume functions according to Ekö (1985).

Simulation of future stand development

The collected tree data on the 10-m radius plots before cutting was used for simulations. Hence, all forecasted stand developments are based on the same initial stand conditions. Besides the four experimental treatments described above, two additional simulated treatments with 5 cm reduced/increased target diameters were also tested (T+5, T-5).

The growth of trees larger than 5 cm DBH was simulated by a set of empirical models:

1. A basal area growth function for individual trees according to Elfving (2004) which is independent from stand age.
2. Functions to estimate the age of single trees at breast height according to Elfving (2003). The functions can adopt stand age optionally as independent variable. But, the results presented refer to the stand age-independent estimation of single tree ages. (However, the stand age-dependent estimation was used for validation. In that case, stand age was defined as the age of the tree with mean basal area diameter. The age of the tree with mean basal area diameter was estimated from the number of internodes counted in the field at trees with that size.)
3. Tree mortality was estimated according to Fridman & Ståhl (2001).

Fridman & Ståhl (2001), Elfving (2003), and Elfving (2004) used the Swedish National Forest Inventory (Ranneby et al., 1987) to parameterize their functions.

Elfving´s (2003, 2004) models were based on permanent sample plots of the Swedish National Forest inventory (RIS, 2008). The age function of single trees in uneven-aged stands was derived from sample plots classified as uneven-aged forest (Elfving, 2003). "Uneven-aged" plots were defined by minimum two age classes (with 20 years intervals) and minimum 20% standing volume in each class (RIS, 2008).
For the purpose of validation of Elfving´s single tree models, a more robust stand growth model for even-aged stands by Ekö (1985) was applied. The age at breast height of pine and birch trees was set 90 years. For spruce, 60 years was assumed, and for oak and beech 40 years.
For comparisons with the development of a planted spruce stand on the same site, the forest simulator DT was applied, which is based on single tree growth functions by Elfving (2004), but calibrated with Ekö's (1985) stand growth functions (*cf.* Nilsson & Fahlvik, 2006). For the simulation with DT, 1800 established spruce trees per ha with 7 m mean height after 20 years were assumed.

For this study, a simulator was developed which integrates the models by Elfving (2003, 2004) and Fridman & Ståhl (2001), as well as ingrowth scenarios described below to forecast and evaluate the stand development for the next 50 years. Input variables refer to site conditions (latitude, altitude, distance to coast, site indices for spruce and pine, vegetation characters, soil moisture), stand characteristics (age, indicator variable for uneven-aged, number of years since thinning) and individual trees features (species, DBH and height). Data from measurements in spring 2007 was used as initial values for the simulations. The calculation procedure was repeated 25 times per plot, and summarized as average value. Repeated simulations were made due to the inclusion of stochastic elements in the mortality functions. To estimate stand volume from BA, stand volume functions according to Ekö (1985) were applied. These functions are less accurate but also less biased, especially when it comes to repeated simulations. Therefore, volume predicted by stand volume functions are considered more robust within simulations of this study.
For the simulated target diameter cuttings, single-tree removals were specified according to their diameter derived from single-tree BA projections. When total standing volume on all plots was larger than 300 m^3/ha in average, a target diameter cutting was simulated. If the remaining standing volume would be less than 100 m^3/ha, the cutting would be delayed too (simulations with 150 m^3/ha minimum volume after cutting were tested additionally).

Ingrowth scenarios In addition to the empirical tree growth models, hypothetical scenarios of future ingrowth into the tree layer (≥ 5 cm DBH) were formulated. Three different scenarios were defined to cover a wide range of possible, reasonable ingrowth.
The minimum scenario was derived from the current regeneration, before the first growing season after first cutting. The average of the last 3-year height shots was calculated to estimate future minimum height growth per species and height class. In addition, mortality rates described in Table 2 were assumed, based on lowest seedling survival of spruce reported in literature (Nilson & Lundquist, 2001; Holgén & Hånell, 2000; Wikberg, 2004).

Table 2. Annual mortality of small trees assumed in the minimum ingrowth scenario.
Antagande om årlig mortalitet hos småträd enligt scenariot med låg inväxningstakt scenariot.

	< 1 m	1-2 m	> 2 m
Spruce	10%	5%	1%
Birch	20%	15%	5%
Oak	10%	5%	1%
Beech	10%	5%	1%

The maximum ingrowth scenario assumed no mortality and height growth rates of 30 cm per year. Such rates represent spruce sapling growth on similar site under open land-conditions (Hägglund, 1981). The third, moderate scenario was based on average height growth and average mortality rates used wthin the other two scenarios.

Table 3. Summary of assumptions made for the ingrowth scenarios.
Sammanfattning av antaganden för olika inväxningsscenarier.

Scenario	without scarification			after scarification		
	regeneration reference	annual height growth	annual ingrowth with 5 cm dbh	regeneration reference	annual height growth	final ingrowth with 5 cm dbh
Minimum	advanced regeneration in gaps	last 3-years of the current regen. in gaps (tab. 13)	1 tree/ha	scarification under shelterwood (2000 spruce trees/ha or 1000 birch and 1000 pine trees)	last 3-years of the current regen. in gaps	1000 trees/ha in gaps (equal to 2% annual mortality)
Medium	advanced regeneration in gaps	20 cm	4 trees/ha	scarification under shelterwood (5000 spruce trees/ha or 2500 birch and 2500 pine trees)	20 cm	2000 trees/ha in gaps (stem number reduced by cleaning at the next harvest)
Maximum	advanced regeneration in gaps	30 cm	10 trees/ha	scarification under shelterwood (20000 spruce trees/ha or 10000 birch and 10000 pine trees)	30 cm	2000 trees/ha in gaps (stem number reduced by cleaning at the next harvest)

Box 1. Technical ingrowth implementation:
New trees were implemented on sample plots with the lowest BA. The proportion of selected plots was equal to the gap proportion of the stand found after cutting. On these plots intending to represent gaps, new trees with 5 cm DBH were adopted in 5 year-steps.
Additionally, different scenarios were constructed for the treatment with soil preparation. According to literature, 1000-50000 seedlings per ha can be expected five years after scarification under shelterwood (Nilsson, Gemmel, Johansson, Karlsson & Welander, 2002; Nilsson, Örlander & Karlsson, 2006). But, no description of the development of young trees older than ten years under shelter was found. Based on 2-5% annual mortality found for younger regeneration after scarification under shelter (Holgén & Hånell, 2000; Nilsson et al., 2002; Nilsson et al., 2006), 0-4% mortality for 0.5- 2 m high saplings in uneven-aged forest (Nilson & Lundqvist, 2001), and very low mortality rates in young stands (Petterson, 1992), generally 2% mortality was assumed for individuals established by scarification until reaching 5 cm DBH. The minimum scenario was derived from 2000 seedlings/ha established in scarified gaps after five years, and height growth rates according to the current advanced regeneration. In that case, 1000 trees/ha with 5 cm DBH were assumed in gaps 40 years after scarification. In the medium and maximum scenario, seedlings with 20 and 30 cm annual height growth were assumed to grow into the tree layer after 25 respective 20 years. Then, a fixed number of 2000 trees/ha in gaps was expected in both scenarios as an effect of cleaning.
On plots with extremely low BA (< 10 m^2/ha), pine and birch was assumed as ingrowth instead of spruce.

Results

Documentation of stand structure

Stand structure before cutting

Before harvest, the standing volume across all treatments was 322 m^3/ha (SE = 12.1 m^3), plus 8.6 m^3 deadwood. The BA of living trees amounted to 35.2 m^2/ha (SE = 1.6 m^2) with 44% pine (SE = 3.9%), 39% spruce (SE = 3.5%) and 16% broadleaves (SE = 1.7%). On the blocks, the standing volume was 270, 353 and 368 m^3/ha (Table 4). It ranged from 104 to 510 m^3/ha on plots. Basal area was 31.8, 38.1 and 38.5 m^2/ha on blocks, and ranged from 16.7 to 53.2 m^2/ha on plots.
In terms of total tree number, the proportion of pine was 16% (SE = 1.6%) and spruce 49% (SE = 4.0%). The relative number of oak trees was 27%, which differed considerably from its 9% basal area proportion (Table 4). Total tree number per ha was 999 (plus 32 dead trees).

Table 4. Tree species composition before cutting in the stand and the blocks
Trädslagsfördelning innan huggning inom hela beståndet och inom respektive block.

	Total stand			Block 1			Block 2			Block 3		
Species	N/ha	BA [m^2/ha]	Vol [m^3/ha]	N/ha	BA [m^2/ha]	Vol [m^3/ha]	N/ha	BA [m^2/ha]	Vol [m^3/ha]	N/ha	BA [m^2/ha]	Vol [m^3/ha]
Pine	164	15.4	162	137	12.4	126	217	21.5	227	151	13.6	146
Spruce	489	13.8	118	392	9.8	78	418	11.2	90	716	21.6	195
Birch	51	2.6	22	78	4.2	35	44	1.8	14	40	2.0	17
Beech	21	0.4	2	26	0.5	3	28	0.6	4	10	0.1	1
Oak	271	3.0	18	458	4.8	29	257	3	18	119	1.2	8
Others	3						2			4		
Total	999	35.2	322	1090	31.8	270	965	38.1	353	1040	38.5	368

The initial diameter distribution of the total stand is shown in Figure 5. Large tree classes (DBH > 30 cm) were dominated by pine (70%). In lower size classes, spruce (55%) and oak (33%) were most frequent. In the DBH class from 5 to 15 cm, the oak proportion increased to 45%. A few very large spruce trees were also found.
An exponential function used to correlate tree size and total tree number per DBH class resulted in $R^2 = 0.81$, while the coefficient of determination was 0.70 for a linear function. The average quotient of tree numbers from one DBH class to the next 1 cm class was 1.14. The quotient ("Q-factor") between 4 cm classes was 1.33.
The general pattern of size class distributions and tree species composition were similar in all blocks. But, the oak proportion was higher in Block 1. The highest proportion of spruce was found in Block 3 (Figure 6).

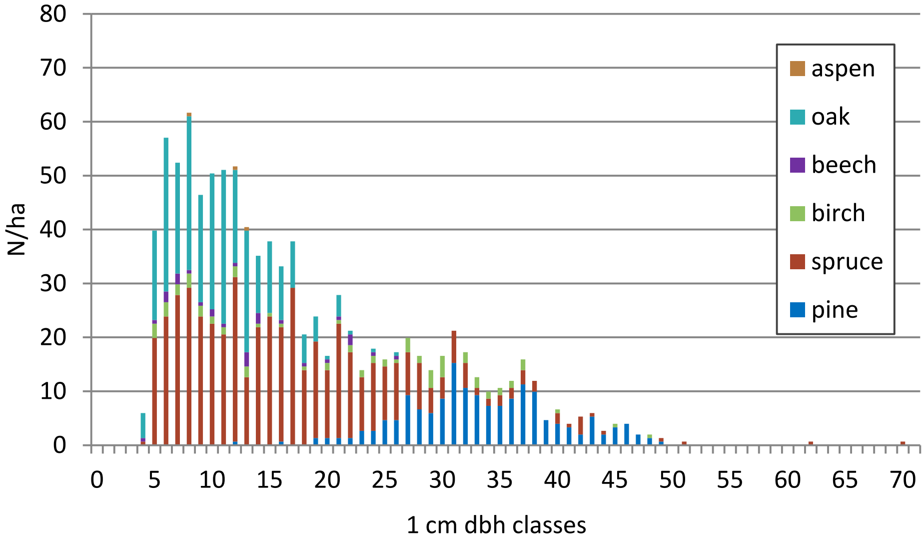


Figure 5. Diameter and tree species distribution in the stand before cutting.

BHD- och trädslagsfördelning inom hela beståndet innan huggning (asp, ek, bok, björk, gran, tall).

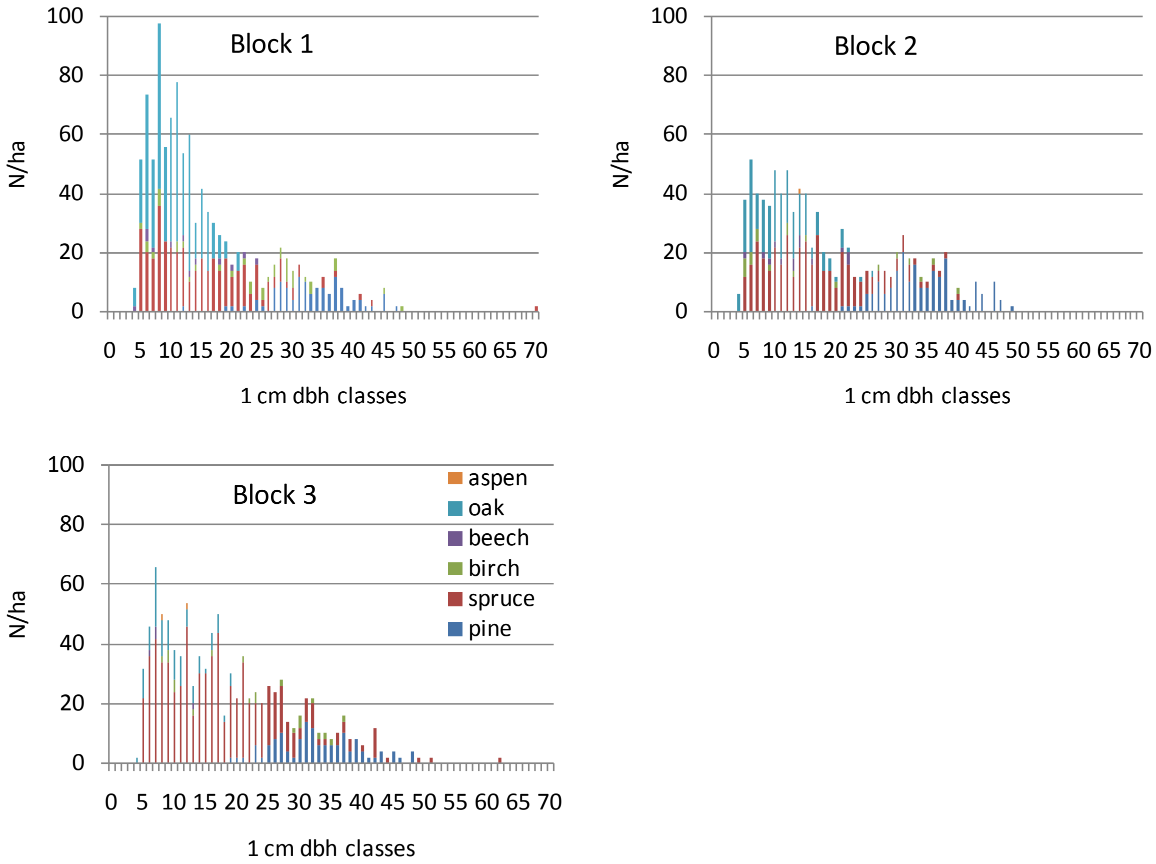


Figure 6. Diameter and species distributions in each block before cutting.
BHD- och trädslagsfördelning inom de tre blocken.

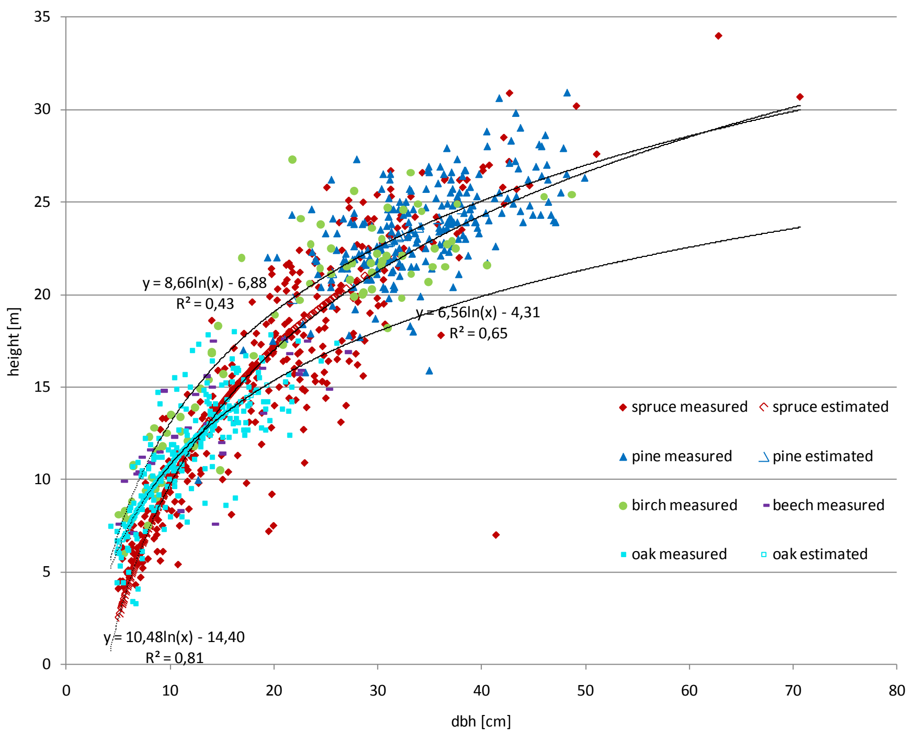


Figure 7. Tree heights (all species, 886 measured heights and 636 estimations based on logarithmic heights curves of tree species). *Trädhöjder och höjdkurvor för tall (blå), gran(röd) och ek.*

The stand height was 27 m. (The maximum tree height in Figure 7 displays a spruce likely established before pine was seeded.) Height curves for all single tree species are given in Appendix A.
31% of trees were found in the upper stand layer, while 50% resp. 19% occurred in the medium and lower layer (Table 5). The proportion of pine trees in the upper layer was 57%, while spruce comprised 39%.

Table 5. Percentage of stem number, basal area and standing volume in the three stand layers before harvest (stand- and blockwise).
Fördelningen av stamantal, grundyta och beståndsvolym över tre olika höjdklasser innan den första huggningen.

	Total stand			Block 1			Block 2			Block 3		
stand layer	N	BA	Vol	N	BA	Vol	N	BA	Vol	N	BA	Vol
< 8.9 m	19%	2%	1%	21%	4%	2%	18%	2%	1%	16%	2%	1%
8.9-17.8 m	50%	25%	18%	56%	32%	24%	50%	24%	17%	48%	23%	17%
> 17.8 m	31%	73%	81%	23%	64%	74%	32%	74%	82%	36%	75%	82%
total stand	999 trees/ha	35.2 m²/ha	322 m³/ha	1090 trees/ha	31.8 m²/ha	270 m³/ha	965 trees/ha	38.1 m²/ha	353 m³/ha	1040 trees/ha	38.5 m²/ha	368 m³/ha

Regarding the social hierarchy of trees, a relatively even distribution of dominant and suppressed trees was indicated in Table 6. 64% of dominant trees were pine, but 80% of co-dominant trees were spruce. 42% of suppressed trees were oak, 52% were spruce.

Table 6. Percentage of trees in social hierarchy classes according to Schotte (1912).
Trädens fördelning över olika sociala klasser definierade enligt Schotte (1912).

Individuals	Social class
34.2%	Suppressed
27.4%	Sub-dominant
13.9%	Co-dominant
24.5%	Dominant

Stand structure after cutting

Summarizing the three management treatments, the standing volume was reduced from approximately 320 m³ down to 180 m³ per ha (Table 7). In the two treatments T and TS the standing volume decreased from 314 and 357 m³ down to 181 and 196 m³ per ha. In treatment TN, the volume decreased from 301 to 173 m³/ha. Standard errors on plot level were 21-26 m³ for removals and 16-26 m³ for the remaining volume (Table 7).

Table 7. Standing volume and standard error on plot level [m³/ha] before and after cutting on differently treated plots. *Beståndsvolym och standardfel innan och efter den först huggningen, baserat på 12 provytor per behandling.*

	T	TS	TN	C
Before cut	314 (23)	357 (25)	301 (17)	314 (26)
Removal	133 (22)	161 (26)	128 (21)	0
After cut	181 (18)	196 (16)	173 (21)	314 (26)
Plot number	12	12	12	12

The diameter distributions in Figure 8 were relatively similar between different treatments. However, treatment TN was characterized by a smaller proportion of spruce trees for instance. Treatment T had the lowest proportion of pine.

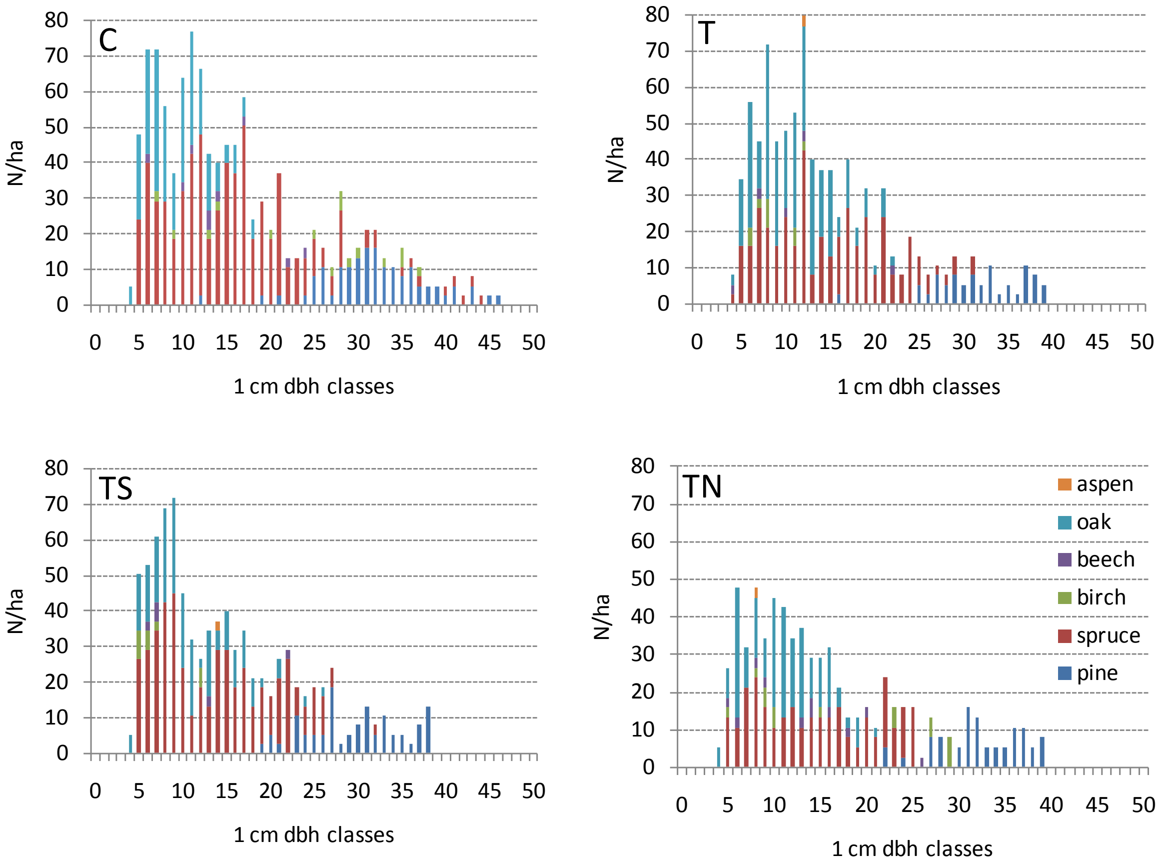


Figure 8. Diameter distributions after cutting on differently treated plots (12 plots per treatment). *BHD-fördelning efter fyra olika behandlingar (12 provytor per behandling).*

Figure 8. Diameter distributions after cutting on differently treated plots (12 plots per treatment). *BHD-fördelning efter fyra olika behandlingar (12 provytor per behandling).*

The stand height decreased to 24 m (T and TS treatment) and 25m (TN) after cutting. The percentage of trees in the medium layer increased, while the lower layer remained rather constant (Table 5 and 8). In the upper layer (> 16 m), about 45% of trees were pine and 49% spruce.

Table 8. Percentage of stem number, basal area and standing volume in three stand layers after first harvest. *Fördelningen av stamantal, grundyta och beståndsvolym över tre olika höjdklasser efter den första huggningen.*

	T			**TS**			**TN**		
	N	BA	Vol	N	BA	Vol	N	BA	Vol
Lower layer	14%	2%	1%	16%	3%	1%	16%	3%	1%
Medium layer	58%	32%	24%	54%	30%	22%	56%	31%	23%
Upper layer	28%	66%	75%	30%	67%	77%	28%	66%	76%
Total stand	873 trees/ha	21.4 m²/ha	181 m³/ha	902 trees/ha	22.7 m²/ha	196 m³/ha	700 trees/ha	19.8 m²/ha	173 m³/ha

Table 9 shows theoretical removals, if a particular treatment would have been applied completely on all 48 plots. Then, the conventional target diameter cutting would have been reduced the standing volume from 322 to 180 m³ per ha (12 and 9 m³ SE). Treatment TN would have reduced the volume to 197 m³ per ha (11 m³ SE).

Table 9. Initial stand characteristics and theoretical removals if a particular treatment would had been applied on all 48 plots. *Initial beståndskarakteristik och teoretiska uttag om de olika behandlingarna hade tillämpats på samtliga av 48 provytorna.*

Species	before cut				removals according to T or TS				removals according to TN			
	N [ha^{-1}]	BA [m²/ha]	dg [cm]	Vol [m³/ha]	N [ha^{-1}]	BA [m²/ha]	dg [cm]	Vol [m³/ha]	N [ha^{-1}]	BA [m²/ha]	dg [cm]	Vol [m³/ha]
Spruce	489	13.8	18.9	131	440	9.0	16.1	78	422	7.8	15.3	65
Pine	164	15.4	34.6	145	109	8.6	31.7	76	136	11.1	32.3	100
Birch	54	2.6	24.6	21	26	0.4	13.4	3	38	1.0	18.2	8
Beech	21	0.4	15.1	3	21	0.4	15.1	3	21	0.4	15.1	3
Oak	271	3.0	11.8	21	271	3.0	11.8	21	271	3.0	11.8	21
Total	*999*	*35.2*	*21.2*	*322*	*866*	*21.3*	*17.7*	*180*	*887*	*23.3*	*18.3*	*197*

Canopy gaps

In the gap survey, 174 gaps were recorded. The total gap area was 28.620 m², equal to 15% of total stand area. But the logging area was smaller: Excluding control treatment and some wet and steep sections, approximately 15 ha were logged. Furthermore, 49 gaps did not contain recently cut trees and covered 3.960 m² in total.

