Forestry and Climate Change Mitigation

- Climate change mitigation potential for different rotation lengths in Norway spruce forests, Götaland, Sweden with a short and a long term perspective

Gustaf Gustafson

Supervisor: Ola Sallnäs

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Master Thesis no. 135

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Norway spruce forests in Okome, Halland, Götaland, Sweden (Photo: Gustaf Gustafson)

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Supervisor: Ola Sallnäs

Examinator: Eric Agestam

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Sammanfattning

Under de senaste åren har klimatfrågan hamnat allt mer i fokus igen och det råder i stort sett inget tvivel längre om att klimatförändringen huvudsakligen är orsakat av förhöjda halter av växthusgaser (GHG) i atomsfären och då främst koldioxid (CO_2). Ökningen från 280 ppm år 1750 till 379 ppm 2005 beror till 80 % på förbränning av fossila bränslen, men nästan hela den resterande ökningen härrör från markanvändningsfrågor och då främst avskogningen i tropikerna. Skogsekosystem utgör idag 30 % av den globala landarealen och 42 % av det terrestra kollagret är bundet i skogsmark, skogen och skogsbruket är också ett av de få sätt där vi aktivt kan avlägsna koldioxid från atmosfären. För Europa är det beräknat att skogsskötsel kan bidra med 60 % av minskningen av CO_2 utsläpp om kostnaden är satt till 100US$/t CO_2 eller lägre. På grund av detta har skogssektorn fått en betydande roll i det globala klimatarbetet och skogsskötsel berörs av artikel 3.4 i Kyoto protokollet där ökad kolinlagring; direkt inducerad av mänsklig aktivitet får räknas, det vill säga ej t.ex. en ökning orsakad av atmosfäriskt kvävenedfall. För skogrika länder med stabil skogsmarksareal som t.ex. Sverige är denna artikel den mest relevanta och i dagsläget har den svenska skogen ett årligt nettoupptag av CO_2 på 40 miljoner ton vilket nästan motsvarar de svenska koldioxidutsläppen från förbränning av fossila bränslen på mellan 50-60 miljoner ton årligen. Skogsektorns olika sätt att minska nettoutsläppen av CO_2 brukar delas in i fyra olika huvudgrupper:

A. Öka eller bibehålla skogsmarksarealen
B. Genom skogsskötsel öka kollagret på bestånds och landskapsnivå
C. Substitution av energikrävande material (betong, stål, etc.)
D. Bioenergi som substitution av fossila bränslen

Det finns åtskilliga vetenskapliga artiklar som behandlar hur skog skall skötas för att nettoutsläppen CO_2 till atmosfären skall minimeras och vilken skötselstrategi som bäst svarar upp till dessa krav. En sak som de dock har gemensamt är att de applicerar sina skötselstrategier på en tidshorisont som åtminstone sträcker sig över en omloppstid och ibland även över flera hundra år. Detta kan te sig logiskt inom skogsbruk med dess traditionellt sett långa tidshorisonter som ofta är styrda av den biologiska omloppstiden som maximerar totalproduktionen virke. Men i en kontext av att minska nettoutsläppen av CO_2 anses det oftast att åtgärder tagna inom en trettioårsperiod är av högsta vikt med tanke på osäkerheten gällande klimatmekanismer, som till exempel ändrade havsströmmar. Detta poängteras bland annat i Sternrapporten och detta synsätt är allmänt vedertaget inom de flesta andra sektorerna som t.ex. energi med mål i EU till 2020. Dessa kortare tidsperspektiv eller delmål saknas i de flesta undersökningarna gällande skogsskötsel och reducering av nettoutsläppen CO_2. Därför har jag i mitt examensarbete fokuserat på att jämföra hur tidshorisonterna 30 år respektive 300 år påverkar valet av bästa skötselstrategi för att minska nettoutsläppen av CO_2.
Skötselstrategierna som testades var om det var mest fördelaktigt att höja, sänka eller att bibehålla nuvarande avverkningsintensitet, detta gjordes genom att förkorta respektive förlänga omloppstiden med 20 år jämfört med nuvarande omloppstid (BAU). Det som studerades var hur allokeringen av kol i olika pooler och poolernas betydelse skiftade med tidshorisonten. Jag jämförde även skillnaden mellan de olika bonitetsklasserna i ett BAU scenario.
För att simulera detta använde jag mig av kolberäkningsprogrammet CO2FIX V 3.1. Det är en simuleringsmodell på ekosystemsnivå som kvantifierar kolpooler och kolflöden. Modellen skiljer på kol allokerat i biomassa, mark, produkter och bioenergi som är en substitutionspool som egentligen bistår av kol lagrat som icke förbränt fossilt bränsle. För att studera detta i ett större landskapsperspektiv skapade jag en syntetisk skog, med produktiv granskog i Götaland,

