



Carbon balance of coniferous forests in response to different harvesting strategies: A model based analysis

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Preface

This Master thesis is made at 30 point individual course Level E and fulfils the requirements for a final thesis for a Master of Environmental Science: Soil, Water, Biodiversity at the Swedish University of Agricultural Sciences and at the University of Hohenheim. It was carried out at the Department of Ecology of the Swedish University of Agricultural Sciences during the author's stay under the obligatory exchange of EnvEURO programme. The work was done in spring semester 2009.

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Abstract

The aim of this study was ultimately to suggest a harvesting strategy for northern coniferous forests that would be the best choice of carbon management for optimising carbon storage regarding the concerns of both wood production and carbon stored in the forest pools not harvested.

For two climatic diverse sites in Sweden, Asa (57°08'N, 14°45'E) and Flakaliden (64°07'N 19°27'E), a comparison has been made between three different forest management scenarios by use of a process-based modelling approach. The three scenarios addressed were a control scenario, a clear-cutting scenario and a single-tree selection scenario. The focus was on the carbon balance of the sites and how this was affected by the different ways of management.

For the simulation of the trees in the forest the daily time-step based model BIOMASS was used. This model runs on daily meteorological inputs and consists of a large amount of sub-models interacting with each other. For the heterotrophic part of the forest, the Q-model was applied. The Q-model is a model simulating decomposition of organic matter. The BIOMASS model could successfully be parameterised in such a way that it was able to reproduce sufficiently both the CO₂ - fluxes and evapotranspiration fluxes of the target forest, but also the realistic development of a forest at the specific site.

All scenario runs were run for 300 years on the climatic data of one-year repeated climate, to exclude effects of changing climate. The control scenario was run until it reached an equilibrium point, the clear-cutting scenario was run until the final harvest of 100 years and then repeated 2 times. The single-tree scenario was run in small time intervals and always the same small proportion of harvest was taken out. Harvesting residues were decomposed, but the harvested stems were considered to be taken away after the harvests and did not contribute to the heterotrophic respiration.

Concerning the carbon pools, the scenarios followed the expected behaviour, the control and the single-tree selection balanced out, whilst the run on Asa went much faster to an equilibrium state than the run in Flakaliden. The carbon pool of the clear-cutting scenario was rising fast, even if some thinnings had been applied it was rising until the trees were harvested fully. The control scenario stored the most amount of wood. The highest accumulated net ecosystem exchange (NEE) for Asa and for Flakaliden was in the single-tree selection, followed by the clear cut scenario and the control scenario. A comparison between the two different harvesting strategies concerning the amount of wood which could be harvested resulted in the outcome that both harvesting strategies would result in approximately the same amount of wood. The clear-cutting management was a little more effective at the Northern site, whilst the single-tree selection seemed to work better in the South. This first attempt of a modelling comparison of single-tree selection management with traditional harvesting strategies indicate that the single-tree selection was the best managing form regarding total carbon accumulation and under certain circumstances may even be interesting for economic reasons because of the continuous income from harvests. Single-tree selection should be considered a serious alternative to traditional harvesting management.

1. Introduction

1.1. The background

1.1.1. Importance of Swedish coniferous forests for the world carbon balance

Carbon fluxes and especially the distribution of carbon into different pools in the forest ecosystem have drawn a lot of attention in the last decades. They are particularly important because of their potential for rapid responses to climatic changes. About 25% of the global terrestrial ecosystem carbon is made up by temperate forest ecosystems (Kleja et al. 2008). They store carbon both above and below-ground and can constitute an important sink for atmospheric CO₂ on a global scale (Lindroth et al. 2008). Temperate forest carbon balance is therefore monitored with large research effort all over the world (e.g. Pypker & Fredeen 2002; Yanai et al. 2003; Medlyn et al. 2005). Coniferous forests account for the largest parts of the temperate forest regions, consisting of only a few characteristic tree species, mainly spruce and pine (Pfister et al. 2007). The Scandinavian coniferous forests which are composed to a great extent of Norway spruce (*Picea abies* (L.) Karst.) are the largest in Europe (Chrimes 2004). Since most of the other coniferous forests of the world are also to a great extent dominated by spruce, the investigation of a Norway spruce ecosystem can be compared and applied to a large amount of forest land all over the world. The research on Swedish coniferous forests is therefore highly relevant to future scientific and managing purposes.

1.1.2. Harvesting strategies for spruce forests in Sweden

Different harvesting strategies have been used in Swedish spruce forests in the last centuries, ranging from total clear-cuts on a very large scale over partial cuttings of less than a hectare to single-tree selection (Lundqvist 1989).

In the traditional clear-cutting systems the forests are grown to a certain level which is shortly after the annual increase of wood biomass reaches its peak. Then they are thinned by one or two harvests to increase growth again until they are finally cut. The number of years which are necessary for the trees to grow to a desired height and diameter depend highly on the climate and soil conditions (Anonymous 1989).

The main difference between clear-cutting management and the other form of harvests is that foresters, when managing without clear cutting, harvest only a portion of trees at the stand level at any time. The forest remains a forest with trees and not a vast open area with only trunks and understorey vegetation. If given the possibility of reseeded the managed area, the removal of a certain amount of trees at certain time steps results then in an uneven-aged stand (Chrimes 2004). Uneven-aged silviculture requires that, at harvest, there must be sufficient ingrowth from below to replace trees that are harvested and that formerly shaded trees can develop into full grown mature trees. The aim of single-tree selection harvests is to sustain stand growth and to control or balance the residual stand density with different size and/or age classes, and the result is a reverse-J shaped diameter distribution (Lundqvist 1989). Two other kinds of partial harvests are mainly used in uneven-aged stands: high-grading and diameter-limit harvesting. In high-grading only certain species or large and high-valued trees are harvested, whereas diameter-limit harvests remove all trees larger than a specified diameter (Chrimes 2004). Both harvesting techniques are also applicable to the management of both even-aged and uneven-aged stands.

From the second half of the nineteenth century until the early 1950s, the high-grading partial cuttings dominated Swedish forestry (Nilson 2001). Today the Swedish forests are currently managed traditionally with clear-cutting systems. One of the main reasons for this is that laws of the late 1940s were enforced under the Swedish Forestry Act (Chrimes 2004) to forbid the practice of partial harvesting because these partial harvests were regarded unfavourable for timber production. In present days, there is increasing interest in Sweden for sustainable forest management strategies and multiple-use of forests. In spruce forests, different forms of uneven-aged silviculture have been reported to successfully fulfil the requirements for both biodiversity and timber production (Lähde et al. 2001).

Since the laws against single-tree selection are not in power anymore, now more frequently, mainly among private forest owners, there has been a turning 'back to the roots' applying single-tree selection management.

1.1.3. Research on carbon balance and harvesting strategies of forests

As stated above, research on the carbon fluxes of a forest ecosystem is done to a great extent. Some of the studies try to measure the whole ecosystem net exchange of CO₂ (e.g. Medlyn et al. 2005; Lindroth et al. 2008)). These measured fluxes are, however, the result of two very large opposite fluxes, one going into the system (assimilation) and one out of the system (respiration). Each of these large fluxes is again a result of a large number of smaller fluxes from a number of sub-compartments in the system. The fluxes are in turn controlled by a large number of factors, among which some dynamically react upon themselves. A complete understanding of these complex systems is therefore still not reached. To explain the entire system, some studies approach only parts of these carbon fluxes in a forest ecosystem, mostly dividing it into "above ground" and "below ground" fluxes or looking upon it on an even smaller scale (e.g. Law et al. 1999; Morén & Lindroth 2000; Ingwersen et al. 2008).

The CO₂ fluxes have been studied on a shoot, tree and ecosystem scale (Wallin et al. 2001). But even though some of the parts which make up the forest carbon fluxes of a forest are therefore well researched, the whole complex system has yet to be investigated. The application of mathematical models to elucidate the behaviour of these complex systems by comparison of the modelled results to the actual measurements has become a favoured tool in present research (e.g. Baldocchi & Wilson 2001; Medlyn et al. 2005). Modelling something as complex as a forest, however, is always a tightrope walk between a too simple model which does not reflect the measured data sufficiently and a too complex model which cannot be explained fully or even handled by the researcher and up to now there does not exist any standard user-optimized modelling program for forest ecosystems.

1.2. Aim of the study

Most studies which consider the different harvesting strategies of coniferous forests have been motivated by economic reasons or the impact on biodiversity (e.g. Berg et al. 1994; Andreassen & Øyen 2002; Lundqvist et al. 2007).

But some studies have also measured and investigated the response of the carbon balance regarding clear cutting harvesting strategies or even selection cutting (e.g. Fernandez et al. 1993; Laporte et al. 2003; Freeman et al. 2005). The response of a temperate coniferous forest carbon balance to the different harvesting strategies applied in Sweden, especially the single-tree selection strategy has not yet been analysed by means of modelling.

Therefore the aim of this study is

- To investigate how time, sequence and size of management interventions impact on the carbon balance of a forest.
- To use a process based model for this investigation. It should simulate the coniferous forest with all the carbon pools and fluxes as close to reality as possible.
- To study important forest management strategies and compare them in three different scenarios.
- To make a comparison between two sites of different latitude since the harvesting strategies might work differently in different climatic conditions.
- To give a suggestion as to which harvesting strategy would be the best under which climatic condition regarding carbon accumulation and wood production.

1.3. The harvesting scenarios

All harvesting scenarios start with the same conditions: Young spruce seedlings are planted on a total clear-cut area which is in equilibrium with itself regarding CO₂ fluxes. Upon these sites different managing strategies will be performed.

1.2.1. First scenario: Control scenario

The trees are just grown and are not disturbed by any harvests. The living carbon biomass should in theory increase sigmoidally and then reach a certain level where the ecosystem is more or less in equilibrium (Fig1). Since it does not store more carbon biomass after reaching the plateau, it should be expected that after that point the forest ecosystem will be regarded as neutral to its surroundings.

1.2.2. Second scenario: Clear-cutting management

The trees are grown for a certain number of years, depending on the traditional rotation period of that climate. Then two thinnings are executed and finally the trees are completely harvested at the traditional point of harvest. Regarding the tree biomass, the start of this scenario should look the same, but from the thinnings on it will have a different shape (Fig 1). From that point on, there will be a lot of stem biomass removed from the system, but all the foliage, branch and root biomass will be left on site and subject to heterotrophic respiration. Finally, when the total clear cut takes place, all stem biomass is removed, and harvesting residues will be left at the site, entering the pool of dead organic matter which from now on will be a source for CO₂ to its surroundings.

1.2.3. Third scenario: Single-tree selection

The trees are grown for a shorter number of years, after which the selection harvest of single trees will start. The number of years is again dependent on the respective climate. The time steps between the selective harvests are quite short and only a small amount of the trees is taken out at each harvest. Regarding the tree biomass, we will expect the same start as before, but then the shape of the curve should look like a saw which is closer to the curve of the control (Fig1), than to the clear-cut curve. Each time when the Single-Tree Selection occurs,

only a smaller amount of stem biomass will be removed from the system. Foliage, branch and root biomass will also be left on site, subject to heterotrophic respiration. When the forest reaches its equilibrium, the Single-Tree Selection should always take out an amount of stems which equals the amount that otherwise would have died from the system because of natural thinning.

These scenarios are of course simplifications of the complexity that is found in the real world and should be regarded as model forest scenarios. For a simple approach we assumed a nutrient (nitrogen) non-limited system and with no losses of carbon, e.g. dissolved organic matter. We also assumed a forest consisting only of trees, excluding interactions with ground vegetation.

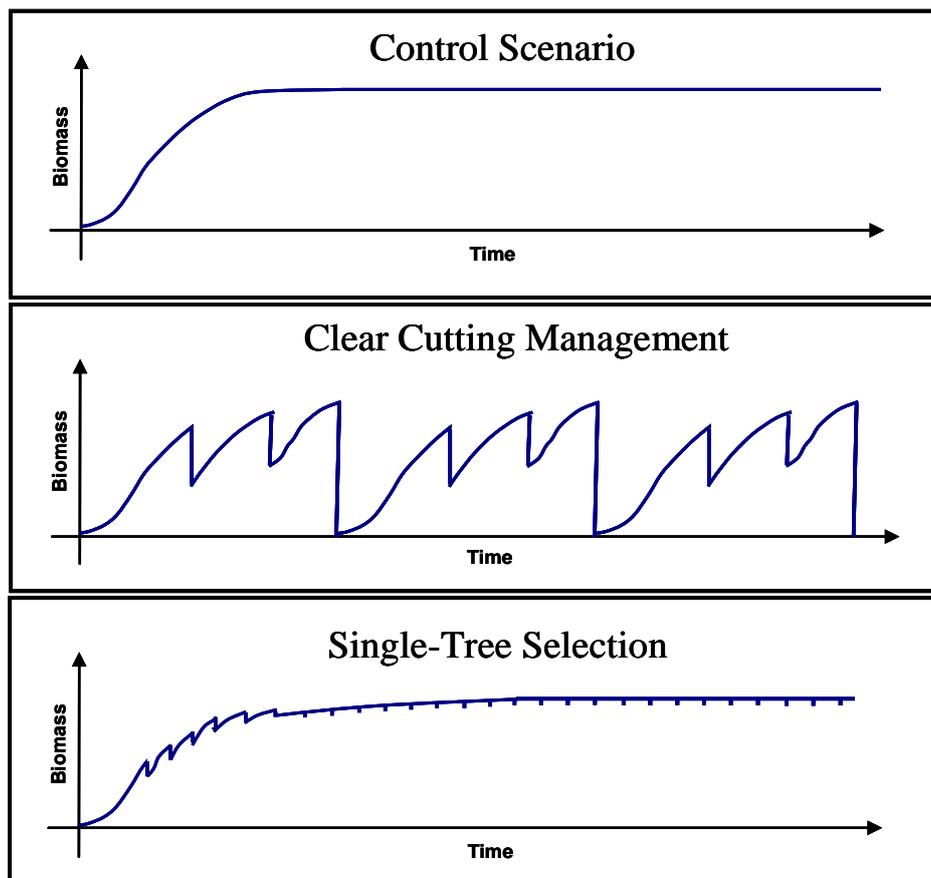


Fig. 1: Expected living biomass over time in the three Scenarios.