Figure 9. Floor of a medium-sized forest gap with about 500 m² canopy opening (after soil preparation). *Medelstor beståndslucka (ca. 500 m²) efter markberedning.*

Different sizes of canopy gaps were found. The largest gap was 1.723 m². In this gap, 25 trees were harvested in 2007, and 26 older tree remnants were also found. 112 gaps were smaller than 100 m², making up to 24% of the total gap area (Figure 10 A). In this size class, 2.9 remnants of trees were found per gap (of which 1.4 trees were cut in 2007). 16% of gaps (representing 13% of gap area) were recorded in the 100-200 m² class. Gaps larger than 1000 m² covered 18% of total gap area. Eleven gaps between 500 and 1000 m² covered 24%.

Figure 10B points out about 15-20 cut trees or remnants for gaps with 500 m² and about 30 such gap makers for 1.000 m²-openings.

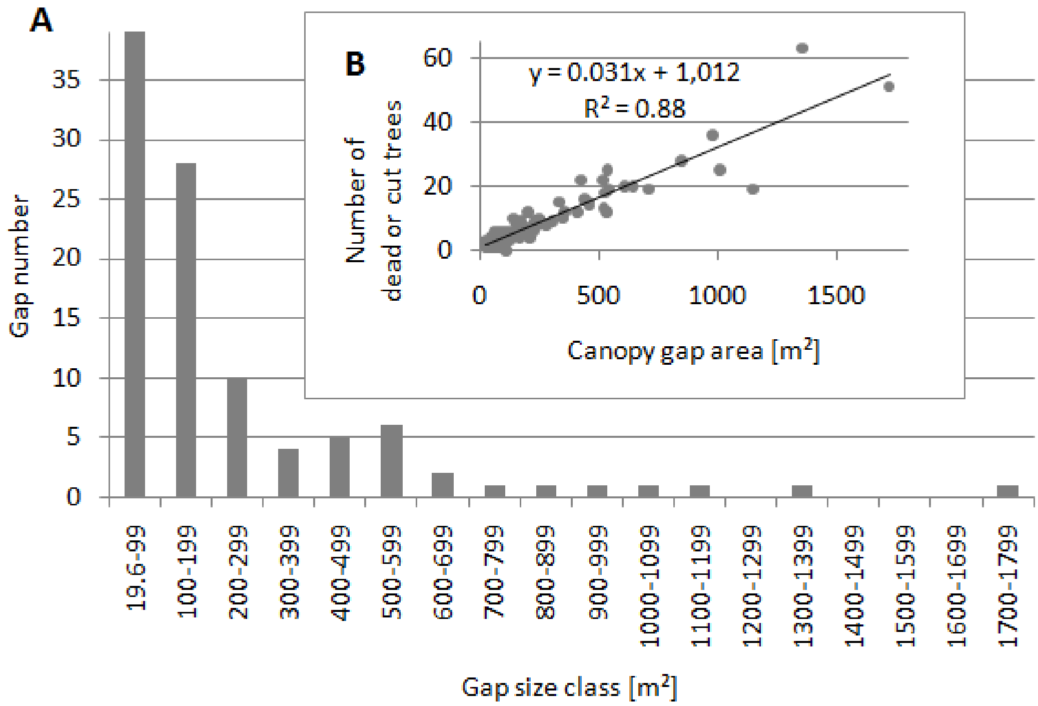


Figure 10. Gap size distribution (A) and relationship between gap size and number of removed (or dead) trees in the gap (B). *Fördelning av beståndsluckor (Bild A) och samband mellan luckstorlek och antalet avverkade träd per lucka (Bild B).*

Figure 11 and 2 demonstrate how gaps were scattered in the stand. More large gaps were found in block 2 and 3. There was also a tendency of gap occurrence along the skid roads. Regarding the gap making trees, 558 fresh and 329 older stumps, plus 172 remnants identified as wind thrown, were found in gaps. In nine gaps, single living trees in the gap were found.

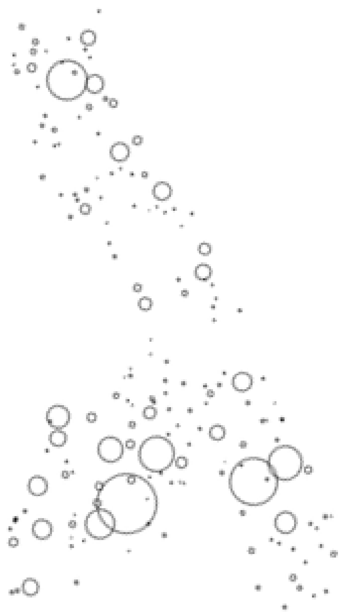


Figure 11. Spatial distribution of differently sized gaps (illustrated as circles which are based on the GPS coordinates in the gap centre). *Geografisk läge för luckor med olika storlek.*

The crown coverage recorded in the centre of gaps to characterize light conditions amounted from 75% in smallest gaps to 2% in the largest gap (Figure 12). Figure 13 illustrates that diffuse site factors below 10% compared to open land conditions occur under closed canopy, while the relationship between diffuse site factor and crown coverage is rather between 10 and 70%. In conclusion, the maximum diffuse site factors in gaps ranged from 30% in small gaps to 70% in the largest gap.

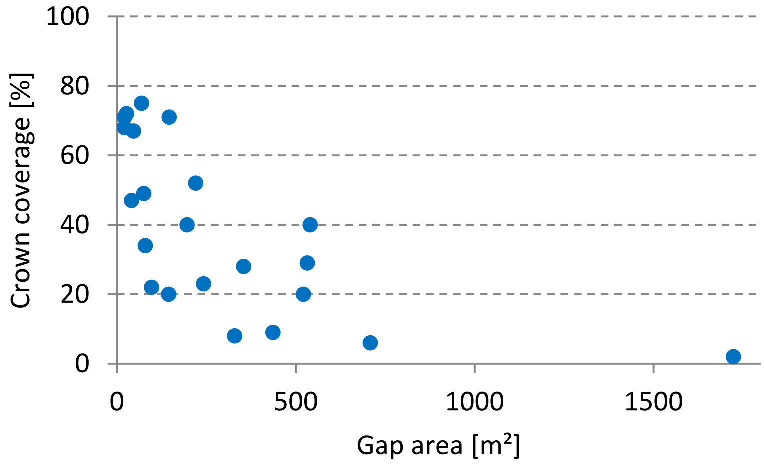


Figure 12. Gap size and crown coverage (covering the 24 degree opening of an imaginary cone from a terrestrial view) recorded in the centre of gaps. *Samband mellan luckstorlek och krontäckning (–bedömt i luckcentrum och vertikalt uppåt inom en öppningmed +/- 12° vinkel).*

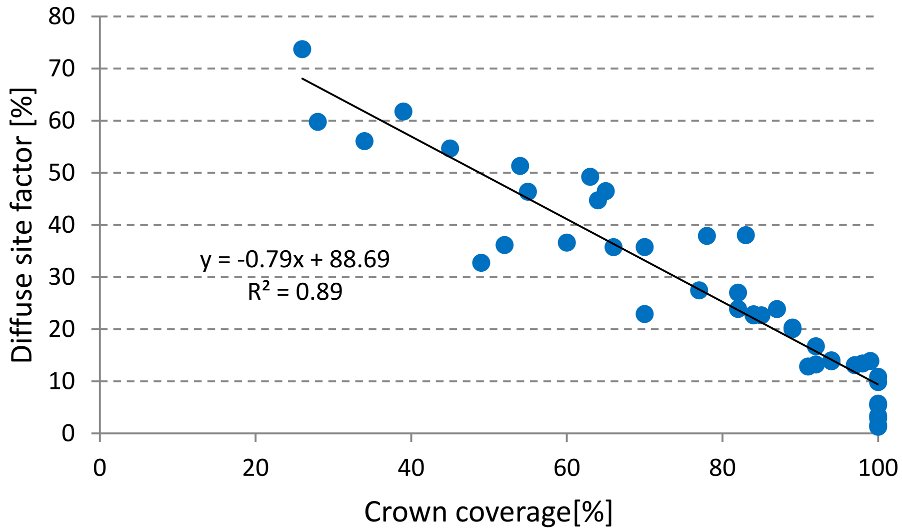


Figure 13. Correlation between diffuse site factor and crown coverage, evenly distributed across the whole range of light conditions in the forest. *Samband mellan Diffuse site factor och krontäckning över hela ljusgradienten*

On the 192 permanent regeneration plots in the stand, the crown coverage was in average 89.8% (+/- 1.2 % SE), ranging from 12 to 100%.

Regeneration
In the stand, 51 individuals were found on 196 sample plots. Only 19% of the plots were occupied with regeneration. Figure 14 shows a spot where some regeneration occurred. The regeneration density was 530 individuals/ha. On occupied plots, the density was 3.000 plants/ha. Half of these plants were smaller than 50 cm (Table 10).

Figure 14. Single, naturally regenerated seedlings of spruce and beech in the stand.
Enstaka självföryngrade plantor av gran och bok inom beståndet.

Table 10. Absolute number of regenerated trees in different height classes on the regeneration plots (Total sample area 960 m²). Height class 20-49 cm in parenthesis. *Antal plantor inom olika höjdklasser registrerade inom provtagningsområdet med en total areal av 960 m^2 (192 ytor á 5 m^2 systematisk fördelad inom beståndet).*

Height class [cm]	10-49	50-99	100-199	200-299	≥ 300
Spruce	13 (6)	4	3	5	5
Birch		1			
Oak	1 (1)			1	1
Beech	3 (3)	3			
Rowan	10 (3)	1			
Total	27 (13)	9	3	6	6

Average top shoot length per year was about 5 cm across all tree species (Table 11). Dominant tree species in the regeneration was spruce (54%), followed by rowan (20%). The frequency of beech was 11% and oak was 5%. 68% of those trees were smaller than 1 m. No pine was found.

Table 11. Average annual top shoot length [cm] considering the last three years growth of the highest individuals per species on the regeneration plots. *Årlig höjdtillväxt [cm] hos de högsta plantorna per yta i föregående tabellen under de tre år som föregick huggningen.*

Height class [cm]	10-49	50-99	100-199	200-299	≥ 300
Spruce	2	2	6	3	8
Birch	-	-	-	-	-
Oak	15	-	-	-	5
Beech	-	6	-	-	-
Rowan	4	10	-	-	-

Regeneration in gaps 2.854 individuals were counted in gaps. Thus, regeneration density was 1.003 individuals/ha. No regeneration was found in 16 of the 174 gaps. Most frequent was spruce (46%), rowan (22%) and birch (17%). Beech and oak represented 4% each. Salix, poplar and other species represented 2% of trees. The proportion of pine was below 0.5% (Figure 15). The distribution in height classes in Table 12 shows a dominance of the lowest class for all main species with an exponentially decreasing number of seedlings in larger size classes. The proportion of tree species was relatively stable over different size classes, although the decrease of oak and beech seedling numbers was less pronounced than for others. 1298 trees/ha were found in gaps < 200 m², and 820 trees/ha in gaps > 200 m². The standard error of the tree density in single gaps was 141 trees/ha.

Table 12. Absolute seedling number observed in gaps distributed over height classes (Total sample area 28.620 m²). *Antal plantor (mindre än 5 cm BHD) inom olika höjdklasser registrarade i beståndsluckorna.*

Height class [cm]	20-49	50-99	100-149	150-199	200-249	250-299	≥ 300
Spruce	672	310	131	93	41	21	32
Birch	284	129	48	16	7	2	5
Oak	77	14	8	5	9	3	7
Beech	48	33	21	5	3	6	3
Pine	14	1	-	-	-	-	-
Rowan	392	136	76	27	-	-	1
Others	71	84	15	-	2	-	2
Total	1 558	707	299	146	62	32	50

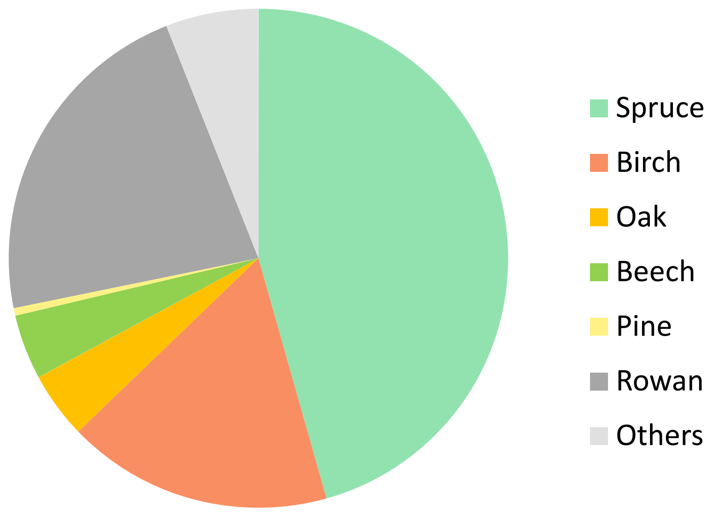


Figure 15. Tree species distribution of the regeneration in gaps.
Trädslagsfördelning hos självföryngringen i luckorna omedelbar efter huggning (gran, björk, ek, bok, tall, rönn, övriga trädslag).

Average top shoot length of spruce was 11 cm, with about 5 cm for small seedlings and about 20 cm for the tallest individuals (Table 13). Top shoot length across all species was 12.5 cm.

Table 13. Annual top shoot lengths [in cm] of the last three years of regeneration in gaps in height classes [in cm]. Number of shoot length measurements in parenthesis. *Årlig höjdtillväxt [cm] hos de högsta plantorna per lucka under de tre år som föregick huggningen (Antal av mätningar i parentes).*

	20-49	50-99	100-149	150-199	200-249	250-299	≥ 300	All size classes
Spruce	3.8 (48)	6.4 (57)	9.3 (43)	13.1 (51)	9.7 (39)	6.4 (36)	19.1 (60)	11.2 (334)
Birch	20.5 (26)	16.4 (42)	18.0 (22)	13.6 (12)	26.7 (12)	16.8 (6)	28.6 (7)	18.9 (127)
Oak	6.1 (63)	10.6 (19)	19.5 (14)	6.4 (11)	5.6 (20)	7.7 (6)	12.5 (19)	8.7 (152)
Beech	6.2 (12)	9.5 (44)	15.9 (12)	23 (3)	22.2 (20)	31.5 (16)	24.4 (9)	15.8 (102)
Pine	6.5 (29)	7.3 (3)	0	0	0	0	0	6.6 (32)
Others	9.5 (133)	13.6 (117)	21.8 (37)	17.9 (10)	15 (2)	0	17.8 (5)	13 (304)

Estimated from the heights of the largest individuals in the regeneration and the height curves of trees above 5 cm DBH, the height of spruce (and pine) with 5 cm DBH was assumed as 4 m. For other tree species, the height was approximately 5.5 m (see Figures A6-A8 in Appendix A).

The last height shoot was damaged by browsing on 57% of the broadleaved tree species. This was observed for the 474 individuals measured for height. In contrast only 2 % of the spruce seedlings were browsed (Table 14).

Table 14. Browsing damages of different tree species of regeneration in gaps. *Betesskador hos olika trädslag I självföryngringen.*

Tree species	Total tree number	Damaged by browsing	Damaged by harvest
Spruce	128	2%	22%
Oak	74	51%	22%
Birch	73	42%	19%
Beech	43	37%	28%
Pine	12	33%	8%
Rowan	106	73%	3%
Willow	20	90%	5%
Others	18	50%	11%
Total	474	41%	16%

Simulation study

The derivation of ingrowth scenarios
As stated in the methodology section, ingrowth scenarios with one, four and ten new trees per year and ha were used. However, the minimum ingrowth scenario represents expected ingrowth based on the features of advanced regeneration today. Table 15 shows expected ingrowth in five year steps on a 19 ha base, calculated from tree numbers in Table 12, height growth in Table 13, and mortality rates in Table 2. One new tree per year and ha would be equal to 95 new trees every 5 years in Table 15 (95 trees/19 ha = 1 tree x 19 ha x 5 years).

Table 15. Expected ingrowth based on characteristics of current advanced regeneration in gaps (black) and additional numbers (grey) to fulfill the average rates (bold) of the scenarios. Numbers are new trees on 19 ha total stand area after 5 years. *Förväntad inväxning inom hela beståndsarealen på 19 ha enligt tre olika scenarier (Minimum scenariot antar 10 cm årlig höjdtillväxt och hög mortalitet, Maximum: 30 cm per år och ingen dödlighet. Se samfattning)*

		year	2013	2018	2023	2028	2033	2038	2043	2048	2053	2058
scenario		period	5	10	15	20	25	30	35	40	45	50
M		spruce	30	19		34	150	114	141	*154*	*154*	*154*
I	**1 tree**	birch	2		5	15	36					
N	**per ha**	oak		6			2		6	2	4	4
		beech		3	5	7	15	14	16			
M												
E		spruce	52	116	344	465	526	*526*	*526*	*526*	*526*	*526*
D	**4 trees**	birch	4		6	35	138					
I	**per ha**	oak	7		13	11	60					
U		beech	3		8	22	55					
M												
M	**10**	spruce	94	535	672	1171	1171	1171	1171	1171	1171	1171
A	**trees**	birch	14	193	284							
X	**per ha**	oak	19	27	77							
		beech	28	59	48							

Assuming the height growth in Table 13 and mortality rates in Table 2, the black numbers in Table 15 indicate tree numbers that would pass the 5 cm threshold in five year periods. Most of the small trees would have reached 5 cm DBH after 15, 25 or 35 years depending on the scenario. The grey figures indicate tree numbers that had to be added to achieve the average ingrowth rates applied in the scenario construction. The ingrowth during this latter period corresponds to 1.6, 5.5 and 12.3 trees per year and ha for the whole stand.

Box 2. Calculation of mortality estimates indicated by adjacent height classes
The presumed mortality in Table 2 was corroborated by the decline of tree numbers from one height class to a larger class (Table 12) and the estimated time period to grow from the medium height of one class to another (e.g. from 35 cm to 75 cm for the two smallest height classes). The mean annual height growth of both classes (Table 13) determined the time period to grow to the next height class (e.g. spruce in the smallest class: 7.8 years = (75 cm - 35 cm)/5.1 cm). This time period and the tree number in both height classes were used to calculate an annual decline of tree number (which is in the example

$9.1\% = 1 - (\frac{311\ trees}{672\ trees})^{\frac{1}{7.8}\ years}$).

All tree species showed a reasonable trend of decreasing mortality with increasing height. While tree number decline of spruce and oak was stable, the limited number of individuals caused a high variation for beech. However, more apt mortality rates used for the simulation (Table 2) resulted in the same number of beech trees for the final scenarios as the rates of 5% (< 1m), 15% (1-2 m) and 0% (> 2 m) derived directly from advanced regeneration. In general, mortality rates of tree species derived from advanced regeneration were similar to rates assumed in Table 2.

Future increment and harvests

Without tree removals, the growth simulation projected a BA increase from 35 to 53 m²/ha during the 50 year simulation period (Figure 16). If losses by natural mortality were included, the MAI of BA was to 0.53 m^2 per year and ha.
For silvicultural treatments, the simulation projected BA levels from 18 to 35 m²/ha, with 20-25 years intervals between tree removals (Figure 16). The MAI ranged between 5.6-6.4 m³/ha, depending on ingrowth. Natural mortality caused annual losses of four trees per ha (equal to 0.8 m³/ha). All management treatments did not indicate a growth regression.

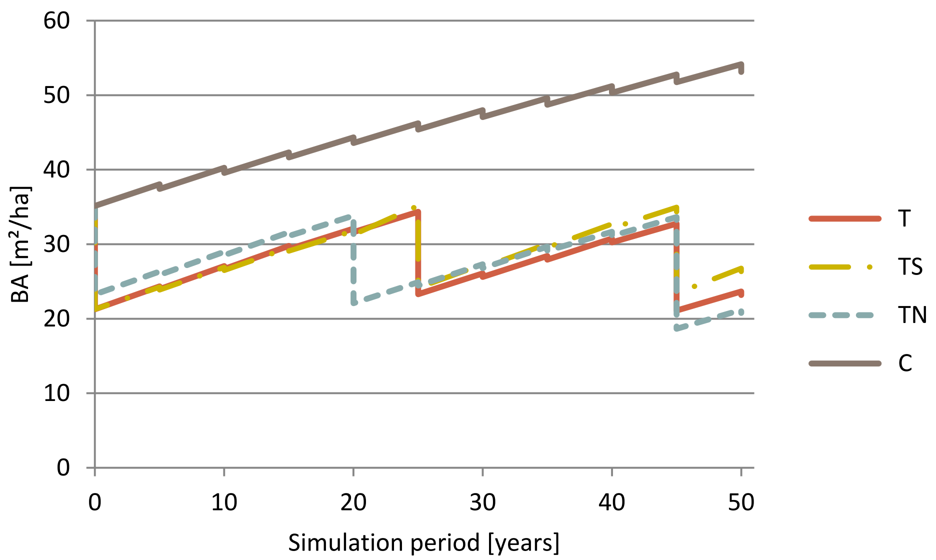


Figure 16. Basal area development of different treatments according to Elfving (2004). Projections are based on stand age-independent single tree-ages (Elfving, 2003), 100 m³/ha minimum standing volume after cut, and the medium ingrowth scenario.
Grundytans utveckling enligt vid tillämpning av de fyra olika behandlingarna T, TS, TN och C.

Initial volume estimates according to Ekö (1985) differed 0-13 m³/ha from the values calculated according to Söderberg (1992). Stand age-independent and -dependent projections did not differ significantly as shown in the next two section.

Control treatment In terms of projected volume, MAI was 6.7 m³ per ha. No ingrowth was implemented due to high stand densities on all plots over time. Starting with 322 m³/ha, the standing volume increased to 571 m³/ha (Table 16). The stand age-dependent estimation predicted 574 m³/ha volume and 53.4 m²/ha BA. Mortality reduced the tree number from 999 to 764 trees/ha. These losses represented 84 m³/ha dead wood during the whole simulation period (resp. 8.3 m²/ha BA), constantly increasing over the simulation period from 1.2 to 2.2 m³/ha annually. The total volume production during the period amounted to 334 m³/ha. Supplementing Table 16, Table C2 and C3 in Appendix C provide numbers to each scenario and growth model. - During the simulation period, BA growth declined from 0.57 m²/ha in the first decade to 0.48 m²/ha in the last decade.

Table 16. Control. Initial and simulated stand characteristics after 50 years. Projections are based on 48 plots and the stand age-independent estimation of single-tree ages.
Behandling C (kontroll). Initial och simulerad beståndskarakteristik efter 50 år för alla 48 provytor.

	start of simulation				MAI		total	end of simulation			
Species	N	BA	dg	Vol	BA	Vol	mortality	N	BA	dg	Vol
	[ha]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[m³/ha]	[ha]	[m²/ha]	[cm]	[m³/ha]
Spruce	489	13.8	18.9	131	0.25	3.3	35	393	23.1	27.3	260
Pine	164	15.4	34.6	145	0.18	2.4	31	139	21.6	44.5	233
Birch	54	2.6	24.6	21	0.02	0.2	6	38	2.8	31.1	25
Beech	21	0.4	15.1	3	0.01	0.2	1	15	0.8	26.2	9
Oak	271	3.0	11.8	21	0.06	0.7	12	179	4.8	18.5	43
Total	*999*	*35.2*	*21.2*	*322*	*0.53*	*6.7*	*84*	*764*	*53.1*	*29.8*	*571*

At the start of the simulation period, half of the plots ranged between 30 and 40 m²/ha BA (Figure 17). After 50 years, 50% of the plots ranged between 46 and 58 m²/ha. The extreme values among the 48 plots were 33 and 71 m²/ha.

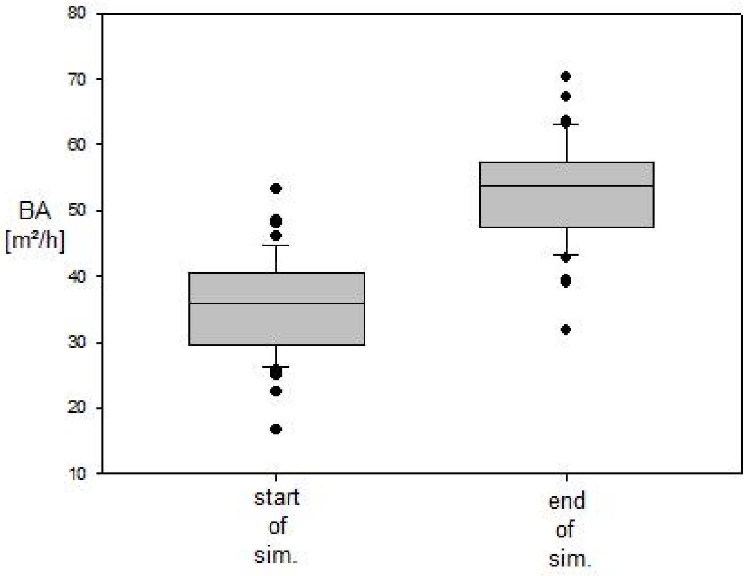


Figure 17. Initial variation of basal area on plots and projected basal area for the control treatment after 50 years.
Grundytans variation mellan provytorna i början och slutet av simuleringsperioden enligt behandling C.

Figure 18 shows the decrease in numbers of small trees over time. For instance, trees with DBH < 19 cm decreased from 600 to 250 trees per ha. There are no trees in the smallest diameter class with 5-6 cm DBH.