Sverige som förebild. Jag delade upp min syntetiska skog i tre olika bonitetsklasser; låg, medel och hög bonitet.
Mina simuleringar visade att tidshorisonten hade en väsentlig betydelse för valet av bästa skötselalternativ. När 30 års tidshorisont var applicerad var den förlängda rotationsperioden det bästa alternativet för att reducera nettoutsläppen av CO_2 i alla bonitetsklasser. Anledningen till detta var biomassapoolen hade störst betydelse med 30 års tidhorisont. Storleken på den stigande årliga kolsänkan i biomassan och marken som en förlängd omloppstid ledde till jämfört med BAU, var 0,87 TgC. En ökning som är giltig under artikel 3.4 i Kyotoprotokollet, dock får Sverige maximalt räkna 0,59 TgC årligen som sänka under denna artikel. Jämfört med den förkortade omloppstiden minskade dock den årliga bioenergi substitutionspoolen med 0,95 TgC, en sänka där allt är avräkningsbart som en minskning i förbrukning av fossila bränslen under Kyotoprotokollet.
Summerat över alla pooler ledde förlängd omloppstid till att den årliga kolinlagringen ökade med 0,66 TgC (6%) jämfört med förkortad omloppstid och med 0,24 TgC jämfört med BAU.
Detta resultat ändrades fullständigt när tidshorisonten ändrades till 300 år, vilket framför allt berodde på att poolernas inflytande och betydelse ändrades. Till exempel sjönk andelen kol allokerat i biomassa och markkolpoolen från 73 % till 29 % i BAU scenariot. Den längre tidshorisonten ledde också till att skillnaden på den årliga biomassa och marksänkan minskade till 0,08 TgC jämfört med BAU scenariot. Skillnaden minskade också i bioenergi-poolen mellan förlängd och förkortad omloppstid, men bara till 0,59 TgC/år. När förändringarna summerades ledde detta till att den förkortade omloppstiden reducerade netto-utsläppen av CO_2 över 300 års horisont mest. Jämfört med förlängd omloppstid ökade den årliga kolsänkan med 0,41 TgC (14 %) och jämfört med BAU var ökningen 0,11 TgC (3 %). Detta resultat visar tydligt hur de olika poolernas betydelse förändras beroende av tidshorisonten och hur betydelsen av bioenergipoolerna ökar med tanke på att de inte blir mättade såsom ekosystemspoolerna.
Jämförelsen mellan de olika bonitetsklassernas potential som kolsänka visade att höjd tillväxt är det mest effektiva sättet att minska nettoutsläppet av CO_2 till atmosfären oberoende av tidshorisonten. En skillnad i tillväxt på 20 % ledde till att skillnaden av kolsänkans storlek i stort sett också var 20 %.

