MASTER THESIS

MSc European Forestry Erasmus Mundus

Analysing stand level biomass production potentials for selected silvicultural regimes in Norway spruce and European beech

handed in by

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ABSTRACT

Forest biomass production potentials for selected stand treatment programmes in Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* L.) are presented. The scenarios address the question, what the potential biomass productions for the different assortments are within each management strategy and how robust the results are under changing climatic conditions. For every forest management strategy, three biomass uses (sawn wood, pulpwood and biofuel including harvest residues, branches and leaves/needles) were investigated with regard to (1) the economic implications for the forest owner, (2) climate change mitigation potential with regards to (i) in-situ C storage, (ii) biofuel, and (3) an estimate of sustainable site productivity. Four concepts for forest management were used both under current and changing climatic conditions using the recently hybrid forest patch model PICUS v1.4. The concepts are a current practiced spruce (MS1), an alternative spruce concept mimicking rather low initial density and shorter rotation (MS2), a traditional beech concept (MB1) and an alternative valuable timber production concept (MB2).

MS2 and MB2 reduced moderately the total volume production. Extracted volume (harvested extracted commercial volume from commercial thinning and final harvest) was moderately reduced under MS2 but identical under MB2. However, higher annuities were generated by those alternative management concepts. It is unfeasible to increase annuities from timber production and C storage in the forest stand at the same time. In any management concept the climate change scenarios used in this study appear to give a negative effect on both total volume production and extracted volume. . As expected, the potential for biofuel production increased strongly under the intensified extraction. No major differences regarding sustainable site productivity could be detected from the model analysis. However, indepth analysis of model output is required here. Ranking all analysed options for a species shows that no single option is best for all objectives. In spruce the option MS2-E0-variant2 achieved the best average rank over the objectives, in beech option MB2-E0-variant2 was ranked best on average.

Keywords**:** Biomass potential, Carbon storage, Biofuel production potential, *Fagus sylvatica; Picea abies*, Climate change, PICUS v1.4

ZUSAMMENFASSUNG

In dieser Arbeit werden die Potentiale von Fichten- (*Picea abies* [L.] *Karst*) und Buchenbeständen (*Fagus sylvatica* L.) hinsichtlich ihrer Biomasseproduktion in ausgewählten walbaulichen Behandlungsprogrammen untersucht. Weiterhin werden in verschiedenen Szenarios diese Behandlungsprogramme unter veränderten Klimabedingungen auf ihre Robustheit getestet. Die analysierten Behandlungsprogramme wurden hinsichtlich der (1) ökonomischen Anreize (Annuitäten) für den Waldbesitzer, (2) der Potentiale zur Abmilderung des Klimawandels durch (i) in-situ C- Speicherung, und (ii) durch Verwendung als Biobrennstoffe sowie (3) der standörtlichen Nachhaltigkeit untersucht. Die entworfenen Walbaukonzepte beinhalten einmal die traditionelle Bewirtschaftung der Fichte in der Forstpraxis (MS1), eine simulierte Behandlungsweise mit niedriger Stammzahlhaltung und kürzerer Umtriebszeit (MS2), ein Programm zur traditionellen Buchenbewirtschaftung (MB1) und ein alternatives Programm zur Wertholzproduktion (MB2).

In MS2 und MB2 ist jeweils ein leichter Rückgang der Gesamtwuchsleistung zu verzeichnen. Trotzdem wurden höhere Gewinne in den beiden alternativen Behandlungskonzepten MS2 und MB2 generiert. Die Ergebnisse zeigen, dass es nicht möglich ist gleichzeitig C-Speicherung und Erlös zu maximieren. In jedweder Behandlungsweise hatten die Klimaszenarien, die in dieser Studie angewandt wurden, einen negativen Einfluss auf das produzierte Gesamtvolumen und auf die Rundholzmenge. Wie erwartet wurde die Produktion an Biobrennstoff durch die intensivere Entnahme erhöht. In bezug auf die standörtliche Nachhaltigkeit konnten in den Modellanalysen keine wesentlichen Unterschiede zwischen den Optionen gefunden werden. Eine detailliertere Analyse der simulierten Bodenprozesse wäre jedoch für belastbare Ergebnisse notwendig. Keine Option konnte in allen Aspekten auf Rang 1 gesetzt werden. Für Fichte erwies sich MS2-E0-variant2 als im schnitt bestgereihte Option, für Buche was dies MB2-E0-variant2.

Stichworte: Biomassepotential, Kohlenstoffspeicherung, Biobrennstoffproduktion, *Fagus sylvatica; Picea abies;* Klimawandel, PICUS v1.4

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ACRONYM

3-PG	Physiological Principles in Predicting Growth
IPCC	Intergovernmental Panel on Climate Change
MS1	The current practice spruce management concept that was analyzed in this study
MS2	The alternative spruce management concept that was analyzed in this study
MB1	The traditionally practiced beech management concept that was analyzed in this study
MB2	The alternative beech management concept that was analyzed in this study
BL	Baseline climate scenario
A1B	Predicted future climate scenario by IPCC the storyline is: future integrated world with rapid economic growth, new and efficient technologies and a balanced technology emphasis on all energy sources
A2	Predicted future climate scenario by IPCC the storyline is: a very heterogeneous future world, continuously increasing population, economic development is primarily regionally oriented, technological change more fragmented and slower than other storylines
B1	Predicted future climate scenario by IPCC the storyline is: continuously increasing population (<A2), intermediate levels of economic development, more diverse technological change than A1 storylines, oriented towards environmental protection and social equity
DBH	Diameter Breast Height
E0	Standard extraction mode
E1	Intensified extraction mode
Variant1	Biomass utilization that reflects current business as usual concerning roundwood use
Variant2	Biomass utilization in which industrial wood that is usually used in pulp and paper industry in this case is allocated to be bioenergy source
NPV	Net Present Value
MAI	Mean Annual Increment
1B	Roundwood assortment for 15-19 cm diameter class
2AB	Roundwood assortment for 20-29 cm diameter class
3AB	Roundwood assortment for 30-39 cm diameter class
4AB	Roundwood assortment for 40-49 cm diameter class

Table of Content

Figure List

Figures **Page**

Table List

Tables **Page**

1 Introduction

1.2 Background

Biomass as a source of bioenergy could play an important role in a future renewable energy system. It can be seen from the fact that plant-based fuels and biogas-based electricity have been gaining importance in recent years. Recognition of the environmental cost of fossil fuels, together with concern over their depletion within the next few decades, has broadened the research for alternative energy resources including biomass energy. This will lead to increased production and economic performance demands of biomass.

Biomass in general and forest biomass in particular are currently receiving new attention based on three key attributes which are their renewability (Bull, 1994), CO_2 near-neutrality (Johnson, 2009) and current availability (Fagernäs et al., 2006). Thus replacing fossil-derived energy with biomass can reduce greenhouse gases and mitigate global climate change (Börjesson et al., 1997; Gustavsson et al., 2007; Sohngen and Alig, 2000). Furthermore, Seidl et al. (2007) explain that in general there are three ways that active management of existing forests can contribute to climate change mitigation: through increased carbon dioxide storage in-situ (vegetation and soil), increased storage in wood product pools, or the substitution of fossil fuels by bioenergy.

As so far bioenergy market is primarily policy driven, the main drivers of the increased use of biomass for bioenergy in Europe are commitments under the Kyoto Protocol (McKay, 2005; Nilsson, 2006) and energy diversification policy (McKay, 2005; Chum and Overend, 2001). Under the Protocol, the EU has committed itself to reducing its GHG emissions by 8% during the first commitment period of 2008-2012 to below 1990 levels. This target is shared between the 15 EU Member States at of the time (EU15) EU's ratification moment in May 2002 under a legally binding burden-sharing agreement. Moreover, in respond to probability of events affecting the energy supply security and the vulnerability of society to energy supply disruptions are likely to increase in the near future (Correljé and Van der Linde, 2006), energy diversification is one of the instruments to decrease EU energy import dependence thus ensure security of energy supply in the future.

In EU policy on bioenergy in compliance of Kyoto Protocol, the aims are at increasing renewable energy sources from 6% to 12% at 2010 (European Commission, 1997). Recently in

December 2005 as part of the overall EU objective of improving competitiveness, sustainability and security of supply, the Commission launched a Biomass Action Plan (European Commission, 2005). The development of biomass energy from wood is one of the set out measures of the Action Plan, includes measure to promote biomass in heating, electricity and transport. The major portion of wood-energy used for primary energy generation is in the form of heat for individual homes or district in which mainly due to the development of Combine Heat and Power installation in certain EU countries, especially in Scandinavia and Austria (Fagernäs, 2006).

The increase used of renewable energy sources, including forest biomass, is a marked characteristic of energy policies at both Europe and national level. Therefore there is a high intensity toward forest owners to enhance utilization of forest residues for energy purposes. However, there are several barriers in bioenergy utilization for making a sustainable management as a reality. Among others, this can be local availability of biomass due to a lack of long-term practical experience in exploitation of forest residues (branches, tops and leaves) and economic barrier.

If we look closer to the forest management unit, in intensified harvesting method, most forest residues that were usually left in the forest recently have been used intensively for bioenergy. Since intensive harvesting of forest residues for bioenergy is always associated with nutrient export from the ecosystem this may cause nutrient depletion and potentially resulting in a long-term reduction in site productivity. For that reason, future biomass availability or future energy supply is still uncertain. The extent to which soil organic matter is negatively affected depends on the quantity of tree biomass removed. Therefore, in his scientific paper, Fagernäs (2006) suggested that good practices guidelines are urgently required.

There have been several studies assessing yields that can be achieved with management practice changes aiming at biomass for biofuel optimization. For example Sterba (1988), who examined Norway spruce in Austria, concluded that differences in volume growth are consistent with differences in the nutritional status. He analyzed the nutritional status of the remaining trees after thinning as well as three years later by investigating the elemental concentration in the top whorl of the remaining trees. The lowest increments were evident on plots with the lowest nutrient content in the top whorl. Whole tree harvesting after thinning results in the lowest mean volume of the remaining stand where the reductions of three-year mean annual volume increment per hectare relative to commercial stem wood harvesting regimes was 13.3%, if the felled trees were left on the cutting site for one year prior to removal, the mean annual volume increments reduced by 6.8%.

More recent experiments and stand level assessments of *Eucalyptus globulus*, *Pinus radiata* and *Pinus pinaster* species in Spain done by Merino et al. (2005) strengthened that conclusion. They have demonstrated that intensified utilization of forest biomass could possibly have negative impacts on site nutritional status. This leads to differences in the amount of soil nutrients, which strongly affects the plant uptake and thus growth rates. Result of mechanistic biogeochemical modeling environment to study sustainable forestry under *Picea abies* plots by Merganičová et al. (2005) shows that litter under commercial stem harvesting method exhibit an improved carbon and nitrogen that present for about 16 years. Only half of that improved nutritional status time period present in litter under the whole tree harvesting method. This shorter increased nutritional status time could strongly affects the nutrition plan uptake and thus might reduce growth rates.

Furthermore, several studies (Weetman and Algar, 1983; Hornbeck et al., 1990) hypothesized that negative effect on site productivity of whole tree would be most prominent at dry and poor sites. It is a result of the risk for decreased amount of soil organic matter in which would potentially lead to reduction of water and nutrient retention capacity.

The common economic barrier is the profitability issue of management concept changes into biomass production for energy in relation to the present management practice. The intensive residues extraction provides an extra source of income for the forest owners but at the same time also affects the ecological state of the forest site in the long term thus income gaining might decrease. Consequently the individual forest owner is faced with a large number of options regarding product combination target of timber, bioenergy and the potential impact on the ecosystem especially for climate change mitigation. Accordingly, they may face difficulties making a decision. Results from various management strategies on biomass production in each assortment (sawn wood, pulpwood and firewood) can assist the forest owners to make a comprehensive decision on combination target products that will be the most beneficial for them. Then this current paper also addresses potential responses of spruce and beech to the predicted environmental changes to investigate the sensitivity of growth and timber yield to management and climate change.

Almost in all European countries beech (*Fagus sylvatica* L.), which plays dominant role concerning the makeup of broadleaves tree, is managed oriented on future crop trees aiming for big dimensions and best quality logs (Spiecker, 2002). Appreciation of beech wood has increased constantly because of astonishing benefit forest owners could get from mature stands (Tarp, 2000). There were two beech stand managements using different final stem number per hectare that were investigated in this paper.

Those alternative managements were investigated due to the fact that valuable trees need to have large diameters and big crowns. Different stand management concept was used aiming to investigate which final stand density producing better tree dimensions and final economical benefit for the forest owner. By using less number of future crop trees actually approximately the same valuable timber can be achieved in a relatively shorter rotation because the diameter dimension is bigger in low density stand per hectare.

Norway spruce is one of the most common and economically important coniferous species in Europe. Its good yield and quality performance on very different site conditions favored this species over a long period. Highly productive sites in southern Sweden have potential yield of 11 $m^3ha^{-1}year^{-1}$ (Eriksson and Johansson, 1993), 14.7 $m^3ha^{-1}year^{-1}$ yield can be reached in West Norway (Øyen and Nygaard, 2008), in the coastal area of northern Germany the average increment is 11 $m^3ha^{-1}year^{-1}$ (Krzak et al., 1988), in the south of Belgium the yield range from 10-12 $m^3ha^{-1}year^{-1}$ (Praag and Weissen, 1986).