2. Materials and methods

2.1. Study sites

The sites which were used for the model scenarios are Asa and Flakaliden (Fig. 2). In both sites the major tree species is Norway spruce (*Picea abies* (L.) Karst.) (Fig3). The trees of the stand on both sites have an age of approximately 40 years. The sites were chosen because of the large climatic difference between them. Properties of the sites are summarised in Table 1.

Flakaliden was clear-cut in 1963 and Asa in 1966, the former forest generation in Flakaliden was a Norway spruce stand of an age of over 100 years, while in Asa existed a mixed forest of spruces and pines of 80-120 years (Kleja et al. 2008). Both were planted with Norway spruce seedlings directly after the clear-cut.



Fig. 2: Location of the study sites in Sweden

2.2. Data acquisition and handling

To simulate the dynamics of a Norway spruce forest grown on these sites as well as possible, flux measurements of evapotranspiration and CO₂ which have been taken directly on the sites, were used for validating a process based model (cf. Aubinet et al. 1999). The flux measurements were taken by an eddy-flux measuring system located 3 m above the highest tree of the site (Fig. 3). Gap-filling of the climatic data was done with data from official weather stations, which were located near the measuring masts. The obtained data of the flux-measurements and the climatic data were afterwards post-processed for further usage by the programs P-Graph and Microsoft Excel. The process based model was run on climatic data which were measured directly on these sites. These were standard variables; incoming solar shortwave radiation, temperature, air humidity and precipitation.

Table 1: Characteristics of the study sites (after Kleja 2008)

	Asa	Flakaliden
Latitude	57° 08' N	64° 07' N
Longitude	14° 45' E	19° 27' E
Altitude (m a.s.l.)	190-200	310-320
Mean annual temperature (°C)	5.5	1.2
Mean length of growing season (days)	190	120
Mean annual precipitation (mm)	688	523
Major tree species	<i>Picea abies</i>	<i>Picea abies</i>
Stand age in 2001	38	42
Basal area (m ² ha ⁻¹)	26	20
Soil type according to FAO (1990)	Podsols	Podsols
Vegetation zone	Boreo-nemoral	Boreal



Fig. 3: The 15-m mast at Flakaliden where the CO₂-flux measurements are taken. In the background are Norway spruce trees. Foto: Anders Båth and Achim Grelle (<http://www-carbonsweden.slu.se>)

2.3. Modelling approach

2.3.1. Model overview

The main model used for carrying out the simulations for the scenarios was the BIOMASS model (McMurtrie et al. 1990; McMurtrie & Landsberg 1992; McMurtrie et al. 1992a; McMurtrie et al. 1992b; McMurtrie & Wang 1993; McMurtrie 1993; Gholz et al. 1994). This model simulates the growth of the forest and the litter productions and can be altered to perform the harvests in the thinning scenarios. The different parts of the tree are divided by the model in separate pools (Fig. 4). The final output of this model includes the leaf area index (LAI), the gross primary production (GPP), the net primary production (NPP), for all the separate pools of the trees the total amount of biomass each year, the annual autotrophic respiration, the annual production and finally the annual amount of litter.

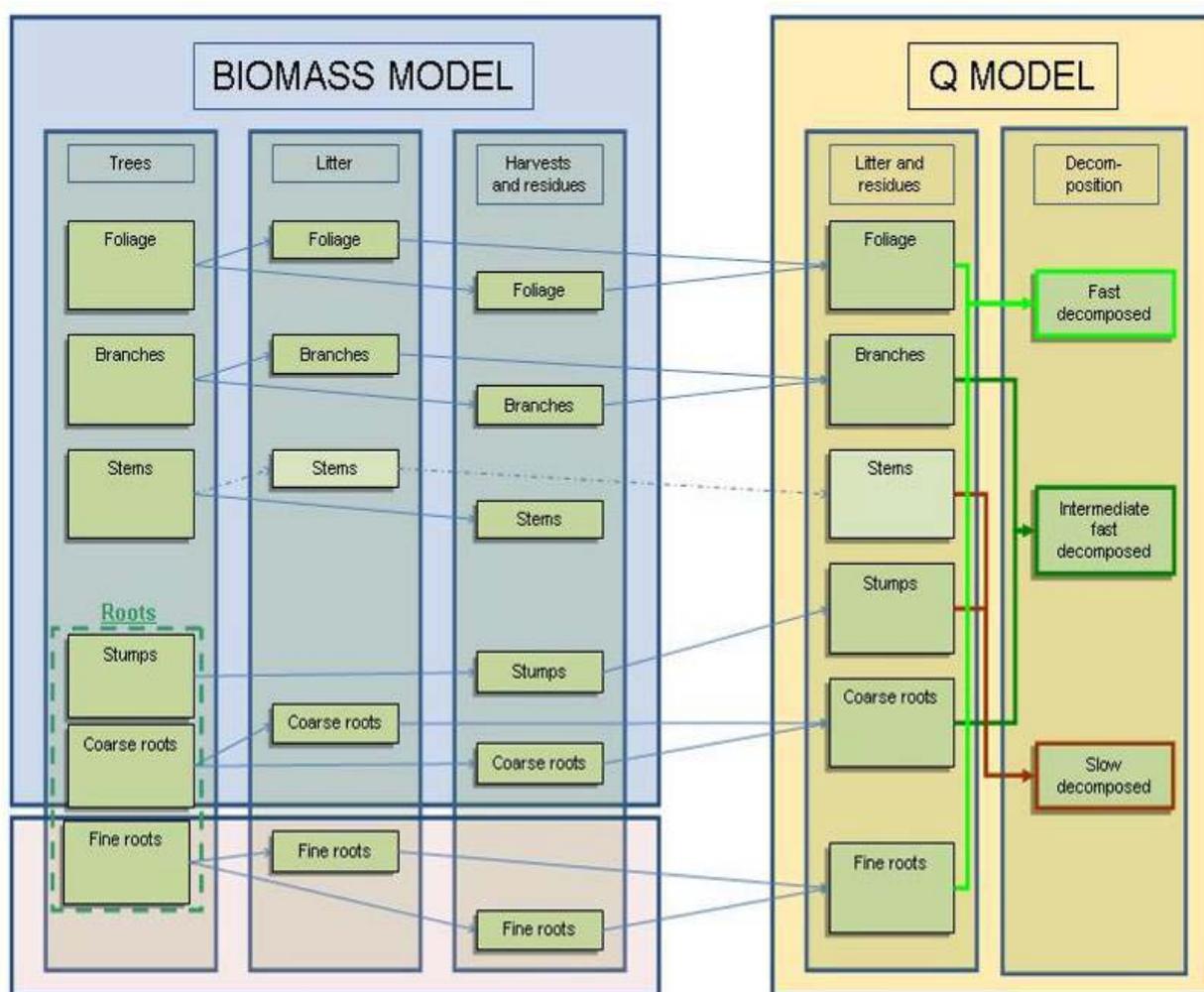


Fig. 4: Overview of the used models.

The heterotrophic respiration is not covered by this model and is executed by the Q-model (Agren & Bosatta 1987; Agren et al. 2007). The Q-model divides the dead organic matter into three different classes, respectively, to decomposition and treats them differently. Because the BIOMASS model is not considering fine roots as a separate pool, they are considered a fraction of the pool of roots; the rest is considered coarse roots. Since fine roots have a much shorter lifespan and a faster decomposition rate than the normal roots, the fine roots have been split from the root pool of the BIOMASS model to be processed separately by the Q-model. The partition of fine roots from the root pool is estimated after Ågren (2007). Stumps are also treated by the BIOMASS model as part of the roots. Since they decompose more slowly than the average coarse roots, they should be treated as stem wood for decomposing purposes instead of coarse roots. After a harvest, the harvested coarse root pool is divided into a pool of coarse roots and stumps.

2.3.2. The BIOMASS model

The BIOMASS model is based on a large number of sub-models describing radiation interception, canopy photosynthesis, allocation of photosynthates among plant organs, biomass growth, litter fall and water balance (Fig 5). The theory of these sub-models with a

detailed description of the equations can be found in the detailed guide of the model (McMurtrie et al. 1990; McMurtrie & Landsberg 1992; McMurtrie et al. 1992a; McMurtrie et al. 1992b; McMurtrie & Wang 1993; McMurtrie 1993; McMurtrie et al. 1994).

BIOMASS

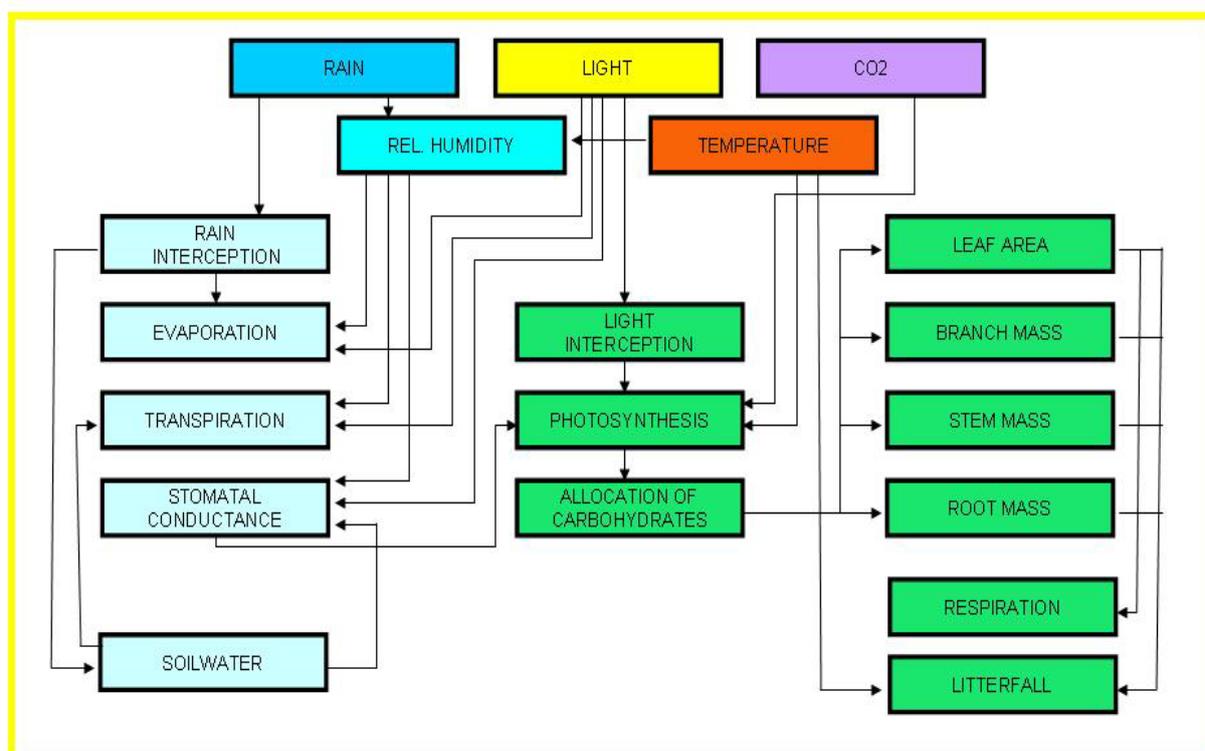


Fig. 5: Schematic diagram of the BIOMASS model.

BIOMASS requires daily meteorological inputs of shortwave radiation, maximum and minimum air temperature, precipitation, and humidity of the air. Gross primary production is calculated from a radiation interception model which requires information on canopy architecture and a model of leaf photosynthesis by C₃ plants, based on biochemical properties. Tree crowns are regarded to be ellipsoidal in shape, and the canopy is divided into three horizontal layers, each with different photosynthetic parameters, the most important is here light interception (Gholz et al. 1994). Radiation absorption is used by a sub-model to calculate canopy photosynthesis. The sub-model considers separately the interception of direct and diffuse radiation, being estimated for both sunlit and shaded foliage. The rate of photosynthesis is obtained by the summation of contributions from foliage above and below light-saturation which depends on the solar zenith angle and the distribution of leaf angles. Photosynthates are allocated to growth of the compartments of foliage, branches, stems, and coarse roots, according to an allocation scheme. The autotrophic respiration is separated into growth respiration and maintenance respiration. Litter production takes place in all compartments of the tree. The water balance sub-model includes precipitation, interception, percolation, run-off, and the transpiration of trees. The water balance constrains growth through stomata regulation and the shedding of foliage.

The model was adjusted to the boreal conditions by modifying functions describing post-winter recovery and autumn decline of photosynthetic capacity (Bergh et al. 1999; Wallin et al. 2001).