Nyckelord: *Omloppstid, nettoutsläpp* CO_2*, koldioxidssänka, tidshorisont, substitution, CO2FIX V 3.1, klimatförändring, skogsskötsel, Kyoto protokollet*

Abstract

During the last year the awareness about the anthropogenic induced climate change due to increasing level of Green House Gases (GHGs), like for example carbon dioxide (CO_2) has increased drastically. The atmospheric content of CO_2 which is the GHG that the forest sector mainly can influence has increased from 280 ppm pre-industrial time (1750) to 379 ppm 2005. Currently the concentration exceeds the natural concentration during the last 650 000 year (180-300 ppm). 80 % of this increase is caused by combustion of fossil fuel and the remaining share mainly origin from the Land-Use Change, Land-Use and Forestry sector (LUCLUF). At present forests cover 30 % of the global terrestrial land area and it is the most important terrestrial carbon sink. Therefore forestry has an important role to play in climate change mitigation work; the LUCLUF sector is included in the Kyoto protocol and article 3.4 handles forest management as a way to mitigate climate change. For forest rich countries such as Sweden with sustainable forest management applied, forests are an important carbon sink and the Swedish forests are estimated to be an annual sink at around 40 Mt. CO_2.
The mitigation options for the forest sector are often divided into four main options:

A. Increasing or maintaining the forest area
B. Changing forest management: Increasing carbon density at plot and landscape level
C. Substitution of energy intensive materials
D. Bioenergy

For forest rich countries with stable forest area option B, C and D are most important. Altogether there are a lot of scientific papers and articles written about these options and their potential, but they always apply a time horizon that reaches over at least one rotation period. Even if the Stern report for example point out that action taken within the nearest 30 years is most important. The purpose with my master thesis is to examine the time horizons influence on if the best mitigation strategy is to prolong or to shorten the rotation age with 20 years compared to a business as usual scenario (BAU), which was used as a reference scenario. I applied those scenarios on a synthetic Norway spruce forest based on the current state in the Norway spruce forest in the region Götaland, Sweden. I divided my synthetic forest into three yield classes, low, medium and high and I also calculated the differences in climate change mitigation potential for this yield classes in the BAU scenario.
For analyzing the different rotation lengths influence I used the carbon accounting model CO2FIX V 3.1. It is an ecosystem-level simulation model that quantifies carbon stocks and fluxes in the forest ecosystem (biomass and soil), forest products and bioenergy substitution pools.
For simulating the time horizons influence on net CO_2 emission I applied a 30 years horizon for the short term and a 300 years horizon for the long term horizon. My simulations clearly showed that the time horizon has a huge influence on which mitigation strategy that is to prefer and when the applied time horizon shifted, the best mitigation strategy shifted as well.
In the 30 years horizon, prolonged rotation age with 20 years had the highest mitigation potential in all yield classes, through that the biomass carbon pool had the biggest impact on reducing net CO_2 emissions. This resulted in that the annual carbon sink due to forest management under the Kyoto protocol article 3.4 for Norway spruce forest in Götaland would be 0.87 TgC for the prolonged scenario compared to the BAU scenario. This amount is more than the eligible sink for forest management for whole Sweden under article 3.4, which is 0,59 TgC/year. On the other hand a shortened rotation age increased the annual bioenergy substitution effect with 0,95 TgC, compared to the prolonged scenario, an increase where the whole amount would be accountable as a decrease in fossil fuel consumption under the Kyoto

protocol. Altogether the prolonged scenario increased the annually carbon sink measured over all pools with 0,66 TgC (6 %) compared to the shortened scenario and with 0,24 TgC (2 %) compared to the BAU scenario.
When 300 years time horizon was applied the relative mitigation potential shifted for the different management scenarios. The share of carbon allocated to the biomass and soil carbon pool declined from 73 % to 29 % in the BAU scenario. In addition to this the annual carbon sink through forest management in the biomass and soil carbon pool decreased to 0,08 TgC for the prolonged scenario compared to the BAU scenario. Also the annual difference in bioenergy substitution carbon pools decreased, but only to 0,59 TgC.
Summarizing all shifts, the 300 years horizon led to that the best mitigation scenario was the shortened scenario. Compared to the prolonged scenario it annually increased the carbon sink with 0,41 TgC (14 %) and with 0,11 TgC (3 %) compared to the BAU scenario. This result clearly visualizes the different carbon pools characteristics and how the importance of carbon pools that do not get saturated such as bioenergy pools increase over a longer term compared to the biomass carbon pool that get more or less saturated over a longer term.
The comparison between the different yield classes' mitigation potential per hectare showed that a difference in increment with i.e. 20 % affected the net CO_2 emissions reduction in a similar way and therefore the importance of increment must be taken into account when it have the biggest influence.