In Central Europe, Norway spruce (*Picea abies* [L.] Karst) has a long history of cultivation since the middle of the 19th century. This species has been planted intensely thus has changed natural forest into artificial forests and has led to the introduction far outside its natural range. But in many European countries, the choice of tree species is changing. While in the past coniferous species were favored, the share of broadleaved tree species is now increasing. Norway spruce for example has been shifted to be mixed with broadleaves. According to Spiecker (2002), mixed stands have been found to be more resistant against various forms of damage, more diverse in their fauna and flora composition than pure, single-species stands.

1.3 Objectives

These stand management concepts address the question, what the potential biomasses for the different assortments are within each management strategy and how robust the results are under changing climatic conditions. For every forest management strategy, three biomass utilizations in which for sawn wood, pulpwood and firewood, are going to investigate with regard to:

a) Economic implications for the forest owner
b) Climate change mitigation potential with regards to in-situ C storage and biofuel use
c) Sustainable site productivity

2 Methods and Materials

2.2 PICUS v1.4

To simulate standing biomass development for all forest stands scenarios the recently hybrid forest patch model PICUS v1.4 (Seidl et al., 2005) was utilized. PICUS v1.4 is a modular modelling framework aiming at the combination of the ecological generality and applicability of patch models and the physiological foundation of process-based model concepts.

The initial structure of this model is the classical three-dimensional patch model PICUS v1.2 (Lexer and Hönninger, 2001) then hybridized with the physiologically based stand-level production module of the 3-PG (Physiological Principles in Predicting Growth; Landsberg and Waring, 1997) resulting in PICUS v1.3. The coupling of both elements is described in detail in Seidl et al., 2005. The 3-PG model is a physiology-based, stand-level model of net primary production using simplified concepts of radiation-use efficiency, carbon balance and partitioning for monospecific stands with a simple tree population structure. Its main rationale is to combine ecological realism with regard to stand structure and inter- and intra-species competition with robust physiological approaches for forest management decision support under changing environmental conditions (Seidl et al., 2005). The coupling of both patch model and 3-PG elements is described in detail in Seidl et al. (2005).

In model version 1.4, components of the model include a sub-model for the simulation of forest management interventions based on management scripts allowing for high flexibility in terms of spatially and structurally explicit harvesting and planting operations (Seidl et al., 2007). Recently, a process-oriented soil sub-model to keep track of belowground carbon and nitrogen processes and to dynamically update site nutrition status, a biogeochemical process model of carbon storage and nitrogen fluxes in forest soils (Currie et al., 1999) has been included.

This paper only presents a brief overview on the model structure and logic, a detailed description is written by Lexer and Hönninger (2001). The structural resolution of PICUS v1.4 is 10x10 meter patches. The vertical dimension of a simulated forest is represented explicitly by crown cell of 5 m depth up to a maximum height of 60 m. These 10x10x5 m cells contain all information on the distribution of tree biomass in space. Tree biomass is evenly distributed within the cells. PICUS considers interaction among neighboring patches as well as the effect of slope and orientation on incoming radiation and the shielding effect of the surrounding topography. The range of spatial interaction between patches depends on the characteristics of the vegetation on the simulated patches (i.e. tree height, crown length), site characteristics (slope, orientation, latitude) and season (i.e. solar altitude, sun angle and direction).

The model performance was evaluated to allow assessment of various aspects of forest ecosystem dynamics. In a series of simulation experiments, Seidl et al. (2005) showed that PICUS v1.3 indicated a realistic response to a climate change sensitive experiments, volume production and stand structure. It was shown that large-scale forest inventory data can be valuable for PICUS v1.4 model evaluation, particularly when they cover large environmental gradients and do not come from intensively managed forests (Didion et al., 2009).

2.3 Study Area

The study area was in the city of Amstetten, the western part of Lower Austria province situated at approximately 300-400 above sea level (**Figure 1**). Climate is characterized as subcontinental. Forest ecoregion is classified as "7.2 Nördliches Alpenvorland - Ostteil" based on Kilian et al. (1994). The area is characterized by cambisol soil with pH 4.2 and water holding capacity of 165mm.

Figure 1. Map of the study area in the Province of Lower Austria.

2.4 Experimental Design

Four concepts for forest management were investigated, both under current climatic condition and under changing climatic conditions that have been assessed by IPCC (Intergovernmental Panel on Climate Change, 2007). A more detailed description of the future climate scenarios are expressed in 20 year running average of the temperature and precipitation different between the future climate scenarios and the mean baseline climate (see **Figure 2**) and climate scenario assumptions are presented in **Table 1**. All four stand management concepts start from the same initial stand condition.

There are two management concepts in each species of Norway spruce and European beech: (i) a current practice spruce of 100 years rotation length (MS1), (ii) an alternative spruce management with shorter rotation period, final cut at the age of 90 years (MS2), (iii) a traditionally practiced beech management (MB1), (iv) beech stand management alternative aiming at valuable timber production (MB2).

In this paper the effects of thinning, species, rotation length, extraction mode and biomass utilization variant on potential growth of each timber assortment and its interaction with a site nutrient status and bioenergy system including carbon sequestration and carbon substitution were appraised. On the forest owner perspective, the differences between these four stand management concepts become important as a support data to choose a better management that can offer more profit.

Table 1. Summary of storylines for future emission scenarios assumptions (IPCC, 2007)

Storyline	Description
A1B	Future integrated world with rapid economic growth, new and efficient technologies and a balanced technology emphasis on all energy sources.
A2	A very heterogeneous future world, continuously increasing population, economic development is primarily regionally oriented, technological change more fragmented and slower than other storylines.
B1	Continuously increasing population (<A2), intermediate levels of economic development, more diverse technological change than A1 storylines, oriented towards environmental protection and social equity.

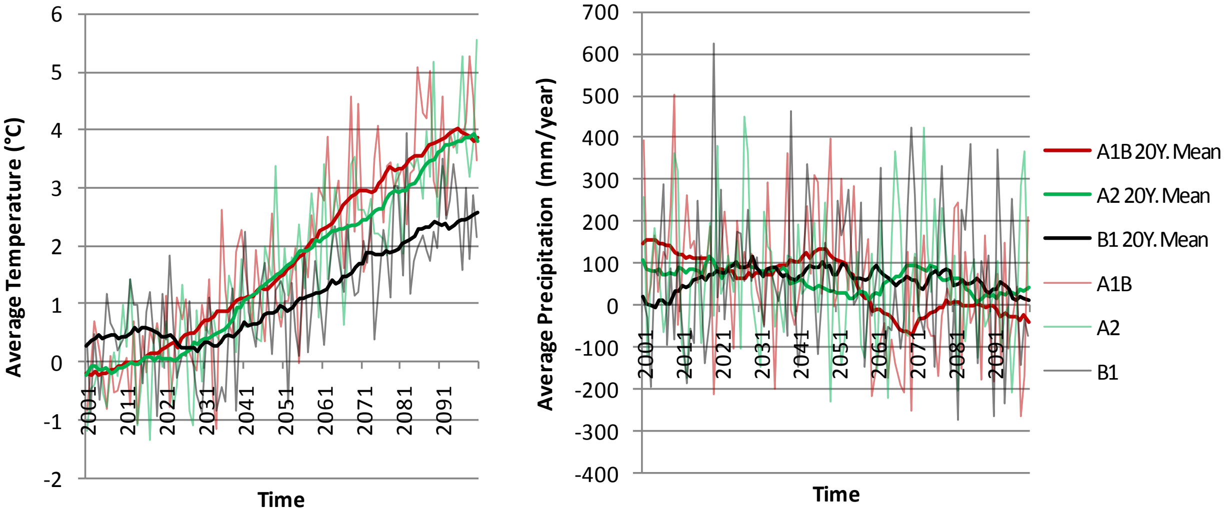


Figure 2. The 20 year running mean of the temperature (°C) and precipitation (mm year^{-1}) different between each future climate scenarios and mean baseline climate (IPCC, 2007) for the 100 years of the simulated period (2000-2100).

2.4.1 Spruce Stand Management Concept

MS1 is a Norway spruce management that reflects the current practice of the forest owner in the sites and is used here as a baseline for comparison to the second spruce management. MS1 is typically stand management done by small forest owners.

This concept shows implementation of forest tending in the form of one pre-commercial thinning, three selective thinnings and clear cut at the end of a rotation period of 100 years. Initial stand density of this concept is 3300 stems ha^{-1}, mimicking a rather high initial density. After 20 years of simulation, the pre-commercial thinning is carried out (reduce 45% of basal area), followed by the thinnings in the years 30 (20%), 50 (25%) and 70 (20%).

MS2 is an alternative management and uses a shorter rotation length of 90 years. In this stand management concept the stand structure of the growing stock at the beginning of the rotation period is different, it uses 2 500 stem ha$^{-1.}$ There is no pre-commercial thinning in order to reduce the silvicultural cost and thinning carried out in the years 30 (35%), 45 (30%) and 60 (25%).

This alternative concept was intended to examine the economic and productivity effect of less dense initial stage stand, less intensive management and shorter rotation. Regeneration was assumed to be planted. **Figure 3** shows more detail on the stand structures during the rotation.

2.4.2 Beech Stand Management Concept

Valuable broadleaved species of beech is important for producing high-quality wood mainly used in the veneer and furniture industries. And the quality of the beech timber is highly dependent on its silviculture management. To achieve quality objective two important general principles are targeted (Spiecker, 2008):

a) Dimension: approximately 60 cm diameter with
b) Quality, aiming for first log of best quality (A): straight grained, clean and free from any growth defects for instance dead or living branches, bark disease indicating wood decay.

In this paper, management of beech stands up to harvesting of crop trees is divided into 3 steps based on Spiecker (2008). These stages and their silvicultural details are described briefly.

a) Stand establishment
b) Tending of young stand (stage of qualification)
c) Thinning (stage of dimensioning)

Stand establishment. Natural regeneration under shelterwood system is used in order to reduce costs of stand establishment. This method taking all ecological characteristics of the species into account in which its shade tolerance is used to regenerate under shelterwood created by remain mature tress which also functioning as seed sources. Wagner et al. (2010) emphasize natural regeneration methods must leave a dense shelter of old trees to succeed with Fagus. The shelterwood system seems to create favorable growth conditions for regeneration success (Madsen and Larsen, 1997). The main effects of the shelterwood are reduced competition from ground vegetation and a smaller risk of frost damage (Angestam et al., 2003).

Tending of young stand. In this stage the main objective is getting the desired quality of a sufficient number of future crop trees. It is done between the stand age of 5-10 years or at top height of 2 meters by selecting trees of bad quality only in the upper canopy, removal of individuals with thick and steep branches, crooked trees and trees with pest defects.

Thinning. Thinning aims at getting the desired dimension of final crop trees, the diameter growth should be on a high level. Using thinning from above which means that only dominant or co-dominant individuals that are just neighboring the future crop trees are removed to allow the selected trees to grow rapidly. Thinning allows the trees to expand their crown and since relation between crown diameter and stem diameter is adequately represented by a straight line

(Hemery et al., 2005), the release of crown can accelerate the diameter growth.

There were two beech management concepts used in this paper. Regeneration was assumed to be natural due to site conditions and stand characteristics. The beech baseline concept (MB1) is traditional beech stand management that actual practiced on the sites during previous decades. It uses five thinnings from below and targets 488 final stems ha^{-1} within a 100 year rotation. Thinning carried out in the years 30, 45, 60, 75 and 90. The current structure beech stands in the sites are the result of this traditional management that had been practiced for decades. The second beech management concept (MB2) targets 180 tree ha^{-1} and more intense thinning. This management aims at valuable timber production. Six thinnings were applied in the year 30, 45, 60, 75 and 88. **Figure 3** shows more detail on the stands structure throughout the rotation. These silviculture regimes were designed to investigate the answer of whether we should grow less trees with larger crown or more trees with smaller crown thus smaller diameter breast height (DBH) and higher clean bole (stem without branches).

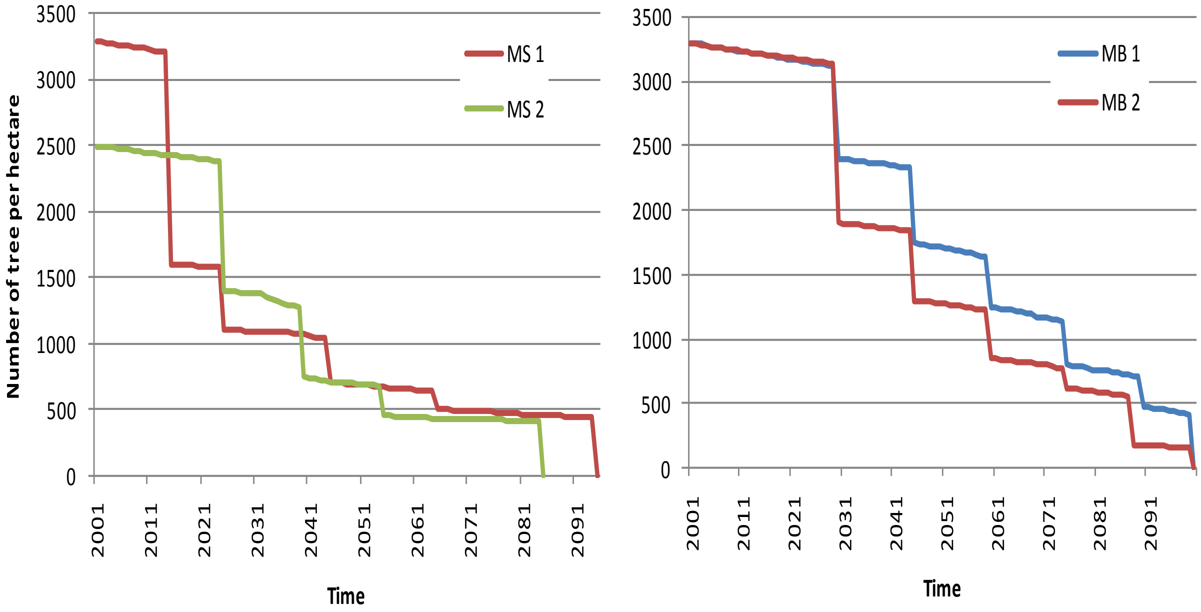


Figure 3. Stand density (n ha^{-1}) for all spruce and beech management concept. MS1 the current practice spruce management, MS2 the alternative spruce management, MB1 the traditional beech management and MB2 the alternative beech management.