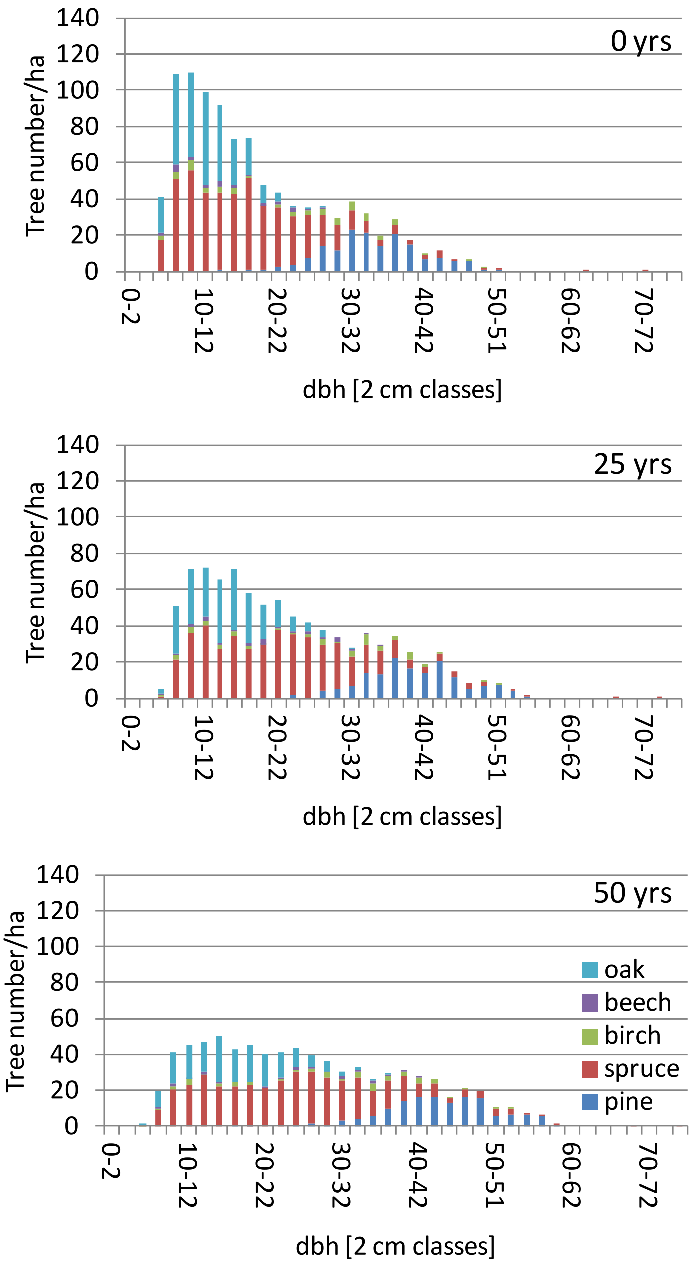


Figure 18. Initial and projected diameter distributions [in 2 cm classes] projected for the control treatment at age 0, 25 and 50 (stand age-independent estimation of tree ages).
Initial och beräknad BHD-fördelning efter 25 och 50 år inom behandlingen C utan avverkning [2 cm BHD klasser!].

Treatment T After 50 years, tree number decreased by 194 trees per ha. The MAI for this period was projected with 5.8-6.3 m³/ha, depending on the ingrowth scenario (Table C5 in the Appendix). According to the moderate ingrowth scenario, about 120 m³/ha of the standing volume would be removed after 25 and 45 years (Table 17). Standing volume did not fall below 150 m³/ha after the next two simulated harvests, independent from the two thresholds initially set for simulation. As long as standing volume before cut was minimum 300 m³/ha, no effects of the two thresholds on harvest removal and remaining stand volume were detected. Simulation results with other ingrowth scenarios are shown in Table C5 in Appendix C.

Table 17. Treatment T - medium ingrowth scenario, initial and simulated stand parameters after 50 years (based on 48 plots, stand age-independent single-tree ages).
Behandling T med moderat inväxningsscenario - initial och simulerad beståndsparametrar efter 50 år.

	start of simulation				removals after				MAI		end of simulation			
Species	N	BA	dg	Vol	25 years		45 years		BA	Vol	N	BA	dg	Vol
	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]
Spruce	440	9.0	16.1	77	4.2	46	4.6	52	0.30	3.3	410	13.0	20.1	127
Pine	109	8.6	31.7	76	6.0	60	5.2	51	0.11	1.3	21	2.4	37.5	22
Birch	26	0.4	13.4	3	0.2	2	0.1	1	0.01	0.1	32	0.4	12.8	3
Beech	21	0.4	15.1	3	0.4	4	0.5	5	0.02	0.2	8	0.3	22.1	3
Oak	271	3.0	11.8	21	0.3	2	1.3	12	0.13	1.1	200	7.1	21.2	55
Total	*866*	*21.3*	*17.7*	*180*	*11.0*	*114*	*11.7*	*121*	*0.56*	*5.9*	*672*	*23.2*	*21.0*	*209*

A block-wise simulation according to the medium ingrowth scenario revealed MAI ranging from 5.8 m³/ha in block 2 to 6.3 m³/ha in block 3 with higher proportion of spruce (Table C7-C12 in Appendix C). Cutting intervals were about 25 years. The volume proportion of spruce increased from 58 to 81% in block 3, and from 30 to 42-44% in the two others.

The MAI of BA was 0.56 m²/ha (or 0.53 and 0.60 with min and max ingrowth). Thus, BA growth was predicted 7% higher for treatment T compared to the control, while volume growth was 11% lower than the control!
During the simulation period, BA growth declined from 0.62 m²/ha in the first decade to 0.51 m²/ha in the last decade.

Figure 19 shows the variation of BA between sample plots (according to the moderate ingrowth scenario and stand age-independent single tree-ages). The mean values were reduced by 15 m²/ha during the simulation period, but the variation did not decrease after cuttings.

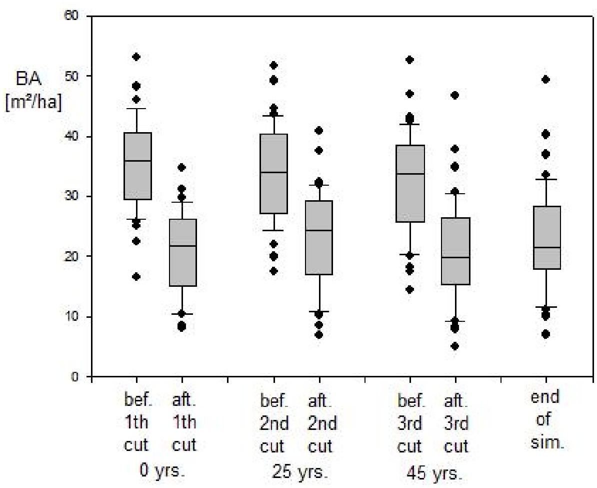


Figure 19. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on plots at different times during the simulation (treatment T).
Grundytans variation mellan provytorna i början och slut av simuleringsperioden (Behandling T).

Beside reduced tree number, the diameter distributions in Figure 20 indicated a lack of small trees and a surplus of trees with 15-20 cm DBH after 50 years. The minimum ingrowth scenario resulted in a bell-shaped distribution with a high number of trees between 15-30 cm DBH. More evenly distributed tree numbers across size classes was projected within the moderate scenario. The maximum scenario indicated a peak in DBH class 8-10 cm with 150 trees after 25 years, and a decrease of tree numbers with increasing size for trees larger than 15 cm DBH after 50 years. For smaller trees, a decreasing number was projected.
The proportion of spruce at the end of the simulation period was 55-66% of the total tree number, and 55-59% of total BA.

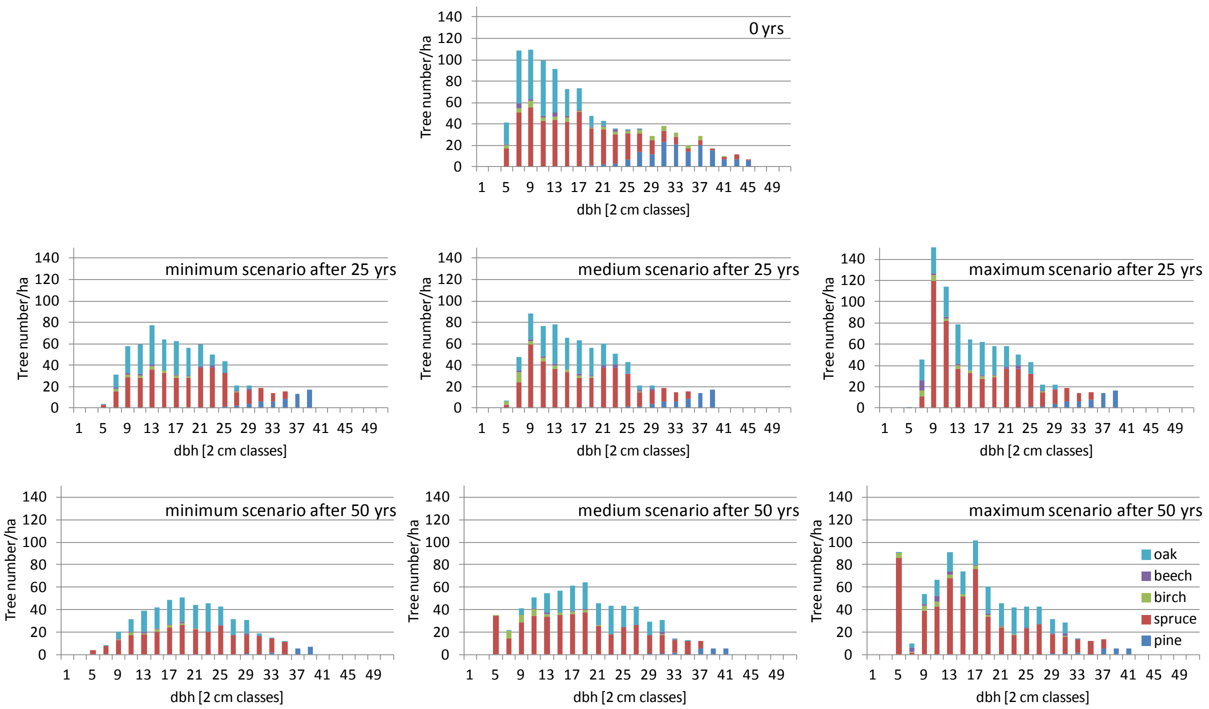


Figure 20. Projected diameter distributions according to treatment T and different ingrowth scenarios at the age of 25 and 50 years (based on 48 plots and stand age-independent single-tree age). *Beräknade BHD-fördelningar efter 25 och 50 år enligt behandling T med tre olika inväxtscenarierna.*

Treatment TS Depending on new trees after scarification, the MAI was 5.8-6.4 m³/ha volume respective 0.55-0.64 m²/ha BA (see Table C13 in Appendix C for different ingrowth scenarios). At the end of the simulation period, the number of living trees was 30-100% higher compared to treatment T. The final standing volume, five years after the last harvest, was 214 m³/ha according to the moderate ingrowth scenario (Table 18).

Table 18. Treatment TS - moderate ingrowth, initial and simulated stand parameters after 50 years (based on 48 plots, stand age-independent single-tree ages). *Behandling TS med moderat inväxningsscenario - initiala och simulerade beståndsparametrar efter 50 år.*

	start of simulation				removals after				MAI		end of simulation			
Species	N	BA	dg	Vol	25 years		45 years		BA	Vol	N	BA	dg	Vol
	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]
Spruce	440	9.0	16.1	78	4.2	45	4.5	51	0.30	3.3	545	13.4	17.7	128
Pine	109	8.6	31.7	76	6.0	60	5.2	51	0.13	1.4	143	3.0	16.4	26
Birch	26	0.4	13.4	3	0.2	2	0.1	1	0.01	0.1	48	0.4	10.3	3
Beech	21	0.4	15.1	3	0.4	4	0.5	5	0.02	0.2	8	0.3	22.0	3
Oak	271	3.0	11.8	21	0.3	2	1.3	12	0.13	1.1	208	7.1	20.9	55
Total	*866*	*21.3*	*17.7*	*180*	*11.1*	*113*	*11.58*	*120*	*0.59*	*6.0*	*952*	*25.2*	*18.0*	*214*

According to the maximum scenario, the standing volume would be 239 m³/ha. For the minimum scenario, 172 m³/ha were estimated just after harvest (see Tables C13 in Appendix C). Stand age-dependent single-tree ages caused lower growth predictions the more ingrowth was assumed (Table C14 in the Appendix). The variation of the BA on plots during the simulation period in Figure 21 was very similar to treatment T.

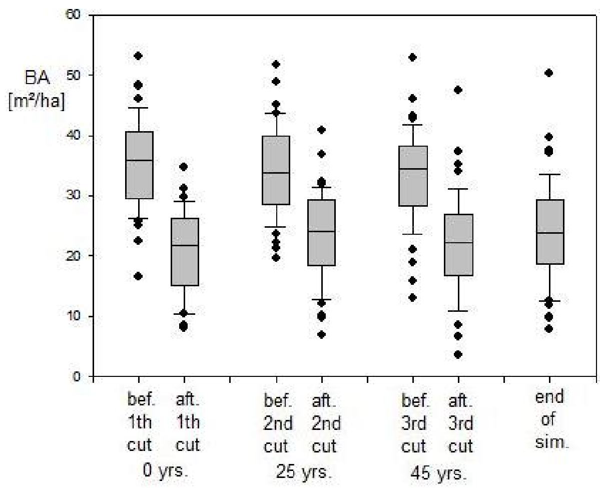
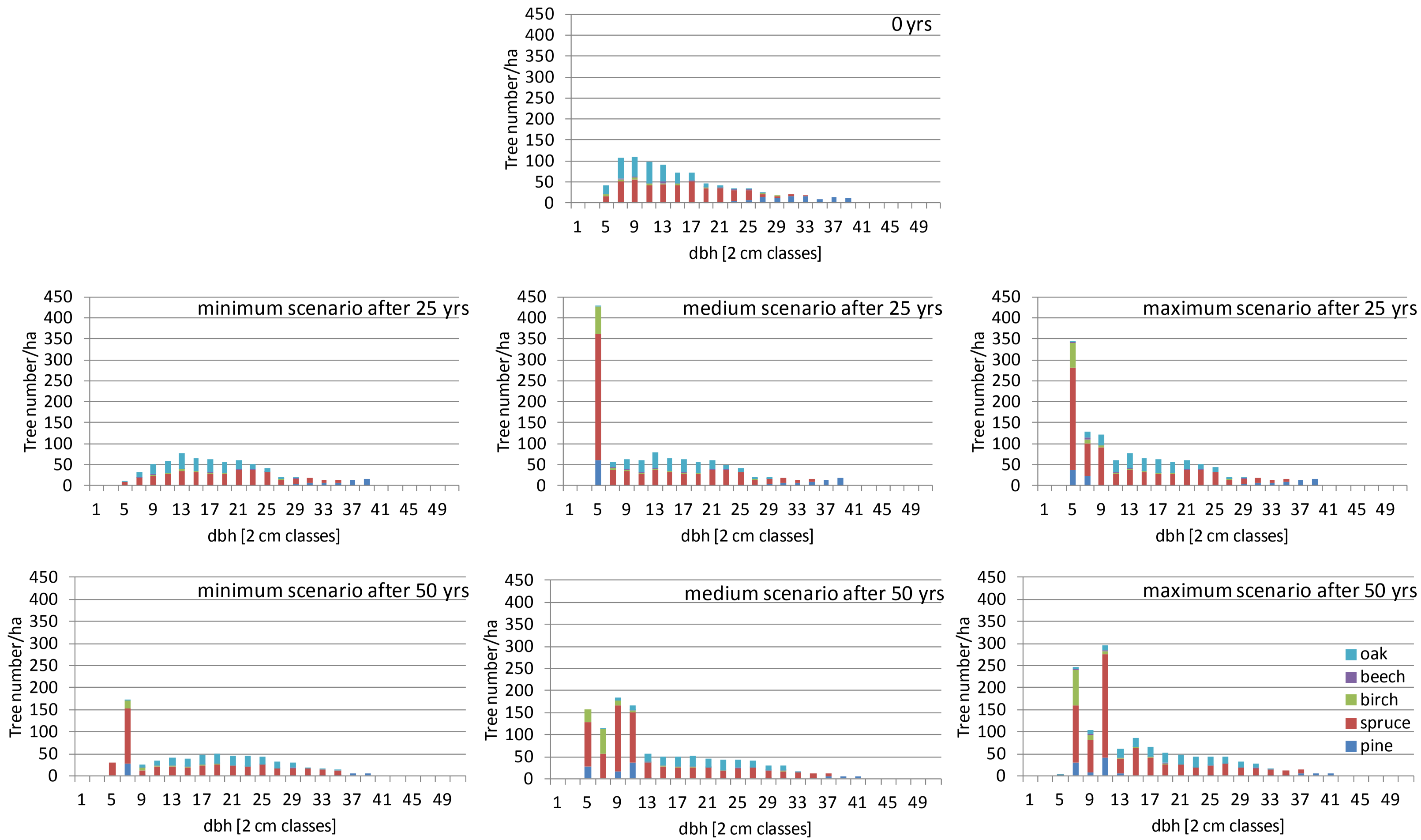


Figure 21. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on plots at different times during the simulation (treatment TS). *Grundytans variation mellan provytorna i början och slutet av simuleringsperioden (Behandling TS).*

Future diameter distributions show a large number of small trees after 25 or 50 years (Figure 22). In the medium scenario, 618 trees/ha with 4.5-12 cm DBH were estimated, with 1113 trees/ha in total. The minimum scenario resulted in 262 trees below 12 cm DBH and 692 trees/ha in total, while the maximum scenario projected 591 trees below 12 cm DBH and 1201 trees/ha in total. During the simulation period, BA proportion of spruce increased from 39% to 57%. In terms of tree number, spruce increased from initially 50 to 60-63% (Table C13 in the Appendix).

Figure 22. Projected development of the diameter distribution according to treatment TS and different ingrowth scenarios at the age of 25 and 50 years (based on stand age-independent single-tree age).

Beräknad BHD-fördelning efter 25 och 50 år enligt behandling TS med tre olika inväxtscenarierna.



Treatment TN had the lowest standing volume after 50 years, and a low number of trees (Table 19). The MAI was simulated with 5.6-6.1 m³/ha volume respective 0.53-0.61 m²/ha BA. Figure 23 indicates a decreased variation of BA on plots after heavier removals by the 3rd cutting.

Table 19. Treatment TN - moderate ingrowth scenario, initial and simulated stand parameters after 50 years (based on stand age-independent single-tree ages). *Behandling TN med moderat inväxningsscenario - initiala och simulerade beståndsparametrar efter 50 år.*

Species	start of simulation				removals after				MAI		end of simulation			
	N	BA	dg	Vol	20 years		45 years		BA	Vol	N	BA	dg	Vol
	[ha^{-1}]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[m²/ha]	[m³/ha]	[ha^{-1}]	[m²/ha]	[cm]	[m³/ha]
Spruce	422	7.8	15.3	65	5.1	53	6.6	70	0.25	2.7	304	6.9	17.0	60
Pine	136	11.1	32.3	100	6.0	60	8.0	81	0.14	1.6	29	3.2	37.4	29
Birch	38	1.0	18.2	8	0.6	5	0.3	3	0.01	0.1	32	0.5	14.8	4
Beech	21	0.4	15.1	3	0.0	0	0.0	0	0.02	0.3	22	1.4	28.8	15
Oak	271	3.0	11.8	21	0.1	1	0.1	1	0.13	1.1	222	8.4	21.9	65
Total	*887*	*23.3*	*18.3*	*197*	*11.7*	*119*	*15.0*	*155*	*0.55*	*5.7*	*609*	*20.4*	*20.7*	*174*

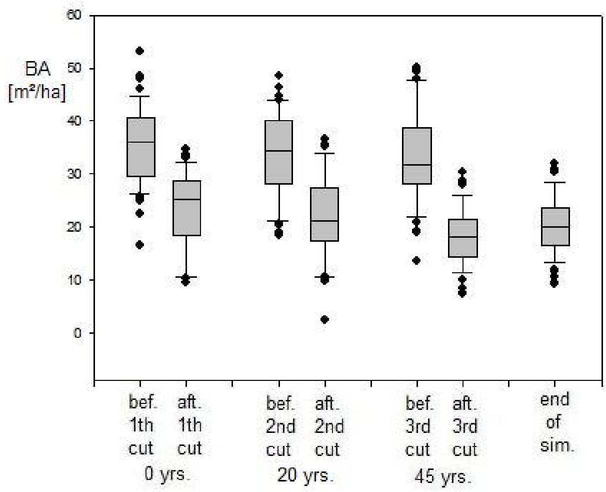


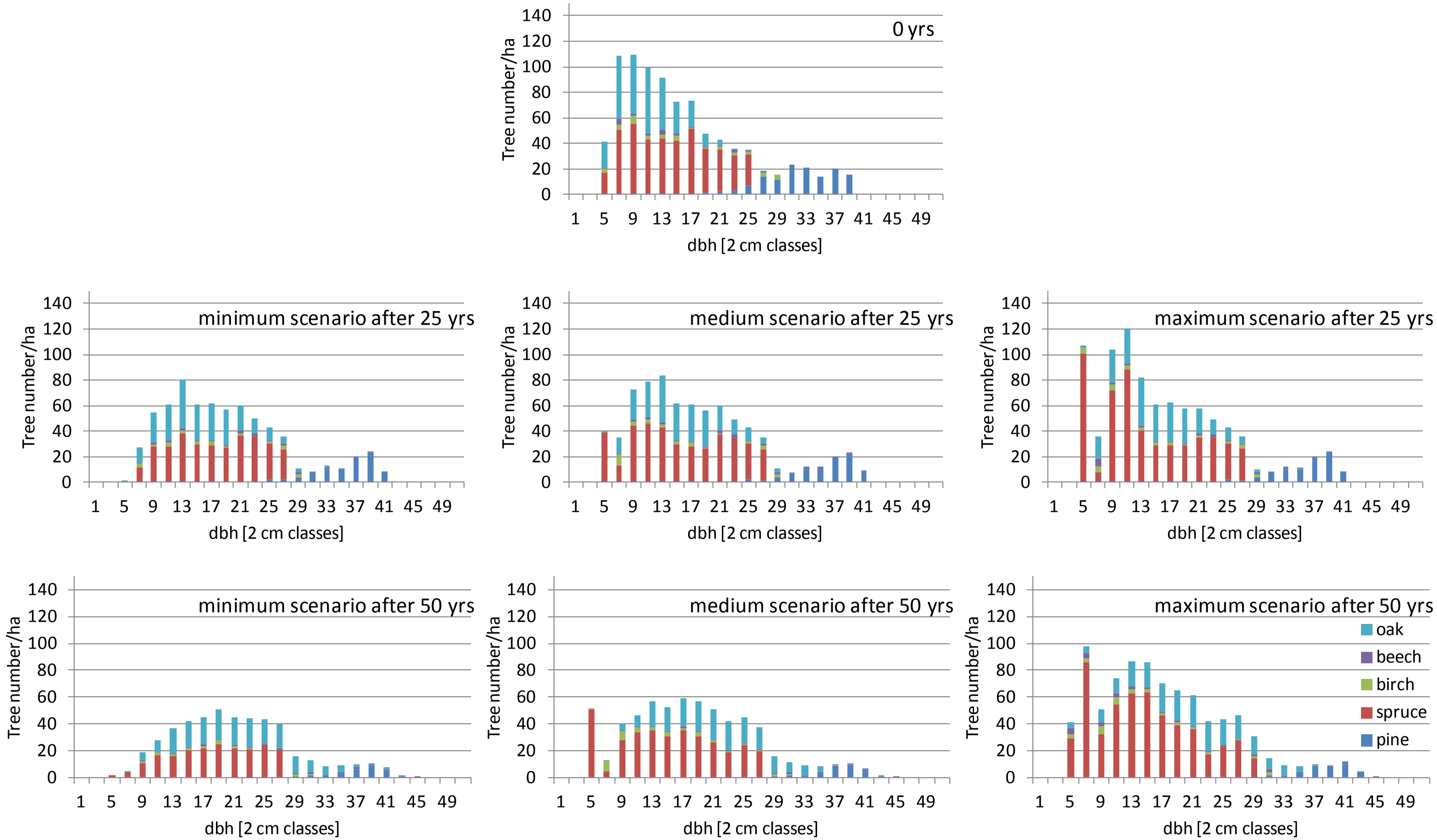
Figure 23. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on plots at different times during the simulation (treatment TN). *Grundytans variation mellan provytorna i början och slutet av simuleringsperioden (Behandling TN).*

The diameter distributions with moderate ingrowth displayed a lower number of small trees and a more pronounced surplus of medium-sized trees than at the start of simulation (Figure 24). Only the maximum scenario demonstrated the potential after 25 years to maintain a similar stand structure as today. After 50 years, a lack of trees with DBH < 12 cm was indicated.

The final proportion of spruce was 43-60% of trees, depending on assumed ingrowth. For trees with DBH < 20 cm, the spruce proportion was 5-6% higher.

Figure 24. Projected development of the diameter distribution in treatment TN according to ingrowth scenarios at the age of 25 and 50 years (based on 48 plots and stand age-independent single-tree age).

Beräknad BHD-fördelningar efter 25 och 50 år enligt behandling TN med tre olika inväxtscenarierna.



Alternation of target diameters Cuttings with 5 cm higher target diameters (treatment T+5) resulted in higher stand densities than treatment T with original target diameters (ranging from 27 to 40 m²/ha over the simulation period). Harvest removals were lower, but 20-25 years cutting intervals were similar to treatment T.
Cuttings according to 5 cm lower diameters reduced BA from approx. 35 to 15 m²/ha, the cutting interval increased to 35 years (Figure 25). The MAI was 0.55 and 0.57 m²/ha BA for treatment T+5 and T-5. MAI in terms of volume resulted in 0.6 m³/ha differences annually between Treatment T+5 and T-5 (Table 20 and 21).

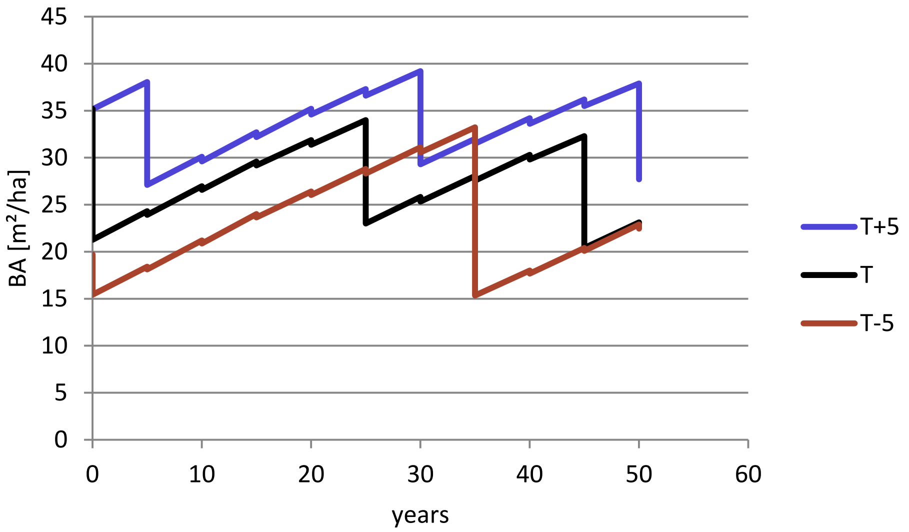


Figure 25. Basal area development according to cutting with 5 cm higher (blue), 5 cm lower target diameters (red), and the original target diameters (black). Projections are based on stand age-independent single-tree ages and 100 m^3/ha minimum standing volume after cut. *Grundytans utveckling enligt behandlingen T (svart) i jämförelse med 5 cm högre (blå) och 5 cm lägre (röd) måldiameter.*

With larger diameters, the variation of the BA on plots increased somewhat during the simulation period (Figure 26), covering a large range just before cutting from 17 to 61 m²/ha, but also after cutting from 7 to 53 m²/ha. The diameter distributions in Figure 27 indicated a very small number of trees between 5-10 cm DBH after 50 years.