2.3.3. The Q-model

The Q-model is a yearly-based decomposition model, which covers the complete heterotrophic respiration part of the forest in this work. The decomposition of the different litter fractions is calculated according to a concept where the invasion rates of decomposers organisms depend on the litter type, i.e. the litter quality (Hyvönen & Ågren 2001; Eq. 1-5).

$$G_n(t) = (1 + \alpha t)^{-z} \quad (1)$$

$$G_w(t, t_{\max}) = \frac{2}{t_{\max}} \frac{1}{\alpha(1-z)} \left[(1 + \alpha t)^{1-z} - \left(1 - \frac{t}{t_{\max}} \right) \right] + \frac{2}{t_{\max}^2} \frac{1}{\alpha^2(1-z)(2-z)} \left[1 - (1 + \alpha t)^{2-z} \right] + \left(1 - \frac{t}{t_{\max}} \right)^2 \quad t < t_{\max} \quad (2)$$

$$G_w(t, t_{\max}) = \frac{2}{t_{\max}} \frac{1}{\alpha(1-z)} (1 + \alpha t)^{1-z} + \frac{2}{t_{\max}^2} \frac{1}{\alpha^2(1-z)(2-z)} \times \left[(1 + \alpha(t - t_{\max}))^{2-z} - (1 + \alpha t)^{2-z} \right] \quad t > t_{\max} \quad (3)$$

$$\alpha = f_c \beta \eta_{11} u_0 q_0^\beta \quad (4)$$

$$z = \frac{1 - e_0}{\beta \eta_{11} e_0} \quad (5)$$

Here $G_n(t)$ determines the fraction of initial carbon remaining in a needle or fine root pool after time t and $G_w(t, t_{\max})$ describes the same function for the woody components with t_{\max} the time it takes for decomposers to completely invade these litter components. The other parameters used are $f_c = 0.5$ (carbon concentration in decomposer biomass), $b = 7$ (a shape parameter determining how steeply the decomposer growth rate changes with substrate quality), $g_{11} = 0.36$ (a parameter determining how rapidly substrate quality decreases). The parameter u_0 is coupled to the growth rate of the decomposers which depends on climate, and is correlated with latitude (Eq.6.).

$$u_0 = 0.0855 + 0.0157(50.6 - 0.768 \text{ Latitude}) \quad (6)$$

The calculation of the remaining carbon is made as a function of years for each litter pool separately. The total soil carbon consists of the sum of remaining litter pools of different ages and from different tree components. Since there is no vertical partitioning of soil carbon in the model all soil carbon is included. This assumes that climatic variability with depth can be neglected, as well as differences in the interaction between soil carbon and the mineral soil matrix.

The calculations are executed in triangular matrix in Excel where the input of litter and harvest leftovers for each year decomposes. The Q-model treats needles and fine roots as fast-composing components, stems and stumps as slow composing components and branches and coarse roots as composing at an intermediate speed.

2.4. Fitting of the BIOMASS model

The BIOMASS model was not originally designed for the purpose of this work. It has been changed previously to match the climatic conditions of Sweden, but it had to be parameterized to simulate the forests on the two sites as close as possible to reality. There have been two steps in the parameterization of the model.

2.4.1. Short-time comparison with the flux measurements

On-site flux measurements of CO₂ and evapotranspiration from the two years of 2001 and 2002 were available for both Flakaliden and Asa. To make sure that the model reflects reasonable values for the fluxes, the BIOMASS model was run with climate data of these two years for both sites. The evapotranspiration flux was directly compared to the transpiration values delivered by the BIOMASS model. For a comparison with the CO₂-fluxes, it would have been necessary to use a simulated value for the net ecosystem exchange (NEE). Since BIOMASS does not cover the heterotrophic part of the NEE and the Q-model runs only on a yearly basis, the NEE had to be calculated differently. To calculate the heterotrophic respiration (R_H) an exponential function depending on temperature was applied, where t is the temperature in degrees Celsius (Eq.7).

$$R_H = 0,2 \cdot e^{\left(\frac{\ln(3,5)}{10t}\right)} \quad (7)$$

To get the total NEE, these calculated values were then subtracted from the values for the net primary production (NPP), simulated by BIOMASS. Then the NEE and the CO₂-fluxes were compared. The parameters of the BIOMASS model were then altered to achieve a better fit to these values.

2.4.2. Comparison of the long-time run with literature values

Since the short-time comparison with the flux-measurements can only indicate a reasonable behaviour of the model at a momentary stage, but not guarantee the same for the growth in the long run, it had to be ensured, that the control scenario runs with the model would reach the characteristics values, the literature could provide for a given age for each of the sites. The values used in this way for the long-time parameterization are summarised in Table 2.

The values of the BIOMASS simulations have been compared at year 39 to the values for Asa and at year 43 for Flakaliden. The parameters have been altered to fit the values as well as possible. After a reasonable fit, the resulting parameters have been tested against the flux-measurements again.

Table 2: Stand characteristics of Asa and Flakaliden (after Lindroth 2008)

	Asa	Flakaliden
Projected leaf area index	3.7	3.4
Site class index (tree height at 100 years)	31	17
Stand age in 2002	39	43
Tree density (no. ha ⁻¹)	2834	2603
Maximum tree height (m)	25.1	12.7
Basal area (m ² ha ⁻¹)	32.3	20.7
Stem biomass (g C/m ²)	4360	1600
Foliage biomass (g C/m ²)	569	529
Live branch biomass (g C/m ²)	1690	1330
Dead branch biomass (g C/m ²)	114	54
Stump biomass (g C/m ²)	503	232
Coarse root biomass (g C/m ²)	824	289
Fine root biomass (g C/m ²)	394	279

2.5. Management plan and treatment of the scenarios

All scenarios have a length of 300 years. The climate data, on which the model will run, will only be the year 2001, which is then repeated 300 times. This is done to exclude interactions with changes in climate, which would confuse the interpretation of the results. The amount of 300 years, which correspond to three rotations in this study, is necessary to get stable simulations results. For the clear-cutting scenario e.g., this will allow us to study the carry-over effects of two clear-cut rotations to the last rotations period.

2.5.1. Control scenario

In the control scenario there will be no harvest or other artificial thinnings. The only thing which is not running dynamically is the vertical crown size (green height), due to technical reasons of the program. This is increased at 3 time steps, at year 20 and at year 100 reflecting both how high the tree is and how far down the tree can still grow needles. Since Norway spruce trees grow rarely older than 150 years in artificially planted stands, from year 100 on a tree dying will be introduced by adding a certain percentage of stem-litter. Since regeneration of new trees under old trees is not possible in the BIOMASS model, the number of stems is kept constant to reflect that a new tree is continuously replacing an old dying tree.

2.5.2. Clear-cutting management

In the clear-cutting management, three thinnings will be executed before the final harvest in Asa and two thinnings in Flakaliden. The thinnings will be done at years 30, 50 and 70 after planting for Asa and at years 55 and 75 for Flakaliden. In Asa with each thinning the total biomass and the amount of trees will be reduced by 20%, and in Flakaliden by 27%. Since BIOMASS treats the number of trees independent of the amount of tree biomass, the reduction of both values by the same percentage guarantees that the average size of the trees stays the same right after thinning. The final harvest will happen both in Asa and in Flakaliden at year 100. At the final harvest, the living biomass is reduced to zero. After the final harvest the BIOMASS simulations will start over from a clear cut two times until the end of the scenario at 300 years. The Q-model will deal with the dead organic matter of the rotation period before, which will give carry over effects to the following periods. The stem biomass here will not be added to the Q-model and therefore not be subject to heterotrophic respiration since the stems are harvested and taken away from the site.

2.5.3. Single-tree selection

In single-tree selection, the thinnings were executed a little bit earlier and at shorter intervals. The thinning started at year 20 in Asa and at year 30 in Flakaliden. Afterwards a thinning was done every 5 years in Asa and every 10 years in Flakaliden. The values for the time steps are taken from the literature (Lundqvist 1989). The aim is here according to theory to achieve a steady state in the biomass and leaf area index. This time only a smaller percentage of the biomass will be taken out but the amount of trees will stay the same as in the control scenario. This is to mirror the growing of younger trees in the place of the old tree which has been taken out. To reflect the different size of the trees in a forest managed with single-tree selection, the needles of the older trees will have the possibility of growing down further than in a forest where all trees have the same height. The green height of the single-tree selection scenario will therefore also stay the same height after 100 years like in the control. Like in the clear-cutting management, the harvested stem-biomass will not be subject to heterotrophic respiration.

3. Results

3.1. Validation of the Models

3.1.1. Flakaliden

After the fitting of the model to the measurements of the CO₂-fluxes (cf. Morén 2000), the BIOMASS model could sufficiently replicate the fluxes at the two sites. For Flakaliden, results are shown in Fig.6. The regression line between the measured CO₂-fluxes and the calculated NEE had an R² value of 0.70. Only some few very low values in the measurements could not be reproduced.

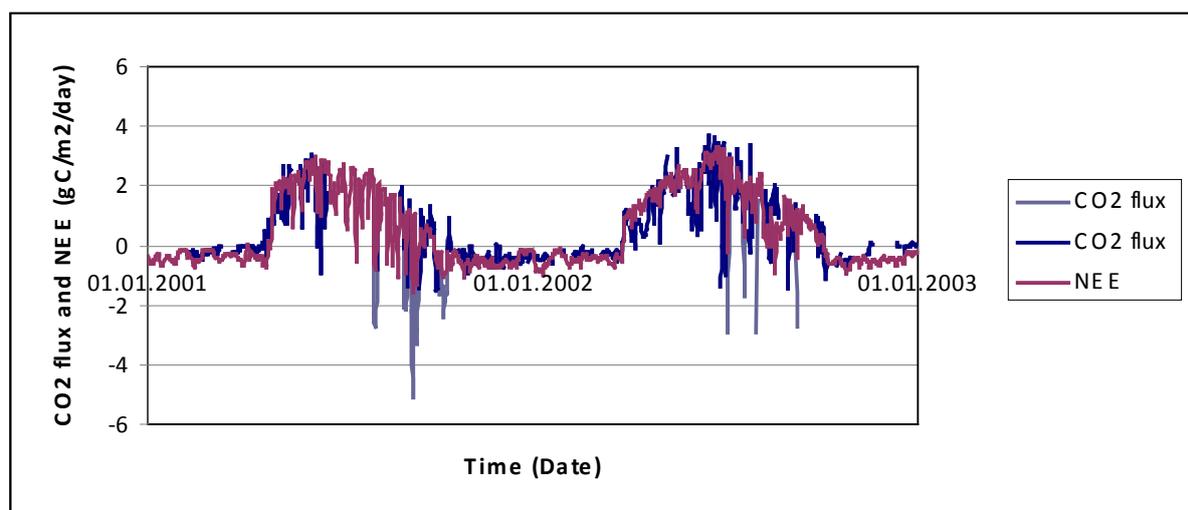


Fig. 6: Measured CO₂-fluxes and calculated net ecosystem exchange (NEE) of Flakaliden for the years 2001 and 2002. The light blue line shows all the CO₂-fluxes while the dark blue line shows only the fluxes higher than -1.5 gC/m²/day. The lower values were not possible to reproduce by the BIOMASS model.

Regarding the comparison of the evaporation, also the BIOMASS simulation reflected the measurements of Flakaliden sufficiently (Fig 7). The regression line had an R^2 -value of 0.71.

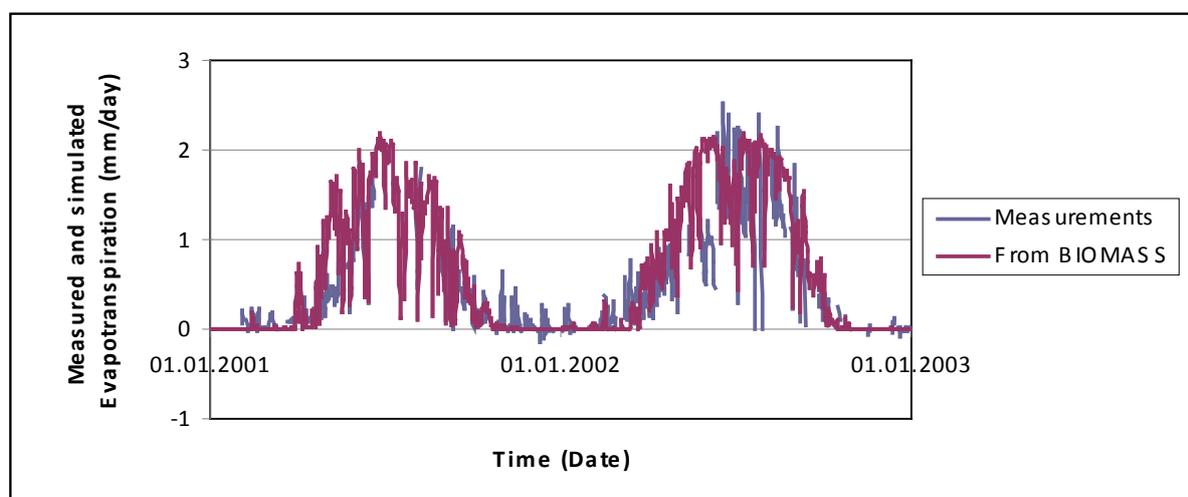


Fig. 7: Measured and by BIOMASS simulated evapotranspiration fluxes of Flakaliden for the years 2001 and 2002.