2.4.3 Biomass Extraction Mode

For each management concept in each climate scenario, two level of biomass extractions were used aiming to analyze biomass potential for biofuel purpose, its consequences to long term site nutrient status and economic implication for the forest owners. Those biomass extraction levels were standard harvest mode and intensified extraction mode. Intensified extraction currently has been implemented intensively in Europe due to fulfill increased bioenergy sources demand.

In standard extraction mode (hereafter abbreviated E0) under spruce concepts, only stem (commercial volume and fuelwood from tops) was extracted from the forest stand. In standard extraction under beech concepts, commercial volume and fuelwood from stem and branch were extracted. The residues (stump, branch (only in spruce) and leaf) were left on site. Commercial volume is defined according to the Austrian timber grading guidelines as timber with diameter larger than 7cm. And, wood with diameter less than 7 cm is utilized as fuelwood. However, please note that commercial volume in beech includes a share from branches in the tree crown. Furthermore, the roundwood was graded into size assortments (compare **Table 3** and **Table 4**).

In contrast to standard extraction, intensified extraction (E1) shows the harvesting of biomass parts that extracted in E0 as well as the residues. However, extraction of all residues is technically impossible. In this work, after commercial stem harvesting, all logging residues (except stump) were manually removed from the stand using assumption of 70% recovery rate. It means approximately 30% of all residues were left on the site. In this treatment, biomass after pre-commercial thinning was not extracted since considered as uneconomical activity. Only under this extraction mode, fuel wood and residues were processed further as chips to provide a higher quality and more user friendly wood energy product.

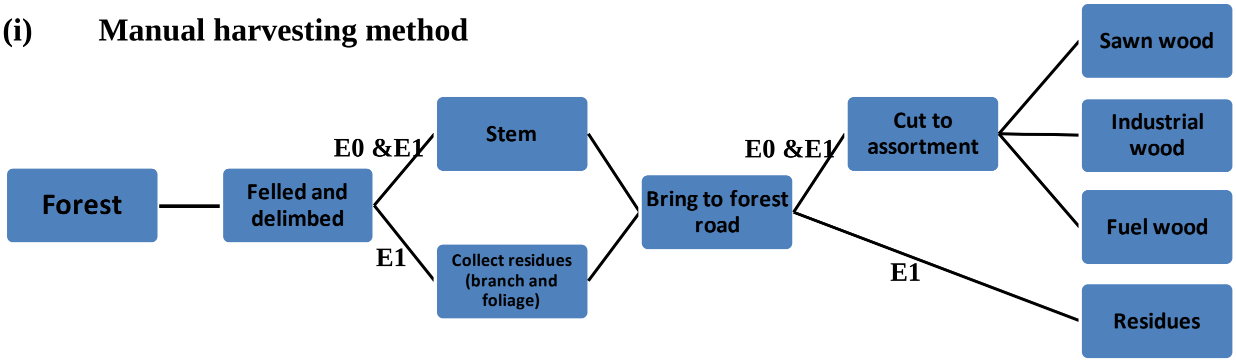
Based on Neumann (2003), the costs of spruce planting and pre-commercial thinning in artificial regeneration are varies, respectively are 1500 to 3000€ ha^{-1} and 350 to 1000€ ha^{-1}. In this work, mean values of those prices were used (2250€ ha^{-1} and 675€ ha^{-1}).

Two harvesting methods were assumed, (i) harvesting uses motor-manual logging and tractor with cable winch and (ii) fully mechanized method with harvester and forwarder. Different harvesting cost between thinning and final cut is due to hourly harvesting productivity, more stem volume can be harvested in final cut than in thinning due to larger stem mean diameter.

Motor manual logging costs for thinning and clear cut derive from Pröll (2003) and KWF (2007).

Chain saw cost was assumed 24.2€ hour^{-1}, the productivity in thinning was assumed 1.1 m^{3}hour^{-1} and 3 m^{3} hour^{-1} in clear cut therefore the manual logging in thinning and clear cut respectively were 21.5€/m^{3} and 7.8€/m^{3}. Then each cost was added by the cost of tractor and cable winch in order to take out the timber to the forest road. Tractor and cable winch cost in thinning was assumed 10.5€/m^{3} (Pröll, 2003), and in clear cut was 8 €/m^{3} (Landwirtschaftskammer NÖ, 2007). All costs for mechanized harvesting were assumed based on average cost in Landwirtschaftskammer NÖ (2007). More detail harvesting costs are presented in **Table 2** and production chain of each harvesting method is depicted in **Figure 2**.

(i) Manual harvesting method



(ii) Mechanized harvesting method

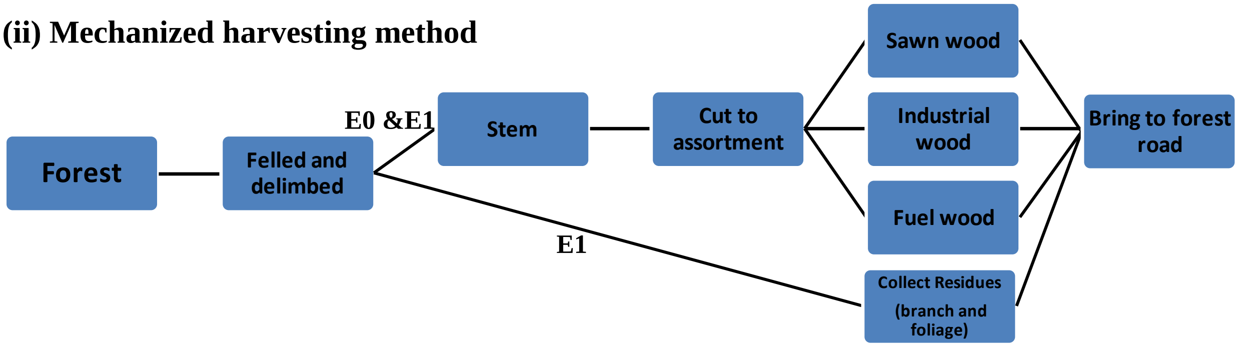


Figure 4. Manual and mechanized harvesting chain included the extraction modes for each method. *E0* the standard extraction mode only stems were extracted and residues were left on site, *E1* the harvesting of all above ground parts of the trees (70% recovery rate).

Meanwhile, costs for biofuel purpose such as harvesting of residues and wood chip production were assumed based on Nurmi (2007) and Kühmaier et al. (2007) respectively. Residues harvesting cost is 24.5€ tBM^{-1}, roundwood chip production is 1.87€ srm^{-1} (srm= one cubic meter heaped up chips) and residues chip production is 4.81€ srm^{-1}. Furthermore, by using assumptions that 1srm spruce is equal to 0.4 m^3 (Austrian Energy Agency, 2009) and spruce wood density is 403 kg/m^3 (Larsson et al., 1998) therefore chip production costs can be converted into 11.6€ ton^{-1} for roundwood and 29.8€ ton^{-1} for residues. For beech, the costs are 8.1€ ton^{-1} and 20.7€ ton^{-1} respectively assuming 580 kg/m^3 wood density (IPCC, 2003).

In **Table 3**, price assumptions of roundwood, industrial wood and fuel wood of spruce are presented (Statistik Austria, 2010). Those values derive from the mean price of 7 year data from year 2003 to 2009. Fuel wood consisted of tops, branches and small trees with diameter below the requirements of industrial wood (< 7 cm).

Chip price was assumed 62.5€ ton^{-1} dry wood (Neugebauer et al., 2005). A weighted average price of spruce sawn wood price data was used. A high timber quality portion of about 75% spruce sawn wood would be typical for the average timber in the experimental region. The rest of the timber (25%) was allocated for industrial wood. Since perfect information on future prices and costs cannot be expected, prices and costs were assumed to be constant during the time modeled.

For European beech, the price applied on each timber assortment was the mixed price between B and C-quality derives from Rössler and Neumann (2006) that all adjusted to average 2003-2009 price level (Statistik Austria). The percentage quality of the different stem assortment assessed by Rössler and Neumann (2006) was also taken into account. It is shown that 25% of the harvested volume falls as A and B-quality and 75% as C-quality. Timber dimension more than 30 cm is considered to be utilized as sawn wood and the rest is to be processed in pulp and paper industry and fuel wood. Beech prices assumption is presented in **Table 4**.

Table 2. Cost (€/m³) assumption for thinning and clear cut in both harvesting methods (Pröll, 2003; KWF, 2007 and Landwirtschaftskammer NÖ, 2007)

Harvesting Method		Thinning	Clearcut
1	Motor-manual felling	21.5	8
	Tractor with cable winch	10.5	7.8
	Total	**32.0**	**15.8**
2	Harvester	10.9	8.7
	Forwarder	7.3	5.7
	Total	**18.2**	**14.4**

Table 3. Average price (€/m³) of Norway spruce over assortments for diameter classes (Statistik Austria, 2010)

			Sawn wood				
	Fuel wood	Industrial wood	1B	2AB	3AB	4AB	≥5
Diameter (cm)	<7	7-14	15-19	20-29	30-39	40-49	≥50
Price (€/m³)	22.4	29.8	59	72.4	74.3	72.4	72.4

Table 4. Average price (€/m³) of European beech over assortments for diameter classes (Rössler and Neumann, 2006 and Statistik Austria, 2010)

	Fuel Wood	Industrial wood			Sawn wood		
			1B	2AB	3AB	4AB	≥5
Diameter (cm)	<7	7-14	15-19	20-29	30-39	40-49	≥50
Price (€/m³)	33.9	34	34	34	58.3	67.8	75.8

2.4.4 Biomass for biofuel utilization

For each management concept in each climate scenario, two biomass utilization variants were investigated with regard to biomass for biofuel production potential, C substitution and economic implication to the forest owner. Simulated harvested roundwoods were graded into dimensional assortments based on individual tree dimensions according to Sterba and Griess (1983) for spruce and Sterba et al. (1986) for beech. The assortments are assigned to different production lines (e.g. sawmill industry, pulp and paper industry) or used as fuel wood.

Biomass utilization variant 1 reflects current business as usual concerning roundwood use. Roundwood assortments are utilized as sawn wood, industrial wood assortment to be processed at pulp and paper industry and tops are utilized as fuelwood. Variant 2 is different to variant 1 solely regarding to an increased use of wood for bioenergy. In Variant 2, industrial wood that is usually used in pulp and paper industry in this case is allocated to be bioenergy source. Overall stand management concepts can be seen in **Figure 5**.

However, the use of roundwood directly for energy purposes strongly depends on the prices of sawn wood, pulp and paper and energy. Although quite extreme, both of these variants represent reasonably possible alternatives and they interestingly illustrate the potential impact of increased bioenergy use on the carbon substitution.

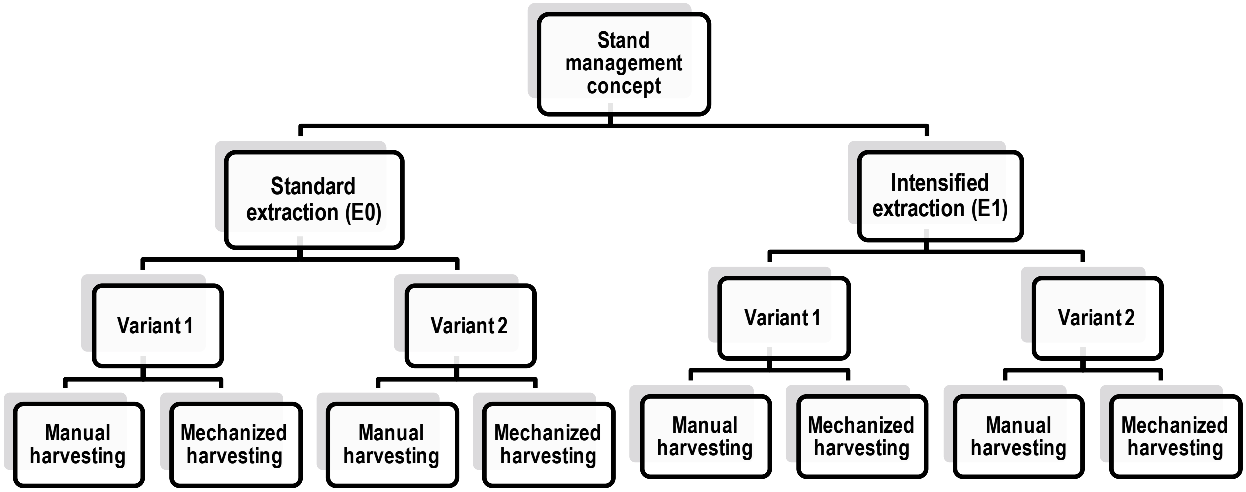


Figure 5. The diagram of the overall experimental design. Each stand management concept (MS1, MS2, MB1 and MB2) under each climate scenario (BL, A1B, A2 and B1) is investigated under two extraction modes (E0 and E1), two biomass utilization scenarios (variant1 and variant2), and two harvesting methods (manual and mechanized harvesting).