Table 20. Simulated initial stand parameters and after 50 years, with mean annual increment and harvest, according to treatment **T** with **5 cm higher target diameters** (stand age-independent single-tree ages, moderate ingrowth). *Behandling T med 5 cm högre måldiameter (moderat inväxt) - initiala och simulerade beståndsparametrar efter 50 år.*

	start of simulation				MAI		Time of	1th cut	2nd cut	3rd cut	end of simulation			
Species	N	BA	dg	Vol	BA	Vol	cutting	removal	removal	removal	N	BA	dg	Vol
	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[years]	[m/ha]	[m/ha]	[m/ha]	[ha⁻¹]	[m²/ha]	[cm]	[m³/ha]
Spruce	489	13.8	18.9	131	0.27	3.3		44	39	47	347	14.09	22.7	143
Pine	164	15.4	34.6	145	0.15	1.8		52	58	52	51	6.40	39.8	62
Birch	54	2.6	24.6	21	0.01	0.1		16	4	1	21	0.36	14.8	3
Beech	21	0.4	15.1	3	0.02	0.2		0	2	5	11	0.46	23.2	4
Oak	271	3.0	11.8	21	0.10	0.9		1	1	5	199	6.52	20.4	52
Total	*999*	*35.2*	*21.2*	*322*	*0.55*	*6.2*	5/30/50	*114*	*105*	*110*	*629*	*27.83*	*23.7*	*265*

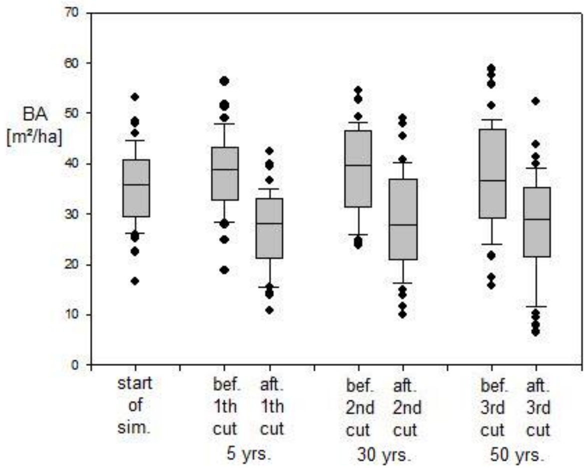


Figure 26. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on plots at different times during the simulation (treatment T+5). *Grundytans variation mellan provytorna i början och slutet av simuleringsperioden (Behandling T men med 5 cm högre måldiameter).*

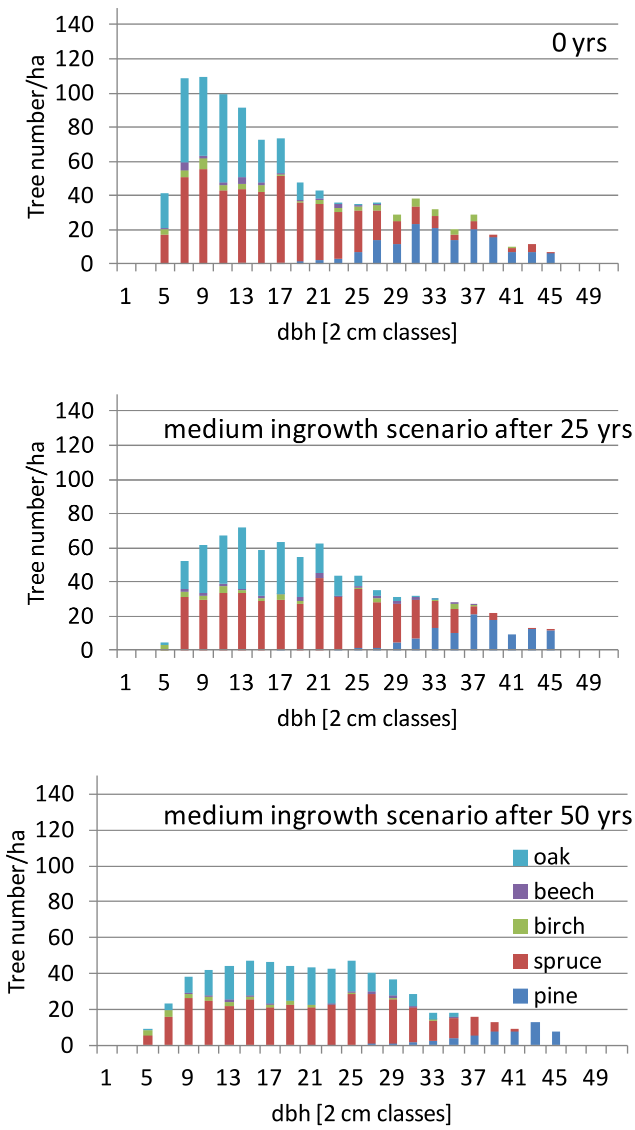


Figure 27. Initial and projected diameter distributions according to cuttings with 5 cm higher target diameters at the age of 0, 25 and 50 years (moderate ingrowth). *Beräknad BHD-fördelningar efter 25 och 50 år enligt behandling T med 5 cm högre måldiameter (moderat inväxning).*

Table 21. Simulated initial stand parameters and after 50 years, with mean annual increment and harvest, according to treatment **T** with **5 cm lower target diameters** (stand age-independent single-tree age, medium ingrowth scenario). *Behandling T med 5 cm lägre måldiameter (moderat inväxt) - initiala och simulerade beståndsparametrar efter 50 år.*

Species	start of simulation				MAI		Time of	1th cut	2nd cut	end of simulation			
	N	BA	dg	Vol	BA	Vol	cutting	removal	removal	N	BA	dg	Vol
	[ha^{-1}]	[m²/ha]	[cm]	[m³/ha]	[m²/ha]	[m³/ha]	[years]	[m/ha]	[m/ha]	[ha^{-1}]	[m²/ha]	[cm]	[m³/ha]
Spruce	401	7.2	15.1	59	0.32	3.4		69	85	551	13.45	17.6	124
Pine	71	4.8	29.4	40	0.07	0.8		104	67	9	0.97	36.1	9
Birch	22	0.2	10.6	1	0.01	0.1		20	1	55	0.42	9.8	3
Beech	19	0.3	14.0	2	0.02	0.2		1	7	8	0.31	22.8	3
Oak	271	2.9	11.8	21	0.15	1.2		0	19	195	7.31	21.9	57
Total	*783*	*15.4*	*15.8*	*124*	*0.57*	*5.6*	0/35	*194*	*180*	*818*	*22.46*	*18.7*	*195*

5 cm lower target diameters resulted in heavy removals of 179-212 m³/ha and low standing volumes of 124 and 122 m³/ha after cut (with moderate ingrowth). An important difference to treatment T were longer harvest intervals of 35-40 years (Table C21 in the Appendix). But, BA and volume increased steadily after such heavy removals. Compared to treatment T, the MAI decreased from 5.9 to 5.6 m³/ha (Table C21).

The more or less bimodal diameter distribution after 50 years in Figure 29 points on a larger number of small trees than the original target diameter cutting. But, decreasing BA variation between plots can indicate more homogeneous stand structures too (Figure 28).

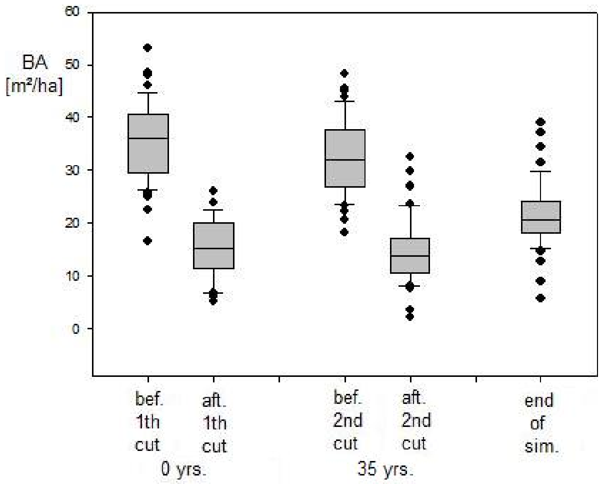


Figure 28. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on plots at different times during the simulation (treatment T-5). *Grundytans variation mellanprovytorna i början och slutet av simuleringsperioden (Behandling T med 5 cm lägre måldiameter).*

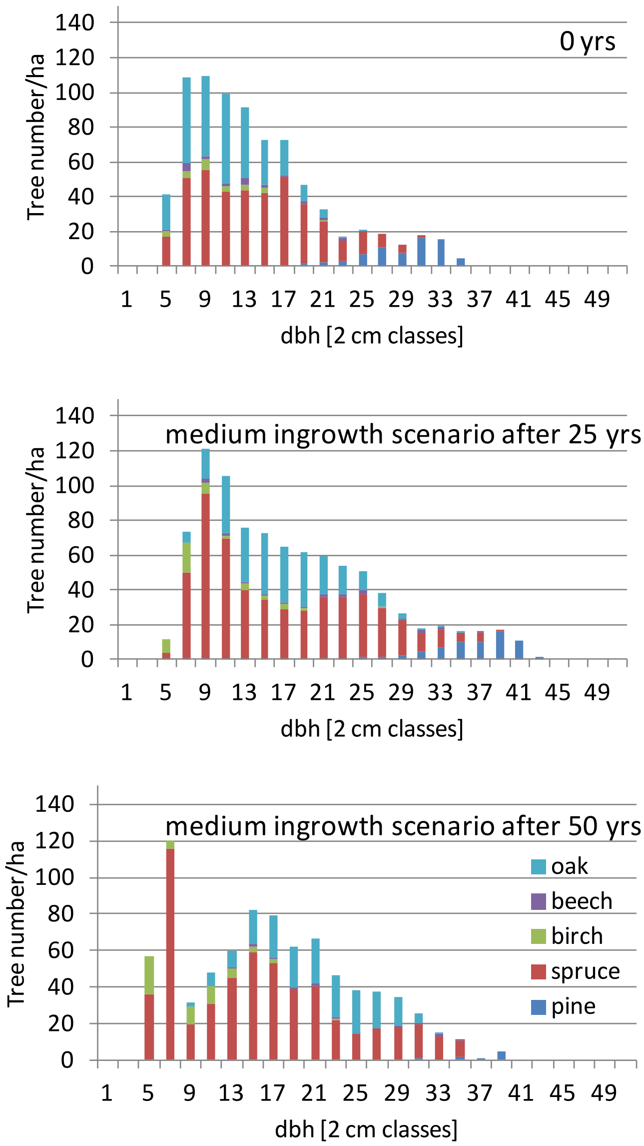


Figure 29. Initial and projected diameter distribution according to cuttings with 5 cm higher target diameters at the age of 0, 25 and 50 years (moderate ingrowth scenario). *Beräknad BHD-fördelningar efter 25 och 50 år enligt behandling T med 5 cm lägre måldiameter (moderat inväxning).*

Projected tree species composition Current diameter distributions indicated already future changes from pine towards more spruce and oak in the overstory. The proportion of spruce trees increased in all treatments with moderate ingrowth. In the control, the proportion increased by 2.5% after 50 years (Table 22). Even in treatment TN, the spruce proportion increased by 2.3%. Only according to the minimum scenario, its proportion decreased by 3.9%. The maximum ingrowth scenario indicated an increase by 8.8%. In treatment T and TS, an increase by 10.2 respective 6.4% was projected. In the treatments with alternated target diameters an increase by 5.2 and 16.1% spruce of total tree number was projected.
In terms of BA, the proportion increased by 4.4% in the control treatment. An increase by 13.4 and 10.8% was simulated for treatment T and TS. In treatment TN, the BA proportion was projected relatively constant with 0.3%. Alternated target diameters resulted in increases of 11.4 and 13.3%.

Table 22. Projected changes of spruce proportion after 50 years depending on treatment and ingrowth scenario (no projections according to the minimum and maximum ingrowth scenario were made for treatment T+5 and T-5). *Beräknade förändringar av granandel efter 50 år, beroende på behandling och inväxningsscenario (N% = relativ stamantal, BA% = relativ andel av grundyta).*

Treat-	N%			BA%		
ment	min	medium	max	min	medium	max
C	+2.5	+2.5	+2.5	+4.4	+4.4	+4.4
T	+3.4	+10.2	+11.8	+11.6	+13.4	+16.0
TS	+14.1	+6.4	+8.3	+13.9	+10.8	+15.2
TN	-3.9	+2.3	+8.8	-2.9	+0.3	+4.5
T+5	-	+5.2	-	-	+11.4	-
T-5	-	+16.1	-	-	+13.3	-

Estimated income according to simulation results

With 110-140 m3 harvest removals (equal to 88-112 m3 marketable wood) in 20-25 year intervals, a considerable positive income is possible. Constant future prices equal to the average from 2006-2011 (source: SÖDRA price list), no saw timber for broadleaves, timber quality 1 for pine stems classified in the stand as quality class 1, and pallet timber for crown compartments and pine trees with quality class 2 were assumed. Calculations were based on 125 SEK/m³ harvesting costs, equal to the first cutting. Under such conditions, about 30000 ± 5000 SEK can be expected as net revenue at each harvest according to treatment T and TS. However, the gross income proportion of pine was 62% at the first harvest, and will decrease rapidly. 35% of the first income according to treatment T came from pine logs with timber quality 1. These high quality logs had a volume proportion of 24% of the marketable wood. No price differences between quality classes for spruce were assumed. Log lengths were calculated according to Nilsson & Fahlvik (2006). Table 22-24 present the estimated income and costs according to these presumptions and a discount rate of 2%, according to the three different treatments T, TS, and TN. Table 25 describes income and costs if the final felling would be clearcutting. (Results for 0 and 4% interest rates are shown in Appendix E.)

Table 22. Yield table for treatment T. Figures were calculated per ha. Interest rate 2%.

Produktionstabell för behandling T, värden per ha, ränta 2%.

		Stand before thinning			Removed							Net		Annual	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	NPV
	[yrs]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	52								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	18								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	35518	35518		
Spruce	25	459	15.6	152	61	4.2	45								
Pine	25	103	11.8	113	44	6.0	60								
Broadleaves	25	287	6.6	51	16	0.9	8								
Total	25	849	34.1	316	121	11.0	113	6.1	Harvest	39845	11300	28545	17399		
Spruce	45	423	16.2	163	62	4.7	53								
Pine	45	57	7.3	71	36	5.1	51								
Broadleaves	45	276	8.8	71	28	1.9	17								
Total	45	756	32.3	305	126	11.7	121	5.9	Harvest	43290	12100	31190	12794	2185	65711

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table 23. Yield table for treatment TS. Figures were calculated per ha. Interest rate 2%.

Produktionstabell för behandling TS, värden per ha, ränta 2%.

		Stand before thinning			Removed							Net		Annual	NPV
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	year 0
	[yrs]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	53								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	19								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	30518	30518		
	0								Soil prep.		2500				
	0								Cleaning		2500				
Spruce	25	641	15.8	151	63	4.2	45								
Pine	25	191	12.0	113	44	6.0	60								
Broadleaves	25	307	6.7	51	17	0.9	8								
Total	25	1139	34.5	315	124	11.1	113	6.0	Harvest	39845	11300	23545	14351		
	25								Soil prep.		2500				
	25								Cleaning		2500				
Spruce	45	555	16.6	165	63	4.5	51								
Pine	45	137	7.8	75	38	5.2	51								
Broadleaves	45	283	8.9	71	28	1.9	18								
Total	45	975	33.3	311	129	11.6	120	6.1	Harvest	43290	12000	26290	10784	1607	55653
	45								Soil prep.		2500				
	45								Cleaning		2500				

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table 24. Yield table for treatment TN. Figures were calculated per ha. Interest rate 2%.

Produktionstabell för behandling TS, värden per ha, ränta 2%.

		Stand before thinning			Removed							Net	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV
	[yrs]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	68	6.0	64						
Pine	0	164	15.4	144	28	4.3	44						
Broadleaves	0	346	5.9	45	17	1.6	13						
Total	0	999	35.2	318	113	11.9	121		Harvest	30886	12100	18786	18786
Spruce	20	436	12.7	119	84	5.1	53						
Pine	20	131	14.4	136	42	6.0	60						
Broadleaves	20	303	6.6	51	16	0.7	6						
Total	20	870	33.7	306	142	11.7	119	6.0	Harvest	46843	11900	34943	23516
Spruce	45	379	12.7	123	103	6.6	70						
Pine	45	84	11.0	108	55	8.0	81						
Broadleaves	45	280	9.7	80	11	0.4	4						
Total	45	743	33.4	311	169	15.0	155	5.7	Harvest	59851	15500	44351	18193

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table 25. Yield and cost projections for clearfelling, planting of spruce on this site, and typical even-aged forest management with 60 years rotation. Figures calculated per ha with the forest simulator DT (Nilsson & Fahlvik, 2006). Interest rate 2%.

Produktionstabell för kalavverkning och granplantering, värden per ha, ränta 2%.

	Time [yrs.]	Stand before thinning N	Stand before thinning BA [m²]	Stand before thinning V [m³]	Removed N	Removed BA [m²]	Removed V [m³]	MAI [m³]	Treatment	Income [SEK]	Cost [SEK]	Net income [SEK]	PV [SEK]	Annual revenue [SEK]	NPV (year 0) [SEK]
Spruce	0	489	13.8	129	489	13.8	129			32904					
Pine	0	164	15.4	144	164	15.4	144			72079					
Broadleaves	0	346	5.9	45	346	5.9	45			9223					
Total	0	999	35.2	318	999	35.2	318		Harvest	114206	31800	64406	64406		
	0								Soil prep.		3000				
	0								Planting		15000				
	7								Cleaning		1000	-1000	-871		
	15								Cleaning		1500	-1500	-1115		
Spruce	30	1783	27.5	165	796	10.7	64	5.5	Thinning	11954	8240	3714	2050		
Spruce	40	637	21.3	177	318	9.3	76	7.9	Thinning	19660	6251	13409	6073		
Spruce	60	573	40.4	454	573	40.4	454	9.9	Harvest	160584	15325	145259	44272	2665	114816

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

The net income by partial felling was about 30000 SEK every 20-25 years compared to more than 100000 SEK every 60 years by clearfelling. Subsequent costs by site preparation, planting and pre-commercial thinning, as well as moderate income by thinning have to be taken into account too (Table 25).
Considering only today, the net income by target diameter cutting at year 0 is roughly 50% compared to clear-cutting.

The net present value (NPV) can consider longer time horizons, assuming the current costs and prices. Discounting the costs of the next 20 years to year 0 by an interest rate of 2%, the NPV plus the initial income would amount to 62421 SEK for the clearfelling strategy and 30418 SEK for treatment TS. For treatment T, the NPV would amount to 35618 SEK. Choosing another time horizon of 40 years, the NPV plus the initial income would amount to 70544 SEK for clearfelling and 44769 SEK for treatment TS (53017 SEK for treatment T). For 60 years, the NPV plus the initial income by the second final harvest would amount to 114816 SEK for clearfelling, and 55553 SEK for treatment TS. Generally, these differences ranged from 48-63%, depending on time period. Choosing another interest rate of 3%, differences between clearfelling and treatment TS would range from 49 to 61%. See Table E1-E8 in the appendix for 0 and 4 % interest rates!

Cash flow calculations do not depend on interest rates. The income according to treatment TS in Table 23 resulted in an average net annual revenue of 1600 SEK according to (while treatment T and TN are equal to 2200 respective 2000 SEK annually). Following the clear-felling option, the net annual revenue over the 60 year period with income from two clear-cuts amounted to 3738 SEK (or 2665 SEK if first clear-cut is neglected). Referring to cash flow, the profitability of target diameter cutting is about 43-59% over the simulation period, compared to even-aged spruce management.

To even out different 50 and 60 years time periods and different years of considerable income, a net present value in perpetuity (for infinite harvest cycles) was calculated. In case of even-aged management, the value corresponds to the soil expectation value according to Faustmann's (1849) formula plus income of the first harvest. In that case, a continuous stand development with regular harvest intervals every 22 years could be assumed for treatment TS. In addition, a lower income due to the future lack of pine trees was assumed in Figure 30 (average price for pine was 520 SEK/m3 and for spruce was 375 SEK/m3). As a rough guess, 120-150 m3/ha total volume over bark, equal to 96-120 m3 marketable wood with an average price of 350-400 SEK/m3 minus 125 SEK harvesting costs would provide 21600-33000 SEK income. Subtracting costs for scarification and cleaning, the net income could be 16600-28000 SEK regularly every 22 years (Figure 30). Based on such sketches of the future, the NPV in perpetuity would vary between 68000-77000 SEK for treatment TS and 130000 SEK for continuous clearfelling and re-planting. Time lines with presumed incomes and costs are presented in Figure 30 and 31 (with light colors for assumptions outside the simulation period).

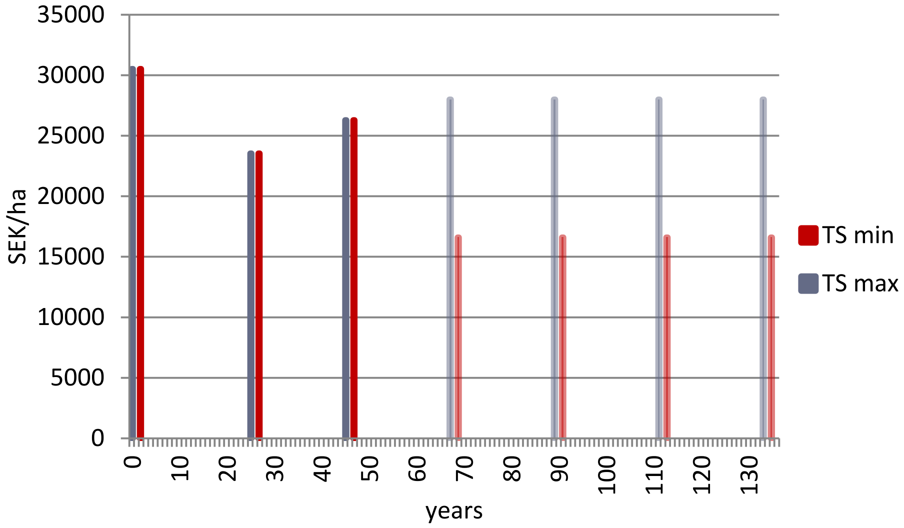


Figure 30. Hypothetical income when treatment TS would be continuously applied (sketch as basis for the calculation of the net present value for infinite harvest cycles).
förväntade teoretiska intäkter vid behandling TS med markberedning skulle resultera i kontinuerliga måldiameterhuggningar varje 22 år, beroende på hållbar utveckling av nya träd för att ersätta mogna träd (priser antas vara konstanta).

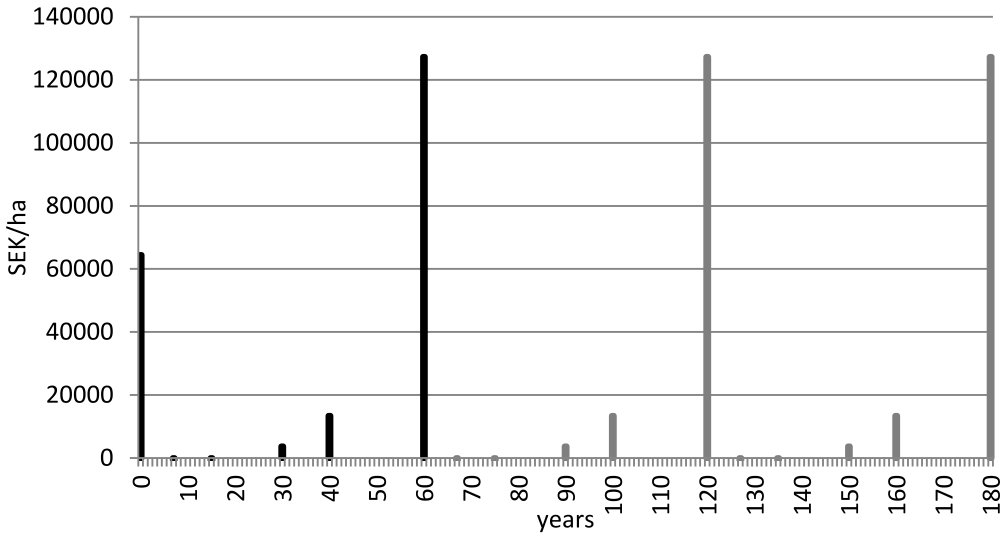


Figure 31. Hypothetical income according to even-aged spruce management (sketch as basis for a net present value calculation for infinite rotation cycles).
Förväntade teoretiska intäkter vid kalavverkning och plantering av gran, upprepat med en omloppstid på 60 år (priserna antas vara konstanta).

Discussion

Initial stand structure, canopy gaps and regeneration

Gaps
Different sizes of gaps provided a wide spectrum of different environmental conditions. The range of light ratios to open-land conditions in the center of gaps was similar to the total range reported under shelterwood (Strand, Ottoson-Löfvenius, Bergsten, Lundmark & Rosvall, 2006). In addition, lower light conditions at the edge of gaps and under canopy increased the spectrum compared to ordinary shelterwood. Hence, the first hypothesis of this study could not be falsified: The target diameter cutting did create an irregular pattern of gaps in different size classes with light conditions more diverse than in uniform shelterwoods. But, maximum radiation in the largest gaps did not exceed values obtained in shelterwoods (Strand et al., 2006).

Stand characteristics
The major characteristic of this stand was the heterogeneous forest structure with trees in all sizes and different ages. A stem number of 1000 trees per ha would imply a high density in old even-aged stands, but this number is normal in uneven-aged forests. E.g. Lundqvist (1989) found 567-1624 trees/ha before and 333-980 trees/ha after the first cut. The BA of 35.2 m²/ha represented the upper level reported for boreal single tree selection forests before first cut (Lundqvist, 1989). However, the variation of BA from 10 to 50 m²/ha on single plots indicated a large variability in stand density.
The variation of tree heights dependent on DBH was also larger than usually found in even-aged stands (i.e. Söderberg, 1992).