The parameterization of the BIOMASS model with the aim of simulating growth and development of the Flakaliden forest stand was one of the most challenging parts of this work. As stated above, the BIOMASS model consists of a large number of mathematical sub-models which even dynamically interact with themselves. It was therefore hard to estimate all the changes in the outcome when a single parameter was changed. Since the BIOMASS model is not a steady-state based model and was not programmed for the purpose of this work, the values of the first runs did not match the target values of the literature. It took a large amount of changes in various parameters to reach a version of the model which could reproduce the target values of literature close enough. A list of the target values and their corresponding values from the BIOMASS runs are shown in Table 3. The version of the BIOMASS model which delivered these results was then tested against the fluxes again. The previous figures are the comparison with the final parameterization of the model.

Table 3: Comparison of the target values for the parameterization and the corresponding values from BIOMASS. Both columns describe the Flakaliden stand of 43 years. The values for stumps, coarse roots and fine roots are treated in BIOMASS together as root pool.

	Literature (Lindroth 2008)	BIOMASS
Projected leaf area index	3.4	3.1
Stem biomass (g C/m ²)	1600	1636
Foliage biomass (g C/m ²)	529	520
Live branch biomass (g C/m ²)	1330	907
Stump biomass (g C/m ²)	232	
Coarse root biomass (g C/m ²)	289	1066
Fine root biomass (g C/m ²)	279	

3.1.2. Asa

The final version of the Flakaliden parameterisation was then applied to Asa. The aim of this work was to construct a version of the BIOMASS model which could flexibly work on all climatic factors and could simulate the growth and development of any Norway spruce forest dynamically when given the corresponding climate data. So when the final version was tested

against the Asa fluxes and the values from literature, it should match these target values sufficiently without making any further changes to the parameters. When this final version was tested against the CO₂-fluxes of Asa, it matched the measurements, but not as well as in Flakaliden (Fig.8). The regression line here showed an R²-value of 0.62.

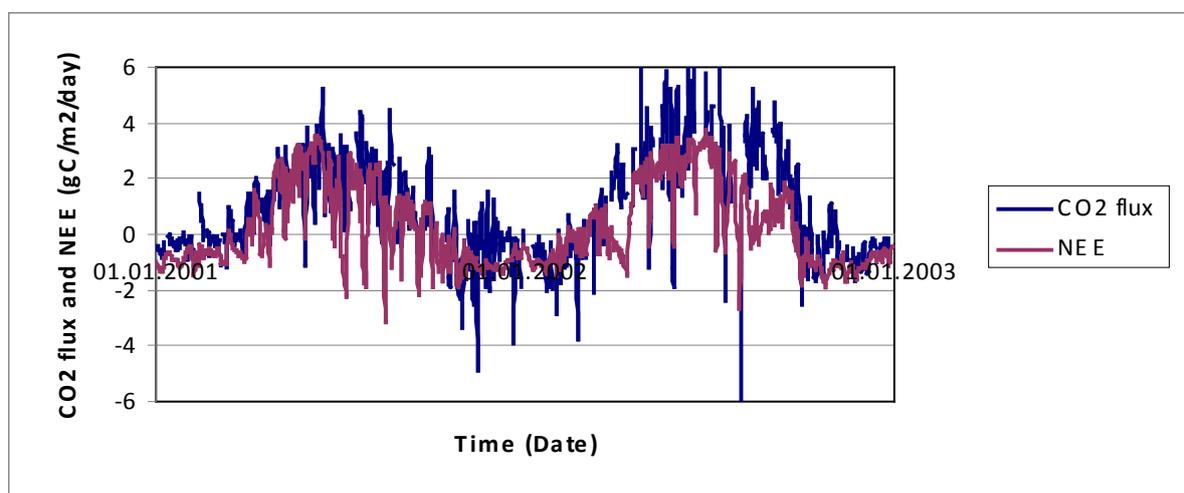


Fig. 8: Measured CO₂-fluxes and calculated Net ecosystem exchange (NEE) of Asa for the years 2001 and 2022.

A comparison between the measured evapotranspiration fluxes of Asa and the simulated ones from BIOMASS showed that there were similar results, the simulated curve was close to the measured, but the fit was also here not as good as in Flakaliden (Fig. 9). Here the regression line between the two evapotranspiration values showed an R²-value of 0.60.

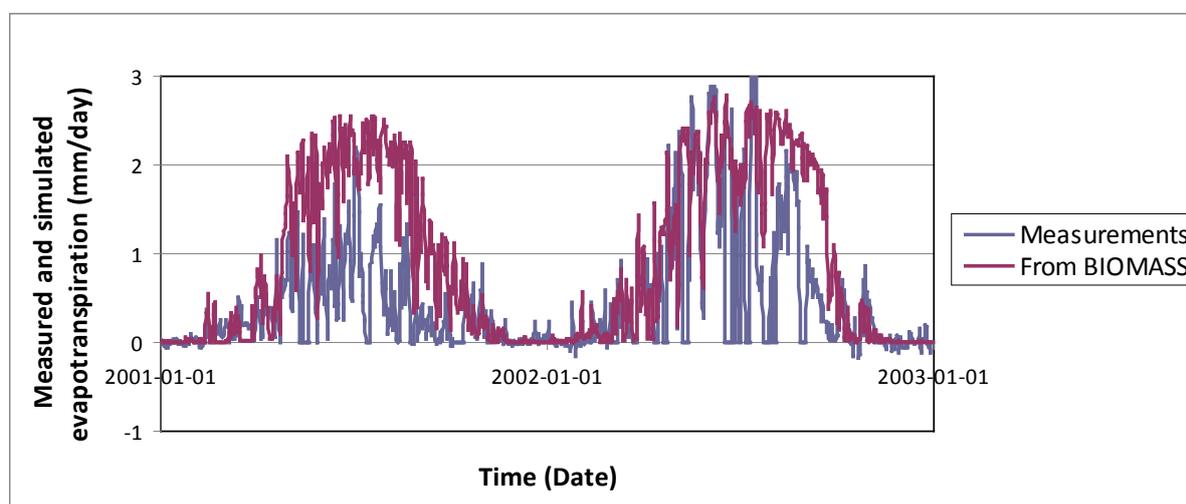


Fig. 9: Measured and by BIOMASS simulated evapotranspiration fluxes of Asa for the years 2001 and 2022.

As indicated by a comparison between the Asa long time run and the target values from literature, the values matched surprisingly well, only the amount of foliage and the resulting LAI was too high compared to the literature value. A comparison of the values is shown in Table 4.

Table 4: Comparison of the target values for the parameterization and the corresponding values from BIOMASS. Both columns describe the Asa stand of 39 years.

	Literature (Lindroth 2008)	BIOMASS
Projected leaf area index	3.7	6.4
Stem biomass (g C m ²)	4360	3801
Foliage biomass (g C m ²)	569	856
Live branch biomass (g C m ²)	1690	1977
Stump biomass (g C m ²)	503	
Coarse root biomass (g C m ²)	824	1912
Fine root biomass (g C m ²)	394	

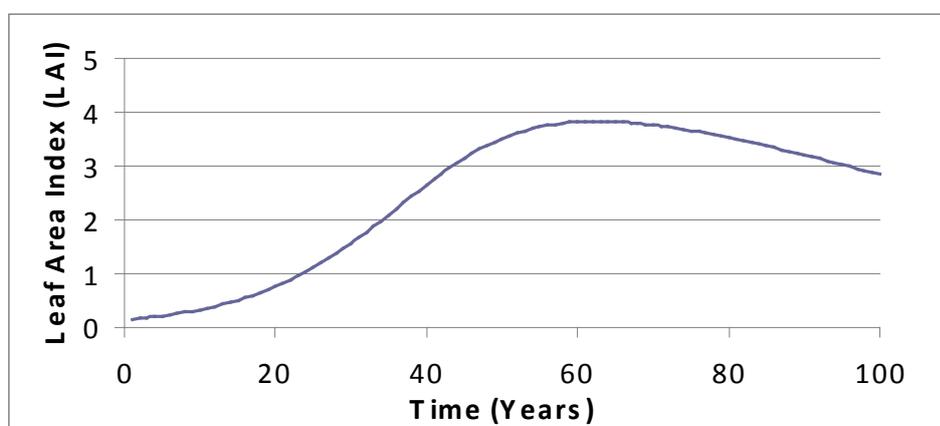
Since this final version of the BIOMASS model fulfilled sufficiently all the demands needed for this work, and since only small changes of the parameters had drastic results on this outcome of the simulations, the parameters have not been changed from this version and all the runs have been done with it.

3.2. The harvesting scenarios

3.2.1. The first 100 years of the control scenario: “The growing years”

For the parameterization and for later input in the Q-model it is necessary to keep track on all the different output values that the BIOMASS model can provide. E.g. in the first place the leaf area index (LAI), the annual increment of stemwood, the gross primary production (GPP), the net primary production (NPP), the respiration of the different compartments of the tree, the allocation of the photosynthates to the different compartments and the litter production of the different compartments. When the model has already reached its steady state, all these values will more or less stay the same, but in the growing years the development of these factors is interesting and necessary to monitor to understand the results for the carbon balance. These results are here only presented for Flakaliden, since the results for Asa show no differences which would give additional information to this study.

The LAI (Fig.10) grows and reaches the value of 3 after 43 years. An LAI of more than 3 indicates full cover, i.e. the projected canopy cover on the forest floor is 100%. But afterwards it grows even more until the year 60 when it begins to decline because the other parts of the tree respire too much to keep this large amount of leaves.

**Fig. 10:** Leaf area index of the Control Scenario of Flakaliden in the first 100 years.

The LAI is also an indicator of the annual increase of stemwood. There will be a rapid annual increase of stemwood when there are a lot of leaves to keep the production of photosynthates

high. When the production of leaves declines, the production of wood will also grow slower soon. Fig.11 shows that the current annual increment (CAI) of wood decreases after the year 43. Afterwards there is still an increase of wood, but at a lower speed. The accumulated mean annual increase (MAI) intercepts the curve of the CAI around the year 90. Since from this point the current annual increase drops below the mean annual increase, which in turn will start decreasing MAI, this would be the right time to harvest from an economic point of view.

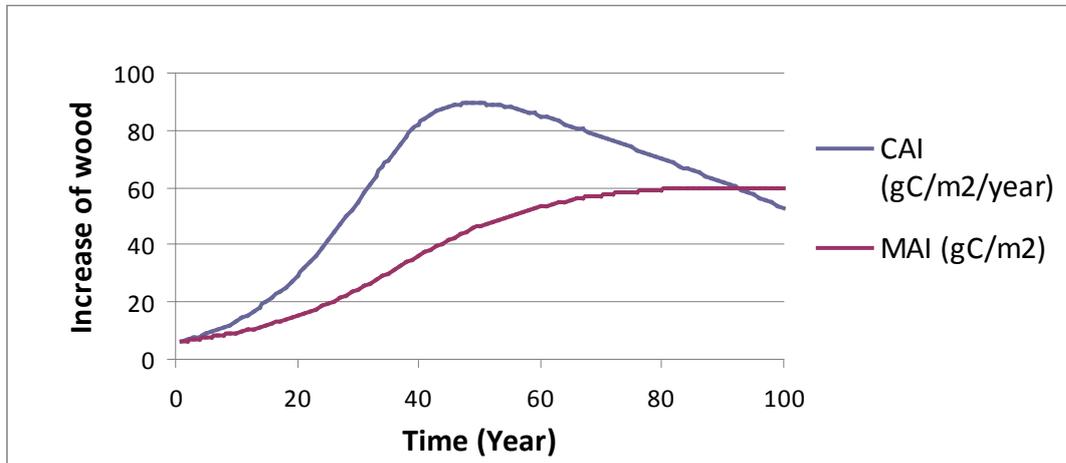


Fig. 11: Current and mean annual increase of Wood for Flakaliden in the first 100 years.

The GPP and the NPP are also strongly correlated to the leaf area index, because the total assimilation through photosynthesis depends on the area of leaves. Fig.12 shows that GPP and NPP follow the same development as for the LAI.

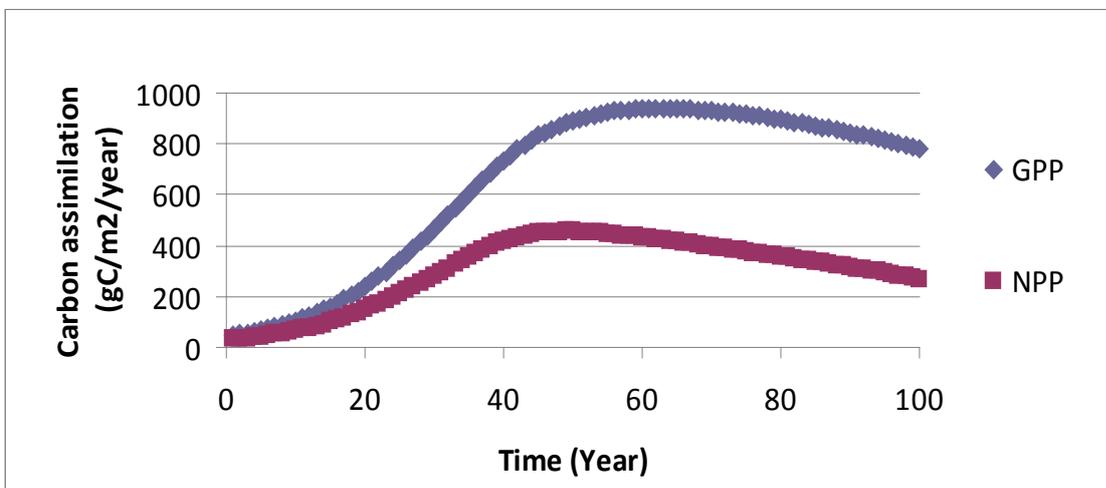


Fig. 12: Carbon assimilation for the Control Scenario of Flakaliden in the first 100 years.