2.5 Data analysis

The mean value of the 10 simulations is presented in regards of the total volume production (commercial volume from natural mortality, all type of thinning interventions and the final harvest at the end of the rotation) over the rotation, extracted volume (harvested extracted commercial volume from commercial thinning and final harvest), assortment structure, annuity, carbon storage (belowground, aboveground and in-situ C), biomass production for biofuel, the C substitution and sustainable site productivity.

To assess model variability on total volume production, testing stochasticity of 10 simulation runs of simulated spruce (MS2) and beech (MB2) management concepts for current analysis was done. Stochastic simulations naturally generate variability in output variables. As shown in **Figure 6**, the stochastic simulations showed that standard deviation of the 10 simulated total volume production over the simulation under the spruce concept in the end of the rotation length (90 years) was ±9 m^3 ha^{-1} around mean value of 1751 m^3 ha^{-1}. Standard deviation under beech concept in the end of rotation (100 years) was ±9 m^3 ha^{-1} around the mean value 1095 m^3 ha^{-1}.

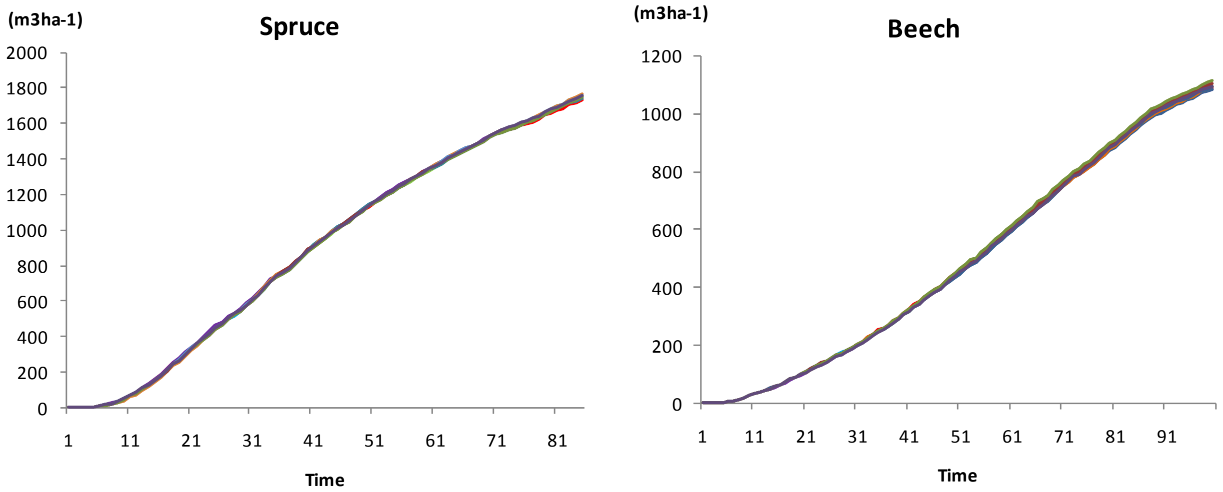


Figure 6. The distribution of total volume production (commercial volume from natural mortality, all type of thinning interventions and the final harvest at the end of the rotation) over the rotation of the 10 simulations under spruce and beech stand management concepts.

2.5.1 Economic Analysis

Furthermore, the revenue and costs were included in the analysis in order to calculate the annuity of timber production for the management unit. The dynamical evaluation of economic benefits in this work is expressed as annuities. The annuity method can be interpreted as constant series of equal annual payments (Möhring and Rüping, 2008). Thus the ascertained annuity of forest production can be called annual timber production value.

In this paper, a valuation concept based on annuities as a yearly earning rate is used instead of the usual procedure for capitalized earning value concept Net Present Value (NPV). It appears that using NPV on benefit valuation in this paper can be problematic since the valuation periods of each stand management concepts are different (90 and 100 year rotation).

Advantages provided by annuity method presented by Mohring and Rüping (2008) can be summarized as follows: (i) the calculated annual timber production value can be easily interpreted as annual gross margin of the timber production, (ii) different rotation periods can easily be compared, (iii) those annual timber production values can be tabulated for different tree species, yield classes and management regimes, etc, thus guaranteeing easy application, (iv) the conversion of annual payments into present values is possible and can be easily be achieved.

The annuity formula is as follow:

$$a = \sum_{t=0}^{n} \frac{Rt - Ei}{(1+i)^t} \cdot \frac{i.(1+i)^n}{(1+i)^n}$$

where *a* is the annuity (€ ha^{-1} year^{-1}), *t* the point in time (years since beginning of the accounting period), *Rt* the revenues at *t*, *Et* expenditure at *t*, *n* the length of accounting period (year), and *i* the interest rate. By applying the annuity equation to the entire forest rotation length (u) the formula gets following notation:

$$a_u = \left(\frac{A_u}{(1+i)^u} + \sum_{a=1}^{u} \frac{D_a}{(1+i)^a} - c \right) \cdot \frac{i.(1+i)^u}{(1+i)^u - 1}$$

where *u* the rotation length, A_u the clear-cut revenue net of harvesting cost in year *u*, D_a the thinning revenue net of harvesting cost in year *a* and *c* the plantation cost.

The interest rates used for calculating annuity were 0.5%, 1.5% and 2.5% to show the annuity sensitivity. Further discussion on the economics evaluation in terms of the annuity advantages against NVP and how to estimate financial losses of forest-land owners when changing the management strategy can be found in Mohring and Rüping (2008).

2.5.2 Climate Change Mitigation Potential

There are two main tasks outlined for C sequestration potential of stand management concepts on a hectare basis. The first was to obtain the mean C stock over the simulation period as a comparison approach among stand management concepts (mean storage approach). The second task was to measure changes in the net C stock over time. Forecasting forest development over the rotation period permitted an estimation of C fluxes (flow approach).

This work quantified ecosystem C sequestration, both in-situ C storage in which separated into aboveground (stem, branch, leaf and standing deadwood C) and belowground (soil organic carbon, litter, humified matter, fine woody debris and downed dead wood C) components and C from potential fossil fuel substitution by bioenergy from forest biomass.

It is assumed that the full harvested biomass for fuelwood is to substitute coal under scenario biomass-fired steam-electric power for coal-fired steam-electric power substitution based on Baral and Guha (2004). On an average, the C to energy ratio for wood is about 25.32 kg C GJ^{-1}

whereas for coal it is 24.56 kg C GJ^{-1}. The typical values for efficiency of conversion to electricity are about 33% for coal and about 25% for wood (Marland and Marland, 1992). Accordingly, this implies that 1 kg of C in wood is able to displace 0.73 kg of C in coal. The carbon content of the biomass (dry weight) was assumed to be 50%. However, the analysis did not assume a full net emission where the fossil emissions from biomass harvesting activity, transport and the biomass processing industry would have had to be accounted for.

2.5.3 Site Productivity

Total volume production throughout rotation length in each stand management concept, mean annual increment (MAI) and available soil N were chosen as the dependent indicators in combination with literature when assessing the effect of biomass extraction modes. From the model simulations, those indicators were obtained, aiming to investigate the worthiness to risk site sustainability under the intensified extraction mode to gain higher annuity.

3 Results

3.2 Total Volume Production, Extracted Volume and Annuity in Norway spruce Management Concepts

Under baseline climate scenario (BL). Alternative spruce management scenario (MS2) reduced moderately the total volume production and extracted volume by 10% and 4%. However, identical extracted volume between standard (E0) and intensified extraction mode (E1) in both spruce concepts was detected (**Figure 7**).

The total volume productions under current practice concept were 1941 and 1913 m^3 ha^{-1} (MS1-E0 and MS1-E1), of which 31% and 33% were unutilized (645 and 598 m^3 ha^{-1}), and the extracted volumes were 1296 and 1315 m^3 ha^{-1}. While the total volume productions under the alternative management concept were 1737 and 1735 m^3 ha^{-1} (MS2-E0 and MS2-E1), 28% of those values were unutilized (approximately 485 m^3 ha^{-1}, regardless of extraction mode), and the extracted volumes under both extraction modes were approximately 1252 m^3 ha^{-1}.

It was found that mean diameter breast height (DBH) under MS2 became larger than that under MS1 after the last selective thinning (30% basal area) at the age of 60 years. Regardless of extraction mode, MS2 contained slightly higher shares of 5AB assortment which accounted for 3-5% despite its lower sawn wood per hectare (1256 m^3 ha^{-1}) due to lower final stem number per hectare. In MS2, both extraction modes characterized by the most timber of assortment 2AB (32%), then 3AB (30-32%), industrial wood (20%), 1B (8%), 4AB (4-5%) and 5AB (3-5%) (**Figure 8** and **Appendix 1**). Regardless of extraction mode, the stems in MS1 contained the most timber of assortment 3AB (40%), then 2AB (33%) industrial wood (13%), 1B (6%), 4AB (6%) and little of big-size timber more than 50 cm DBH or assortment 5AB (2%). This stand management concept is distinguished by the greatest total sawn wood per ha due to higher final stem number per hectare despite its low shares of assortment 5AB (see assortment classification in **Table 3**).

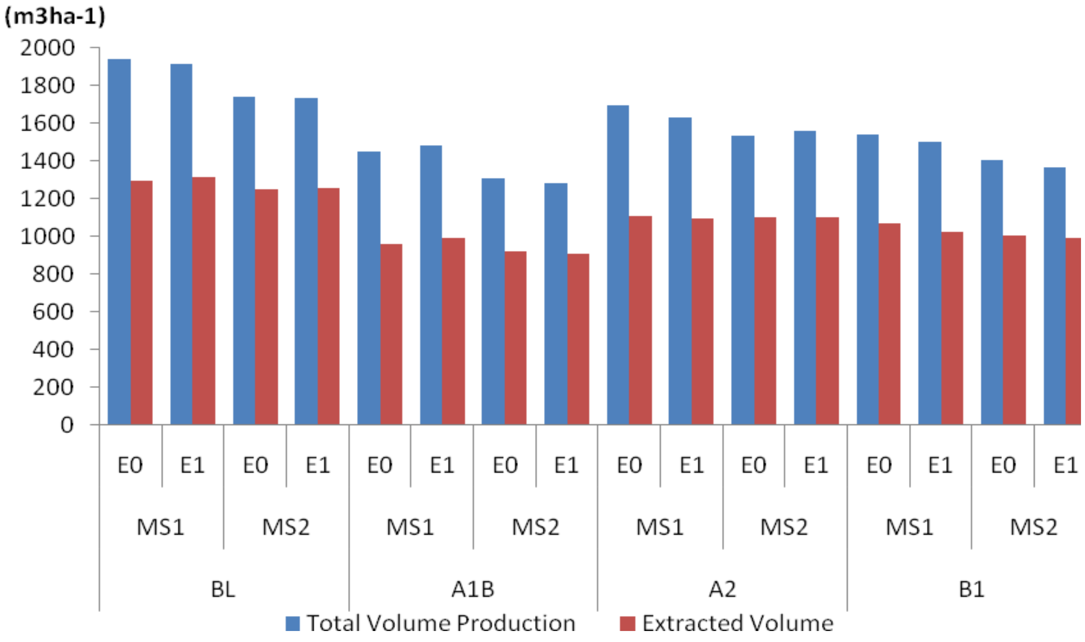


Figure 7. Effect of spruce management concept, climate scenario and extraction mode on total volume production and extracted volume.

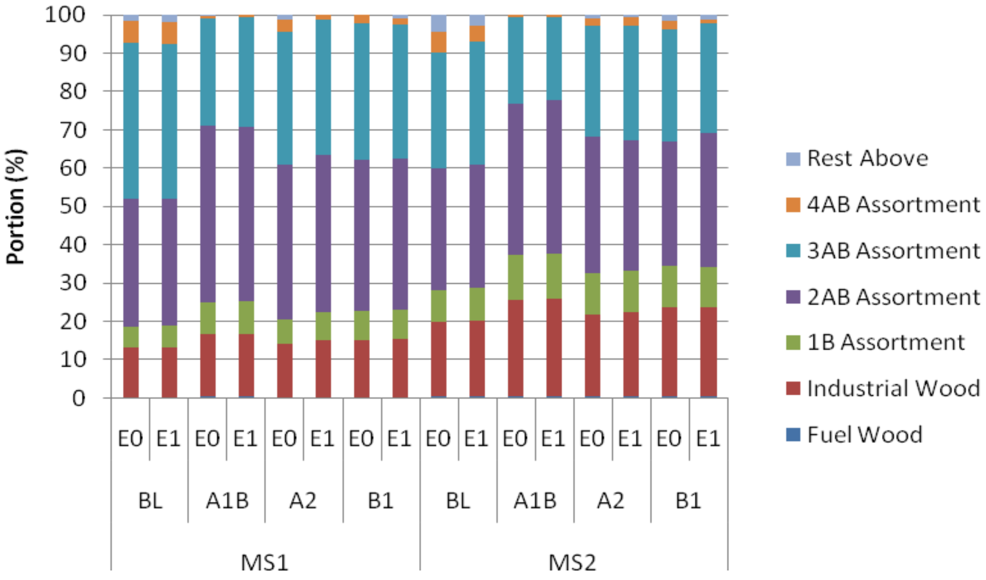


Figure 8. Spruce assortment structure (%) (see assortment classification in Table 3) under baseline and climate change conditions.