Single tree sizes The trees covered a large range of sizes from seedlings to mature trees at the time of the first target diameter cutting. The stand represented an old managed forest in an advanced stage of succession with heterogeneous tree species composition and forest structure. But, it did not represent an uneven-aged managed forest under equilibrium conditions where shade tolerant species tend to dominate (Lundqvist, 1989; Lähde, Laiho, Norokorpi & Saksa, 2002; Lüpke, 2004). and where a large number of small trees can replace the largest trees after harvest. Too many trees were part of the upper stand layer. Although a slightly exponential decrease of tree numbers with increasing tree size was found, the decrease could be more pronounced with more trees below 10 cm DBH and less trees between 20-40 cm DBH. In combination with the regeneration results, the initial diameter distributions indicated a lack of trees below 7 cm DBH. Thus, a sustainable supply of new trees cannot be expected without newly established seedlings.
There are few examples of diameter distributions of boreal spruce selection forest under quasi-equilibrium conditions (where the initial stand structure is maintained for long periods). For instance Lundqvist (1989) demonstrated a relative tree number decline in 4 cm DBH classes from 20-35% of total tree number in class 8.5-12.5 cm, over 15-20% at 20 cm, to 5-10% at 30 cm, with largest trees about 40-50 cm DBH. In the study stand in Halland, 40% of trees were found in class 8-12 cm, and 25% in class 18-22 cm (neglecting the 200 trees/ha below 8 cm DBH for the comparison). However it should be noted that Lundquist (1989) study is on spruce managed with selection cutting. The equilibrium conditions could be different in a mixed stand managed with target diameter cuttings (Cameron, 2007).

Standing volume Estimations of the optimum standing volume of uneven-aged boreal spruce forests range between 150-250 m³/ha (Chrimes, 2004), indicating a steep decline of increment below 100 m³/ha. This finding is in line with empirical yield studies in Scandinavia by Bøhmer (1957), Lundqvist (1989) and Andreassen (1994).
Other references from central European Plenterwald forests have to be used cautiously in Scandinavia, because tree growth and regeneration establishment are favored by climate (i.e. Kunstler, Albert, Courbaud, Lavergne, Thuiller, Vieilledent, Zimmermann & Coomes, 2011). In addition, the tree species composition is different with fir, spruce and beech. However, these references can also help to set a frame of growth expectations for the relatively southern site of the study stand compared to the northern references mentioned above. While Mitscherlich (1952) concluded that 200-500 m³/ha standing volume would have no significant influence on growth, Schütz (1997) highlighted the importance of an optimum stand volume: Depending on defined target diameters, optimum stand volumes should amount to approx. 250 m³/ha for 60 cm, and 350 m³/ha for 110 cm target size, at least for the example region in Switzerland. Since target diameters in south Sweden are smaller, the optimum standing volume has to be lower than 250 m³/ha. In-between the frame from 100-250 m³/ha indicated in the literature, 150-200 m³/ha appear most reasonable as optimum standing volume, considering the large latitudinal differences of the reference forests.
Considering the study stand, the development can be characterized by a succession from old pine forest towards uneven-aged forest. Boreal single tree selection stands can only be considered as a long-term target for the stand development of this forest type with a continuous forest cover. Currently, 322 m³/ha standing volume appear high regarding the establishment of regeneration and optimum stand growth in the transformation stage. For instance, the volume of a 95 years old, pure pine stand on this site would amount to 340 m³/ha (Persson, 1992).

The tree species composition highlighted the difference to uneven-aged forest under equilibrium conditions. Compared to spruce, the pine overstory with lower light interception is supposed to improve the conditions for tree growth and establishment. Even so, the relative number of smallest trees was lower in the study stand than in references to single tree selection stands.
With respect to the overstory composition, single spruce trees with DBH > 30 cm were found in all blocks or treatments, thus a scattered distribution can be assumed. The spruce proportion is increasing with smaller sizes, but remains relatively constant between 5-17 cm DBH. In these size classes, the proportion of oak is also high and could suggest to be an important tree species for the future. However, the estimated growth of oak on this site is very low (Carbonnier, 1975) and generally decreases under shelter (Noack, 2006). From this perspective, the small tree size can be seen as an effect of slow growth rates of oak trees established at similar time when spruce trees entered the stand. The different proportion of small oak and spruce trees in block 1 and 3 was found to be notable for future comparisons regarding ingrowth and growth, but the general patterns were regarded as similar for the overall stand analysis and simulations made within this study.

Box 2. Enrichment planting
The study neglected enrichment planting. But principally, the planting of new trees in gaps can be the save option to achieve sufficient ingrowth! However, this option is more expansive (especially with subsequent protection measures against browsing). Group planting and single tree protection can cause more than the double amount of planting costs on large areas. Practical guidance (planting technique, cost estimations) are given by Hagner (2004). Again, shade-tolerant tree species are more favorable.

Regeneration results clearly demonstrated a lack of regeneration. This conclusion can be drawn from both regeneration surveys, in the stand and in gaps. A usual size of total sample area for natural regeneration uneven-aged stands was used in the systematic stand survey (Nilson and Lundqvist, 2001; Staupendahl, 1997) to deliver representative results for the whole stand. The accuracy of the regeneration density in gaps may be somewhat lower, because the area of many gaps was estimated with the shape of an ellipse (Runkle, 1992) and the survey area was very large in the largest gaps. Such large single survey areas lead to the exclusion of the lowest height class from 10 to 20 cm after the field inventory to assure adequate accuracy. Considering potential error sources, the density in gaps was still twice as high as in the whole stand (385 versus 1003 individuals ≥ 20 cm per ha). Eventually, new gaps were more frequently established around old gaps (as the 49 gaps without any recently cut tree indicated).
The dominance of spruce in the understory under the absence of large-scale disturbances was demonstrated within shelterwood experiments (Nilsson et al., 2002), single-tree selection experiments (Lundqvist, 1989, Lähde et al., 2002) and by observations in pristine forests (Leemans, 1991; Linder, 1998; Shorohova et al., 2009)). The competiveness of the species (e.g. due to small susceptibility against browsing), was also confirmed by this study.

Box 3. Prediction of future ingrowth of oak and other tree species
The focus on spruce as the dominating tree species of ingrowth might be seen as too pessimistic, because future occurrence of other tree species can be underestimated. Especially oak and beech might have a certain potential with the indicated climatic changes (Hickler et al., 2009; Grundmann et al., 2011). However, heavy browsing damages to broadleaves as a general experience in south Sweden and as found in the stand gave reason for the chosen scenarios.
The emergence of current oak trees is not completely clear. The Jay (*Garrulus glandarius*) is suspected for dispersal of acorns as described by Stähr et al. (2006). Accumulated over an unknown time period, Frost (1997) found 54 oak seedlings per ha on average in coniferous forest. On mesic, central European sites with average nutrient supply, Mosandl and Kleinert (1998) and Kätzel et al. (2005) reported 500-2000 oak seedlings per ha accumulated over time in pine stands. Bilke (2005) found 300 seedlings per ha in 100-200 m distances from 100 years old oak trees. He found considerable more individuals if the area was fenced. More conceptually, Reif & Gärtner (2007) assume for natural oak forests, "that long-lasting phases without successful regeneration of young oaks change with phases of successful establishment of a new oak generation", depending on open canopy and low ground vegetation. More information about oak in southern Sweden can be found in Drössler et al. (2012).
The prediction of tree species proportions at the stage of regeneration establishment is rather difficult. A naturally very high variation of determining factors (seed production, dispersal, germination conditions and diseases, climate conditions, soil moisture, browsing etc.) make it hard to predict the actual composition of future tree regeneration. Experienced surprises from natural regeneration experiments intending to establish particular tree species demonstrated how difficult the prediction of regeneration pattern in a particular stand can be (i.e. experiment MB99 Skogaby). After establishment, height growth and survival of established regeneration are still highly stochastic processes compared to single tree growth predictions. Unfortunately, there is no empirical data known by the authors beside the given references above to forecast other tree species. In the study stand, the initial proportion of spruce seedlings was ten times higher than oak. In addition, spruce was least susceptible to browsing, and the second most shade-tolerant tree species in the stand (after beech). Regarding the difficulties of prediction, the most appropriate interpretation approach seems to refer to total future seedling number assumed in the three scenarios without differentiation between the tree species

The highest variation in individual numbers occurs during the initial regeneration stage. As mentioned in Box 3, the occurrence of natural regeneration is hardly predictable. Pukkala (1987) described driving forces as seed crops, stockable area, proportion of full seeds, and germination. Seed production is not easy to predict, depending on weather conditions and its influence on seed years (Ek & Monserud, 1974). The spatial distribution of parent trees is also important (Kolström & Pukkala, 1992; Huth, 2009), especially for oak and beech in this case.
Regarding seedlings, Saksa & Valkonen (2011) could show a negative effect of local BA (determined on a 5 m-radius plot) on the number of 11-130 cm high spruce plants, while no correlation was found for very young seedlings with height < 11 cm. In conclusion, BA appeared very limited to reflect local growth conditions of smallest seedlings, but its influence is expected to increase with larger tree sizes. The latter was also suggested by Granhus (2001). After establishment, there are still many factors which can determine the success of regeneration, in particular water deficiencies, light, competition with ground vegetation, or herbivores in later stages (see Jäderlund et al. 1997; Brang, 1998).

Natural regeneration under different shelter-conditions To enhance natural regeneration in three multi-layered spruce stands, Granhus, Hanssen & Chantal (2008) manipulated the canopy cover in combination with soil preparation by creating a 0.25 ha canopy openings and three shelterwood units (with BA from 11 to 20 m²/ha) in Norway, resulting in 15-30 seedlings per site prepared spot (two years after a rich mast). He found high mortality rates of 20-30% during the 1st winter and 2nd summer after germination.
Saksa (2004) found 6000-25000 seedlings per ha (11-130 cm high) in five uneven-aged forest stands in southern Finland 5-10 years after single tree selection cutting: In average, 200 small trees/ha past the 130 cm tree height threshold annually, but the numbers varied largely from 10 to 1000 between stands. Kolström (1993) observed seedling densities from 100 to 26.500 individuals/ha (0.1-4 m in height).
For spruce plenter forests in Sweden, Lundqvist (1995) estimated approx. 50-100 stems/ha passing 1.3 m height, assuming annual mortality rates about 5% for seedlings < 1.3 m. Holgén & Hånell (2000), Örlander & Karlsson (2000), Glöde (2002), Nilsson et al. (2002), Karlsson & Nilsson (2005), and Nilsson et al. (2006) described about 1000-50000 established seedlings per ha 5-10 years after shelterwood cutting, displaying highly variable tree numbers. Additionally, positive effects of scarification on seedling occurrence and of shelterwood density on survival were demonstrated. Concluding from the studies in this section, a large natural variation of seedling occurrence is possible.
Beside seedling numbers, seedling sizes and height growth are important. The minimum ingrowth scenario assumed 11 cm annual height growth for spruce as found for the advanced regeneration before cutting. This value is comparable to average height shoots reported from a study in central Sweden seven years after thinning from above (30% and 60% removals): Nilson & Lundqvist (2001) referred to 0.5-2 m high regeneration in a multi-layered spruce stand that increased annual height increment from 3-4 to 10-12 cm. Chrimes & Nilson (2005) demonstrated that height increment is better correlated to canopy openness than to BA. In the average, they reported a height increment of 25 mm for seedlings (0.1-0.5 m), of 50 mm for “saplings” (0.5-2 m), and of 75 mm for “small trees” from 2 m height to 5 cm DBH. Both, Nilson & Lundqvist (2001) and Chrimes & Nilson (2005), calculated average height increment of individuals, while the height increment in this study

refers to the tallest seedlings. Dominant seedlings in gaps were considered to represent future new trees better than the average (e.g. Petritan & Lüpke, 2009).
Glöde (2002) studied the height growth of spruce regeneration (1.1 m mean height of seedlings, 2.1 m mean height of dominant seedlings) after shelterwood removal in Sweden. The height shoots increased from approx. 8 cm/a before cutting to more than 20 cm/a six years after cut (with a depression the first two years). Dominant seedlings increased from approx. 15 cm to more than 30 cm per year. No reduction of seedling numbers could be detected.
During the first five years after shelterwood cutting, less than 5 cm mean annual height increment was found in naturally regenerated spruce in southern Sweden (Nilsson et al., 2002; Nilsson et al., 2006). Örlander & Karlsson (2000) could show for one shelterwood experiment (80-160 trees/ha) that the mean accumulated height increment increased from 5.8 cm/a (for seedlings < 20 cm height), over 13.7 cm/a (20-50 cm height) and 21.4 cm/ (50-100 cm), to 30.8 cm (> 100 cm). But, high shelterwood densities (320 trees/ha) resulted in less than 5 cm annual height increment for seedlings < 1 m.
Summarizing these studies, about 10 and 30 cm annual height growth in gaps can represent well the arbitrary thresholds chosen for the simulation.

Mortality of small trees From literature, 2-5% annual mortality can be estimated for 10-50 cm high spruce seedlings in uneven-aged stands (Lundqvist, 1995; Nilson & Lundqvist, 2001; Eerikäinen, 2007). For 50-200 cm tall spruce plants, Nilson & Lundqvist (2001) found 0-4% rates. Mortality under spruce shelterwood without scarification was reported by Nilsson et al. (2002) with about 20 % annually for the first five years (about 50% during the first year after germination). Under pine shelter, 25% mortality were found for a 5 years period (Nilsson et al., 2006), equal to 6% annually in average. From these figures, mortality rates assumed in the minimum scenario appear two times higher. No mortality according to the maximum scenario was likely an underestimation, while the medium scenario reflected well these mortality rates.
Nevertheless, mortality rates assumed in this study stand are a rough estimation. Climate change and micro-site dependent conditions increase the uncertainty of future trees recruitment. But, mortality rates estimated from literature and medium scenario mortality were similar. Oscillating values for beech had to be smoothed. No references to the mortality of birch or trees with 2-5 cm DBH under shelter conditions were indicated in literature. But, tree mortality can generally assumed to decrease with increasing tree size (i.e. Lundqvist, 1995; Eid & Tuhus, 2001; Juknys et al., 2006).

Stand characteristics to describe ingrowth According to Schütz (2001), higher standing volume has a negative effect on tree recruitment. Reversely, regeneration processes determine management options and stand density in the long run (Tahvonen et al., 2010). However, most experiments demonstrate weak correlations between stand BA and regeneration growth or occurrence (e.g. Lundqvist & Fridman, 1996; Bachofen, 1999; Nilson & Lundqvist, 2001; Chrimes, 2004). Beside the higher number of seedlings in gaps, no effect of different volume levels on regeneration was found by this study due to the low number of seedlings in the stand survey.
Chrimes (2004) found a stronger influence of canopy openness on the height growth of seedlings and Kuusipalo (1985) described a relationship between BA and canopy openness (where BA explained 63% of the variation of canopy openness; BA and the proportion of

spruce could explain 75%). Under pine shelter, Strand et al. (2006) revealed stronger correlations with the distance to the nearest tree than with light conditions. All three factors, BA, light and distance to the nearest canopy tree (associated with root competition e.g.) are altered by creating gaps. Therefore, improved growth conditions for advanced regeneration can be expected after cutting. In addition, gaps are considered as important feature to initiate and promote regeneration according to the concept of a natural forest cycle (e.g. Leeman, 1991; Liu & Hytteborn, 1991; Dai, 1996).
However, two main questions remain: 1. When the new regeneration will be established in a particular stand? 2. How many individuals can be expected to grow into the tree layer within a certain time period? The final answer in this case study can be obtained by future measurements only. See also Lundqvist (2012) regarding regeneration and ingrowth estimates in heterogeneously structured forest!

Ingrowth rates Based on data from re-visited permanent sample plots of the Swedish National forest inventory, regression models to estimate the future ingrowth of spruce, pine and birch were developed by Wikberg (2004). According to this model, spruce saplings had the highest probability to grow taller in the understory (Wikberg, 2004). This is in line with the forest ecological theory that spruce is most competitive if fire and other large-scaled disturbances are excluded (e.g. Engelmark & Hytteborn, 1999; Shorohova et al., 2009). Similar conclusions can be drawn from empirical studies (e.g. Lundqvist, 1989; Liu & Hytteborn, 1991; Hofgaard, 1993).
Across all types of current forests in Sweden (excluding very young stands), Wikberg (2004) calculated a general probability of 11% for spruce saplings to pass 40 mm DBH after 5-years. The ingrowth decreased with increasing stand density and age, and increased with increasing site index. The ingrowth rate ranged between 5 and 30%. However, the inventory data used for the model did not refer explicitly to silvicultural measures aiming for regeneration. Contrary, recent thinning reduced the ingrowth probability due to harvest damages. Specifically for the study stand in Halland, 2-4 new trees per ha and year were projected. A reduction of BA to 15 m^2/ha was forecasted to give annually 13 new trees/ha, although this is an extrapolation from the validated model due to the small proportion of such forests.
Pukkala et al.(2009) projected approx. 2-7 new trees/ha per year for heterogeneously structured forests in Finland with 20-35 m^2 BA per ha. For stands with 10 m^2/ha BA, minimum 5 new trees (total tree number 250 trees/ha), and maximum 40-80 new trees (1800 trees/ha) were estimated.

There are some northern European case studies describing observed ingrowth in uneven-aged spruce forests managed by single-tree selection (see also Lundqvist, 2012). Lundqvist (1989) recorded about 4-14 trees per ha and year that past an 8.5 cm DBH threshold in eleven spruce plenter forest stands in Northern and Central Sweden. However, 40% of trees below 8.5 cm DBH were removed at the first cutting in six of the eleven stands. Lähde et al. (2002) documented ingrowth in 23 heterogeneously structured, spruce dominated stands across Finland. He found 170 seedlings (< 1.3 m) per ha growing to saplings (1.3 m height to 9 cm DBH), and 80 saplings/ha passing the 9 cm threshold during 7-14 years monitoring periods after single-tree selection cutting, which is equal to 5-12 trees/ha annually. In average, about 10 trees per ha and year seem to be a reasonable ingrowth in uneven-aged boreal forests.

Another reference of ingrowth from more southern latitudes was provided by Tremer (2008) for the forest district Sellhorn in northern Germany. There, the forest sites are characterized by sandy soils with poor or medium nutrient supply (which is more similar to Swedish conditions than other sites in Germany). Two regeneration inventories in a 7 years-interval were carried out on 869 sample plots in the whole forest district. The stands were even-aged. Dominant tree species were pine (66% of BA of the district) and spruce (25%). Beech and oak comprised 5%, other broadleaves 4% of BA. (No soil preparation or underplanting was conducted.) The largest proportion of ingrowth was found for spruce, equivalent to 13 trees per year and ha (crossing a threshold of 7 cm DBH). However, on many plots no ingrowth was observed. A correlation between ingrowth and crown cover pointed out a linear increase from roughly 7 to 30 trees per ha annually, when crown cover increased from zero to 4.000 m²/ha, and a linear decrease from 30 new trees/ha to zero when crown cover decreased from 4.000 to 12.500 m²/ha. No direct correclation between BA and ingrowth was found (Tremer, 2008).
Considering only the plots where spruce regeneration was found at the first inventory, 26 trees per year and ha were registered in average. Comparing with our study stand, only on 20% of regeneration plots occurred seedlings.
Pooling the studies in Table 26 to one figure, about 10 trees/ha seem to be a reasonable annual ingrowth, although natural variation can be great. Under proper conditions, such an average tree number is supposed to replace 3-4 pole trees (with 10-20 cm DBH) which are needed to replace a harvested tree in a single tree selection forest (Schütz, 2001).

Regarding our study stand, with special regard to the current regeneration state, ten new trees per year and ha appear too high for the next 25 years. Before cutting, one tree per year and ha growing into a 5 cm size class seemed more likely according to regeneration characteristics. But, changing conditions after cutting are supposed to accelerate the rate.

Table 26. Regeneration and ingrowth studies in two- or multi-layered spruce-dominated forests in Northern Europe

Studier av självföryngring och inväxning i två- och flerskiktad skog i norra Europa

tree species	tree size [cm]	tree age [a]	seedling density [N/ha]	annual mortality [%]	height growth [cm/a]	annual ingrowth [N/ha+a]	threshold of ingrowth [cm]	forest type	study type	author
spruce		0.5-1.5		ca. 30				shelterwood	observation	Granhus et al. (2008)
spruce	10-50		1-176	2-7		< 20	height 10	uneven-aged	observation	Nilson and Lundqvist (2001)
spruce	10-50				2.5			uneven-aged	observation	Chrimes and Nilson (2005)
multiple	11-130		6000-25000			200	height 130	uneven-aged	observation	Saksa (2004)
spruce	<130			5		50-100	height 130	uneven-aged	observation	Lundqvist (1995)
multiple	97-148		41000	6-12	14-30			shelterwood	observation	Holgén and Hånell (2000)
spruce	H_{mean} 110		24000-38000		8-20			shelterwood	observation	Glöde (2002)
spruce	H_{dom} 210				15-30			shelterwood	observation	Glöde (2002)
spruce	50-200		6-164	0-4	3-12			uneven-aged	observation	Nilson and Lundqvist (2001)
spruce	50-200				5			multi-storied	observation	Chrimes and Nilson (2005)
spruce	probably 0-400		81000	0-80	5.8-30.8			shelterwood	observation	Örlander and Karlsson (2000)
multiple	10-400		100-26500					uneven-aged	observation	Kolström (1993)
spruce	10-400	average 5	2095	ca. 5				uneven-aged	modelling	Eerikäinen (2007)
spruce	200 - 5 cm dbh		67-688		7.5			multi-storied	observation	Chrimes and Nilson (2005)
spruce						1-6% of saplings	dbh 4	overall	modelling	Wikberg (2004)
spruce						2-4% of saplings	dbh 4	stand-specific	modelling	Wikberg (2004)
spruce						approx. 2-7	dbh 5	"uneven-sized" (BA 20-35 m^2/ha)	modelling	Pukkala et al. (2009)
spruce						4-14	dbh 8.5	uneven-aged	observation	Lundqvist (1989)
multiple						5-12	dbh 9	multi-storied	observation	Lähde et al. (2002)
spruce						13	dbh 7	even-aged	observation	Tremer (2008)

Comparison of ingrowth derived from literature and from advanced regeneration The study revealed differences between ingrowth rates estimated from advanced regeneration and rates concluded from literature. The stand-specific estimations fit well to Wikberg´s (2004) ingrowth model, but represented rates below the average reported in uneven-aged forest. Ingrowth rates can be expected to increase after 15-35 years due to initiated regeneration by reduced stand density and gaps, according to the references from multi-layered managed forests (Pukkala et al., 2009) and shelterwoods (Nilsson et al., 2002).
Regarding maximum stem number of spruce regeneration after scarification, much denser stands than 2000 trees/ha can occur, when trees reach 5 cm DBH. For instance, Falck & Rydberg (1992) and Petterson (1992) documented extreme dense pole stands with more than 10000 trees/ha under shelter and in plantations. But including cleaning as additional measure, 2000 trees/ha were assumed to achieve a sufficient single tree stability and tree growth according to findings by Rumpf & Dittges (2008). Very dense spruce regeneration can develop considerably thinner and less stable dominant trees (Petterson, 1992).

Future stand growth, diameter distributions and simulation constraints

Model data base The simulation used models based on permanent sample plots of the National forest inventory. The model to estimate the specific age of single trees was derived from 14.870 single tree observations on sample plots classified as uneven-aged (Elfving, 2003). Due to the definition of uneven-aged by the forest inventory, plots with advanced regeneration in old even-aged forest could be over-represented. In addition, Lundström (2008) found more plots suitable for single tree selection in northern Sweden. No specific silvicultural measures to promote single trees were recorded by the inventory.
In addition, about 300.000 ha of old pine-spruce forest were determined in southern Sweden (Drössler, 2010), where a notable proportion of stands with two or more height-layers can be assumed.

Comparison with observations and other growth simulations
The plausibility of the BA simulation results was confirmed by two additional growth models (Ekö, 1985; Elfving, 2004), demonstrated in Figure 32 for the control. Both models are based on stand age. For a first validation, the BA development according to Elfving (2004) with 60 and 80 years stand age deviated little from the assumed 70 years (0.8-2.4% difference after 50 years without cutting). But, final growth validation with observed growth after five or more years is still necessary.
The simulation of stand basal area growth according to Ekö (1985) was applied to a model stand on the same site with similar tree species proportions (divided in a 95 years old overstory of pine and birch and in an understory of 60 years old spruce and 50 years old beech and oak). The model by Ekö (1985) indicated a more pronounced growth regression after some decades. The growth projection resulted for instance in 1.8 m²/ha lower BA after 50 years within the control treatment compared to the presented simulation results.
Regarding the stand age-dependent and -independent functions by Elfving (2004), slight differences were revealed. For the total simulation period, similar growth rates were reflected (Figure 32). All three models projected similar BA growth for the control with values ranging from 52.5 to 54.4 m²/ha BA at the end of the simulation period.

The age-dependent growth model by Elfving (2004) was compared with 15 years observation in an uneven-aged spruce stand in Central Sweden, managed by single-tree selection (Lundqvist, Chrimes, Elfving, Mörling & Valinger, 2007). Initial diameter distributions were characterized by a large number of smallest trees (in average 500 trees/ha with 5-10 cm DBH), a pronounced exponential decrease of tree numbers, and about 50 cm DBH maximum. The model overestimated the BA growth on stand level by 11% for thinning from above with BA removals of 33% and 50% (Elfving, 2009). However, several large trees died due to wind damage. For the control, predictions were 2% lower than observed. For small trees with 5-10 cm DBH, the observed values were 20-50% higher than expected from the model (Elfving, 2009). Although the effect on total BA growth is small for short- or medium-term periods, a critical question is how correct the growth of smaller trees after release is reflected by the model. The few observations and the data base of the model do not rule out possibilities that suppressed trees react stronger after silvicultural releases than predicted.
From observation in managed, even-aged stands over several decades, an underestimation of growth of largest trees, and an overestimation of growth of smallest trees was revealed (Fahlvik et al. 2012).
Another test for validation of the age-dependent model by Elfving (2004) was made with 9-16 years observation in pristine forest reserves. The different forest types of the study plots were described by Linder (1998). Here, the increment was underestimated by 5%. 2/3 of the large variation could be explained by the model (Elfving, 2006a).
Furthermore, the age-dependent model was used for simulations by Elfving (2006b) to compare wood production of even-aged and uneven-aged stands. Considering all spruce sites in Sweden, Elfving (2006b) estimated for uneven-aged spruce stands 15% less growth compared to even-aged stands, which was also concluded from single-tree selection experiments in uneven-aged coastal spruce stands in Norway (Andreassen, 1994).
Another simulation study in Sweden, was carried out by Wikström (2008) who compared the growth of single-tree selection stands with even-aged forest by using one BA growth function for all tree species according to Elfving (2005). This function was calibrated for even-aged stands and projected growth rates similar to even-aged stands.