To get the NPP from the GPP the autotrophic respiration has to be taken into account. Fig.13 shows the respiration of the different compartments of the tree. It can be seen that foliage and fine roots are responsible for the largest amounts of respiration in the beginning, but stems and branches grow in importance within time. But from the year 60 on when the LAI goes down, also autotrophic respiration is declining.

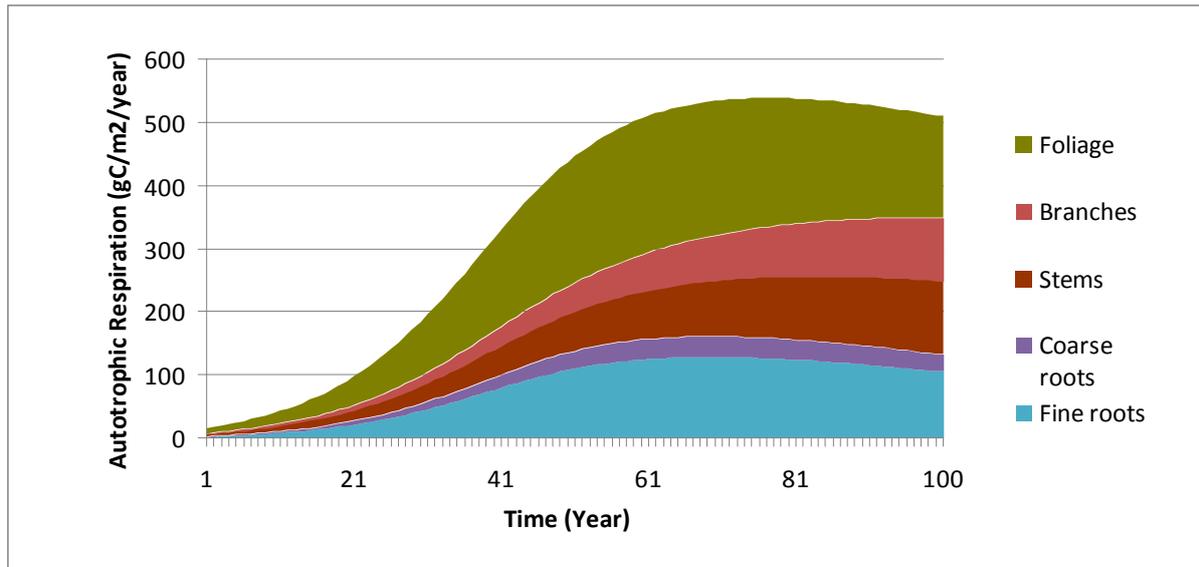


Fig. 13: Autotrophic respiration of the different tree compartments for Flakaliden in the first 100 years.

The allocation of photosynthates is the beginning of the model approach of BIOMASS, all the other compartments are just constructed upon that distribution. In Fig.14 it can be seen that the total allocation and therefore production of tree matter is going down after the year 43. This is coherent with the Fig.11 concerning the CAI and MAI. The total amount of standing biomass that would result from the allocation of photosynthates will be shown in 3.2.2

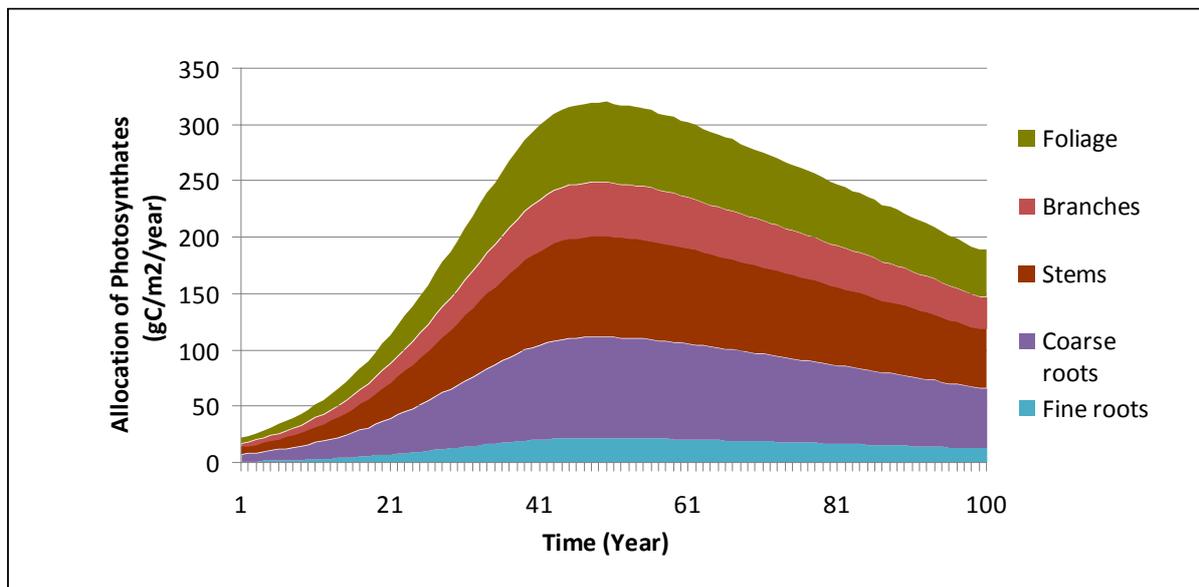


Fig. 14: Allocation of Photosynthates for the different tree compartments in Flakaliden for the first 100 years.

The last step of the BIOMASS model and the first step for the Q model is the litter production. In the first 100 years it is assumed, that trees do not yet die from senescence. Therefore there is no stem litter in Fig.15. The tissues which are most active regarding respiration are also here the biggest litter pools. The total litter biomass follows the curve of the LAI again very similarly.

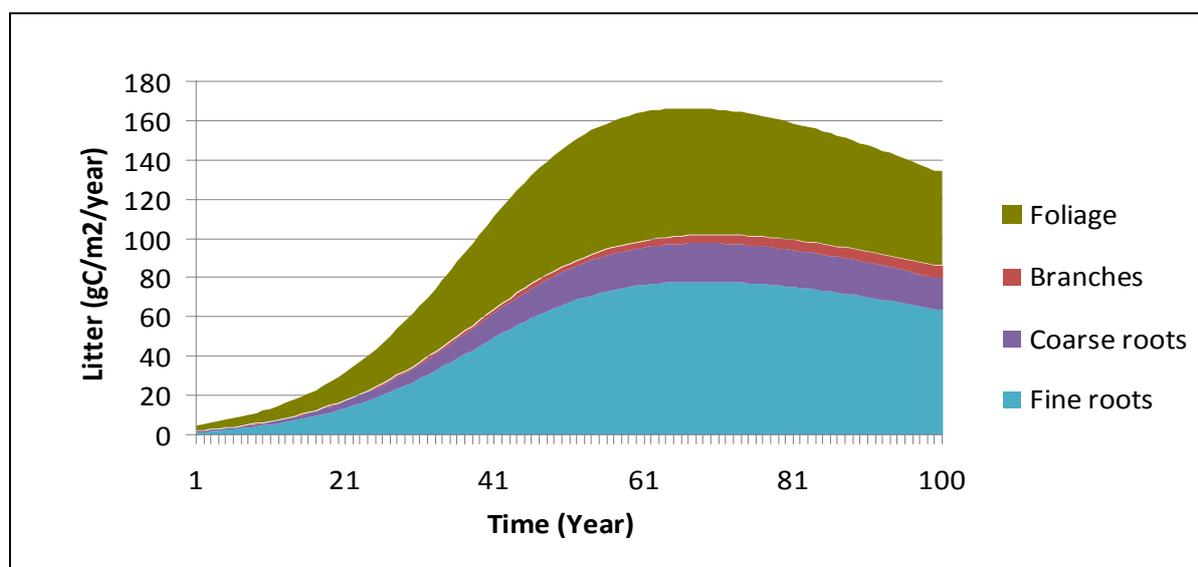


Fig. 15: Litter production of the different tree compartments in Flakaliden for the first 100 years.

3.2.2. Standing biomass in the scenarios

3.2.2.1. Flakaliden

In Fig. 16 the single pools of foliage, branches, stems, coarse roots and fine roots are shown for the whole control scenario of 300 years. The fine roots are here already divided from the coarse roots for a better visualization of the parts of a living tree. The control scenario behaved as in the tuning against the literature values and the biomass of the forest grew to the target amounts. After 100 years, for reflecting the dying of trees because of competition and senescence, a stem litter was introduced. This led to a balance of the standing biomass in the forest as targeted and the total amount of biomass levelled out at approximately 10000 g C/m². The shape of the total amount of standing biomass resembles the expected shape as anticipated in 1.2.1.

The standing biomass in the clear-cutting management scenario followed nicely the thinnings and harvests (Fig.17). Since there is always a taking out of biomass from the forest, it never reaches the high value of the control site. Here also the shape of the total biomass resembles the expected one of 1.2.2.

The standing biomass of the single-tree selection scenario resembles a lot a saw as expected in 1.2.3. (Fig.18). The thinnings of the single-tree selection scenario function here as the stabilizing effect to balance the total biomass of the forest like the stem dying does in the control. The total amount of standing biomass here almost reaches the amount of the control scenario. The proportions between the different pools of biomass are more or less the same regardless of scenario or time.

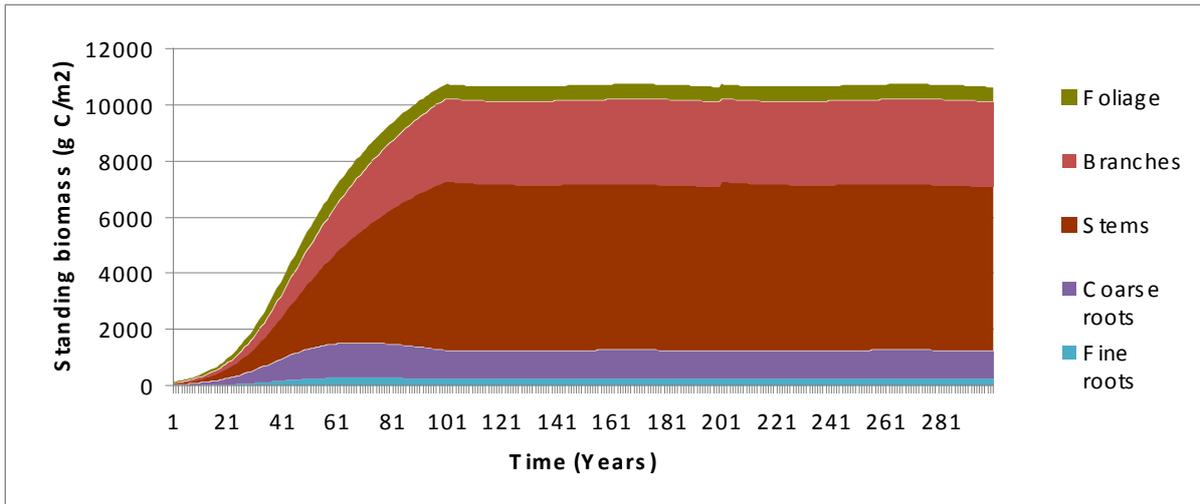


Fig. 16: Standing biomass simulated for the control scenario of Flakaliden for 300 years.

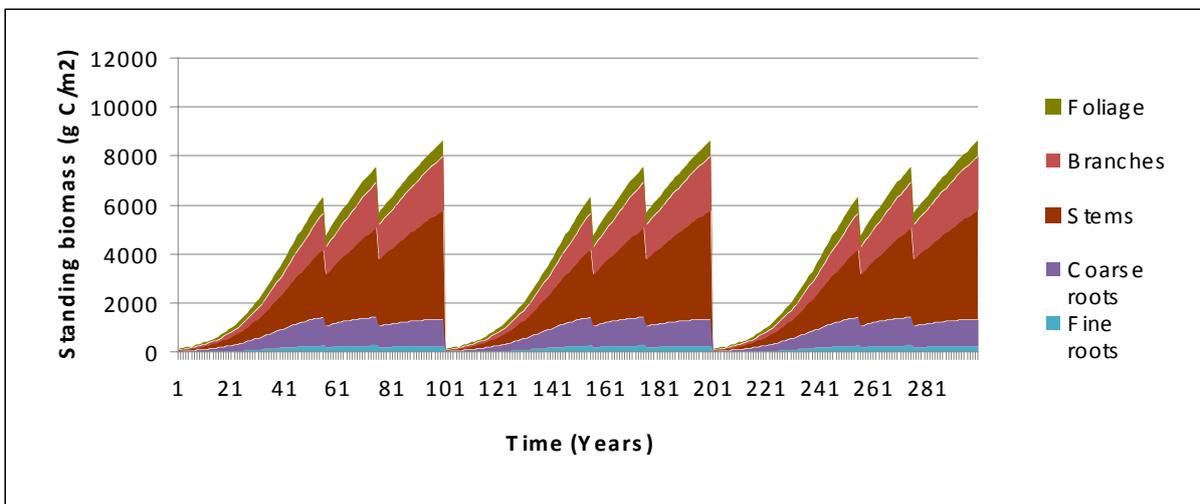


Fig. 17: Standing biomass simulated for the clear cutting management Scenario of Flakaliden for 300 years.