However the management effect on extracted volume differed considerably with regard to the economic performance indicator. For instance, although the extracted volume was 5% higher than the MS2-E0, MS1-E1 annuity was 17% lower. The highest annuity is always in stand management concept under mechanized harvesting method due to cheaper cost compared to manual harvesting cost (see harvesting cost difference in **Table 2**) and when an interest rate of 0.5% is used. The use of manual harvesting potentially reduced the annuity by 21-25% (**Table 5**). Hereafter, the annuities that are going to be used as representative are under mechanized harvesting and 1.5% interest rate.

Regardless climate scenario and interest rate, the highest annuity was always obtained under MS2-E1 (318€ ha^{-1} $year^{-1}$) and the lowest annuity was obtained under MS1-E0 (258€ ha^{-1} $year^{-1}$) (**Table 5**). The calculation indicated that under the MS2-E1 concept, the annuity is always higher compared to that under the MS1-E0. The higher annuity in the MS2 concept was clearly due to larger mean DBH produced coupled with no pre-commercial thinning cost and shorter rotation length than that under the MS1.

Intensified extraction mode under the spruce concepts could slightly increase the annuity due to additional revenue from residues utilization as chips. Under the MS1, the intensified extraction enhanced the annuity by 5% whereas under MS2 intensified extraction increased the annuity by 2%.

Allocating more harvested biomass, in this case industrial wood, into bioenergy production (variant 2) evidently reduced the annuity. Under the MS1 variant 2, the annuity reduced approximately from 9 to 11%. The annuity reduction was quite similar to that under the MS2. The upper limit of annuity reduction occurred under the intensified extraction due to revenue reduction from the trade of biomass for biofuel in form of chips relative to the revenue of biomass for biofuel in unchipped form. It seems that a further processing of fuel wood as wood chip component did not give more economic benefit to the forest owner. The annuity reduction under the variant 2 was even greater when manual harvesting was used.

Table 5. Spruce annuities (€ ha^{-1} year^{-1}) under three interest rates (*i*), four climate scenarios, two extraction modes and two biomass utilization variants.

	Climate Scenario	Extraction Mode	Biomass Utilization	Annuity (€ ha^{-1} year^{-1}) (Manual)			Annuity (€ ha^{-1} year^{-1}) (Mechanized)		
				i= 0.5%	1.5%	2.5%	0.5%	1.5%	2.5%
MS1	BL	E0	Variant 1	373.1	203.3	88.7	438	258.5	136.9
			Variant 2	342.5	180.4	70.6	407.3	235.7	118.7
		E1	Variant 1	384.5	214.8	92.7	449.4	271.1	140.4
			Variant 2	345.6	185.3	69.9	410.5	241.6	117.7
	A1B	E0	Variant 1	253.4	132.9	43.1	305.6	178.9	82.6
			Variant 2	228.9	113.8	28.1	281.1	159.8	67.6
		E1	Variant 1	267.7	142.3	49.3	321.5	189.9	90.5
	se		Variant 2	235.6	117.2	29.3	289.4	164.9	70.5
	A2	E0	Variant 1	308.7	164	64.6	366.2	213.4	107.8
			Variant 2	281.8	143.9	48.5	339.4	193.2	91.6
		E1	Variant 1	305.5	166.2	64	363.4	216.9	107.2
			Variant 2	272	129.8	43.7	329.8	191	86.9
	B1	E0	Variant 1	293.1	152.8	56.2	347.4	198.8	96
			Variant 2	266.9	133.3	40.8	321.2	179.4	80.6
		E1	Variant 1	285.1	150.1	51.7	334.6	193.4	88.6
			Variant 2	253.4	126.1	33.1	302.9	169.3	70
MS2	BL	E0	Variant 1	382.6	233.5	120.9	466.9	311.4	191
			Variant 2	342.7	199.8	92	427	277.6	162.1
		E1	Variant 1	386.6	238.1	125.6	472.5	317.6	197.4
			Variant 2	336.1	195.2	88.8	422	274.7	160.6
	A1B	E0	Variant 1	228	133.0	57.9	268.7	168	87.1
			Variant 2	214.7	123.4	51	255.5	158.4	80.2
		E1	Variant 1	250	146.2	65.1	318.7	210.4	123.4
			Variant 2	209.3	110.9	34.3	278	175.1	92.6
	A2	E0	Variant 1	321.5	195.2	98	401.2	269.3	165.2
			Variant 2	285.0	163.9	71	364.7	238	138.1
		E1	Variant 1	326.1	198.4	100.4	404.9	272.1	167.7
			Variant 2	279.7	158.4	65.8	358.5	232.1	133.1
	B1	E0	Variant 1	287.6	167.8	76.3	356.4	231.5	133.8
			Variant 2	253.3	138.7	51.3	322	202.3	108.8
		E1	Variant 1	289.1	169.3	77.8	355.9	230.9	133.1
			Variant 2	246.8	133.7	47.6	313.5	195.3	102.9

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, I *E1* the intensified extraction mode (stems and 70% residues were extracted). *Variant 1* reflects current business as usual concerning roundwood use, *variant 2* allocates industrial wood to be bioenergy source. See the climate scenario assumptions in **Table 1**.

Under climate change scenarios, the extracted volume of both spruce stand management concepts was apparently reduced compared to that under the baseline climate. Regardless of management concept, climate scenarios decreased spruce growth. The level of impact of climate scenario on the extracted volume was most severe under the A1B scenario continued under the B1 and the minimum impact was under the A2. The extracted volume under A1B decreased relative to baseline climate by 24-27%, under the B1 18-22% and under the A2 12-17% (**Figure 10**). As shown in **Figure 1**, there is a distinct increased temperature and concurrent low precipitation in A1B climate scenario compared to other scenario. In addition to the direct effects low precipitation on decreased growth, increased temperature is expected to lead to increased transpiration and thus to an earlier occurrence of water deficits or drought in summer which all together may decrease the tree growth.

Also under climate change, the sawn wood and industrial wood volume decreased compared to the sawn wood and industrial wood volume under baseline climate as a result of decreasing growth. Consequently, the industrial wood assortment share was greater under climate change and consequently annuities were decreasing. Similarly to the level of impact trend in extracted volume the A1B climate scenario resulted in the greatest annuity value decline, the decreased relative to baseline climate was by 30-32%, the B1 23-30% and the A2 18-21%. The annuity reduction became higher when manual harvesting and interest rate of 2.5% were used (**Table 5**).

3.3 Total Volume Production, Extracted Volume and Annuity in European beech Management Concepts

Under baseline climate scenario. Total volume productions under the beech alternative concept (1102 and 1082 m^3 ha^{-1} for MB2-E0 and MB2-E1) were moderately lower 6% and 8% than those under MB1 (1174 and 1170 m^3 ha^{-1}) in which 29% volume under MB1 (approximately 340 m^3 ha^{-1}) and 24% volume under MB2 (approximately 260 m^3 ha^{-1}) were not utilized. However, identical extracted volumes were detected in all analyzed beech management concepts regardless of extraction mode (**Figure 9**).

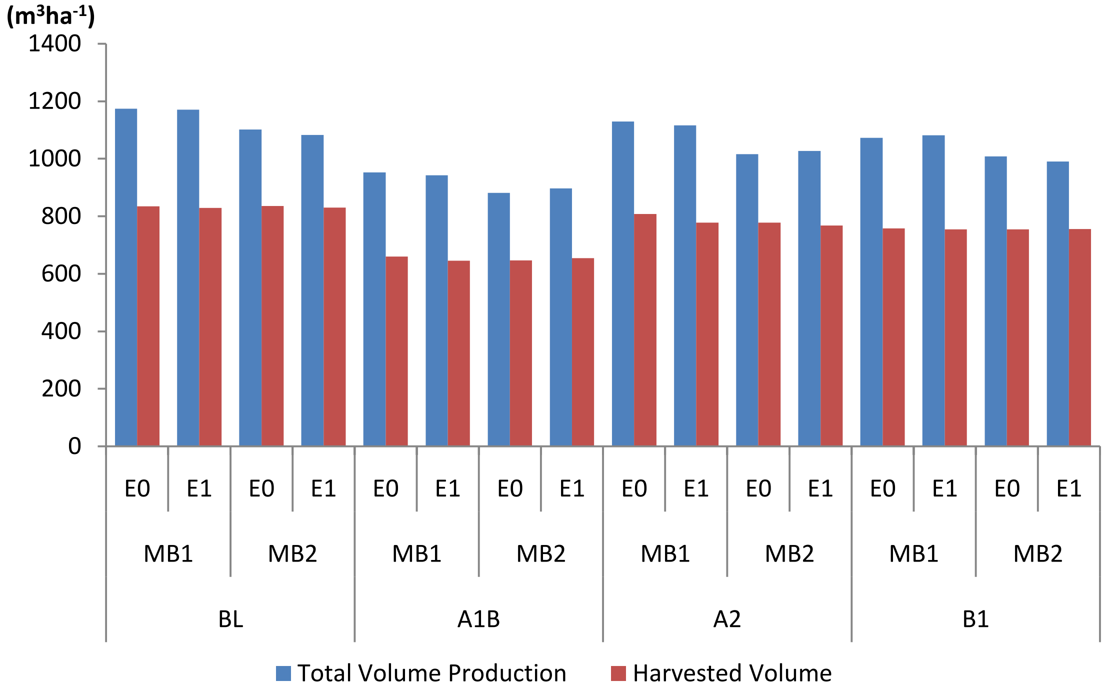


Figure 9. Effect of beech management concepts, climate scenario and extraction mode on total volume production and extracted volume.

But when it comes to timber dimension, there was a considerable result. As expected, heavier thinning from below in MB2 was able to promote diameter growth of remaining trees. Ever since the first thinning at 30 years, mean DBH under this management was larger. The effect of thinning to obtain the desired dimension is apparent in the assortment structure in **Figure 10**. The MB2 turned out to be the best in obtaining higher number of valuable assortments and was able to obtain higher shares of sawn wood per ha (196 m^3 ha^{-1}). Only the MB2 was able to obtain 4AB assortments. Regardless of extraction mode, the assortment structure was dominated by industrial wood (76%), than 3AB (20%) and 4AB (4%).

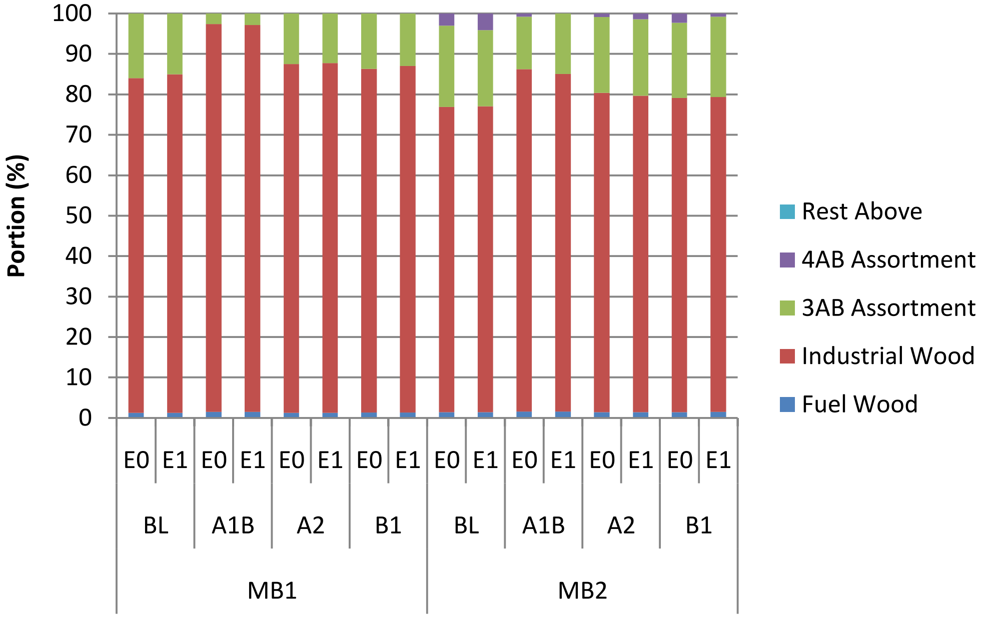


Figure 10. Beech assortment structure (%) (see assortment classification in Table 3) under baseline and climate change conditions.

The MB1 produced smaller mean diameter. This management concept was characterized by a low number of sawn woods per hectare (126 m^3 ha^{-1}) and dominated by assortment industrial wood (84%), than 3AB (16%). No 4AB assortment was produced (**Figure 10** and **Appendix 3**).

Due to larger average diameter, the highest annuity was obtained under the MB2. Regardless climate scenario and interest rate, the highest annuity was always obtained under the MB2-E0 (118 € ha^{-1} $year^{-1}$) and the lowest annuity was obtained under MB1-E1 (104€ ha^{-1} $year^{-1}$) (**Table 6**). The use of manual harvesting method strongly reduced the annuity by 43%.