No increase of growth was indicated during the simulation period. The volume increment was higher in unmanaged forest than in managed forest (both totally and during the last decade). This is contrary to the BA projections and indicates wrong volume estimations. See Table 16 and 17 for instance, where 6.7 m^3/ha MAI in volume was calculated for unmanaged forest and 5.9 m^3/ha for managed forest, while 0.53 m^2/ha MAI in BA was projected for unmanaged forest and 0.56 m^2/ha for managed forest. Therefore, estimations of volume are less reliable in multi-layered forest than BA.

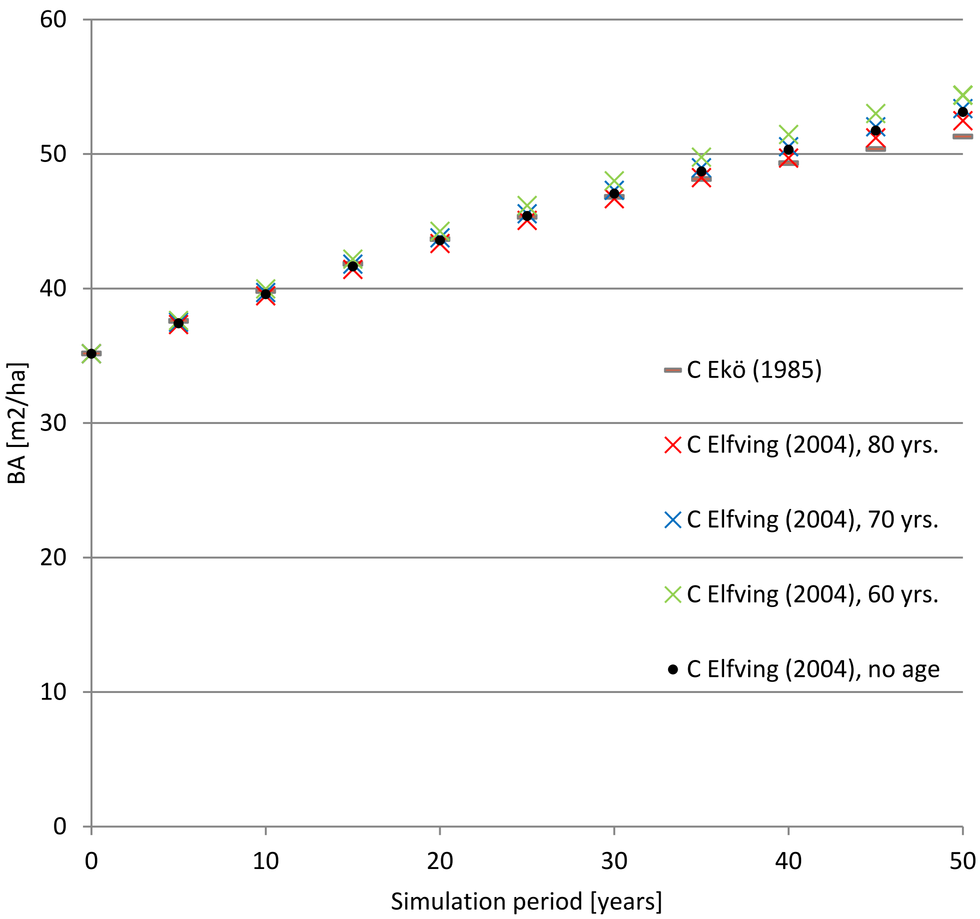


Figure 32. Simulation of BA development of the control treatment according to different growth models (stand age-dependent and -independent estimations of single tree ages, and stand-level BA growth). *Simuleringar av grundytans tillväxt i kontrollbehandlingen med olika tillväxtmodeller.*

Regarding the original treatments with forest management, BA levels before and after cut remained rather constant during the 50 years period. No depletion of the forest was indicated by the simulations of different types of target diameter cutting. The increment did not increase over time, as it might be expected by an increasing proportion of spruce from 40 to 55-60% of BA. In fact, the annual BA increment decreased from 0.6 to 0.5 m^2/ha over the simulation period, eventually pointing on the influence of single tree ages.
Comparing with a spruce plantation on the same site, the MAI projections for volume were very low. Only 60% of the 9.9 m^3 MAI which was projected for a 60-years rotation. Similar ratios were found for treatment TS (61%) and TN (58%). If real volume growth rates after target diameter cutting would be more similar to projections in the control, wood production would be 68% compared to the DT-projection of an even-aged spruce stand. The site potential (= productive capacity of the site according to optimum management excluding risks) was estimated even higher: 10.4 m^3 per ha and year for spruce according to Hägglund & Lundmark (1982).
More reliably, 64% BA growth was estimated for treatment T, compared to 0.88 m^2/ha MAI by the DT simulator. For treatment TS, 67% of the BA growth of an even-aged spruce stand was calculated.

Ingrowth estimations A sufficient numbers of new trees with sustainable tree supply can only be expected under treatment TS, after scarification. Under the minimum and intermediate scenario, treatment T and TN cannot be judged as sustainable if future tree harvests in reasonable time intervals should take place. The intermediate ingrowth scenario pointed on harvest intervals of several decades.

Such expectations are in line with Øyen & Nilsen (2004) who were not satisfied with the recruitment of new trees after selective cutting in irregularly structured stands in Norway, but also with Kint et al. (2006) and Cameron & Hand (2010). The two latter studies described stands with comparable tree species composition and provide background for forest transformation apart from modeling, but from a perspective with empirical observations and the expectations from the science of vegetation dynamics. They expect more than 50 years to develop sustainably heterogeneous forest structures.

Box 4. Discussion of technical ingrowth implementation in this study

The goal within the simulation was to implement ingrowth simply, but logically from silvicultural perspective. Therefore, an approach was chosen with basal area levels that favor the establishment and growth of small trees (Wikberg, 2004). The simplification from crown cover to basal area was supported by estimates with open canopy on sample plots. Table B1 in Appendix B shows the relation between canopy openness and low BA. Kuusipalo (1985) and Chrimes (2004) found similar relationships. In addition, the proportion of plots with BA below 15 m^2/ha was similar to the proportion of gaps. Advantage of this approach was a description by silviculturally controllable stand characteristics, although many other important factors were neglected.

As follow-up consideration of our analysis, a separate implementation of ingrowth in 5-year time steps would probably result in more accurate estimations. Eventually, regeneration numbers in Table 15 might increase more in the last decades. However, another goal was to keep the ingrowth scenarios understandable by assuming 1, 4 and 10 new trees per ha and year, including the state of regeneration today. Still, there is potential that future tree numbers will be lower or exceed the extreme scenarios (particularly if more ingrowth would occur under closed canopy than currently counted). However, the applied maximum scenario assumes two times more ingrowth than estimated for regeneration with 30 cm height growth for the next 15 years. Considering rates described in literature and the snapshot of current regeneration, annual ingrowth larger than five trees per ha under closed canopy and more than 40 trees per ha in gaps seems rather unlikely. Certainly, such hypothetical thinking has to be tested by re-measurements of the regeneration in 10 or 20 years.

Box 5. Possible sources of error when predicting stand basal area, volume and single tree growth
Wrong measurements of empirical data, statistical bias, wrong assumptions in the model constructed, and extrapolation/misinterpretation by the user are potential sources for wrong predictions. The error due to basal area measurements is considered to be very small, because it amounts usually to roughly 1% (Kramer & Akca, 1995) and was carried out by the professional stuff of the experimental forest.
A considerable bias can be expected due to differences between the empirical data base used to build the growth model and the specific stand under investigation. An open question is the proportion of uneven-aged single tree selection and of old pine stands with naturally regenerated spruce trees in the empirical data, both possible according to the definition of uneven-aged forest in the NFI. In addition, the response of suppressed trees after silvicultural release cannot be described properly by the model because of the lack of such detailed information in the inventory data. More generally, structural indices or spatial competition indices related to neighboring trees become more relevant with increasing heterogeneity of the stand structure. Still, distance-dependent growth simulators are also rather limited to describe the growth of single trees under more extreme silvicultural single-tree treatments for several decades (Yue et al. 2008, Albrecht et al. 2009, Mette et al. 2009, Albrecht et al. 2011, Albrecht et al. 2012).
The comparison of the model projection with observations in single-tree selection forest revealed a slight underestimation for the control treatment, and an overestimation for managed forest which is difficult to judge due to the interference with storm (Elfving, 2004). According to Elfving (2004), storm damage could explain the overestimation. If growth rates were biased by 2%, then the final BA values of the control after 50 years would differ 0.8%. After 25 years, BA values before cutting would be 0.7% different. Assuming 5% bias as a worst case, BA values would differ 2-3% after 50 years undisturbed growth. After 25 years, before cutting, the values would differ by 1.7% from the predictions. Differences in total BA growth due to different stand structure on blocks amounted to 2.5% after 50 years. Mathematically, the bias vanishes when comparing to the model projections with each other. Comparing the basal area growth predictions of different treatments for the next 50 years, an error of ± 5% is roughly assumed by the authors. Differences between the predictions and actual future growth are expected to be larger (as predicted growth for even-aged forest already may differ 10-15% from observed growth ion different regions of Sweden).

Form heights cause an additional error when calculating stand volume, in average ± 6% (Kramer & Akca, 1995). Volume functions by Ekö (1985) are probably less accurate then Söderberg's (1992) functions for instance, but are more robust in our model because volume estimations are based on rather correct basal area estimations every five years. Both types of volume functions were not validated for multi-layered stands. In even-aged stands, the volume functions by Ekö (1985) differ by 0-4%. 11% higher volume growth rates in the unmanaged treatment, while basal area growth was slightly higher in managed treatments indicates even larger errors (i.e., the forecast for treatment C was only 6.5 m^3/ha MAI and for T 5.5 m^3/ha, while BA was 0.53 and 0.56 m^2/ha MAI). Therefore, roughly 15% errors in estimation of total volume production after 50 years is assumed by the authors. Effects of storm, insects or climate change were not considered within this simulation study. Finally, there is no empirical material to evaluate predicted growth of oak under such heterogeneous forest conditions.

Regarding the diameter development of a particular tree in uneven-aged forest, the few observations indicated very high variation between trees (Elfving, 2006a). Although average growth was reflected well and two thirds of the variation could be explained, single tree growth varied up to 50 or 200%. Assuming a projected annual diameter growth of 0.2 cm, this tree could also grow 0.1 or 0.4 cm per year. Larger growth responses might particularly occur after silvicultural releases. In extreme cases, a particular tree with initially 20 cm DBH could grow to 25 or 40 cm instead of 30 cm after 50 years.
Considering such a large variation, diameter distributions after 25 years should be interpreted by summarizing two size classes to one 4 cm diameter class. After 50 years, 8 cm diameter classes are recommended for interpretation. However, despite the uncertainty, the simulated diameters were used to determine tree removals according to target diameters.
Finally, an underestimated growth of small trees was indicated by a study in northern Sweden which revealed 20-50% larger growth rates of small trees with 5-10 cm DBH than predicted (Elfving, 2009). According to these rates, newly ingrown trees with 5 cm DBH would not grow to 9 cm after 25 years, but to 10-11 cm DBH.

Projection of future diameter distributions The diameter distributions calculated in 50 years indicated a similar percentage of large trees (> 20 cm) as diameter distributions described by Lundqvist (1989). Regarding small trees, only treatment TS demonstrated accentuated peaks of ingrowth needed for sustainable future timber harvest. In treatment T, only the maximum scenario shows a potential to maintain a stand structure similar to the initial forest today. Under moderate ingrowth assumptions, scarification is necessary to promote a sufficient number of new trees. Considering a total gap area of 15% in the stand (where most of ingrowth is expected to occur after the scarification), a multi-layered, heterogeneous forest structure of the stand is expected in 50 years. Under treatment T and TN, a lack of regeneration is suspected.

More detailed interpretation of future diameter distributions is mostly speculation due to the limitations and the lack of validation of the growth model (Box 5). However, being aware of limitations and errors due to extrapolation, this simulation study could identify and analyze important growth trends relevant for target diameter cutting. Nevertheless, relatively large deviation from projected diameters can be expected for particular trees. Therefore, re-measurements of the experimental plots over several decades are of tremendous importance to increase the empirical knowledge about stand development and growth under continuous cover forestry.

Income comparisons

Estimations of gross income and costs showed that a considerable income was obtained by the first target diameter cutting in winter 2008/09 already (about 30-50% of net income by clear-cut). Considering 60 years or infinite time periods, the NPV of treatment TS was also about 50% compared to clear-felling. The large impact of the first withdrawal on NPV, but also lower growth, cause the lower value. Since treatment T and TN are likely to lack mature trees in 50 years, NPV calculations with indefinite harvest cycles every 20-25 years were not considered (but can be calculated from Table 23 and 24, assuming no income during the next 40 years after simulation).
Comparing the total forest development cycle between a selection system and clear-felling, Andreassen & Oyen (2002) calculated 15% lower NPV for uneven-aged forests in Norway, based on 2% discount rate as in the presented study. Usually 3% and 2.5% interest rate are used in economic analyses of silviculture in Sweden (Brukas & Weber, 2009), while 1% is used in German forestry practice for instance (Möhring, 2001). 2% were chosen in this study, because forest owners interested in continuous cover forestry might rank profitability lower, eventually. Appendix E demonstrates the sensitivity of NPV to 0 or 4% rates. Independently from the choice of interest rate, a major conclusion can be drawn: Clear-felling is more profitable. Only when the income of the first harvest is neglected, target diameter cutting with scarification could achieve a higher NPV if discount rates would be larger than 3.2%. But, there will be periods without income when investments by pre-commercial thinning become necessary. When target diameter cutting is applied, no investment costs will occur or cannot be covered by income at the same time.
Due to difficulties to predict monetary values in 20 years or longer, results have a clear discussion character. Storm and insect damages neglected in the simulation might also alternate the economic results. - Other calculation approaches to compare clear-felling and

partial cutting can be found in Knoke & Plusczyk (2001) and Emmingham et al. (2002) for instance. Emmingham et al. (2002) calculated the financial value within a 10 years-period only, but including NPV, the value of residual timber, the value of bare land, and the value of planted trees together (which was lower in the treatment with clear-felling). Knoke & Plusczyk (2001) expected considerably lower income compared to the clear-felling system for stands under transformation towards uneven-aged forest because of delayed income.

Conclusions

Research conclusions The first hypothesis of the study could not be falsified: (1) Target diameter cutting did create an irregular pattern of gaps in different size classes with light conditions more diverse than found in uniform shelterwoods.

In mature, pine-dominated forest, low forest growth can be expected when applying selective cuttings. By clear-felling, a maximum timber production or a profit maximization can be achieved (because planted spruce stands are expected to produce roughly 50% more wood within the next 50 years). However, target diameter cutting provided considerable income already at the first time of harvest, which was about 50% of the income by clear-cut. Additionally, target diameter cutting is expected to provide more equally distributed income over time. Most likely, there will be no urgent need to cover investments costs without achieving some profit at the same time. Other aspects, like aesthetic values or mimicking natural disturbances may give reason to choose target diameter cutting as the most preferable option. It can even be argued that the future forest would be more resilient in case of single-tree fall caused by storm, because established seedlings and smaller trees could replace gaps in the forest canopy.

The projected BA growth was 63-67% lower compared to a planted spruce stand. Concerning potential modeling errors, the authors expect that the real growth in future will be deviate less than +/-15% from projection. However, single-tree growth forecasts in heterogeneously structured forest are extrapolations in most cases. In addition, future standing volume was less reliable to predict than BA. The proportion of old trees and other tree species than spruce, and the possible underestimation of increment of suppressed trees after release might be seen as reason for the surprisingly low productivity. The forest is currently in a transition phase developing from even-aged towards uneven-aged forest during the whole simulation period. Higher increment is expected in single-tree selection forest under equilibrium conditions. The second hypothesis of the study was rejected: (2) For the next 50 years, forest production in the study stand, managed by target diameter cutting, is lower compared to an even-aged spruce stand planted on the same site.

The different thresholds of target diameter did not result in significant growth differences. Therefore, the third hypothesis could not be verified: (3) No decrease of BA growth in treatment T-5 was indicated by the growth model.

The fourth hypothesis could not be falsified: (4) Ingrowth will have a small impact on projected increment the first 50 years. The largest difference was found between the minimum and maximum scenario according to treatment TS with 0.1 m^2/ha respective 0.6 m^3/ha BA increment annually.

The future tree species composition is expected to change towards more spruce (based on current diameter distribution, regeneration characteristics, and the simulation). According to the forecast, the future proportion of spruce trees increased by 15-20% in treatment T and

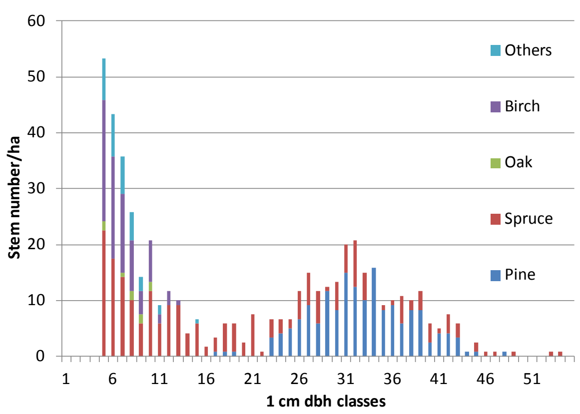
TS, and 2% in treatment TN and the control. More generally, literature indicates that the choice of tree species is limited under continuous forest cover conditions: Shade-tolerant tree species (spruce, beech) are more likely to dominate in the understory in the long run. The fifth hypothesis could not be falsified: (5) Tree species composition will change towards more shade tolerant species during the simulated development.

With the economic calculations presented before, the hypothesis regarding NPV was falsified. The clear-felling strategy would always result in a higher NPV compared to target diameter cutting, especially due to the high initial income. Considering infinite cutting cycles with today prices, the NPV was about 70% higher. Hence, the last hypothesis was rejected: (6) Replanting spruce after clearcut would result in a similar net present value compared to target diameter cutting (based on 2% interest rate).

Silvicultural conclusions most relevant to forest practice The lack of small trees highlighted the importance to aim for more regeneration in the future to continue with target diameter harvests. Therefore, soil preparation is strongly recommended in mature forests. Another option could be enrichment planting which was not included in this study but was described by Hagner (2004). Without additional regeneration measures, a lack of mature trees after 50 years is likely to cause considerably harvest delays.

In order to provide more practical management guidelines for heterogeneously structured stands (with steadily decreasing tree number in larger size classes, see Box 6) on comparable sites in southern Sweden, about 150-200 m^3/ha standing volume after cut could provide a first practical orientation to achieve regeneration and assure stand growth to some extent. In the studied case, continuous harvest intervals of 20-25 years can be expected if a sufficient number of new trees will occur. Without advanced regeneration or scarification measures, 40-60 years between tree harvests are likely after three target diameter cuttings (beyond the time horizons considered in this simulation). However, the diameter distribution of a particular stand can crucially effect harvest levels and intervals. If advanced regeneration is already established to a large extent, tending of young spruce trees might be necessary in very dense regeneration patches to ensure proper single-tree growth and stability (*cf.* Rumpf & Dittges, 2008).

Without silvicultural regeneration measures, the forest will regenerate naturally, but in longer time periods. Developing towards uneven-aged forests, Treatment T and TN could also provide a management option for stands set a-side for natural values according to green management plans (NBF, 2001).



The diameter distribution to the left describes another heterogeneously structured forest with pine overstory and spruce in all size classes, located close to Jönköping, on a good site (T28, G34). A distinct lack of trees with 10-25 cm dbh is demonstrated, compared to Eriksköp (which was not detected visually in the field). Such a distribution would result in an earlier second harvest (in ca. 15 years), but a delayed third harvest (in 45-50 years from now, applying 38 cm target diameter for all tree species)!

Obviously, such heterogeneously structured forests provide feasible alternatives to clear-cutting, i.e. with the seed-tree method to develop future pine forest, or with target diameter cutting to promote continuous forest cover. However, the forest owner is responsible to communicate the management goals in terms of yield, tree species composition, ecological and aesthetic values. Based on such goal settings, forest managers or consultants should give support towards different directions of forest development (not necessarily demanding high production and profitability). With this case study, we hope to provide a bit more guidance to combine the experiences from single-tree selection, shelterwood, seed-tree-method, and clear-cutting to estimate and describe future stand development, growth and costs, in order to fit the owner-specific goals better.

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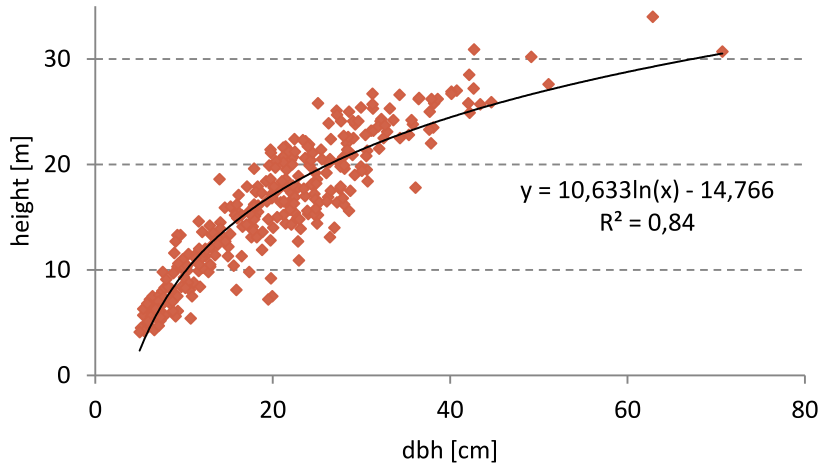
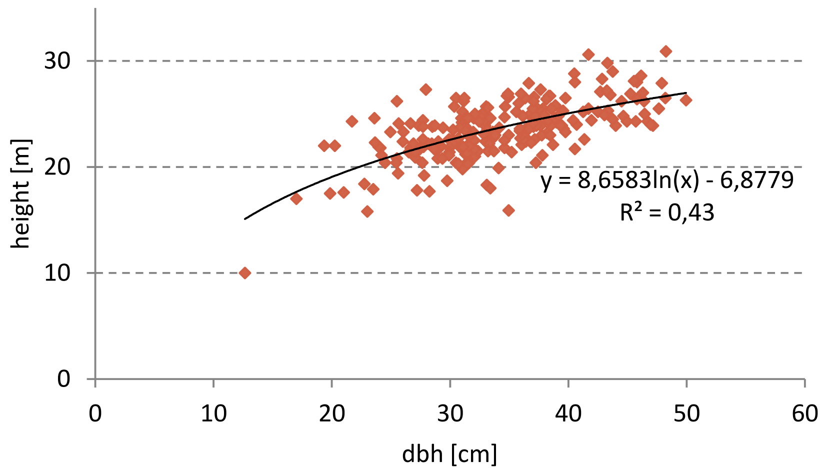
Appendices

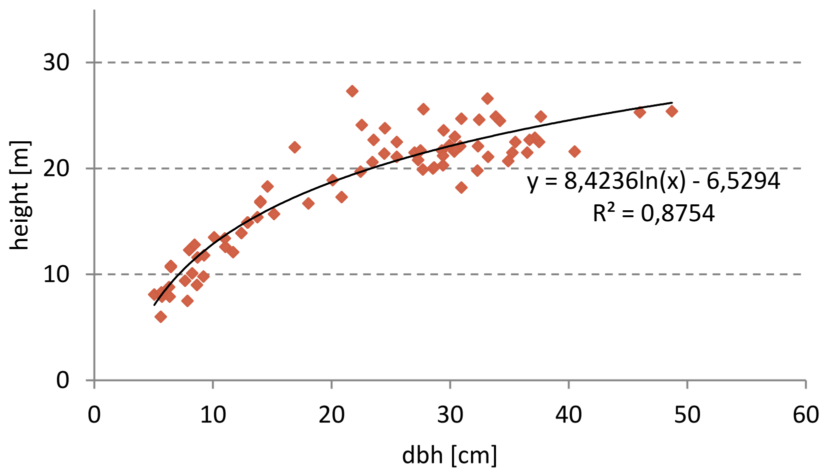
Appendix A



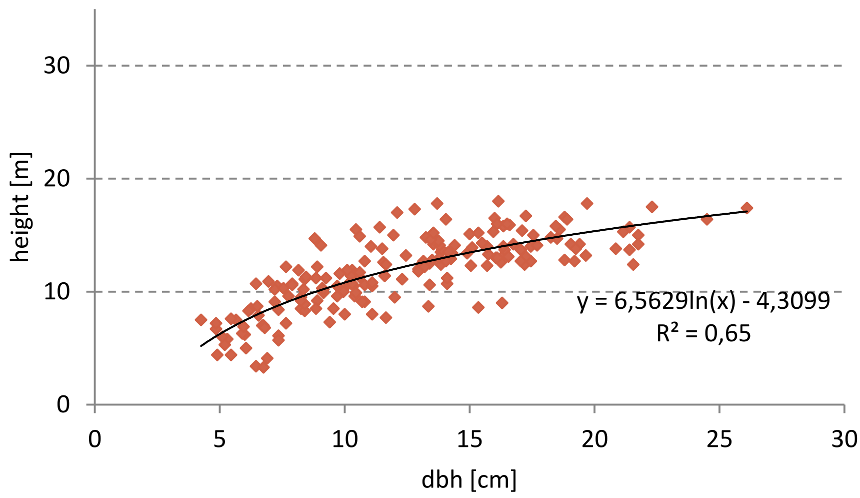
Appendix A, Figure A1. Height curve of spruce