Key words: *Rotation age, net emission CO_2, carbon dioxide sink, time horizon, CO2FIX V 3.1, climate change, forest management, Kyoto protocol*

Abbreviations

BAU	Business as usual
C	Carbon
CAI	Current Annual Increment
CDM - AR	Clean Development Mechanism – Afforestation Reforestation
CH_4	Methane
CO	Carbon oxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CO2FIX V 3.1	Carbon accounting model
EJ	Exajoule (10^{18} Joule)
ENGO	Environmental Non Governmental Organization
FCA	Fuel Cycle Analysis
FPS	Forest Product Sector
GHG	Green House Gases
GPP	Gross Primary Production
Gt	Gigatonne (10^9 metric tonnes)
GWP_{100}	Global Warming Potential, 100 year time horizon
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-Cycle Analysis
LUCLUF	Land-Use Change, Land-Use & Forestry
MAI	Mean Annual Increment
MgC	Megagram Carbon (1 metric tonne carbon)
MgDM	Megagram Dry Matter (1 metric tonne carbon)
Mj	Megajoule (10^6 joule)
MOC	Meridional Overturning Circulation
$MtCO_2$	10^6 Metric Tonnes Carbon Dioxide
N	Nitrogen
NEE	Net Ecosystem Exchange
N_20	Nitrous Oxide
Pg	Petagram (10^9 metric tonnes)
Pj	Petajoule (10^{15} joule)
PPM	Parts Per Million
PPB	Parts Per Billion
SOC	Soil Organic Carbon
TgC	Teragram Carbon (10^6 metric tonnes carbon)
TNMOC	Total Non-Methane Organic Carbon
TWh	Terawatt/hour (10^{12} watt/hour)
UNFCCC	United Nation Framework Convention on Climate Change

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1. Introduction

1.1 Greenhouse gases and climate change

Nowadays there is no doubt that there is an anthropogenic induced climate change due to increasing levels of Green House Gases (GHG) in the atmosphere. Some observations on the ongoing climate changes are that eleven of the twelve warmest years since 1850 occurred in the period 1995-2006 and the linear warming trend for the last five decades is in average 0,13 ºC, which is nearly twice compared to the last ten decades. The global heating can also be measured in the oceans and observations since 1961 show that the average ocean temperature has increased down to depths of at least 3000 metres. This heating of the oceans has been absorbing more than 80 % of the increased radiation caused by the anthropogenic induced greenhouse effect (IPCC, 2007a). The natural greenhouse effect itself is very important for the conditions for life on the earth and without the greenhouse effect the global mean temperature would be 35 ºC lower than today. The most important natural GHGs are carbon dioxide (CO_2) and water vapour (H_2O). This is due to that GHGs absorb some of the reflected infrared solar radiation or reflect it back to the earth. This means that the problem is not the greenhouse effect itself, but the increasing level of GHGs in the atmosphere that strengthens the greenhouse effect.
The greenhouse gases are often divided into three groups (Bernes, 2003):

- Natural greenhouse gases represented by carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)
- Ozone depleting gases F
- Fluoride-containing-non-ozone-depleting gases.