Unlike under spruce management concepts, the intensification extraction continued with chips production of fuel wood under beech management concepts was not economically attractive in the forest owner's perspective. Intensified extraction continued with chips production slightly reduced the annuity by 2% under the MB1 and by 0.5% under the MB2. This may happen due to higher assumed cost of chips production than the assumed chips price. The chips price was the same for both spruce and beech wood chips. However, the assumed chip production was based on weight unit and the assumed beech density (580 kg/m^3) is higher than the assumed spruce density (403 kg/m^3) therefore chips production for beech biomass per volume unit is more expensive.

The annuity loss is greater under the variant 2, annuity reduced by approximately 22% and 9% respectively under the MB1 and MB2 regardless of different interest rate. The annuity reduction was not as great as under the MB1 because of the lower industrial wood extracted volume under MB2 that can be allocated to fuel wood.

Regardless of stand management concept, the annuity loss in standard extraction mode when using variant 2 was not that high. The annuity reduced by less than 1% because of small difference between the assumed beech industrial wood and fuel wood prices (see beech price assumption in **Table 4**).

Under climate change scenarios, extracted volume decreased regardless of management concept. Under the beech concepts, the climate scenarios impact trend on extracted volume was similar to the trend under the spruce concepts. The level of impact was most severe under the A1B scenario continued under the B1 and the minimum impact was under the A2. However those scenarios have stronger effect on spruce than beech. The A1B decreased the beech extracted volume by 21-22%, the B1 9-10% and the A2 3-8% (**Figure 9**).

Consequently to lower extracted volume under climate change scenarios, annuities were also decreasing. The decreased in A1B relative to annuity under baseline scenario was by 25-28%, the B1 12-13% and the A2 3-10%. Annuity reduction became higher when manual harvesting and interest rate of 2.5% were used (**Table 6**).

Table 6. Beech annuities (€ ha^{-1} year^{-1}) under three interest rates (*i*), four climate scenarios, two extraction modes and two biomass utilization variants.

	Climate Scenario	Extraction Mode	Biomass Utilization	Annuity (€ ha-1 year-1) (Manual)			Annuity (€ ha-1 year-1) (Mechanized)		
				i= 0.5%	1.5%	2.5%	0.5%	1.5%	2.5%
MB1	BL	E0	Variant 1	105.0	61.6	34.3	162.4	105.7	67.3
			Variant 2	104.4	61.2	34.0	161.8	105.3	67.0
		E1	Variant 1	99.5	59.4	34.1	157.0	103.9	67.5
			Variant 2	69.2	38.0	19.2	126.7	82.4	52.6
	A1B	E0	Variant 1	62.7	37.2	21.1	111.1	75.3	50.3
			Variant 2	62.1	36.8	20.8	110.6	74.9	50.0
		E1	Variant 1	61.2	37.4	22.2	108.4	74.3	50.3
			Variant 2	48.2	28.3	15.9	95.4	65.2	44.0
	A2	E0	Variant 1	95.0	55.9	31.3	151.9	99.7	64.1
			Variant 2	94.4	55.5	31.0	151.3	99.3	63.8
		E1	Variant 1	89.0	53.4	30.9	143.6	95.7	62.8
			Variant 2	74.9	43.4	23.9	129.4	85.7	55.8
	B1	E0	Variant 1	91.9	53.9	30.0	143.9	93.8	59.9
			Variant 2	91.3	53.5	29.7	143.3	93.5	59.6
		E1	Variant 1	88.4	52.9	30.5	140.4	93.1	60.7
			Variant 2	74.7	43.3	23.9	126.8	83.6	54.1
MB2	BL	E0	Variant 1	97.0	58.5	33.7	173.8	117.9	78.7
			Variant 2	96.5	58.1	33.4	173.2	117.5	78.4
		E1	Variant 1	97.2	59.7	35.6	171.5	117.5	79.5
			Variant 2	83.5	49.3	27.8	157.8	107.0	71.7
	A1B	E0	Variant 1	59.7	36.2	21.2	121.4	85.4	59.4
			Variant 2	59.2	35.8	20.9	120.9	85.0	59.2
		E1	Variant 1	61.7	38.8	23.9	124.2	88.1	62.0
			Variant 2	49.7	29.6	16.9	112.2	78.9	55.1
	A2	E0	Variant 1	93.1	57.6	34.1	165.7	114.1	77.2
			Variant 2	92.6	57.1	33.8	165.1	113.7	76.9
		E1	Variant 1	82.9	51.3	30.9	153.5	106.6	73.3
			Variant 2	69.7	41.2	23.4	140.3	96.5	65.7
	B1	E0	Variant 1	83.4	50.2	28.9	152.9	103.7	69.2
			Variant 2	82.9	49.8	28.6	152.3	103.3	69.0
		E1	Variant 1	81.9	50.5	30.3	150.9	103.8	70.5
			Variant 2	69.0	40.8	23.1	138.0	94.1	63.3

MB1 the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). *Variant 1* reflects current business as usual concerning roundwood use, *variant 2* allocates industrial wood to be bioenergy source. See the climate scenario assumptions in **Table 1**.

3.4 In-situ Carbon Storage

Under baseline climate scenario, mean in-situ C storage over the analyzed spruce stand management concepts was the highest for MS1-E0 (250 t C ha^{-1}) of which 62% (155 t C ha^{-1}) in aboveground C (in the trees) and 38% (95 t C ha-1) in belowground (in the soil). As expected, the MS2 management concept resulted in moderately decreased in-situ C storage due to shorter rotation length (90 years). For that reason the lowest mean C storage either in aboveground, belowground and in-situ was for the MS2-E1.

Over the beech management concepts, the highest mean in-situ C storage was for the MB1-E0 (254 t C ha^{-1}) of which 55% (139 t C ha^{-1}) in aboveground and 45% (114 t C ha^{-1}) in belowground. The MB2 resulted in considerably decreased in-situ C storage where the MB2-E1 resulted as the lowest mean belowground, aboveground and in-situ C storage (**Table 7**).

Intensified extraction mode in general reduced the mean soil C storage due to little carbon input from residues. However the mean belowground C storage in the E1 was almost identical to that in the E0 regardless of stand management concept (**Table 7**).

Table 7. Carbon storage (t C ha^{-1}) according to the mean storage approach in the stand management concepts over the rotation periods under baseline

	Extraction	Mean C stock (t C ha^{-1})		
	Mode	AG	BG	Total
MS1	E0	155	95	250
	E1	154	91	245
MS2	E0	131	92	223
	E1	130	87	217
MB1	E0	139	114	254
	E1	140	112	252
MB2	E0	118	113	231
	E1	117	110	227

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). *AG* the aboveground, *BG* the belowground.

The flow approach showed the same trend as that in mean storage approach. The MS1-E0 and the MS2-E1 resulted as the highest and lowest in-situ C sink, respectively. However soil under intensified extraction in MS1 and MS2 resulted as carbon source instead of carbon sink. The highest decrease of C soil stock was under the MS2-E1 which accounted for 21 ton C ha^{-1} compared to the initial C soil level. Unlike under spruce management concepts, the flow approach showed that soil under the beech management concepts could act as carbon sink at both standard and intensified extraction modes indicating at land use legacies (**Figure 11**).

In general, the beech concepts comprised the highest mean in-situ C storage (**Table 7**). But contrary to the mean approach, as shown in **Figure 11**, the C sequestration tended to be in some degree larger under the spruce concepts due to spruce high productivity characteristic.

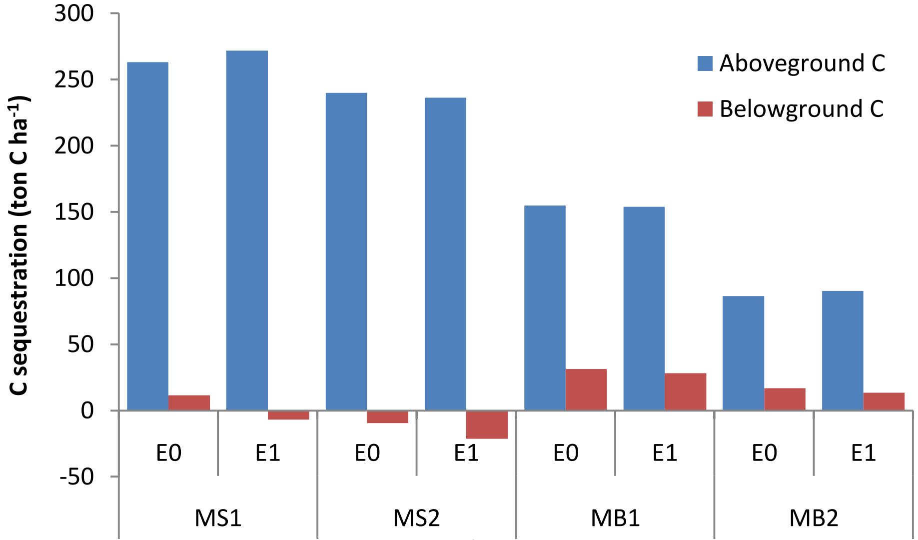


Figure 11. Carbon sequestration (t C ha^{-1}) according to the flow approach in the management concepts over the rotation periods and under baseline. Flow approach shows changes in the net C stock over time.

Under climate change scenarios, the aboveground, belowground and in-situ C stock based on the mean approach decreased regardless of tree species and stand management concept but the relative change was smaller under beech. The mean in-situ C storage under the spruce and beech concepts responded differently toward climate change scenarios. Regardless of management concept and extraction mode, under the spruce concepts the B1 scenario resulted in the C storage greatest decrease (12-14%), followed by the A1B (11-13%) then the A2 (4-7%), whereas in beech the order was the A1B (5-6%), the B1 (4-5%) then the A2 (1-2%) (**Table 8**).

Table 8. Mean carbon storage difference (%) according to mean approach in the stand management concepts under climate change scenarios relative to baseline

	Extraction	A1B			A2			B1		
	Mode	AG	BG	Total	AG	BG	Total	AG	BG	Total
MS1	E0	-17	-2	-11	-5	-1	-4	-17	-6	-12
	E1	-17	-1	-11	-10	-1	-7	-18	-3	-13
MS2	E0	-18	-7	-13	-8	-1	-5	-21	-3	-13
	E1	-17	-2	-11	-7	-1	-4	-22	-3	-14
MB1	E0	-8	-1	-5	-1	-1	-1	-7	-2	-5
	E1	-10	-1	-6	-2	-1	-1	-7	-1	-4
MB2	E0	-10	-1	-6	-3	-1	-2	-8	-1	-4
	E1	-9	-1	-5	-2	-1	-1	-7	-2	-4

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). *AG* the aboveground, *BG* the belowground. See the climate scenario assumptions in **Table 1**.

In terms of carbon sequestration, spruce is more susceptible to climate change rather than beech. For instance, under the A1B climate scenario spruce in-situ C storage decreased by 11-13% whereas decreased by 5-6% for beech. However, that in the current analysis no explicit disturbance regime has been considered. The flow approach also showed that soil under beech concepts could still act as carbon sink for all climate scenarios. Similarly under baseline scenario, soil under the MS2 in both extraction modes and under the MS1 intensified extraction became carbon source instead of carbon sink in all climate scenarios (**Table 9**).

Table 9. Carbon sequestration (t C ha^{-1}) according to the flow approach in the stand management concepts over the rotation periods under climate change scenarios

	Extraction	A1B			A2			B1		
	Mode	AG	BG	In-situ	AG	BG	In-situ	AG	BG	In-situ
MS1	E0	193	0	193	227	7	234	221	2	223
	E1	199	-12	187	222	-10	212	221	-11	210
MS2	E0	168	-15	154	202	-12	190	198	-14	184
	E1	167	-25	142	203	-22	181	195	-26	169
MB1	E0	129	26	155	149	27	176	147	29	176
	E1	127	22	149	148	28	175	146	27	173
MB2	E0	70	14	83	81	14	96	77	16	93
	E1	70	10	80	83	14	97	82	12	94

Mean C stock minus the initial C stock gives the mean C stock flux. *MS1* the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). *AG* the aboveground, *BG* the belowground. See the climate scenario assumptions in **Table 1**.

3.5 Biomass for Biofuel

In this study, the E1 yielded considerably greater amounts of biofuel than that under the E0 which means that the E1 option is important for the biofuel quantity. The E1 in spruce concepts enabled the removal of an additional 63.2 and 68.8 dry ton ha^{-1} of above ground biomass. Under the beech concepts, the additional biomass potential for biofuel was considerably lower enable to gain 20.9 and 25.5 dry ton ha^{-1} greater than that under the E0. The above mentioned higher additional biomass potential values were under the alternative managements (MS2 and MB2) (**Table 10**).

As already mentioned, variant 2 (use of industrial wood directly for energy purposes) is at present not economically attractive but from this work we could assess how high the C substitution potential would be. Higher biomass could be allocated for biofuel under the beech concepts due to the higher share of industrial wood than that under the spruce concepts. Variant 2 under the MB1 enabled to allocate additional 441 and 408 dry ton ha^{-1} biomass potential for biofuel. Due to larger mean diameter per hectare the MB2 enable to allocate less biomass under variant 2 which accounted for 372 and 369 dry ton ha^{-1}. The above mentioned higher values of additional biomass potential were under the standard extraction mode.

Furthermore, there were additional 181 and 184 dry ton ha^{-1} biomass potential for biofuel in the MS1-variant 2. In the MS2-variant 2, the additional biomasses were 200 and 202 dry ton ha^{-1}. The above mentioned higher values of additional biomass potential were under the standard extraction mode (**Table 10**).