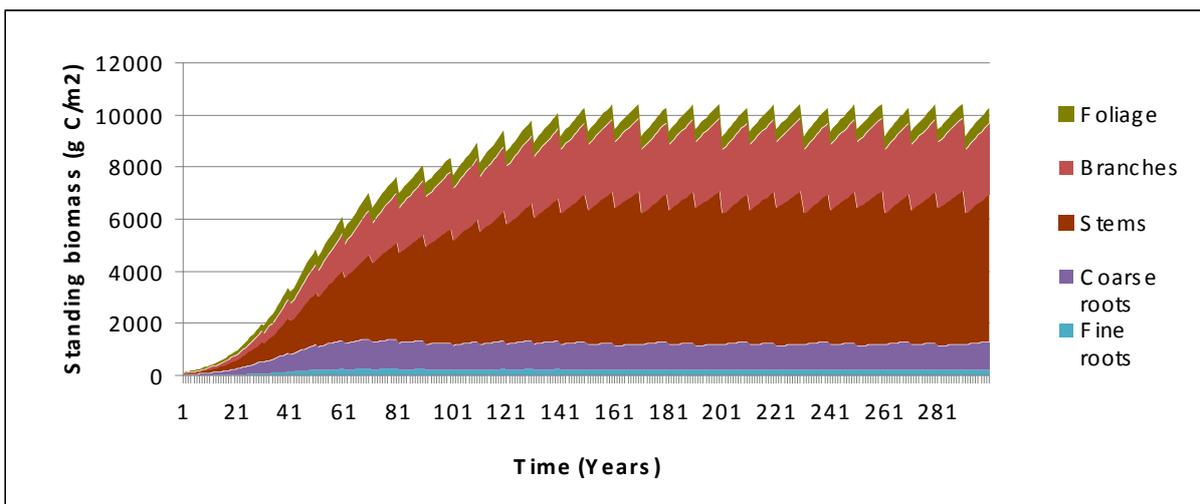


Fig. 18: Standing biomass simulated for the single-tree management scenario of Flakaliden for 300 years.

3.2.2.2. Asa

In Asa, similar results are shown. Also here the stem dying works as a balancing factor to stop the rapid growth of the forest and shift the total biomass to a stable level (Fig. 19). In this simulation it goes up to 15000 g C/ m².

In Asa the growth after the thinnings is much higher than in Flakaliden, until the harvesting point at year 100 even with three thinnings, the forest has almost reached the top value of the control scenario (Fig.20).

With a thinning of every 5 years instead of 10 years like in Flakaliden, the amount of biomass levels out very smoothly in the single-tree scenario. The saw shape is here so close that it almost resembles a control scenario, but the amount of wood taken out is so high that it never reaches significantly over 10000 g C/ m² (Fig.21).

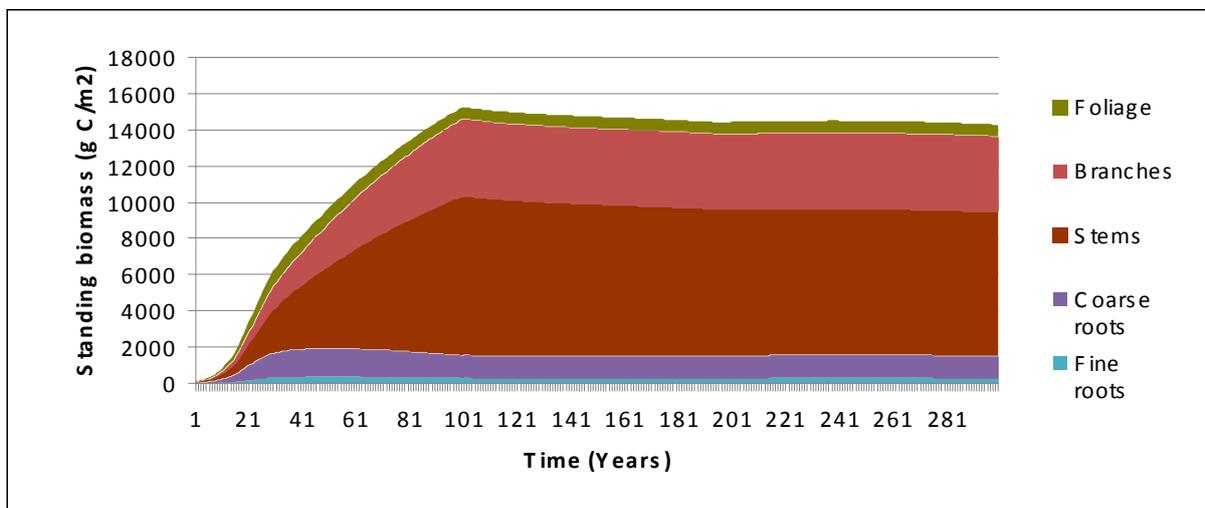


Fig. 19: Standing biomass simulated for the control scenario of Asa for 300 years.

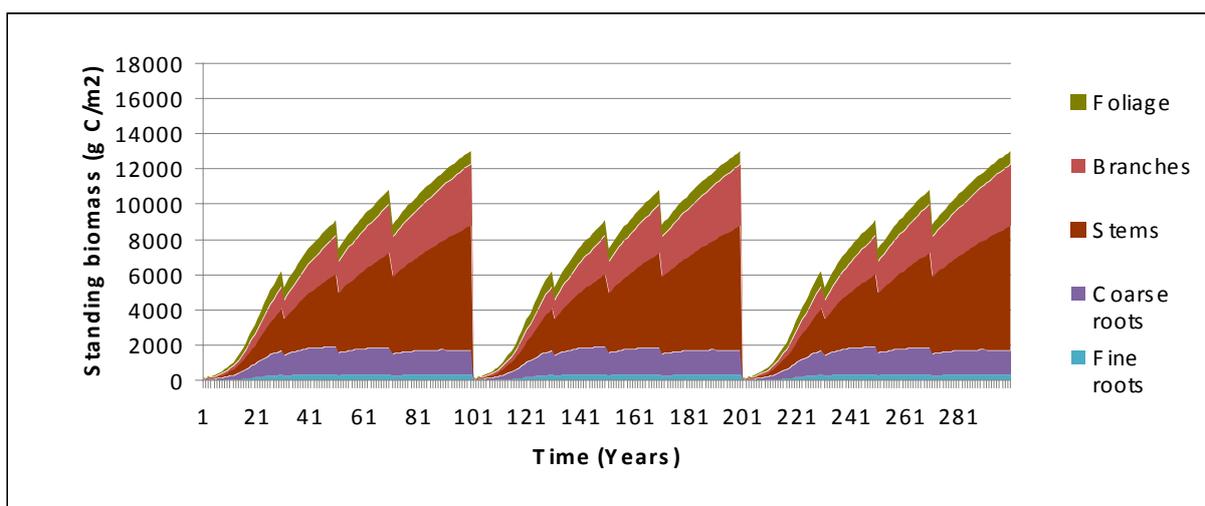


Fig. 20: Standing biomass simulated for the clear cutting management Scenario of Asa for 300 years.

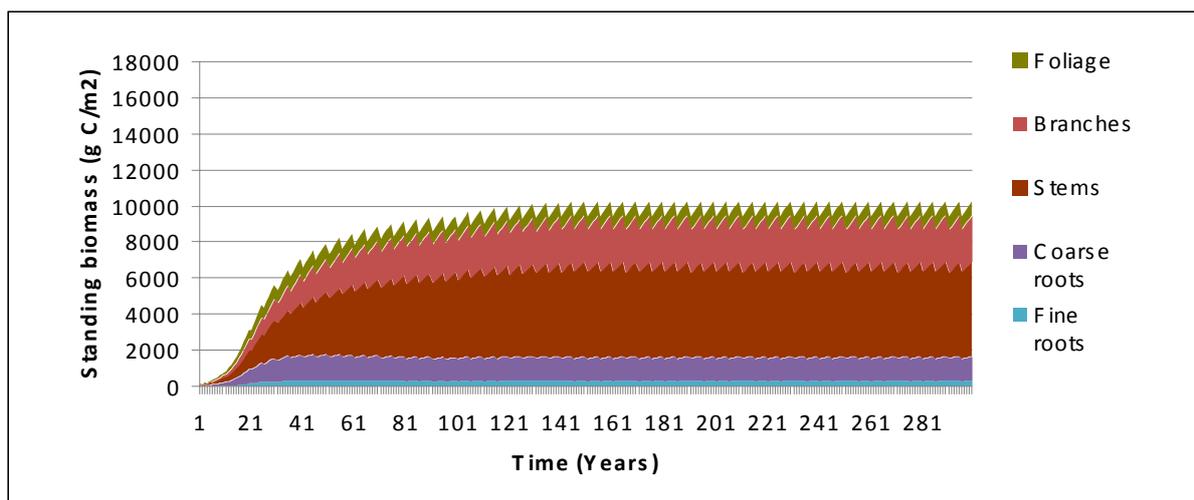


Fig. 21: Standing biomass simulated for the single-tree management Scenario of Asa for 300 years.

3.2.3. Carbon pools

In Fig. 22 all pools of carbon for all scenarios at both sites are shown, beginning with the control scenario and ending downwards with the single-tree selection. The green line always marks the standing biomass, the purple line the dead organic matter and the blue line the sum of both. As expected, the carbon pools for Asa were always higher than in Flakaliden, but especially in the clear-cutting scenario it is very obvious. In the control scenarios all pools are stabilizing. In the clear-cutting scenario there are high fluctuations especially after the final harvest, then the amount of dead organic matter rises dramatically, but also disappears quite fast again. In the single-tree selecting scenario all the pools seem to stabilize too. It can be observed that the total carbon pools rather follow the curve of the standing biomass and the dead organic matter pool is only a minor part in the total carbon pool on site.

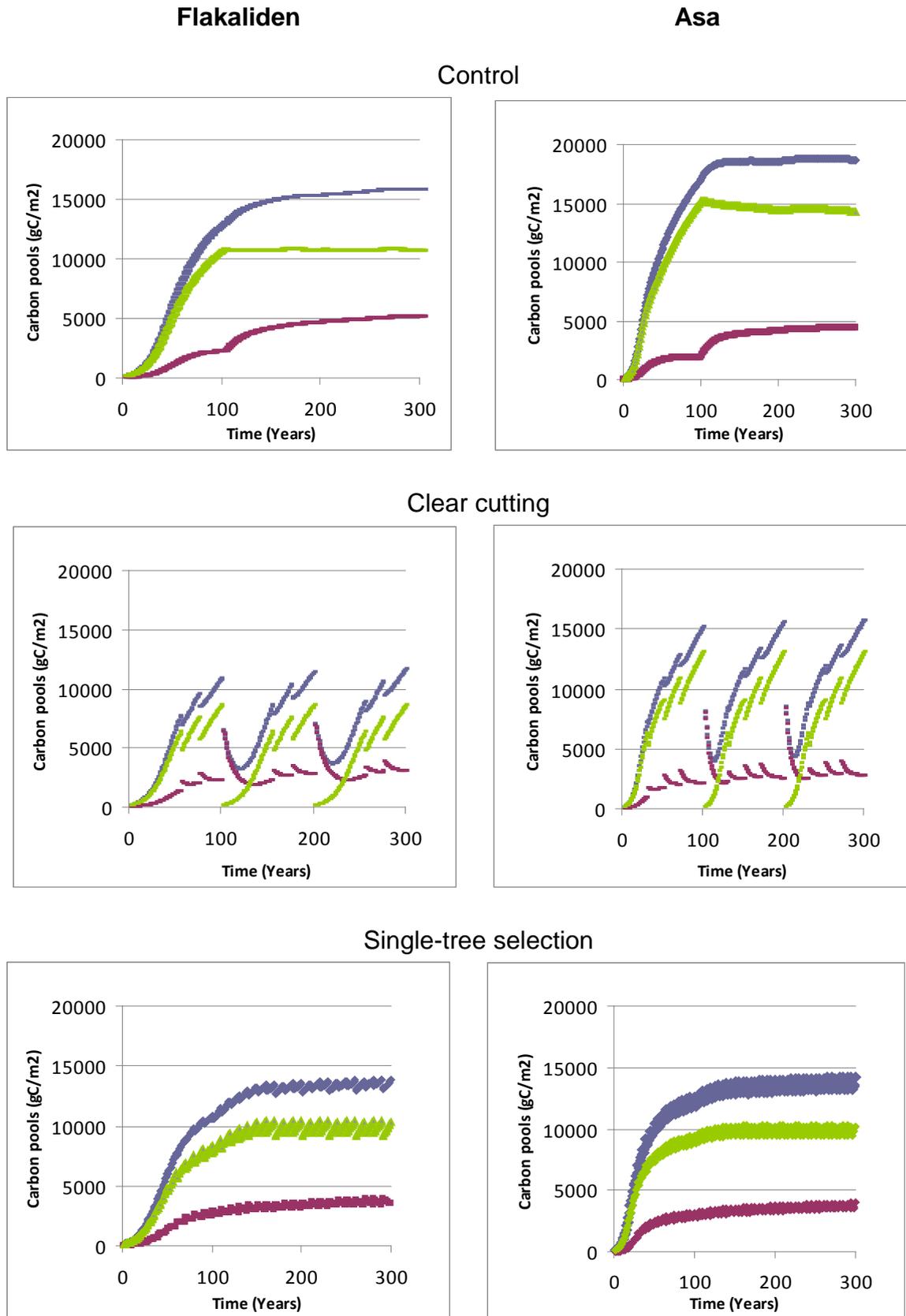


Fig. 22: Carbon pools for all scenarios at both Flakaliden (left) and Asa (right) for 300 years. The green curve represents the standing biomass, the purple curve the dead organic matter and the blue line the total sum of carbon on site. The control scenarios form the first line, followed by the clear cutting scenarios and the single-tree selection scenarios.