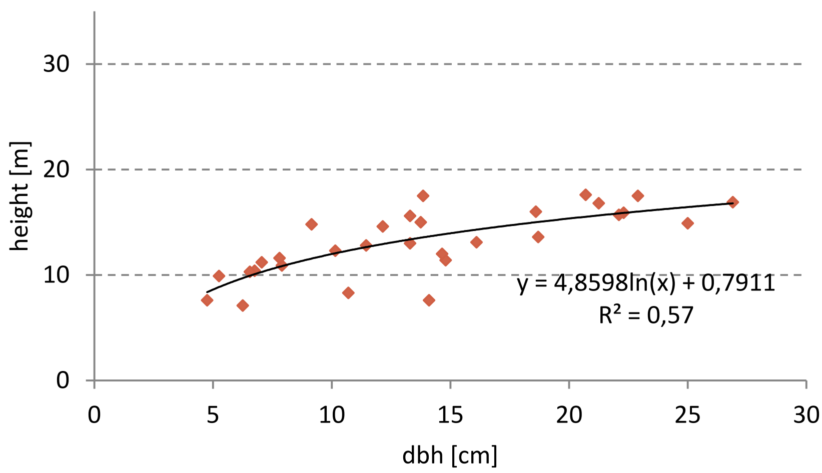
Appendix A, Figure A2. Height curve of pine



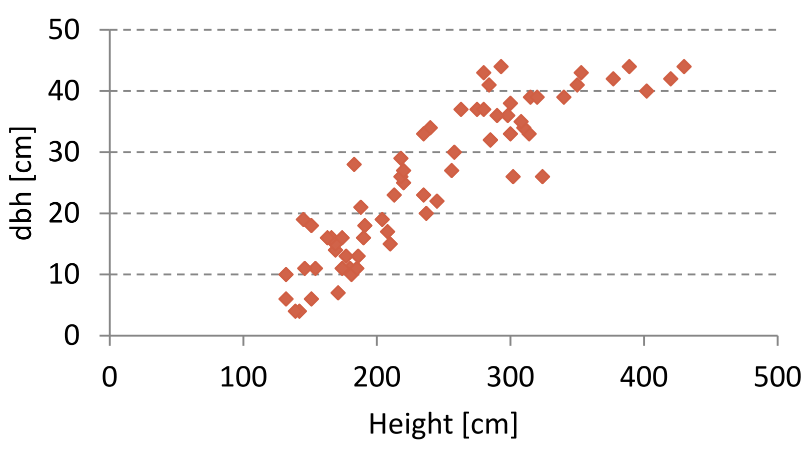
Appendix A, Figure A3. Height curve of birch



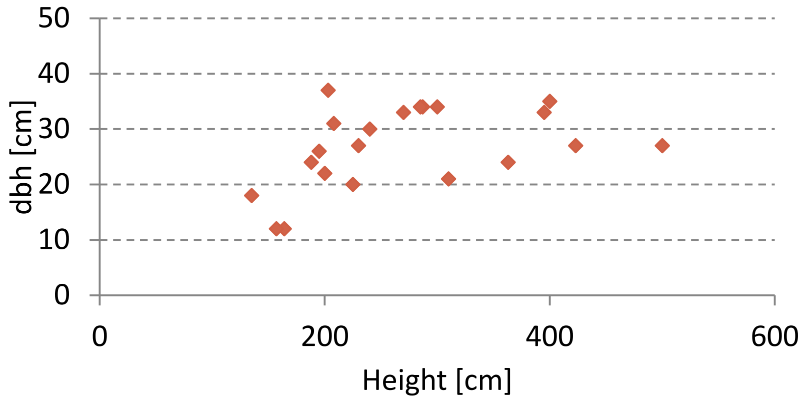
Appendix A, Figure A4. Height curve of oak



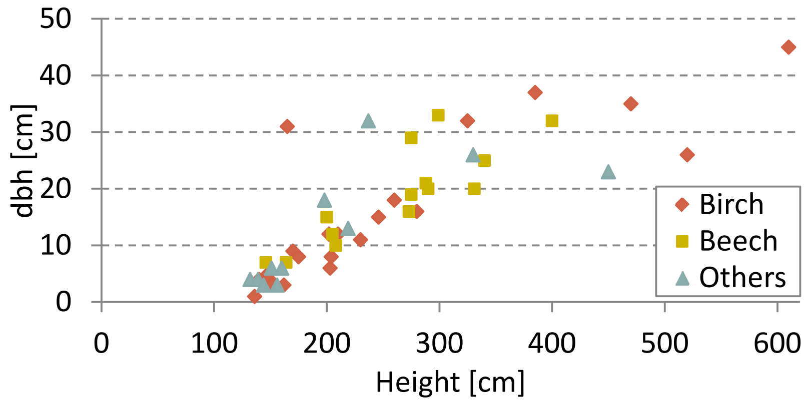
Appendix A, Figure A5. Height curve of beech



Appendix A, Figure A6. Relation between dbh and tree height of small spruce trees below 5 cm dbh



Appendix A, Figure A7. Relationship between dbh and tree height of small oak trees below 5 cm dbh



Appendix A, Figure A8. Relationship between dbh and tree height of small trees of birch, beech and the rest of other tree species below 5 cm dbh

Appendix B

Ingrowth scenarios

An assumption for the general scenario construction was made by plots with basal area below 15 m²/ha representing gaps, and plots with less than 10 m²/ha representing large gaps. This simplification is rough, but also logical to combine the plot data with gap information (Table B1).

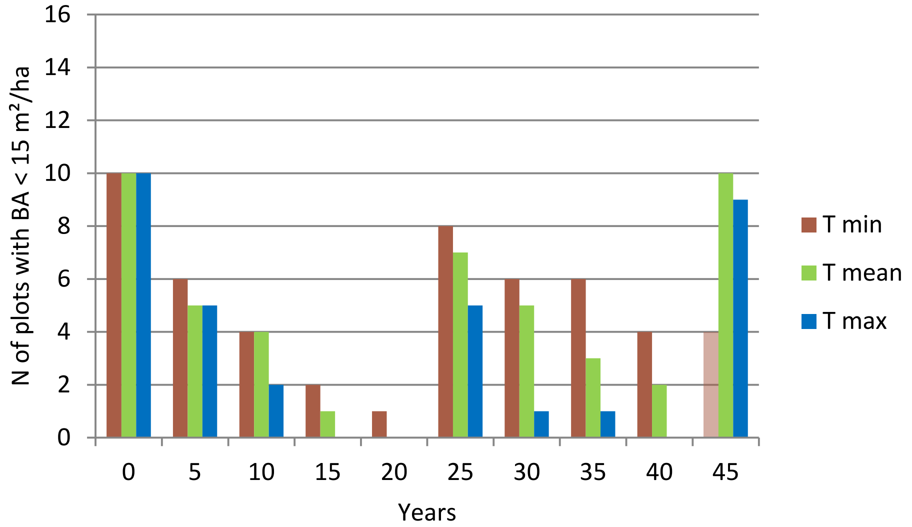
Appendix B, Table B1. Basal area on systematic sample plots and visually estimated gap percentage of the plot area without forest canopy after the first cutting

gap area on the plot	BA after thinning	gap area on the plot	BA after thinning
75%	**10.6**	0	**14.3**
75%	**12.4**	0	26.5
66%	**14.4**	0	25.0
50%	**8.3**	0	30.4
50%	21.1	0	25.2
45%	21.3	0	**14.8**
35%	**14.5**	0	24.4
35%	30.0	0	25.7
10%	**10.4**	0	25.8
10%	17.7	0	24.0
0%	15.1	0	29.6
0%	18.6	0	27.7
0%	21.9	0	38.9
0%	15.5	0	32.5
0%	22.2	0	26.1
0%	22.1	0	27.1
0%	15.4	0	28.0
0%	24.8	0	29.5

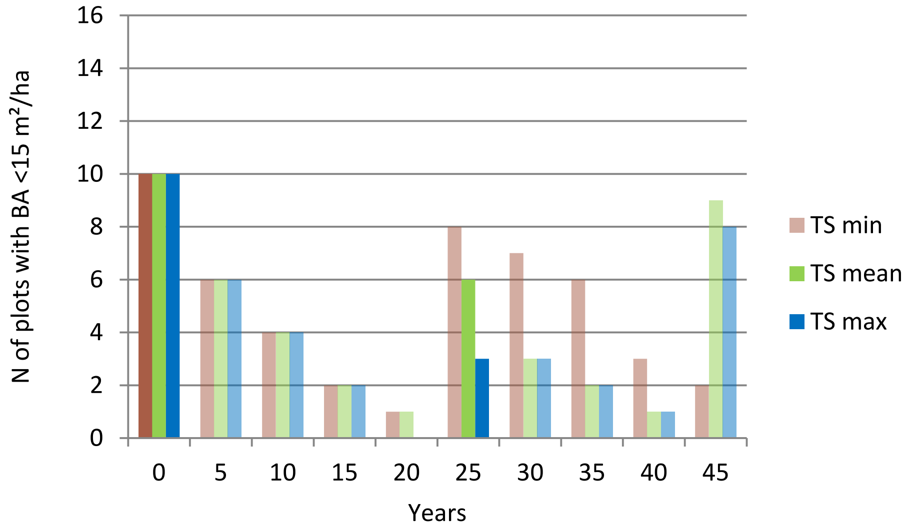
Appendix B, Table B2. Implemented ingrowth in the simulator on plots representing gaps without and with scarification

scen.	BA on the plot		operational ingrowth on a gap-plot without scar.	operational ingrowth on a gap-plot after scarification
MIN	10-15 m^2	spruce	2 after 10 years	31 after 40 years
	< 10 m^2	pine		16 after 40 years
		birch		16 after 30 years
MEAN	10-15 m^2	spruce	6 after 5 years	63 after 25 years
		birch	1 after 10 years	
	< 10 m^2	pine		31 after 25 years
		birch		31 after 25 years
MAX	10-15 m^2	spruce	22 after 5 years	63 after 20 years
		birch	2 after 5 years	
		oak	1 after 10 years	
		beech	2 after 10 years	
	< 10 m^2	pine		31 after 20 years
		birch		31 after 20 years

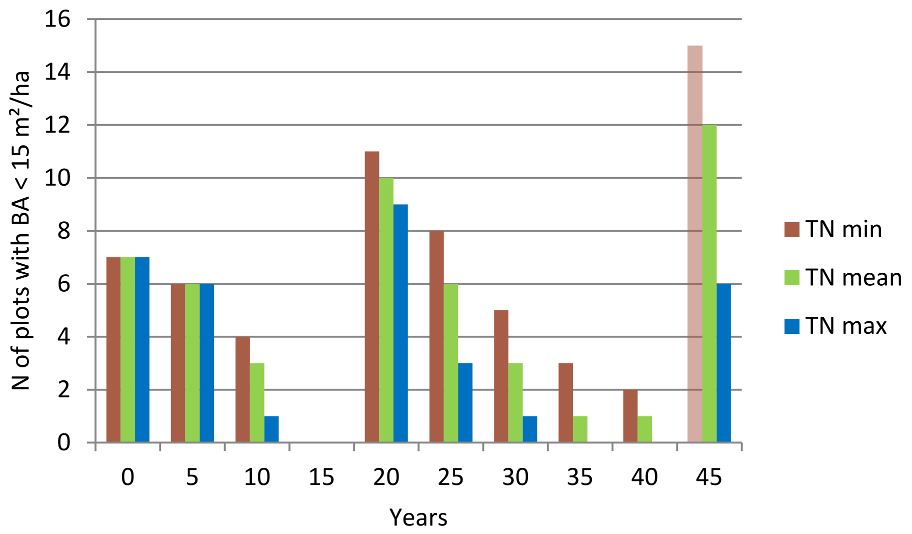
See figure B1-B3 regarding the occurrence of plots with BA < 15 m^2/ha over the simulation period. (Plots with low BA after 45 years did not contribute with new trees. Under the minimum scenario, only the first 40 years could result in new trees under the simulation period.) Concerning treatment TS, large gaps were represented by 14 plots with BA < 10 m^2/ha, while plots with BA < 15 m^2/ha were simulated 48 times within the next 50 years.



Appendix B, Figure B1. Number of plots with basal area < 15 m^2/ha at different simulation steps where ingrowth was implemented, according to treatment T, stand age-independent single-tree ages, and different ingrowth scenarios



Appendix B, Figure B2. Number of plots with basal area < 15 m^2/ha at different simulation steps, according to treatment TS, stand age-independent single-tree ages, and different ingrowth scenarios. Full color indicates plots when ingrowth was implemented.



Appendix B, Figure B3. Number of plots with basal area < 15 m^2/ha at different simulation steps where ingrowth was implemented, according to treatment TN, stand age-independent single-tree ages, and different ingrowth scenarios

Appendix C - Simulation output data

Appendix C, Table C1. Simulated initial stand characteristics per hectare of the unmanaged **control** treatment as starting point for the 50 years simulation on all 48 sample plots

	Species	N	BA [m²/ha]	dg [cm]	Vol [m³/ha]
S	Spruce	489	13.77	18.9	131
T	Pine	164	15.44	34.6	145
A	Birch	54	2.59	24.6	21
R	Beech	21	0.37	15.1	3
T	Oak	271	2.98	11.8	21
	Total	*999*	*35.15*	*21.2*	*322*

Appendix C, Table C2. Simulated stand characteristics, mean annual increment, and mortality after 50 years without management (**control**). Figures were calculated per hectare, based on 48 sample plots, **stand age-independent** single-tree age, and three different ingrowth scenarios (see explanations in the text)

							MAI		mort.
	Species	N	BA [m²/ha]	dg [cm]	Vol [m³/ha]		BA [m²/ha]	Vol [m³/ha]	in total [m³/ha]
	Spruce	392	23,09	27.3	260		0.25	3.2	33
M	Pine	139	21.67	44.9	238		0.18	2.5	31
I	Birch	37	2.90	31.5	26		0.02	0.2	5
N	Beech	15	0.82	26.5	10		0.01	0.2	1
	Oak	181	4.82	18.4	43		0.06	0.7	12
	Total	*765*	*53.29*	*29.9*	*577*		*0.53*	*6.8*	*83*
	Spruce	393	23.06	27.3	260		0.25	3.3	35
M	Pine	139	21.60	44.5	233		0.18	2.4	31
E	Birch	38	2.84	31.1	25		0.02	0.2	6
A	Beech	15	0.82	26.2	9		0.01	0.2	1
N	Oak	179	4.80	18.5	43		0.06	0.7	12
	Total	*764*	*53.12*	*29.8*	*571*		*0.53*	*6.7*	*84*
	Spruce	392	23.16	27,4	262		0.25	3.3	34
M	Pine	139	21.61	44,6	234		0.18	2.4	31
A	Birch	37	2.89	31,5	26		0.02	0.2	5
X	Beech	15	0.79	26,2	9		0.01	0.1	1
	Oak	179	4.77	18,4	42		0.06	0.7	12
	Total	*761*	*53.22*	*29,8*	*573*		*0.53*	*6.7*	*83*

Appendix C, Table C3. Simulated stand characteristics, mean annual increment, and mortality after 50 years without management (**control**). Figures were calculated per hectare, based on 48 sample plots, **stand age-dependent** single-tree age, and three different ingrowth scenarios (see explanations in the text).

	Species	N	BA [m²]	dg [cm]	Vol [m³]		MAI BA [m²]	MAI Vol [m³]	nat. mort. [m³]
	Spruce	392	23.00	27.4	261		0.25	3.3	35
M	Pine	139	21.97	44.6	234		0.19	2.4	30
I	Birch	38	2.92	31.1	26		0.02	0.2	5
N	Beech	15	0.84	26.5	9		0.01	0.2	1
	Oak	181	4.81	18.4	43		0.06	0.7	12
	Total	*765*	*53.54*	*29.8*	*573*		*0.53*	*6.7*	*83*
	Spruce	393	22.87	27.2	258		0.25	3.2	34
M	Pine	138	21.88	44.9	237		0.19	2.5	33
E	Birch	37	2.90	31.4	26		0.02	0.2	6
A	Beech	15	0.86	26.6	10		0.01	0.2	1
N	Oak	181	4.86	18.5	43		0.06	0.7	11
	Total	*765*	*53.37*	*29.8*	*574*		*0.53*	*6.7*	*85*
	Spruce	394	22.95	27.2	259		0.25	3.2	34
M	Pine	140	22.15	45.0	240		0.19	2.5	30
A	Birch	38	2.98	31.6	26		0.02	0.2	5
X	Beech	16	0.88	26.6	10		0.01	0.2	1
	Oak	183	4.85	18.4	43		0.06	0.7	11
	Total	*770*	*53.82*	*29.8*	*579*		*0.53*	*6.8*	*81*

Appendix C, Table C4. Simulated initial stand characteristics per hectare according to treatment **T** and **TS** as starting point for the 50 years simulation on all 48 sample plots

		N	BA [m²]	dg [cm]	Vol [m³]
S	Spruce	440	8.97	16.1	77
T	Pine	109	8.58	31.7	76
A	Birch	26	0.36	13.4	3
R	Beech	21	0.37	15.1	3
T	Oak	271	2.98	11.8	21
	Total	*866*	*21.26*	*17.7*	*179*

Appendix C, Table C5. Stand characteristics of treatment **T** after 50 years simulation, annual increment and harvest (figures per ha, based on 48 sample plots, **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **100 m³/ha** standing volume after cut)

		N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	312	11.83	22.0	117		0.27	3.1			52	43	64
M	Pine	21	2.33	37.5	22		0.12	1.3			69	62	57
I	Birch	12	0.28	17.2	2		0.01	0.0			18	2	1
N	Beech	8	0.31	21.9	3		0.02	0.2			0	4	7
	Oak	199	7.05	21.2	55		0.13	1.1			0	2	18
	Total	*552*	*21.80*	*22.4*	*198*		*0.54*	*5.8*		*0/25/50*	*139*	*113*	*147*
	Spruce	410	13.03	20.1	127		0.30	3.3			52	46	52
M	Pine	21	2.36	37.5	22		0.11	1.3			69	60	51
E	Birch	32	0.41	12.8	3		0.01	0.1			18	2	1
A	Beech	8	0.32	22.1	3		0.02	0.2			0	4	5
N	Oak	200	7.06	21.2	55		0.13	1.1			0	2	12
	Total	*672*	*23.18*	*21.0*	*209*		*0.56*	*5.9*		*0/25/45*	*139*	*114*	*121*
	Spruce	555	14.89	18.5	143		0.33	3.7			52	45	51
M	Pine	21	2.28	37.4	21		0.11	1.3			69	60	50
A	Birch	26	0.37	13.4	3		0.01	0.1			18	2	1
X	Beech	19	0.40	16.4	3		0.02	0.2			0	4	5
	Oak	211	7.11	20.7	55		0.13	1.1			0	2	12
	Total	*832*	*25.06*	*19.6*	*225*		*0.60*	*6.2*		*0/25/45*	*139*	*113*	*119*

Appendix C, Table C6. Stand characteristics of treatment **T** after 50 years simulation, annual increment and harvest (figures per ha, based on 48 sample plots, **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **150 m³/ha** standing volume after cut)

		N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	308	22.74	22.0	116		0.27	3.2			52	46	52
M	Pine	21	2.28	37.5	21		0.11	1.3			69	60	51
I	Birch	12	0.27	16.8	2		0.01	0.0			18	2	0
N	Beech	8	0.31	22.4	3		0.02	0.2			0	4	6
	Oak	197	6.99	21.3	54		0.13	1.1			0	3	12
	Total	*545*	*21.59*	*22.5*	*196*		*0.54*	*5.8*		*0/25/45*	*139*	*115*	*121*
	Spruce	412	13.05	20.1	127		0.30	3.4			52	45	52
M	Pine	21	2.29	37.4	21		0.11	1.3			69	60	50
E	Birch	29	0.39	13.0	3		0.01	0.1			18	2	0
A	Beech	8	0.32	22.2	3		0.02	0.2			0	4	5
N	Oak	201	7.06	21.1	55		0.13	1.1			0	2	12
	Total	*672*	*23.11*	*20,9*	*208*		*0.56*	*5.9*		*0/25/45*	*139*	*113*	*120*
	Spruce	560	14.91	18.4	143		0.33	3.7			52	45	51
M	Pine	21	2.30	37.5	21		0.11	1.3			69	60	51
A	Birch	26	0.36	13.2	2		0.01	0.1			18	2	0
X	Beech	19	0.40	16.4	3		0.02	0.2			0	4	5
	Oak	211	7.07	20.7	55		0.13	1.1			0	3	12
	Total	*837*	*25.04*	*19.5*	*225*		*0.60*	*6.2*		*0/25/45*	*139*	*114*	*118*

Appendix C, Table C7. Harvest and initial stand characteristics per hectare on **block 1** according to treatment **T**

	removed				after cutting			
Species	N	BA [m²]	dg [cm]	Vol [m³]	N	BA [m²]	dg [cm]	Vol [m³]
Spruce	34	3.36	35.6	35	358	6.44	15.1	53
Pine	34	4.25	40.0	42	101	8.18	32.0	73
Birch	46	3.57	31.5	30	32	0.63	15.8	5
Beech					26	0.48	15.3	4
Oak					448	4.81	11.7	34
Total	*113*	*11.19*	*35.4*	*107*	*965*	*20.53*	*16.5*	*168*

Appendix C, Table C8. Stand characteristics, annual increment and harvest on **block 1** according to treatment **T** after 50 years simulation (figures per ha, based on **stand age-independent** single-tree ages, with the moderate ingrowth scenario and minimum **100 m³/ha** standing volume after cut)

Species	N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
Spruce	241	8.17	20.8	77		0.24	2.7			35	38	56
Pine	13	1.26	35.6	11		0.11	1.2			42	62	55
Birch	20	0.27	13.2	2		0.01	0.1			30	5	0
Beech	7	0.19	18.2	2		0.02	0.3			0	5	9
Oak	328	10.99	20.6	86		0.20	1.7			0	2	21
Total	*609*	*20.88*	*20.9*	*177*		*0.58*	*5.9*		*0/25/50*	*107*	*112*	*142*

Appendix C, Table C9. Harvest and initial stand characteristics per hectare on **block 2** according to treatment **T**

	removed				after cutting			
Species	N	BA [m²]	dg [cm]	Vol [m³]	N	BA [m²]	dg [cm]	Vol [m³]
Spruce	48	3.77	31.7	40	342	6.76	15.9	56
Pine	84	10.51	40.0	105	127	10.25	32.0	90
Birch	16	1.36	33.0	11	26	0.21	10.2	1
Beech					28	0.57	16.2	5
Oak					247	2.92	12.3	21
Total	*147*	*15.65*	*36.8*	*156*	*770*	*20.72*	*18.5*	*173*

Appendix C, Table C10. Stand characteristics, annual increment and harvest on **block 2** according to treatment **T** after 50 years simulation (figures per ha, based on **stand age-independent** single-tree ages, with the moderate ingrowth scenario and minimum **100 m³/ha** standing volume after cut)

Species	N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
Spruce	339	12.45	21.6	123		0.24	2.7			40	47	
Pine	70	9.51	41.7	93		0.14	1.6			105	68	
Birch	34	0.38	12.0	3		0.01	0.0			11	0	
Beech	18	1.27	29.6	13		0.03	0.3			0	6	
Oak	192	7.65	22.5	63		0.12	1.1			0	5	
Total	*654*	*31.27*	*24.7*	*296*		*0.54*	*5.8*		*0/25*	*156*	*126*	

Appendix C, Table C11. Harvest and initial stand characteristics per hectare on **block 3** according to treatment **T**

	removed				after cutting			
Species	N	BA [m²]	dg [cm]	Vol [m³]	N	BA [m²]	dg [cm]	Vol [m³]
Spruce	68	7.27	37.0	81	619	13.71	16.8	121
Pine	48	5.82	39.4	60	97	7.32	30.9	64
Birch	24	1.75	30.5	14	20	0.26	12.8	2
Beech					8	0.05	9.3	0
Oak					119	1.21	11.3	8
Total	*139*	*14.83*	*36.8*	*155*	*863*	*22.54*	*18.2*	*196*

Appendix C, Table C12. Stand characteristics, annual increment and harvest on **block 3** according to treatment **T** after 50 years simulation (figures per ha, based on **stand age-independent** single-tree ages, with the moderate ingrowth scenario and minimum **100 m³/ha** standing volume after cut)

Species	N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
Spruce	594	20.59	21.0	206		0.41	4.7			81	51	75
Pine	23	2.37	36.2	22		0.10	1.1			60	50	41
Birch	39	0.56	13.4	4		0.01	0.1			14	0	0
Beech	5	0.06	13.1	0		0.00	0.0			0	0	2
Oak	88	2.84	20.3	22		0.05	0.4			0	0	5
Total	*748*	*26.42*	*21.2*	*255*		*0.57*	*6.3*		*0/25/45*	*155*	*102*	*123*

Appendix C, Table C13. Stand characteristics of the treatment **TS** after 50 years simulation, annual increment and harvest (figures per ha, based on **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **100 m³/ha** standing volume after cut)

		N [ha^{-1}]	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	415	10.88	18.3	104		0.28	3.1			53	46	64
M	Pine	44	1.75	22.4	16		0.12	1.3			69	60	59
I	Birch	36	0.33	10.7	2		0.01	0.0			19	2	1
N	Beech	7	0.23	19.8	2		0.02	0.2			0	4	7
	Oak	190	6.23	20.5	48		0.13	1.1			0	3	18
	Total	*692*	*19.41*	*18.9*	*172*		*0.55*	*5.8*		*0/25/50*	*141*	*114*	*149*
	Spruce	689	14.20	16.2	134		0.32	3.4			53	44	51
M	Pine	104	2.77	18.4	24		0.12	1.3			69	60	51
E	Birch	108	0.64	8.7	4		0.01	0.1			19	2	1
A	Beech	8	0.32	22.1	3		0.02	0.2			0	4	5
N	Oak	203	7.13	21.1	55		0.13	1.1			0	2	11
	Total	*1113*	*25.06*	*16.9*	*220*		*0.60*	*6.1*		*0/25/45*	*141*	*113*	*119*
	Spruce	760	16.02	16.4	151		0.35	3.7			53	44	50
M	Pine	105	2.91	18.8	25		0.12	1.3			69	60	52
A	Birch	109	0.72	9.1	4		0.02	0.1			19	2	0
X	Beech	15	0.36	17.3	3		0.02	0.2			0	4	5
	Oak	212	7.18	20.7	55		0.13	1.0			0	2	11
	Total	*1201*	*27.18*	*17.0*	*239*		*0.64*	*6.4*		*0/25/45*	*141*	*112*	*118*

Appendix C, Table C14. Stand characteristics of the treatment **TS** after 50 years simulation, annual increment and harvest (figures per ha, based on **stand age-dependent** single-tree ages, three different ingrowth scenarios and minimum **100 m³/ha** standing volume after cut)