Table 10. The biomass for biofuel potentials from different extraction modes and biomass utilizations in each stand management scenario and its C substitution

	Extraction	Biofuel (ton ha^{-1})		C Substitution (ton C ha^{-1})	
	Mode	Variant 1	Variant 2	Variant 1	Variant 2
MS1	E0	1.1	182.5	0.4	66.6
	E1	64.3	248.3	23.5	90.6
MS2	E0	1.7	201.9	0.6	73.7
	E1	70.5	272.4	25.7	99.4
MB1	E0	53.5	495	19.5	167.5
	E1	74.4	481.8	27.2	175.9
MB2	E0	50.3	421.5	18.3	153.9
	E1	75.8	444.9	27.7	162.4

C substitution assumption is that the biomass for fuel wood is to substitute coal under scenario biomass-fired steam-electric power for coal-fired steam-electric power substitution. *MS1* the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). *Variant 1* reflects current business as usual concerning roundwood use, *variant 2* allocates industrial wood to be bioenergy source.

In **Table 10** and **Figure 12**, the CO2 emission reduction potential per hectare over the rotation period from fossil fuel substitution by spruce and beech biomasses is presented. Results were of course strongly dependent on the amount of potential fuel wood production.

Intensified extraction coupled with variant 2 clearly resulted in a significant increase of C substitution potential. Due to higher additional biomass that could be extracted under intensified spruce concepts, the increased C substitution under these concepts was also stronger compared to that under the beech concepts. For instance, using biomass from the MS1-E1 for electric power generation increased the mitigation potential by 23.6 t C ha^{-1} at the year 100 for substituting coal based electric generation. Whereas under the MB2-E1 was 7 C ha^{-1} at the year 100.

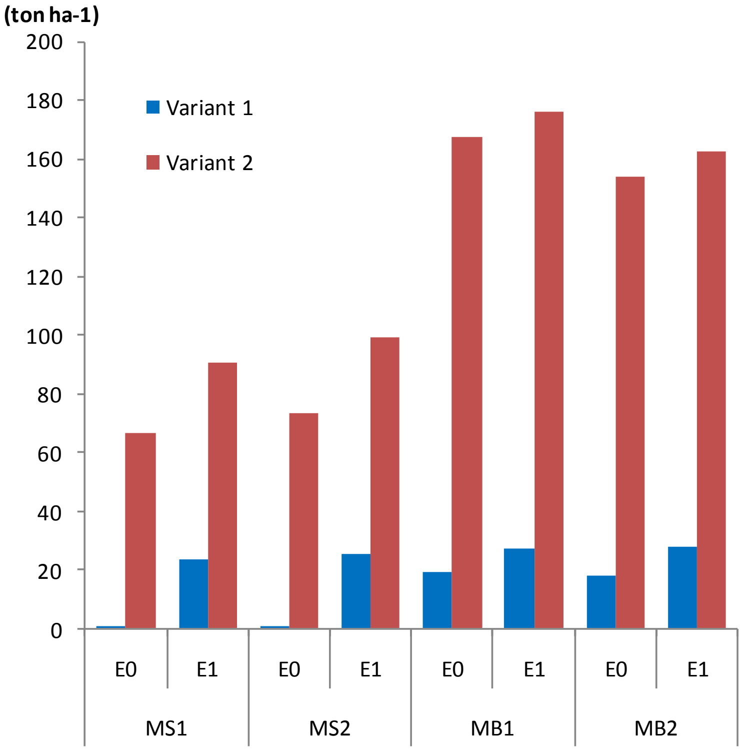


Figure 12. CO2 emission reduction potential per hectare over the rotation periods from fossil fuel substitution by spruce and beech biomass assuming that the full extracted harvested biomass for fuel wood is to substitute coal under scenario biomass-fired steam-electric power for coal-fired steam-electric power substitution.

Even though not economically attractive in the forest owner's perspective, variant2 has an advantage of considerably enhancing C substitution. As shown in **Figure 12**, the strongest mitigation effect under this concept was in the beech management concepts due to high share of industrial wood that could be allocated to biofuel use. The use of biomass from the beech concepts under variant 2 for electric power generation gives a mitigation potential in the range of 168 to 176 t C ha^{-1} at year 100 for substituting coal based electric generation. While in the MS1 was in the range of 67 to 91 t C ha^{-1} at year 100 and in the MS2 was 74 to 99 t C ha^{-1} at year 90.

3.6 Site Productivity

Identical growth responses between the E0 and the E1 were detected. Throughout the rotation period, E1 simulations did not show a clearly reduced total volume production compared to that under the E0 simulations. Identical site productivity difference under the E1 may be due to relatively fertile soil of the simulated site. The relatively high level of N soil deposit may counteract growth reduction due to N removal in the E1. It should also be noted that the E1 theoretically removes all residues, but operationally it leaves a portion of those materials on site. In this work the recovery rate is 70%, it means approximately 30% of all residues were left on the site.

There was also no evidence of any notably difference on other site productivity indicators (mean annual increment (MAI) and mean available soil N between the two extraction modes over the analyzed stand management concepts. From the model simulations, MAI and available soil N were obtained, showed that those two indicators under the E0 and the E1 were identical (**Table 11**).

These findings are partly in contrast to results from experimental work and other simulation studies. What must be noted is that in the current study calibration of the soil decomposition module within PICUS was not possible due to missing quantitative soil data for the simulated sites. Similarly the initialization of N and C pools was based on qualitative assessments.

Table 11. Three simulation indicators for sustainable site productivity assessment under various management scenarios over the simulation period

Parameter	Management Concept	E0	E1	%
Total Volume Production (m^3 ha^{-1})	MS1	1941	1913	-1.4
	MS2	1737	1735	-0.1
	MB1	1174	1170	-0.3
	MB2	1102	1082	-1.8
MAI (m^3 ha^{-1} y^{-1})	MS1	19.4	19.1	-1.5
	MS2	17.4	17.3	-0.6
	MB1	11.7	11.7	0.0
	MB2	11	10.8	-1.8
Mean Available Soil N (kg ha^{-1} y^{-1})	MS1	117.9	116.3	-1.3
	MS2	113.5	112.2	-1.2
	MB1	152.6	152	-0.4
	MB2	145.4	144.5	-0.6

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode, in *E1 E1* the intensified extraction mode (stems and 70% residues were extracted).
* %= (E1 values-E0 values)/E0 values x 100%

3.7 Overall Evaluation on Management Alternatives

None of the options were able to achieve top rank of the indicators we analyzed in both spruce and beech concepts. In spruce concepts, from annuity perspective the first 4 ranks are found within MS2, for in-situ C storage first ranks are found in MS1 and for C substitution the first ranks are shared by MS1 and MS2 (**Table 12**). However, options in MS2-E0-variant2 have best average rank (3). This includes no preference for any of the indicators.

More or less similar rank patters are also found in beech concepts. The first 4 ranks of annuity indicator are found within MB2, for in-situ C storage first ranks are found in MB1 and for C substitution the first ranks are shared by MB1 and MB2. Options in MB2-E0-variant2 have best average ranks (3.3) (**Table 13**).

Table 12. Decision matrix and conclusions for Norway spruce illustrating ranking for each management concept

Indicator	MS1				MS2			
	E0		E1		E0		E1	
	Variant1	Variant2	Variant1	Variant2	Variant1	Variant2	Variant1	Variant2
Annuity	6	7	5	8	2	3	1	4
In-situ C	1		2		3		4	
C Substitution	8	4	6	2	7	3	5	1
Site productivity	Identical							

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years). In *E0* the standard extraction mode, in *E1 E1* the intensified extraction mode (stems and 70% residues were extracted). *Variant 1* reflects current business as usual concerning roundwood use, *variant 2* allocates industrial wood to be bioenergy source.

Rank scale for annuity and C substitution indicators:

1	2	3	4	5	6	7	8

Rank scale for in-situ C indicator:

1	2	3	4

Table 13. Decision matrix and conclusions for European beech illustrating ranking for each management concept

Indicator	MB1				MB2			
	E0		E1		E0		E1	
	Variant1	Variant2	Variant1	Variant2	Variant1	Variant2	Variant1	Variant2
Annuity	5	6	7	8	1	3	2	4
In-situ C Storage	1		2		3		8	
C Substitution	7	1	6	2	8	4	5	3
Site productivity	Identical							

MB1 the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode, in *E1 E1* the intensified extraction mode (stems and 70% residues were extracted). *Variant 1* reflects current business as usual concerning roundwood use, *variant 2* allocates industrial wood to be bioenergy source.

Rank scale for annuity and C substitution indicators:

1	2	3	4	5	6	7	8

Rank scale for in-situ C indicator:

1	2	3	4

4 Discussion and Conclusions

4.2 Discussion

This work aiming at investigating biomass potential production for the different assortments from the operational perspective of forest management, displaying also the issue of climate change in regards to its implication toward the total volume production, extracted volume, C storage and C substitution. This study did not search for a stand management concept with the greatest annuity, C storage and C substitution but rather investigated how robust the results of the selected management concepts are under current and changing climatic condition. An assessment of sustainability of site productivity due to intensified extraction to enhance biofuel production potential was also done based on literature and model output.

The main component of the analysis was the hybrid patch model PICUS v1.4, which was used to simulate the stand management concepts and forest development under the four climate scenarios investigated. In previous study, PICUS had been had been found capable of reproducing realistic response to a climate change sensitive experiments, volume production and stand structure (Seidl et al., 2005). Seidl et al. (2008) showed that PICUS has a plausible agreement of the response of soil C to management. In this study, simulated total gross growth and dominant height values over the rotation period of each management concept were compared to those from yield tables of the site and showed good correspondence.

For the work presented here, different stand management concepts were applied for spruce and beech. Both alternative managements in spruce and beech (MS2 and MB2) were intentionally designed to increase the economic profitability of the forest owner. Results show that alternative spruce management scenario reduced moderately the total volume production (1941 and 1913 m^3 ha^{-1}, respectively for MS2-E0 and MS2-E1) extracted volume (1296 and 1315 m^3 ha^{-1}) by 10% and 4% than those under MS1. Differently, total volume productions under the beech alternative concept (1102 and 1082 m^3 ha^{-1}, respectively for MB2-E0 and MB2-E1) were moderately lower 6% and 8% than those under MB1, but the extracted volumes were more or less identical.

Concerning the economic benefit, lower initial density was able to omit pre-commercial thinning and therefore release MS2 from pre-commercial thinning cost (675€ ha^{-1}). Jointly with bigger mean diameter and shorter rotation (90 years), annuity under MS2 was higher. In MB2, the increase in annuity was solely influenced by the ability of this management in triggering bigger mean diameter which means higher shares of valuable timber assortments and reduction of harvesting cost per volume unit. This result is similar accordingly to several studies (Oosterbaan et al. 2008, Spiecker 2008) describing that more intensive management with less crop trees with larger crowns may produce higher wood quality and dimension. This economic indicator result is however sensitive to the interest rate used in calculating the values of annuity. However, it must be acknowledged that potential negative impacts on wood quality through wider spacing were not considered in this study.

Intensified extraction strongly increase the amount of biomass being removed compared to the standard method by an average of around 62 ton and 23 dry ton of additional biomass per hectare over the rotation period over spruce and beech concepts respectively. This means that the forest owner will benefit more from this method than from any other. Unexpectedly, biofuel chipping reduces the annuities relatively compared to if biofuel is sold as fuel wood. Based on the assumed costs and prices, for instance, forest owner's earning when selling beech biofuel as chips was 23€ ton^{-1}, sold unchipped the earning was 27€ ton^{-1}. It is however sensitive to the wood price because of a wide range of wood prices in Europe. The revenue from chips production is then very sensitive to this price assumption. The assumed chip price (62.5€ ton^{-1}) used in this study was also an average price derived from power plants above and below 5000kW (50€ ton^{-1} and 75-80€ ton^{-1}, respectively) in the Bavaria (Neugebauer et al., 2005). Ericsson et al. (2006) illustrated, the huge variability of chip prices example ranging from 47€ ton^{-1} dry matter in Germany to 94€ ton^{-1} dry matter in Denmark.

Concerning the climate change scenarios, the simulations showed that tree growth was decreasing in the simulated site regardless of management concept. This is in general agreement with various findings pointing at the adverse effect of climate change on spruce and beech growth at sites as used in the analysis (Peuke et al. 2002, Geßler et al. 2007, Rötzer et al. 2009). The level of impact of climate scenario on the extracted volume was the strongest under the A1B scenario, moderately impact under the B1 and the least impact was under the A2. As shown in **Figure 1**, along with a distinct reduction in precipitation, an increase in mean temperature in growing season in the A1B is projected for the period from 2041 to 2070. From the forest growth perspective, the projected reduction of precipitation during the growing season will cause drought stress and thus decrease growth. In addition to the direct effects of low precipitation, increased temperature is expected to lead to increased transpiration and thus longer drought period (Ellenberg 1996, Lebourgeois, et al. 2005).

Climate change scenarios have stronger effect on spruce than beech. This is maybe because beech is more drought-tolerant than spruce (Dixon et al. 1998). Additionally, as shown in **Table 8**, the reduction in biomass increments of Norway spruce might respond more sensitive above than below ground (Meier, 2007and Rötzer et al., 2009). However when interpreting the effect of climatic changes on tree growth, it is necessary to keep in mind that predictions contain uncertainties and error from the climate scenarios as well as from the forest model.