If we compare the three scenarios regarding the total amount of biomass of the Asa and Flakaliden site (Fig. 23 and 24), we can see that the control scenario always has the most carbon stored on the site and the single-tree selection comes on second most in average. It should here be noted that the figures show only the carbon pools on site but not the wood which has been harvested and taken from the site.

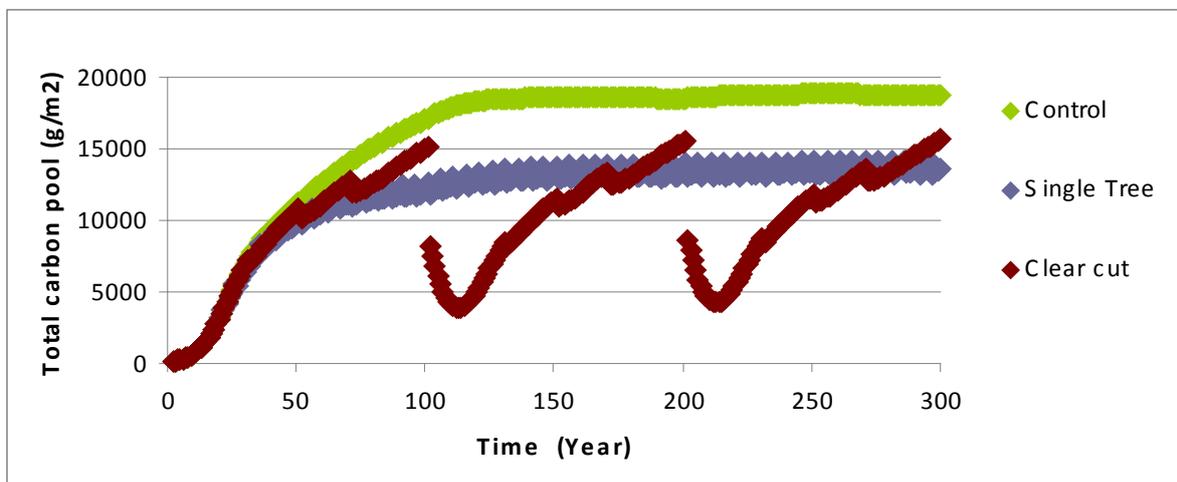


Fig. 23: Total carbon pools on site of all scenarios in Asa for 300 years.

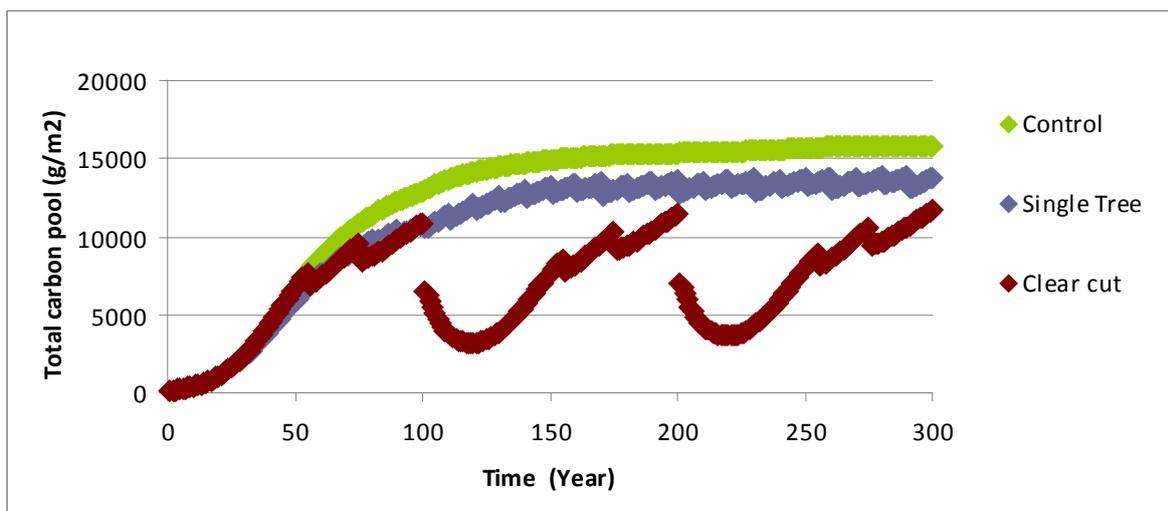


Fig. 24: Total carbon pools on site of all scenarios in Flakaliden for 300 years.

3.2.4. Carbon fluxes

In Fig. 25 the fluxes of all scenarios and at both sites are presented corresponding to the carbon pools presented above. Here the green line represents the GPP, the blue line the NPP, the purple line the heterotrophic respiration and the black line the NEE. The fluxes of the Asa scenarios are much higher than the fluxes of the corresponding scenario in Flakaliden, which is the case for all the fluxes, even if it looks as if the NEE is the same in the control scenarios. But since the NEE is a difference of two fluxes, the corresponding fluxes are always higher in Asa. The NEE is also always positive in the control and the single-tree selection scenarios, only in the clear-cutting scenarios it drops down to approximately -700 gC/m^2 . The fluxes of the control scenarios and the single-tree-selection scenarios again seem to stabilize, whilst the clear-cutting scenario is again subject to some quite dramatic changes.

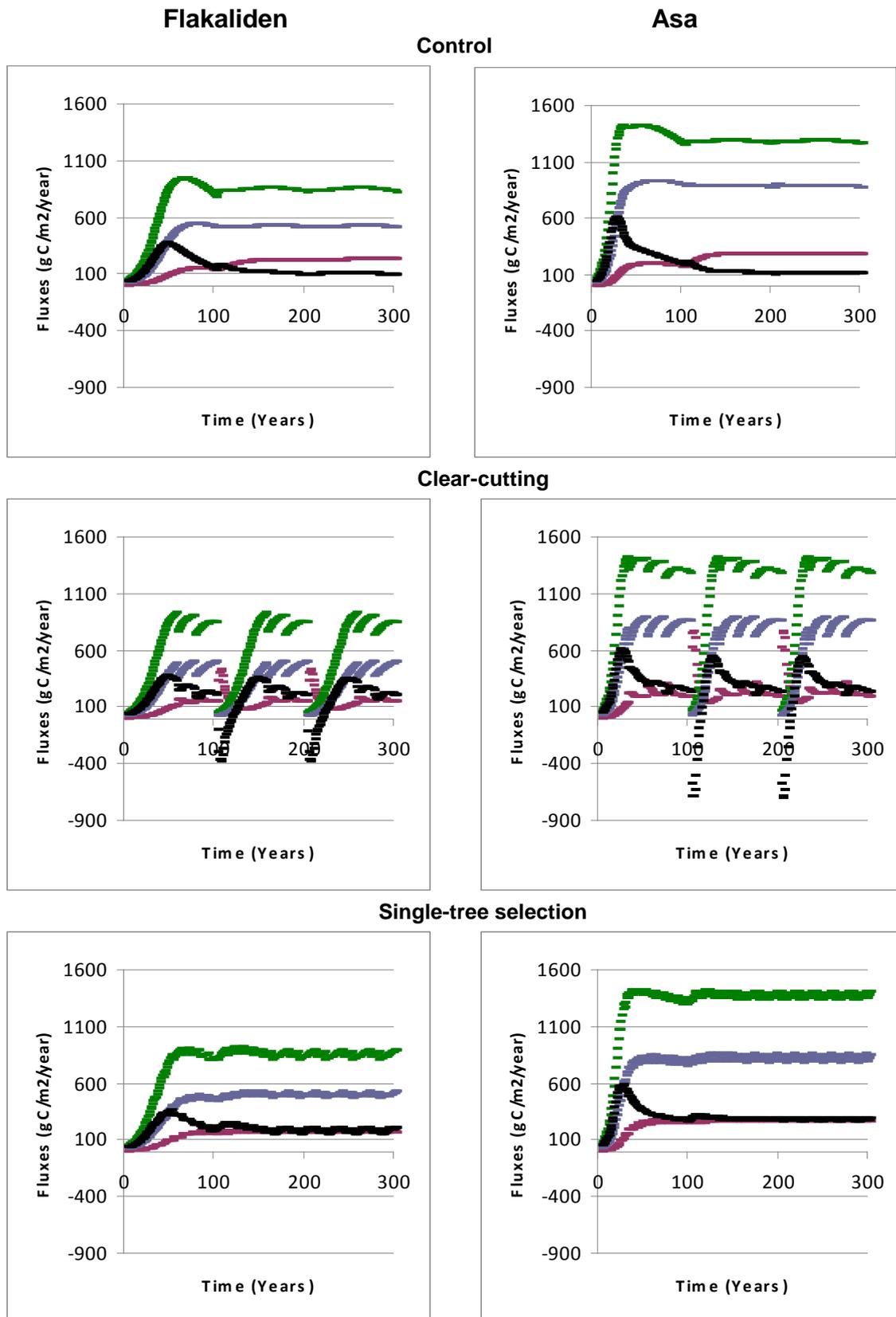


Fig. 25: Carbon fluxes for all scenarios at both Flakaliden (left) and Asa (right) for 300 years. The green curve represents the GPP, the blue curve the NPP, the purple curve the heterotrophic respiration and the black curve the NEE. The Control Scenarios form the first line, followed by the Clear-cutting Scenarios and the Single-Tree Selection Scenarios.

Since it is of interest for the environment how much carbon the forest site stores, a comparison between the different harvesting systems was done. Fig. 26 shows the NEE

compared for all the different scenarios and Fig. 27 the same comparison for the accumulated NEE. The single-tree selection management has the highest accumulated NEE in total, but even with these lots of negative values in the NEE of the clear-cutting scenario, after 300 years the clear-cutting scenario has a higher accumulated NEE than the control scenario.

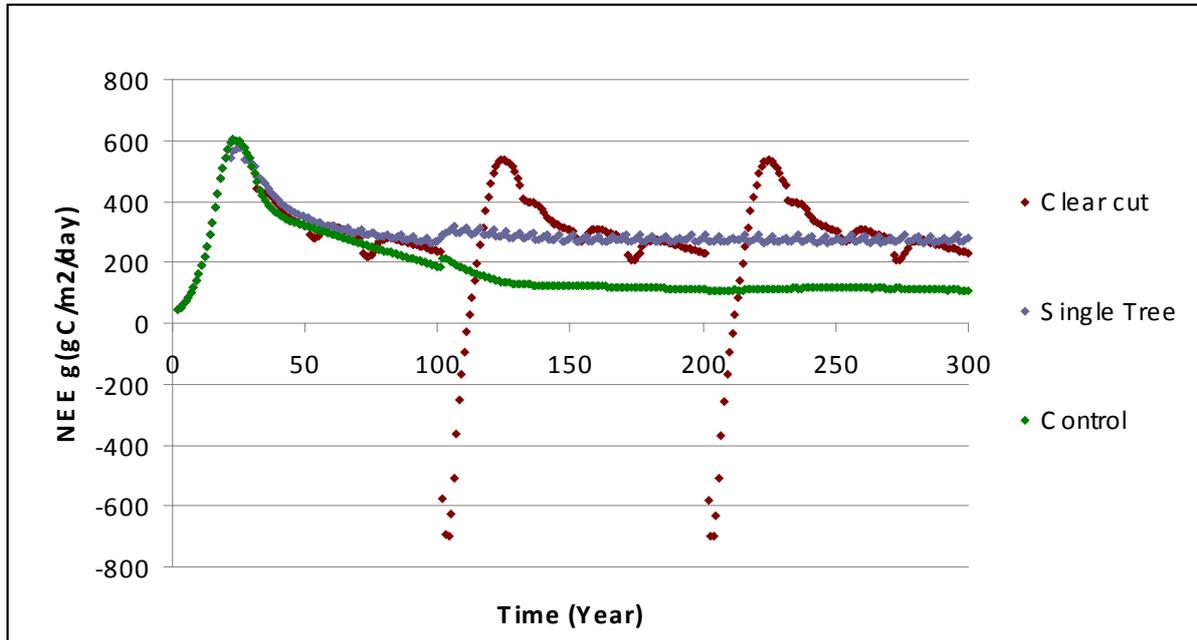


Fig. 26: NEE for all Scenarios at Asa for 300 years.