Another grouping that is made and used by IPCC is between: Long-Lived GreenHouse Gases (LLGHGs) such as carbon dioxide CO_2, methane (CH_4) and nitrous oxide (N_2O) and Short-Lived GreenHouse Gases (SLGHGs) like sulphur dioxide and carbon oxide (IPCC, 2007a). This thesis will only handle the natural greenhouse gases and mainly carbon dioxide, since forestry mainly can affect this group.
The global atmospheric concentration of natural greenhouse gases in the atmosphere has drastically increased since pre-industrial time (-1750). Carbon dioxide which is the most important GHG emission from anthropogenic activities has increased from 280 parts per million (ppm) pre-industrial time to 379 ppm in 2005. This concentration exceeds the natural concentration levels during the last 650 000 years (180-300 ppm). The primary source for this drastically increased CO_2 atmospheric concentration is combustion of fossil fuel, which emitted 7,2 GtC per year (2000-2005) and from Land-Use Change (LUC) like deforestation that emitted 1,6 GtC per year (over the 1990s) but there is a big uncertainty in the estimations for LUC emissions. The concentration of methane has increased from 715 parts per billion (ppb) in pre-industrial time to 1732 ppb in 2005 and the natural range for methane atmospheric concentration during the last 650 000 years has been 320 to 790 ppb. The methane emissions mainly originate from fossil fuel and agriculture, but the contributions from different sources is not well determined and the methane emissions annual growth rate has start to decline since the early 1990s. The third natural greenhouse gas, nitrous oxide has increased from a pre-industrial concentration at 270 ppb to 319 ppb in 2005 (IPCC, 2007a).
For making different greenhouse gases contribution to the greenhouse effect easier to compare the different gases are often transformed to carbon dioxide equivalents (CO_2 e). For

doing this carbon dioxide has been given index 1 in the Global Warming Potential (GWP) scale in the time horizon 100 year (GWP_{100}). The indexes for the other greenhouse gases GWP are based on their radiative forcing (W/m^2, how much they affect the radiation balance in the atmosphere by absorbing or reflect solar radiation) and their atmospheric lifetime compared to CO_2. For example methane have 23 and nitrous oxide 296 in GWP_{100} index, which means that one molecule of methane respectively nitrous oxide is the same as 23 or 296 carbon dioxide equivalents or molecules (Bernes, 2003).