The mean in-situ C stock according to the mean stock approach was lower for both spruce and beech under alternative management concepts. MS1 under baseline climate scenario in the simulated site stored on average 248 t C ha^{-1} and under MS2 was 220 t C ha^{-1}. The decrease in MS2 in-situ C stock is likely a combined result of both decreased aboveground biomass (**Table 7**) and shorter rotation length. As expected, a shortened rotation period under MS2 resulted in lower mean in-situ C stock (Ericsson 2006, Johansson 2008). Furthermore, average C stock of 253 t C ha^{-1} was stored in MB1 and 229 t C ha^{-1} in MB2. The C stock reduction was mainly due to the more extensive management which reduced strongly the above ground biomass. In this study, it was not possible to maximize simultaneously extracted volume and the mean C stock in the forest ecosystem. In general, climate change decreased the total C stock regardless of the management concept.

There have been efforts to respect all the forest ecosystem processes under sustainable forest management. However it is difficult to manage forest in order to maximize both carbon storage and economic benefit. In this study a conflict between those two variables was obvious. Alternative management concepts (MS2 and MB2) could generate higher annuity but at the same time decreased the mean carbon storage.

In the analysis of site productivity, identical total volume production and extracted volume between standard (E0) and intensified extraction mode (E1) over the analyzed stand management concepts was detected. There was also no evidence of any notably difference of simulated MAI and mean simulated available soil N when comparing those two indicators from both extraction modes. These findings are partly in contrast to results from experimental work and other simulation studies. Indeed, the effect of extraction intensity on growth can vary largely. Some existing studies from field experimental works (e.g. Sterba, 1988; Jacobson et al., 2000, Nord-Larsen, 2002; Merino et al., 2005, Walmsley et al., 2009) and simulations (e.g. Wei et al., 2000; Merganičová et al., 2005,) showed that intensified extraction resulted in growth reductions although it is not always found (Smith et al., 1994; Egnell and Leijon, 1997). It should be noted that only a single rotation was analysed in this study, trends in total volume production over multiple rotations may be a better indication of sustainable site productivity. Furthermore, other factors that may influence the current study finding is that site-specific calibration of the soil decomposition module within PICUS was not possible due to missing quantitative soil data for the simulated sites. Similarly the initialization of N and C pools was based on qualitative assessments. Finally, the simulated sites were rich in nutrients and short-term intensified extraction may not have depleted the N-pools.

Increased demand worldwide for wood as a biofuel resource leads to more intensive forestry practices. Using the intensified extraction strongly increase the amount of biomass being removed compared to standard extraction modes. Additional biofuel production potential in intensified extraction spruce options in the current analysis is in a range of 63 to 68 dry ton ha^{-1} compared to the biofuel biomass potential in the standard extraction mode, whereas in beech the potential under intensified mode is from 20 to 26 dry ton ha^{-1} compared to that under standard extraction mode. Less additional biomass in beech compared to that in spruce is because beech branches were already extracted under standard extraction due to its crown architecture, mean while spruce stems were completely left on the forest site.

The additional biofuel was ever more superior when allocating industrial wood as biofuel. The spruce scenarios enabled to allocate additional 181-202 ton ha^{-1} and 369-408 ton ha^{-1} in the beech concepts. This strategy was done to investigate how high the biofuel potential would be because at present this concept is not economically attractive from the forest owner’s perspective. Under the spruce concepts, annuity reduced approximately up to 11% and up to 22% in beech. However, this biomass utilization was predicted by Nabuurs et al. (2007) to happen in Europe due to the EU policies on energy (European Commission 1997). This strategy might be more visible in the future where biofuel price is higher.

4.3 Conclusions

1. Forest owner could gain higher benefit by changing the current stand management concept to the alternative management concepts.
2. In any management concept, the climate change scenarios used in this study appear to give a negative effect on total production and extracted volume in the simulated site.
3. In this study, it is unfeasible to increase the annuity of the forest owner and the increase C storage in the forest stand at the same time. The C storage is lower under the climate change scenarios.
4. Biofuel production potential increases strongly under the intensified extraction. Additional biofuel production potential in Noway spruce concepts is in a range of 63 to 68 ton ha^{-1}, and in European beech the additional is 20 to 26 ton ha^{-1}.
5. Allocating industrial wood as biofuel greatly could increase the biofuel potential, however annuity also decreased significantly up to 30% in Norway spruce and 43% in European beech greatly depending on interest rate and harvesting method applied.
6. Intensified extraction hypothetically could reduce tree growth. However identical site growth responses were detected in the present study, either in Norway spruce or in European beech. Therefore, a thoroughly evaluation on belowground processes in PICUS v1.4 is needed to further increase the reliability of the simulated result.

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APPENDIX

APPENDIX 1. Norway spruce (*Picea abies*) extracted volume share (%) in each assortment

Stand Management	Climate Scenario	Extraction Mode	Assortment Structure						
			Fuel wood	Indutrial wood	Sawn wood				
					1B	2AB	3AB	4AB	>5
MS1	BL	E0	0.2	12.9	5.4	33.4	40.7	5.7	1.6
		E1	0.2	12.9	5.6	33.3	40.4	5.7	1.8
	A1B	E0	0.3	16.3	8.5	46.1	27.8	0.7	0.3
		E1	0.3	16.5	8.3	45.5	28.9	0.5	0
	A2	E0	0.2	13.9	6.4	40.4	34.7	3.3	1.1
		E1	0.3	14.9	7.2	41.2	35.2	1.2	0
	B1	E0	0.3	14.8	7.5	39.6	35.6	2.2	0
		E1	0.3	15.1	7.7	39.5	35	1.6	0.8
MS2	BL	E0	0.3	19.5	8.3	31.7	30.4	5.3	4.5
		E1	0.3	19.9	8.5	32.2	31.9	4.3	2.8
	A1B	E0	0.5	25	12	39.2	22.6	0.7	0
		E1	0.5	25.3	11.7	40.2	21.8	0.4	0
	A2	E0	0.4	21.4	10.8	35.7	29	1.8	1
		E1	0.4	22	10.7	34.2	29.7	2.5	0.5
	B1	E0	0.4	23.2	10.7	32.7	29.2	2.2	1.6
		E1	0.5	23.2	10.5	35	28.7	1	1.1

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, I *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.

APPENDIX 2. Norway spruce (*Picea abies*) extracted volume (m^3 ha^{-1}) in each assortment

	Climate Scenario	Harvesting Mode	Assortment Structure							Total Commercial Volume
			Fuel wood	Indutrial wood	Sawn wood					
					1B	2AB	3AB	4AB	>5	
MS1	BL	E0	2.8	168.2	70.6	433.4	529.1	74.0	20.5	1295.8
		E1	2.9	170.3	74.1	438.9	532.5	75.4	24.2	1315.5
	A1B	E0	2.8	156.3	81.5	442.6	267	7	2.4	956.7
		E1	2.9	164.5	82.8	452.7	287.5	4.6	0	992.1
	A2	E0	2.7	154.4	70.7	447.8	385.2	36.1	12.4	1106.5
		E1	2.8	163.3	79.3	452.8	386.7	13.4	0	1095.4
	B1	E0	2.9	158.5	80.4	422.9	380	23.5	0	1065.4
		E1	2.8	155	78.8	404.9	358.6	16.8	8.5	1022.6
MS2	BL	E0	4.3	245.2	103.8	397.5	382.2	66	56.7	1251.4
		E1	4.3	250.4	107.4	405.4	400.4	54.3	35	1252.9
	A1B	E0	4.3	230.8	110.4	361.2	208.4	6.5	0	917.3
		E1	4.3	230.7	107	366.8	198.9	4	0	907.5
	A2	E0	4.2	236	118.8	393.6	319.7	20	11	1099.1
		E1	4.2	243.3	118.4	378.5	327.7	27.7	5.2	1100.8
	B1	E0	4.5	234	108.5	330.2	294.4	21.8	16.5	1005.4
		E1	4.5	231	104.8	348.8	286.1	10.1	10.8	991.5

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, I *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.

APPENDIX 3. European beech (*Fagus sylvatica*) extracted volume share (%) in each assortment

Stand Management	Climate Scenario	Extraction Mode	Assortment Structure (%)				
			Fuel wood	Indutrial wood	Sawn wood		
					3AB	4AB	>5
MB1	BL	E0	1.2	82.8	16.0	0	0
		E1	1.2	83.7	15.0	0	0
	A1B	E0	1.5	95.9	2.6	0	0
		E1	1.5	95.7	2.9	0	0
	A2	E0	1.2	86.2	12.5	0	0
		E1	1.3	86.5	12.2	0	0
	B1	E0	1.3	85.0	13.7	0	0
		E1	1.3	85.7	13.0	0	0
MB2	BL	E0	1.4	75.5	20.2	3.0	0
		E1	1.4	75.6	18.9	4.1	0
	A1B	E0	1.6	84.7	13.0	0.8	0
		E1	1.6	83.4	15.0	0	0
	A2	E0	1.4	79.0	18.7	0.9	0
		E1	1.4	78.3	18.9	1.4	0
	B1	E0	1.4	77.7	18.6	2.3	0
		E1	1.5	77.9	19.8	0.8	0

MB1 the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.

APPENDIX 4. European beech (*Fagus sylvatica*) extracted volume ($m^3 ha^{-1}$) in each assortment

	Climate Scenario	Harvesting Mode	Assortment Structure		Sawn wood			Total Commercial Volume
			Fuel wood	Indutrial wood	3AB	4AB	>5	
MB1	BL	E0	10.4	699.1	135.2	0	0	834.4
		E1	10.3	702.4	126.2	0	0	828.6
	A1B	E0	9.8	642.1	17.4	0	0	659.6
		E1	9.6	627.1	18.8	0	0	645.9
	A2	E0	10.2	705.3	102.5	0	0	807.8
		E1	10.1	681.8	96.5	0	0	778.3
	B1	E0	9.9	652.3	105.4	0	0	757.7
		E1	10.1	655.4	99.3	0	0	754.7
MB2	BL	E0	11.7	640.1	170.9	25.3	0	836.3
		E1	11.8	636.4	158.8	34.6	0	829.9
	A1B	E0	10.5	556.6	85.3	5	0	647
		E1	10.4	555.1	99.7	0	0	654.8
	A2	E0	11.3	622.7	147.9	6.8	0	777.3
		E1	11.3	609.4	146.8	11.3	0	767.5
	B1	E0	11	594.8	142.3	17.7	0	754.8
		E1	11.2	597.7	151.9	6.3	0	756

MB1 the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.

APPENDIX 5. Mean diameter, mean height and basal area in the end of rotation for all analyzed management concept, extraction mode and climate scenario.

Stand Management	Climate Scenario	Harvesting Mode	Mean DBH (cm)	Mean Height (m)	Basal Area (m^2)
MS1	BL	E0	43	39	62
		E1	43	39	64
	A1B	E0	38	34	49
		E1	38	35	51
	A2	E0	40	37	55
		E1	40	37	55
	B1	E0	40	36	54
		E1	39	36	55
MS2	BL	E0	42	38	57
		E1	42	38	56
	A1B	E0	37	33	43
		E1	37	33	43
	A2	E0	39	36	50
		E1	40	36	50
	B1	E0	39	35	49
		E1	39	34	49
MB1	BL	E0	33	28	35
		E1	33	28	35
	A1B	E0	30	25	30
		E1	30	25	30
	A2	E0	32	27	34
		E1	32	27	34
	B1	E0	32	27	34
		E1	32	27	34
MB2	BL	E0	40	30	19
		E1	40	30	20
	A1B	E0	35	27	16
		E1	35	27	16
	A2	E0	38	29	18
		E1	38	29	18
	B1	E0	39	29	17
		E1	38	29	18

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.

APPENDIX 7. Carbon storage (t C ha^{-1}) according to the mean storage approach all analyzed management concept, harvesting mode and climate scenario

Climate Scenario	Management Concept	Extraction Mode	Carbon Stock (ton C ha^{-1}) Mean AG	Mean BG	Total
BL	MS1	E0	155	95	250
		E1	154	91	245
	MS2	E0	131	93	223
		E1	130	87	217
	MB1	E0	139	114	254
		E1	140	112	252
	MB2	E0	118	113	231
		E1	117	110	227
A1B	MS1	E0	129	93	222
		E1	128	91	219
	MS2	E0	107	86	193
		E1	107	86	193
	MB1	E0	128	113	241
		E1	126	111	237
	MB2	E0	106	111	217
		E1	106	109	216
A2	MS1	E0	147	94	241
		E1	139	90	229
	MS2	E0	120	92	212
		E1	120	87	208
	MB1	E0	138	113	252
		E1	137	112	249
	MB2	E0	114	112	226
		E1	115	110	224
B1	MS1	E0	129	90	219
		E1	126	88	214
	MS2	E0	104	90	193
		E1	101	84	186
	MB1	E0	129	112	241
		E1	131	111	241
	MB2	E0	109	111	221
		E1	109	108	217

MS1 the current practice spruce management (100 year rotation), *MS2* the alternative spruce management (90 years), *MB1* the traditional beech management (100 years) and *MB2* the alternative beech management (100 years). In *E0* the standard extraction mode only stems were extracted and residues were left on site, in *E1* the intensified extraction mode (stems and 70% residues were extracted). See the climate scenario assumptions in **Table 1**.