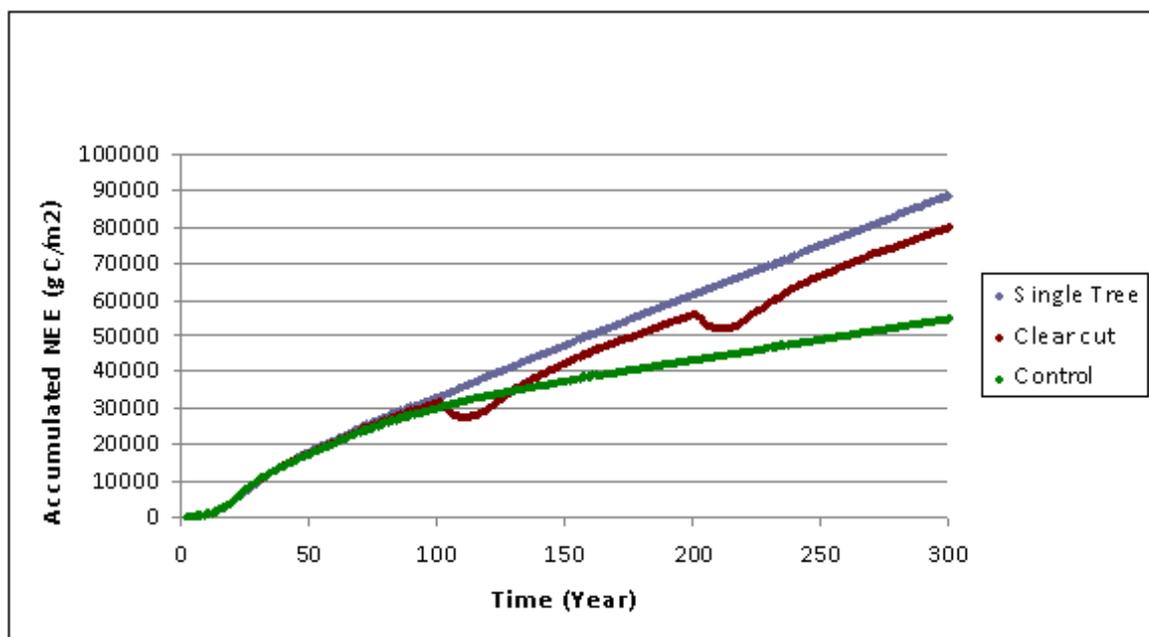


Fig. 27: Accumulated NEE for all Scenarios at Asa for 300 years

The NEE fluxes for Flakaliden (Fig. 28) look a lot more disrupted and less smooth than the fluxes of Asa due to the harvesting schedule which recommends fewer harvests. Therefore, single-tree selection in Flakaliden appears to be a little bit like a clear cutting scenario without final harvest. Regarding the accumulated NEE in Flakaliden (Fig. 29) single-tree selection has the highest NEE. Here in the beginning, after the first harvest, the clear-cutting scenario is

for a long time the one with the lowest accumulated NEE, but after 300 years, the control is the lowest again.

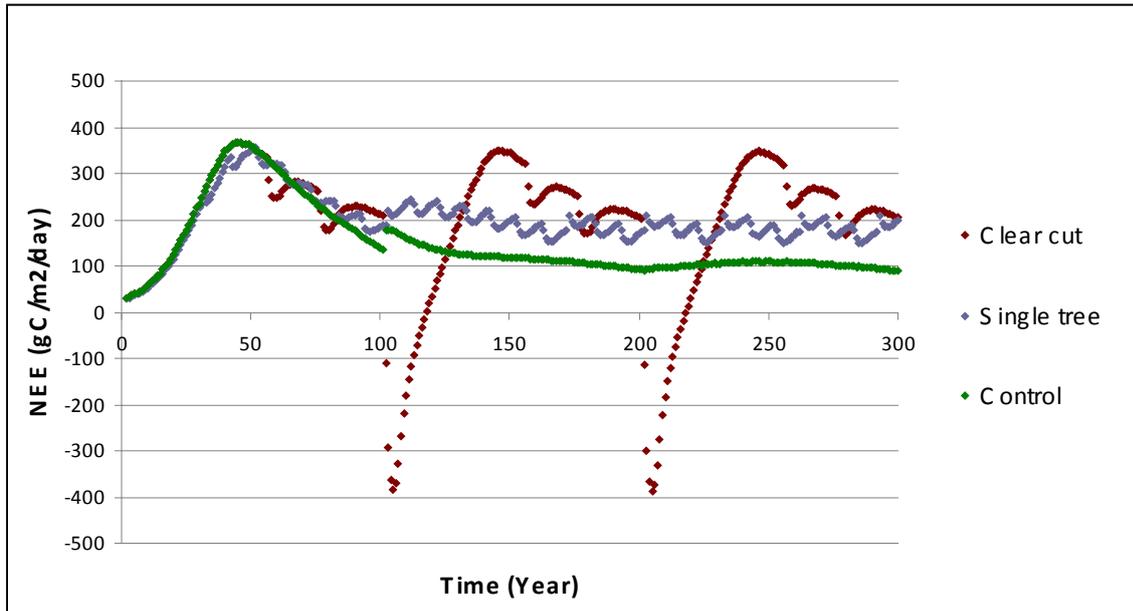


Fig. 28: NEE for all Scenarios at Flakaliden for 300 years

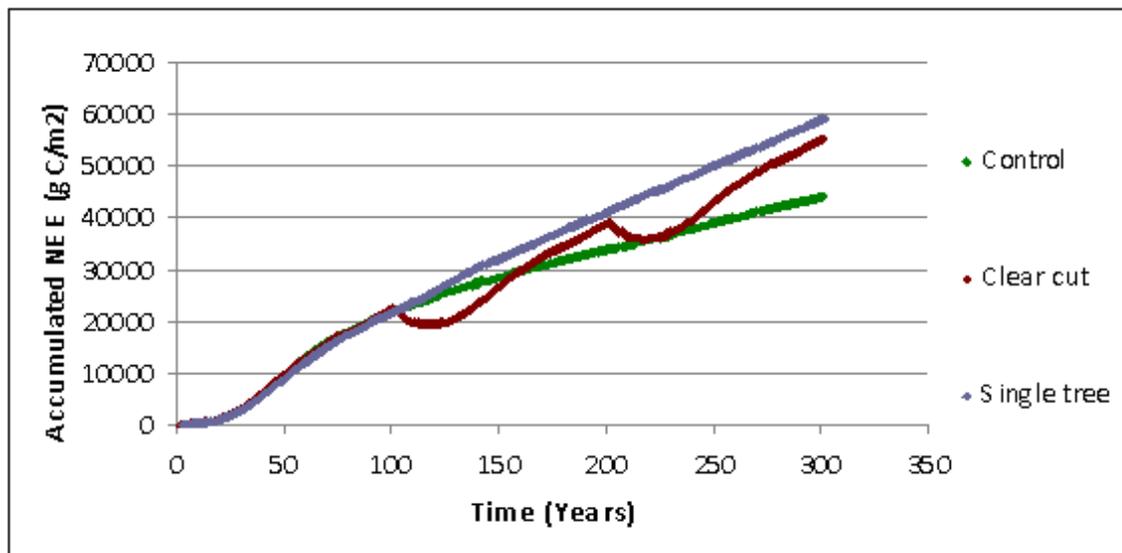


Fig. 29: Accumulated NEE for all Scenarios at Flakaliden for 300 years.

3.2.5. Wood harvested

The last results of interest in this study to present would be the total amount of harvested wood. While the overall purpose of the harvests is not social or environmental benefits, but because of economic value, the total amount of wood harvested in the two managing scenarios is very interesting. To compare the harvest outcome of the different scenarios it is not enough to compare the amount of harvested wood. In the clear-cut area nothing of worth is there any more, on the single-tree site at the end of 300 years, however, there is still a forest which could be harvested as well. To make a justified comparison, we have to add the living

stem biomass in the single-tree scenario to the total amount of wood harvested. The results are shown in Table 5. In Flakaliden, the clear-cutting management gave a little higher yield of wood than for the single-tree management. But in Asa, if we consider the living standing stemwood as well, then the single-tree selection is here even superior to the clear-cutting management concerning the yield.

Table 5: Stemwood and standing biomass for the two management scenarios harvested in 300 years in both Asa and Flakaliden.

	Clear-cutting management	Single-tree selection management	
	Harvest (gC/m ²)	Harvest (gC/m ²)	Standing stemwood (gC/m ²)
Asa	28456.260	26735.452	5220.27
Flakaliden	18044.670	13518.200	4475.34

4. Discussion

The combining of two diverse models for completely different purposes, the process-based BIOMASS model and the Q-model, was successfully accomplished. The planned scenarios have been simulated for both the Flakaliden and the Asa environment.

It was possible to successfully parameterize one version of the BIOMASS model that could reproduce the development of a real forest in nature driven only by climate variables. One parameterization of the model could simulate the carbon values of a forest dynamically to realistic values for both sites just corresponding to the climatic data of that site. Not only the fit to a realistic NEE and development, but also the balancing to an equilibrium has been achieved in the parameterisation (eg. Kleja et al. 2008). It might have been possible to improve the parameterisation but it was considered that the marginal effect of working further on the parameters would not affect the outcome the present study significantly. The evaluation of the “growing years” showed that the parameterised model behaved in an expected way. The results also showed, that a parameterisation leading to a correct development of the LAI is crucial, since LAI is a key-driver for assimilation of CO₂ and thereby production. It was a success that, from our model results purely, we could construct the figure of the crossing of the CAI and the MAI as seen in literature (cf. Lähde et al. 2001).. The total biomass in all scenarios ran almost exactly to the expected and planned shape, only the control scenarios could have been a little more smooth between the growing years and the balancing years. But since the structure of the BIOMASS model did not allow a dynamical increase of the amount of the stem litter, the control scenario looked a little bit angled. The assumption that the thinnings in the single-tree scenarios would act as a balancing mechanism was proven true both in Flakaliden and in Asa, whereas in Asa it stabilised much earlier due to the faster growing and the higher thinning intervals. The total amount of standing biomass in the Asa control scenario was much higher than in the Flakaliden scenario. This is due to a large number of reasons, but the most important are the higher amount of photosynthetically active radiation, the higher mean temperature, and the absence of very low and frequent sub-zero temperatures in spring nights. All these factors make the growing season in Asa longer and more effective than in Flakaliden. The higher fertility of the Asa site was not considered in the modelling.

The percentage distribution of the compartments of the trees given by the BIOMASS model was close to the values measured on-site (cf. Kleja et al. 2008; Lindroth et al. 2008), only the root part could have been a little higher in the end, especially in these stabilising runs of the control scenario.

The results of the carbon pools showed no real surprises, and both standing biomass and dead organic matter developed as expected. Since nothing is ever taken from the soil pool it is not

surprising, that the highest pool of total carbon is accumulated in the control scenarios and not in the other two.

For the purpose of binding carbon from the atmosphere, the control scenario which might be favoured by most “green-thinking” people, was according to our simulations now the worst alternative, even though it stored the most carbon on site at a time. But over the whole period the single-tree selection management had taken the most carbon from the air, followed by the clear-cut management. So for purposes of climate change prevention, the control scenario would be the worst alternative according to the given results.

Of course one question here is very obvious and has to be discussed: The only reason why the single-tree scenario and even the clear-cutting scenario have a higher accumulated NEE might be the fact that the stems are taken out of the system in both harvesting management scenarios and disappear from the site and therefore do not appear in the heterotrophic respiration pool. However, maybe they are burned right away and add CO₂ in the same way as if the wood had been decaying on the site. But there is the possibility that they are stored as building wood or for furniture, etc. In the latter case, then the wood is practically stored for a long time. But even if one did not harvest the stems of the thinnings and let them just decompose, it could be possible that the growing of trees especially in the first 100 “growing years” is faster than the decomposing and therefore there would be still a positive carbon balance. After the very frequent thinnings like in the single-tree scenario in Asa, the annual growth of biomass always increased and therefore this possibility is not unrealistic (cf. Lähde et al. 2001).

It was shown that in the single-tree selection management at Flakaliden, the total amount of harvested wood plus the standing stem wood is almost the same as the harvested wood from the clear-cutting management. In Asa there was clearly more total stem wood in the single-tree selection management.

Therefore, at least in Asa, one should use the single-tree-management also for economic reasons. It could be argued that a clear-cutting harvest is less costly than doing all these thinnings necessary for the single-tree-selection. But on the other hand, the single-tree-selection does not need any planting of seedlings, since the forests should regenerate by itself. In the single-tree-scenario there is also a steady and early income. Especially for smaller forest owners, the prospect of planning to get plenty of money from a clear cut in 100 years in the future is not attractive (cf. Andreassen & Øyen 2002)..

It could be argued that these simulations are not very realistic since other factors, which play an important role in a forest ecosystem and which would actually make a difference for the growth and development of a forest like nutrients, soil quality, runoff of dissolved organic carbon etc., are not considered in the modelling. But simulating the carbon balance of a forest with two different models is a complex task in itself. Taking into account even more factors would increase the number of variables, which dynamically react with themselves through feedback mechanisms, even more and make the modelling even less predictable. It is the simple design of these scenarios which makes the study of the comparison between harvesting strategies possible and interesting.

The whole question of this work gets even more challenging if also interactions with global climate change will be included. And ultimately, if the final question is to be answered: Which forest management scenario is the best to optimise carbon accumulation under climate change at a reasonable cost?

The results of this modelling work, however, favour the single-tree-selection management over the others regarding carbon accumulation, and therefore it should be considered as a serious alternative to the clear-cut management mainly applied nowadays.

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