		N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	426	11.25	18.3	107		0.27	3.1			53	43	63
M	Pine	44	1.85	23.2	17		0.12	1.4			69	62	58
I	Birch	37	0.33	10.8	2		0.01	0.0			19	2	1
N	Beech	7	0.24	20.2	2		0.02	0.2			0	4	7
	Oak	195	6.40	20.5	50		0.13	1.1			0	2	17
	Total	*709*	*20.06*	*19.0*	*178*		*0.55*	*5.8*		*0/25/50*	*141*	*113*	*145*
	Spruce	660	14.65	16.8	139		0.31	3.4			53	42	47
M	Pine	125	2.85	17.0	25		0.12	1.3			69	62	49
E	Birch	129	0.65	8.0	4		0.01	0.1			19	2	1
A	Beech	9	0.33	22.1	3		0.02	0.2			0	4	5
N	Oak	203	7.08	21.1	55		0.13	1.1			0	2	12
	Total	*1125*	*25.56*	*17.0*	*226*		*0.60*	*6.0*		*0/25/45*	*141*	*112*	*114*
	Spruce	717	15.87	16.8	150		0.34	3.6			53	41	48
M	Pine	122	2.88	17.3	25		0.13	1.4			69	62	49
A	Birch	125	0.72	8.5	4		0.02	0.1			19	2	1
X	Beech	15	0.37	17.7	3		0.02	0.2			0	4	5
	Oak	211	7.15	20.8	55		0.13	1.0			0	2	11
	Total	*1190*	*26.99*	*17.0*	*237*		*0.63*	*6.3*		*0/25/45*	*141*	*112*	*114*

Appendix C, Table C15. Stand characteristics of the treatment **TS** after 50 years simulation, annual increment and harvest (figures per ha, based on **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **150 m³/ha** standing volume after cut)

		N [ha^{-1}]	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	340	10.78	20.1	104		0.27	3.0			53	43	63
M	Pine	27	1.80	29.1	16		0.12	1.4			69	62	58
I	Birch	20	0.26	12.8	2		0.01	0.0			19	2	1
N	Beech	8	0.25	20.7	2		0.02	0.2			0	4	7
	Oak	190	6.27	20.5	49		0.13	1.1			0	3	17
	Total	*586*	*19.36*	*20.5*	*173*		*0.54*	*5.7*		*0/25/50*	*141*	*113*	*146*
	Spruce	691	14.32	16.2	136		0.32	3.4			53	45	51
M	Pine	105	2.84	18.5	25		0.12	1.3			69	60	51
E	Birch	108	0.64	8.7	4		0.01	0.1			19	2	0
A	Beech	9	0.33	21.9	3		0.02	0.2			0	4	5
N	Oak	203	7.14	21.1	55		0.13	1.1			0	2	12
	Total	*1117*	*25.27*	*17.0*	*223*		*0.60*	*6.1*		*0/25/45*	*141*	*113*	*119*
	Spruce	774	15.96	16.2	150		0.35	3.7			53	44	50
M	Pine	103	2.90	18.9	25		0.12	1.3			69	60	50
A	Birch	109	0.71	9.1	4		0.02	0.1			19	2	0
X	Beech	15	0.34	17.1	3		0.02	0.2			0	4	5
	Oak	209	7.11	20.8	55		0.13	1.0			0	2	11
	Total	*1210*	*27.02*	*16.9*	*238*		*0.64*	*6.4*		*0/25/45*	*141*	*113*	*117*

Appendix C, Table C16. Simulated initial stand characteristics per hectare according to treatment **TN** as starting point for the 50 years simulation on all 48 sample plots

		N	BA $[m^2]$	dg [cm]	Vol $[m^3]$
S	Spruce	422	7.80	15.3	65
T	Pine	136	11.15	32.3	100
A	Birch	38	0.98	18.2	8
R	Beech	21	0.37	15.1	3
T	Oak	271	2.98	11.8	21
	Total	*887*	*23.28*	*18.3*	*197*

Appendix C, Table C17. Stand characteristics of treatment **TN** after 50 years simulation, annual increment and harvest (figures per ha, based on **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **100 m^3/ha** standing volume after cut)

		N	BA $[m^2]$	dg [cm]	Vol $[m^3]$		BA MAI $[m^2]$	Vol MAI $[m^3]$		Time of cutting [years]	1th cut removal $[m^3]$	2nd cut removal $[m^3]$	3rd cut removal $[m^3]$
	Spruce	227	6.18	18.6	55		0.24	2.6			64	53	71
M	Pine	29	3.18	37.4	29		0.14	1.6			44	61	80
I	Birch	17	0.52	20.0	4		0.01	0.1			13	4	2
N	Beech	18	1.46	32.3	16		0.02	0.3			0	0	0
	Oak	214	8.36	22.3	66		0.13	1.1			0	1	1
	Total	*505*	*19.72*	*22.3*	*169*		*0.54*	*5.6*		*0/20/45*	*122*	*119*	*156*
	Spruce	340	7.34	16.6	64		0.26	2.8			64	53	71
M	Pine	29	3.17	37.3	29		0.14	1.6			44	61	80
E	Birch	33	0.61	15.3	4		0.01	0.1			13	5	2
A	Beech	17	1.37	32.1	15		0.02	0.3			0	0	0
N	Oak	212	8.29	22.3	65		0.13	1.1			0	1	2
	Total	*631*	*20.78*	*20.5*	*177*		*0.56*	*5.8*		*0/20/45*	*122*	*119*	*155*
	Spruce	533	10.76	16.0	96		0.30	3.1			64	53	55
M	Pine	36	4.14	38.4	39		0.13	1.5			44	60	68
A	Birch	33	0.69	16.2	5		0.01	0.1			13	5	2
X	Beech	33	1.55	24.4	16		0.03	0.3			0	0	0
	Oak	232	8.66	21.8	68		0.13	1.1			0	1	1
	Total	*867*	*25.79*	*19.5*	*224*		*0.61*	*6.1*		*0/20/40*	*122*	*119*	*126*

Appendix C, Table C18. Simulated initial stand characteristics per hectare according to the treatment **T** with **5 cm higher target diameters** as starting point for the 50 years simulation on all 48 sample plots

		N	BA [m²]	dg [cm]	Vol [m³]
S	Spruce	489	13.77	18.9	131
T	Pine	164	15.44	34.6	145
A	Birch	54	2.59	24.6	21
R	Beech	21	0.37	15.1	3
T	Oak	271	2.98	11.8	21
	Total	*999*	*35.15*	*21.2*	*322*

Appendix C, Table C19. Stand characteristics, annual increment and harvest according to treatment **T** with **5 cm higher target diameters** after 50 years simulation (figures per ha, based on **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **100 m³/ha** standing volume after cut)

		N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	318	13.78	23.5	140		0.27	3.2			44	39	46
M	Pine	51	6.34	39.8	62		0.15	1.8			52	59	52
I	Birch	14	0.33	17.6	3		0.01	0.1			16	4	1
N	Beech	10	0.43	22.8	4		0.02	0.2			0	2	5
	Oak	198	6.57	20.6	53		0.10	0.9			1	1	5
	Total	*591*	*27.45*	*24.3*	*261*		*0.55*	*6.2*		5/30/50	*114*	*106*	*110*
											0	0	0
	Spruce	347	14.09	22.7	143		0.27	3.3			44	39	47
M	Pine	51	6.40	39.8	62		0.15	1.8			52	58	52
E	Birch	21	0.36	14.8	3		0.01	0.1			16	4	1
A	Beech	11	0.46	23.2	4		0.02	0.2			0	2	5
N	Oak	199	6.52	20.4	52		0.10	0.9			1	1	5
	Total	*629*	*27.83*	*23.7*	*265*		*0.55*	*6.2*		5/30/50	*114*	*105*	*110*
											0	0	0
	Spruce	402	14.62	21.5	147		0.28	3.3			45	38	47
M	Pine	51	6.44	39.9	63		0.15	1.8			51	58	52
A	Birch	18	0.36	15.7	3		0.01	0.1			16	4	1
X	Beech	16	0.49	20.0	5		0.02	0.2			0	2	5
	Oak	203	6.53	20.2	52		0.10	0.9			1	1	5
	Total	*691*	*28.44*	*22.9*	*269*		*0.56*	*6.3*		5/30/50	*113*	*104*	*110*

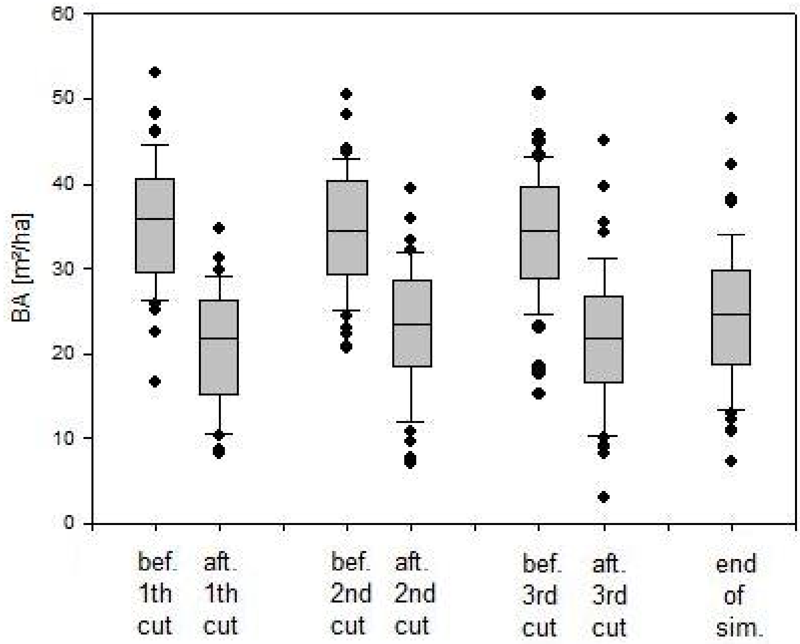
Appendix C, Table C20. Simulated initial stand characteristics per hectare according to the treatment **T** with **5 cm lower target diameters** as starting point for the 50 years simulation on all 48 sample plots

		N	BA [m²]	dg [cm]	Vol [m³]
S	Spruce	401	7.18	15.1	59
T	Pine	71	4.81	29.4	40
A	Birch	22	0.19	10.6	1
R	Beech	19	0.30	14.0	2
T	Oak	271	2.94	11.8	21
	Total	*783*	*15.43*	*15.8*	*124*

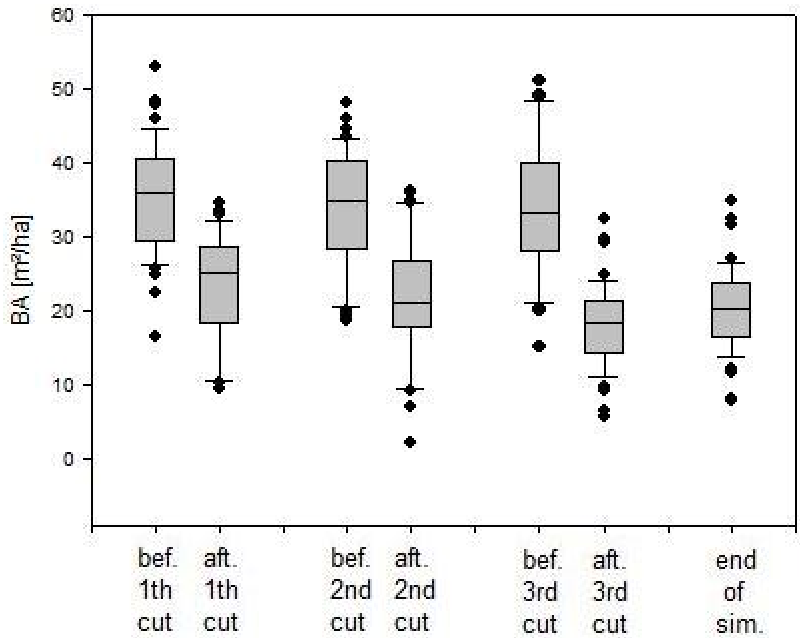
Appendix C, Table C21. Stand characteristics, annual increment and harvest according to treatment **T** with **5 cm lower target diameters** after 50 years simulation (figures per ha, based on **stand age-independent** single-tree ages, three different ingrowth scenarios and minimum **100 m³/ha** standing volume after cut)

		N	BA [m²]	dg [cm]	Vol [m³]		BA MAI [m²]	Vol MAI [m³]		Time of cutting [years]	1th cut removal [m³]	2nd cut removal [m³]	3rd cut removal [m³]
	Spruce	324	9.72	19.6	90		0.27	3.0			69	98	
M	Pine	6	0.51	33.9	4		0.08	0.9			104	74	
I	Birch	8	0.14	15.1	1		0.01	0.0			20	1	
N	Beech	6	0.20	20.2	2		0.02	0.2			1	9	
	Oak	178	6.20	21.1	47		0.14	1.2			0	26	
	Total	*521*	*16.78*	*20.2*	*145*		*0.51*	*5.3*		0/40	*194*	*209*	
	Spruce	551	13.45	17.6	124		0.32	3.4			69	85	
M	Pine	9	0.97	36.1	9		0.07	0.8			104	67	
E	Birch	55	0.42	9.8	3		0.01	0.1			20	1	
A	Beech	8	0.31	22.8	3		0.02	0.2			1	7	
N	Oak	195	7.31	21.9	57		0.15	1.2			0	19	
	Total	*818*	*22.46*	*18.7*	*195*		*0.57*	*5.6*		0/35	*194*	*180*	
												0	
	Spruce	763	16.76	16.7	154		0.39	4.0			69	85	
M	Pine	10	0.98	36.1	9		0.07	0.8			104	67	
A	Birch	33	0.34	11.4	2		0.01	0.1			20	1	
X	Beech	35	0.51	13.6	4		0.02	0.2			1	7	
	Oak	226	7.44	20.5	57		0.15	1.2			0	19	
	Total	*1067*	*26.04*	*17.6*	*226*		*0.64*	*6.2*		0/35	*194*	*179*	

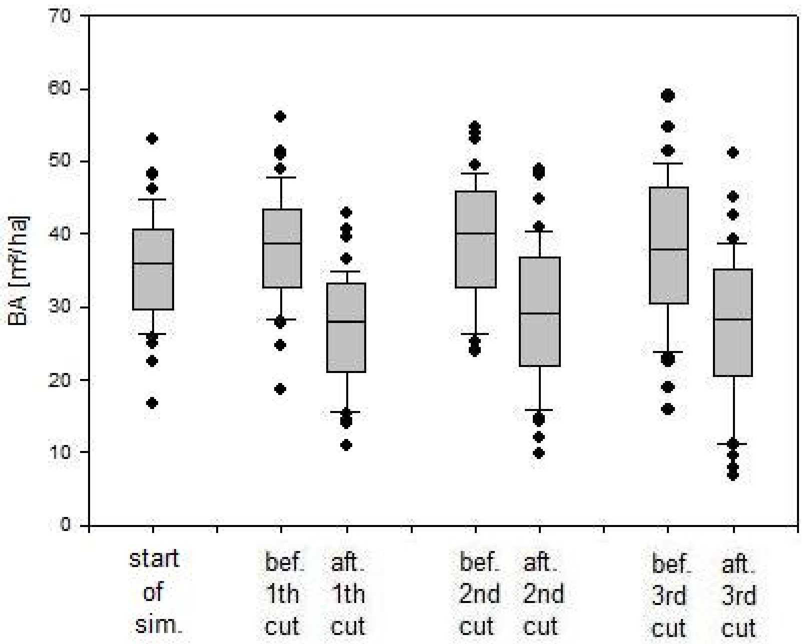
Appendix D – Variation of simulated future basal area on plots



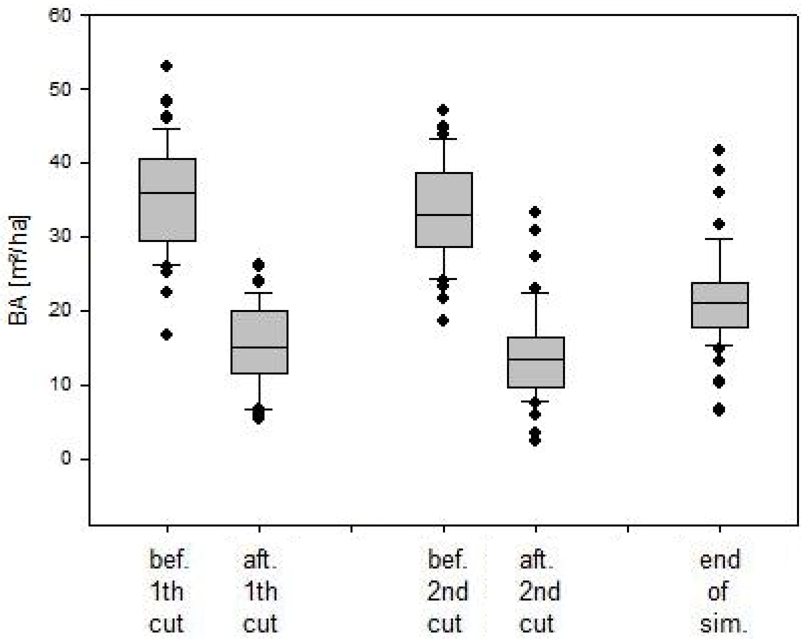
Appendix, figure D2. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on single plots at year 0, 25, 45, and 50 of the simulation (treatment TS).



Appendix D, figure D3. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on single plots at year 0, 25, 45, and 50 of the simulation (according to treatment TN).



Appendix D, figure D4. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on single plots at year 0, 25, 45, and 50 of the simulation (according to treatment T with 5 cm larger target diameters).



Appendix, figure D7. Box plot with median, 10th, 25th, 75th, and 90th percentiles of the basal area on single plots at year 0, 25, 45, and 50 of the simulation (according to treatment T with 5 cm reduced target diameters).

Appendix E

Table E1. Yield table and cost projections for treatment T. Figures were calculated per hectare. 0% interest rate.

		Stand before thinning			Removed							Net		Annual	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	NPV
	[yrs.]	N	[m^2]	[m^3]	N	[m^2]	[m^3]	[m^3]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	52								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	18								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	35518	35518		
Spruce	25	459	15.6	152	61	4.2	45								
Pine	25	103	11.8	113	44	6.0	60								
Broadleaves	25	287	6.6	51	16	0.9	8								
Total	25	849	34.1	316	121	11.0	113	6.1	Harvest	39845	11300	28545	28545		
Spruce	45	423	16.2	163	62	4.7	53								
Pine	45	57	7.3	71	36	5.1	51								
Broadleaves	45	276	8.8	71	28	1.9	17								
Total	45	756	32.3	305	126	11.7	121	5.9	Harvest	43290	12100	31190	31190	2185	95253

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E2. Yield table and cost projections for treatment TS. Figures were calculated per hectare. 0% interest rate.

		Stand before thinning			Removed							Net		Annual	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	NPV
	[yrs.]	N	[m^2]	[m^3]	N	[m^2]	[m^3]	[m^3]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	53								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	19								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	30518	30518		
	0								Soil prep.		2500				
	0								Cleaning		2500				
Spruce	25	641	15.8	151	63	4.2	45								
Pine	25	191	12.0	113	44	6.0	60								
Broadleaves	25	307	6.7	51	17	0.9	8								
Total	25	1139	34.5	315	124	11.1	113	6.0	Harvest	39845	11300	23545	23545		
	25								Soil prep.		2500				
	25								Cleaning		2500				
Spruce	45	555	16.6	165	63	4.5	51								
Pine	45	137	7.8	75	38	5.2	51								
Broadleaves	45	283	8.9	71	28	1.9	18								
Total	45	975	33.3	311	129	11.6	120	6.1	Harvest	43290	12000	26290	26290	1607	80353
	45								Soil prep.		2500				
	45								Cleaning		2500				

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E3. Yield table and cost projections for treatment TN. Figures were calculated per hectare. 0% interest rate.

	Time	Stand before thinning	BA	V	Removed	BA	V	MAI	Treatment	Income	Cost	Net income	PV	Annual revenue	NPV
	[yrs.]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]		[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	68	6.0	64								
Pine	0	164	15.4	144	28	4.3	44								
Broadleaves	0	346	5.9	45	17	1.6	13								
Total	0	999	35.2	318	113	11.9	121		Harvest	30886	12100	18786	18786		
Spruce	20	436	12.7	119	84	5.1	53								
Pine	20	131	14.4	136	42	6.0	60								
Broadleaves	20	303	6.6	51	16	0.7	6								
Total	20	870	33.7	306	142	11.7	119	6.0	Harvest	46843	11900	34943	34943		
Spruce	45	379	12.7	123	103	6.6	70								
Pine	45	84	11.0	108	55	8.0	81								
Broadleaves	45	280	9.7	80	11	0.4	4								
Total	45	743	33.4	311	169	15.0	155	5.7	Harvest	59851	15500	44351	44351	1962	98080

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E4. Yield table and cost projections for the clearfelling strategy, planting of spruce on this site, and typical even-aged forest management with 60 years rotation. Figures calculated per hectare with the forest simulator DT (Nilsson & Fahlvik, 2006). r = 0%.

	Time	Stand before thinning	BA	V	Removed	BA	V	MAI	Treatment	Income	Cost	Net income	PV	Annual revenue	NPV
	[yrs.]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]		[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	489	13.8	129			32904					
Pine	0	164	15.4	144	164	15.4	144			72079					
Broadleaves	0	346	5.9	45	346	5.9	45			9223					
Total	0	999	35.2	318	999	35.2	318		Harvest	114206	31800	64406	64406		
	0								Soil prep.		3000				
	0								Planting		15000				
	7								Cleaning		1000	-1000	-1000		
	15								Cleaning		1500	-1500	-1500		
Spruce	30	1783	27.5	165	796	10.7	64	5.5	Thinning	11954	8240	3714	3714		
Spruce	40	637	21.3	177	318	9.3	76	7.9	Thinning	19660	6251	13409	13409		
Spruce	60	573	40.4	454	573	40.4	454	9.9	Harvest	160584	15325	127259	127259	2365	206288
	60								Soil prep.		3000				
	60								Planting		15000				

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E5. Yield table and cost projections for treatment T. Figures were calculated per hectare. 4% interest rate.

	Time	Stand before thinning			Removed			MAI		Income	Cost	Net income	PV	Annual revenue	NPV
	[yrs.]	N	BA [m²]	V [m³]	N	BA [m²]	V [m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	52								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	18								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	35518	35518		
Spruce	25	459	15.6	152	61	4.2	45								
Pine	25	103	11.8	113	44	6.0	60								
Broadleaves	25	287	6.6	51	16	0.9	8								
Total	25	849	34.1	316	121	11.0	113	6.1	Harvest	39845	11300	28545	10708		
Spruce	45	423	16.2	163	62	4.7	53								
Pine	45	57	7.3	71	36	5.1	51								
Broadleaves	45	276	8.8	71	28	1.9	17								
Total	45	756	32.3	305	126	11.7	121	5.9	Harvest	43290	12100	31190	5340	2185	51565

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E6. Yield table and cost projections for treatment TS. Figures were calculated per hectare. 4% interest rate.

	Time	Stand before thinning			Removed			MAI		Income	Cost	Net income	PV	Annual revenue	NPV
	[yrs.]	N	BA [m²]	V [m³]	N	BA [m²]	V [m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	50	4.8	53								
Pine	0	164	15.4	144	55	6.9	69								
Broadleaves	0	346	5.9	45	29	2.2	19								
Total	0	999	35.2	318	134	13.9	140		Harvest	49518	14000	30518	30518		
	0								Soil prep.		2500				
	0								Cleaning		2500				
Spruce	25	641	15.8	151	63	4.2	45								
Pine	25	191	12.0	113	44	6.0	60								
Broadleaves	25	307	6.7	51	17	0.9	8								
Total	25	1139	34.5	315	124	11.1	113	6.0	Harvest	39845	11300	23545	8832		
	25								Soil prep.		2500				
	25								Cleaning		2500				
Spruce	45	555	16.6	165	63	4.5	51								
Pine	45	137	7.8	75	38	5.2	51								
Broadleaves	45	283	8.9	71	28	1.9	18								
Total	45	975	33.3	311	129	11.6	120	6.1	Harvest	43290	12000	26290	4501	1607	43851
	45								Soil prep.		2500				
	45								Cleaning		2500				

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E7. Yield table and cost projections for treatment TN. Figures were calculated per hectare. 4% interest rate.

		Stand before thinning			Removed							Net		Annual	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	NPV
	[yrs.]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	68	6.0	64								
Pine	0	164	15.4	144	28	4.3	44								
Broadleaves	0	346	5.9	45	17	1.6	13								
Total	0	999	35.2	318	113	11.9	121		Harvest	30886	12100	18786	18786		
Spruce	20	436	12.7	119	84	5.1	53								
Pine	20	131	14.4	136	42	6.0	60								
Broadleaves	20	303	6.6	51	16	0.7	6								
Total	20	870	33.7	306	142	11.7	119	6.0	Harvest	46843	11900	34943	15948		
Spruce	45	379	12.7	123	103	6.6	70								
Pine	45	84	11.0	108	55	8.0	81								
Broadleaves	45	280	9.7	80	11	0.4	4								
Total	45	743	33.4	311	169	15.0	155	5.7	Harvest	59851	15500	44351	7593	1962	42326

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

Table E8. Yield table and cost projections for the clearfelling strategy, planting of spruce on this site, and typical even-aged forest management with 60 years rotation. Figures calculated per hectare with the forest simulator DT (Nilsson & Fahlvik, 2006). r = 4%.

		Stand before thinning			Removed							Net		Annual	
	Time		BA	V		BA	V	MAI		Income	Cost	income	PV	revenue	NPV
	[yrs.]	N	[m²]	[m³]	N	[m²]	[m³]	[m³]	Treatment	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]	[SEK]
Spruce	0	489	13.8	129	489	13.8	129			32904					
Pine	0	164	15.4	144	164	15.4	144			72079					
Broadleaves	0	346	5.9	45	346	5.9	45			9223					
Total	0	999	35.2	318	999	35.2	318		Harvest	114206	31800	64406	64406		
	0								Soil prep.		3000				
	0								Planting		15000				
	7								Cleaning		1000	-1000	-760		
	15								Cleaning		1500	-1500	-833		
Spruce	30	1783	27.5	165	796	10.7	64	5.5	Thinning	11954	8240	3714	1145		
Spruce	40	637	21.3	177	318	9.3	76	7.9	Thinning	19660	6251	13409	2793		
Spruce	60	573	40.4	454	573	40.4	454	9.9	Harvest	160584	15325	127259	12097	2365	78849
	60								Soil prep.		3000				
	60								Planting		15000				

N = number of stands, BA = basal area, V = total volume over bark, PV = present value, NPV = net present value

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