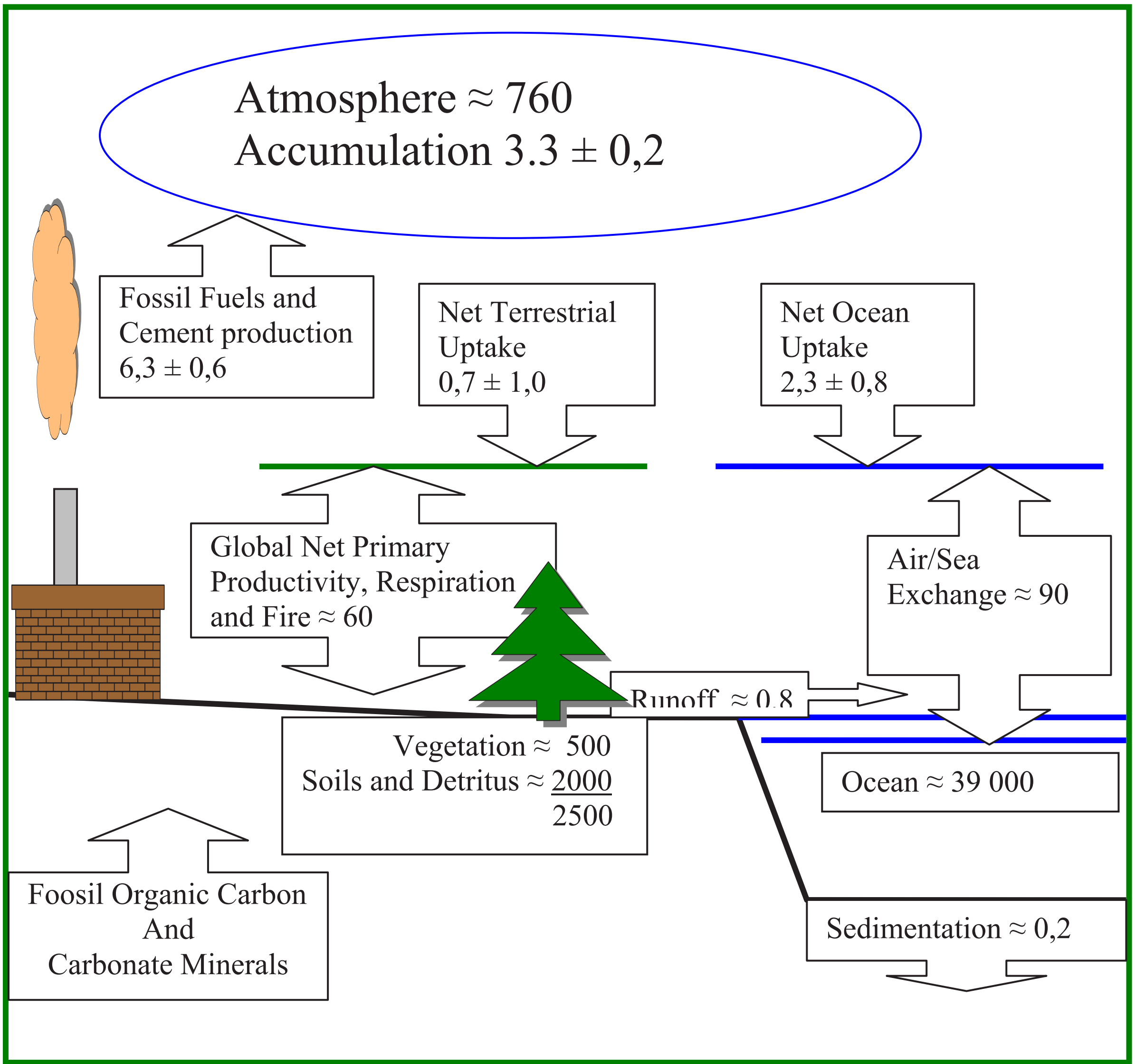

Figure 1. The global carbon cycle, showing annual carbon fluxes in GtC yr^{-1} (boxes with arrows) and carbon stock in reservoirs GtC. (After IPCC, 2000).

1.2 Forests and Forestry's role for reducing GHG net emissions

Global forests cover 3952 million hectare, which is almost 30 % of the total global land area and it is the biggest and most important carbon sink of all terrestrial ecosystems.
In spite of this forestry has contributed to almost 20 % of net CO_2 emissions since pre-industrial time. Which leads to that the annual net CO_2 emission from forestry during the period 1990-2005 in average was 4000 Mt CO_2 and the standing carbon stock in forests decreased with 5,5 % during this period (FAO, 2007). This is strongly correlated with

deforestation, 2000-2005 the annual net loss of forest was 7,3 million hectare and it mainly took place in the tropics. On the other hand forests in the temperate and the boreal zone function as a big carbon sink and correspond to a big amount of the global gross sink on 7700 MtC/year in terrestrial eco-systems. According to this forestry have a major role to play in mitigating climate change and it had also been given an important role in the Kyoto protocol (UNFCCC, 1997) to the United Nations Framework Convention on Climate Change (UNFCCC).
Forestry is included in the sector land use, land use change and forestry (LULUCF) under article 3.3 in the Kyoto protocol

"The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8" (UNFCCC, 1997).

This article is not important for Sweden or other forest rich countries with a stable forest area where no big afforestation, reforestation or deforestation project has occurred since 1990. For example EU15s six most forest rich countries who stands for 85 % of the carbon sink in trees in EU15 forests would be a CO_2 source or only an insignificant sink under Article 3.3 (Liski et al., 2000). For Sweden and other developed forest rich countries article 3.4 is more interesting.

"Additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I" (UNFCCC, 1997).

These human-induced activities can be forest management methods with higher potential to reduce net CO_2 emissions than the previous applied forest management methods. But they must be directly human-induced and reduce the net CO_2 emission. Some examples of forest management methods that can be used are: forest regeneration, forest fertilization, pest management, forest fire management, harvest quantity and timing, low-impact harvesting and reducing forest degradation (IPCC, 2000).
When a country elects to account for forest management they must account all changes in carbon stock on all forest land that is a subject for forest management (Schlamadinger et al., 2007). It is also obligatory to continue reporting according to Article 3.4 in future commitments periods.
However, forest management can only contribute to 20 % of the total mitigation in the LULUCF sector, which is a relative small amount compared to reduced deforestation and reforestation/afforestation which could contribute to 80 % of the mitigation at a global level in the LULUCF sector (Sohngen & Sedjo, 2006).
At an European level forest management could contribute to almost 60 % of the climate change mitigation potential, when the potential cost is set equal to or less than 100US$/t CO_2 (Nabuurs et al., 2007).
For Sweden with a forest area of 27,5 million hectare, which corresponds to 67 % of all land area in Sweden (FAO, 2007) forest and forestry have a major role to play in the climate change mitigation work and estimations show that total 3 GtC is stored in Swedish forest.

Sweden's CO_2e net emissions 2006 reported to UNFCCC according to the Kyoto protocol was 65,7 Mt CO_2e with LULUCF excluded, but with LULUCF included the net emissions was 27,7 Mt CO_2e. This means that the CO_2 net uptake in Sweden from the LULUCF sector was 38 Mt CO_2 2006 (Anon., 2007a). This is one of the reasons for that Sweden has decided to include article 3.4 in the National Inventory Report (NIR) for the commitment period 2008-2012. It shows that forestry will play a major role in Sweden's work for mitigating the climate change; signs on this can also be seen in the Swedish government's bill for a new forestry act. The new act will focus more on that forests is a renewable resource with a potential to sequester CO_2, which is the main reason for that the new Swedish forestry act will focus more on production than the previous one. In the new portal paragraph it will be written that forestry is a renewable resource, which can be seen as way to highlight the forests importance in the national work for climate change mitigation. Other signs that Sweden will give the national forest sector a more important role in the international processes and work is that Sweden will change the national forest definition in line with the FAO definition (Bill, 2007).
How forestry can mitigate the climate change is often divided into four different groups or options (IPCC, 2000):

A. Increasing or maintaining the forest area
B. Changing forest management: Increasing carbon density at plot and landscape level
C. Substitution of energy intensive materials
D. Bioenergy

All these different options will probably also bring positive synergy effects in a direction towards a more sustainable development in general (Nabuurs et al., 2007).
My thesis will handle option B-D and how theirs carbon sequestration potential is affected by the time-horizon.

1.3 Changing forest management: Increasing carbon density at plot and landscape level

Approximate 405+/- 60 GtC have been emitted to the atmosphere and the global carbon cycle during the period 1850-1998 by anthropogenic activities. During the same period the concentration of CO_2 has increased from 285+/-5 ppm to 366 ppm, but this increase only correspond to 40 % of the CO_2 emissions. This means that the oceanic and terrestrial sinks have absorbed the main part of the anthropogenic GHG emissions (IPCC, 2000). The annual terrestrial sink is estimated at 1 GtC, which is a small amount of the carbon in the global carbon cycle with an annual flux at 120 GtC between the terrestrial ecosystems and the atmosphere (Bernes, 2007).
Globally the annual carbon dioxide sink in forests was 3300 Mt CO_2 for the decade 1993-2003, if we ignore forestry's connection with LUC (mainly deforestation) which emissions during the 1990's was estimated to 5800 Mt CO_2 /yr (Nabuurs et al., 2007). This means that even if the global terrestrial ecosystem is a sink the forests globally are a net source.
Europe on the other hand features a slightly increasing forest area and sustainable forest management (SFM) applied on a large part of the forest area, which results in that the European forests is estimated to be sink on 0,09-0,12 GtC/yr.
Even if forests currently are carbon source globally the tropical, temperate and boreal forests, which only stand for 28 % of terrestrial area excluding Antarctica, totally contain 42 % (1146 GtC) of the global carbon stock in vegetation and top 1 m of soils. Other features for mitigating the climate change with forest management is that forests possibilities to absorb

CO_2 are increasing and that it is one of the few ways where human activities actual can remove CO_2 from the atmosphere. The importance of forest management is very obvious in Sweden where the standing volume has increased with 80 % since 1920's (Bernes, 2003). This positive development is not due to reforestation or afforestation, it is through forest management. During previous centuries the Swedish forests had been hard exploited by a growing rural population and forest companies, which led to that the forests in Sweden was a carbon source for centuries. The insight that forest was not an endless resource led to the first national Swedish forestry act 1903 and since these days forest management has improved a lot and around 2000 the annual net uptake from the Swedish forests was 40 Mt CO_2/yr. Which almost correspond to Sweden's emission from fossil fuel that for the last years had varied between 50-60Mt CO_2/yr (Bernes, 2007).
The carbon stocks in forests are allocated to the soil organic carbon (SOC) and to the living biomass (roots, stems, branches, etc.). In average the Swedish forest carbon stock is 85 t /hectare in the SOC and 45 t /hectare in the living biomass. Altogether the carbon stock in the Swedish forests is around 3 billion ton (Morén, 2005). This big amount of carbon stored in the forests means that even a small percentage change can affect the CO_2 flux in a significant way.
According to Article 3.3 in the Kyoto protocol it is obligatory for countries that have signed the protocol to annually report (NIR) changes and fluxes in the terrestrial carbon pool.
There are several different forest management strategies for increasing carbon sequestration in the forests, but the main idea is to increase the standing volume and this can be done in several different ways.
Large set-a-side areas where no forest activities at all take place which means that no biomass is removed from the area and that no other kind of anthropogenic disturbances, like disturbance of the soil take place. This is a very controversial strategy and it is mainly proposed by Environmental Non Governmental Organizations (ENGO:s) and it is not a likely method since it would affect the society in a negative way and drastic decrease the amount of renewable resources, which probably would lead to "leakage" effects, like harder utilizing of forests in other areas. Other disadvantages that often is reported is that the Net Ecosystem Exchange (NEE) reach a steady state when Gross Primary Production (GPP) equals the ecosystem respiration and in some cases these forests will turn into a carbon source. This is for example true for Fiby natural forest outside Uppsala in Sweden that each year emits 3-5 t CO_2/hectare to the atmosphere (Grelle, 2006).
On the other hand some studies show that old-growth forests in the northern hemisphere continue to accumulate carbon for centuries and that they do not reach a steady state, or become a carbon source and therefore these forests stands for 10 % of the global terrestrial carbon sink. They also point out that a huge amount of this carbon would return back to the atmosphere if these forests were disturbed (Luyssaert et al., 2008).
A better and more likely way to increase the standing volume is through joint production, where timber is produced on the same time as the standing volume is increased through prolonged rotation. Simulations for Norway spruce (Picea abies) forests in Germany showed that prolonged rotation with 20 years (from 90-110 years) increased the total carbon stock with 14 Mg/ha at the same time as the product carbon pool only decreased with 0,6 Mg/ha due to lower harvest intensity (Kaipainen et al., 2004). It is worth to mention that this study only looked on the forest ecosystem carbon stock, not net CO_2 emissions.
Advantages with increased standing volume is that it could be a good bridging technology for some decennium until new techniques are fully developed, no big investments in the energy infrastructure sector are needed ahead of the normal replacement cycle.
Quantitatively the forest sink by prolonged rotation would be large enough to fulfilling the requirements for the nearest commitments period in the Kyoto protocol for many European

countries (Noble & Scholes, 2001). Another way to increase the carbon stock is to fertilize the forests with nitrogen, since fertilizing affect the carbon stock in two ways. Firstly by increasing the growth of biomass, which automatic increases the litter fall and the standing volume and secondly, due to that increased N level decreases the C/N quota, which retards the mineralization process in the soil. Fertilizing trails in Sweden with intensive fertilizing shows that the growth can increase with 100 % in southern Sweden and with 300 % in northern Sweden. Another example on fertilizing and its effect is the anthropogenic induced N deposition over southern Sweden and for the last 100 years the forests in southern Sweden has received 1 t. N/ha. Which has resulted in that the carbon stock increased with 10-30 t/ha in living biomass and 8-18 t./ha in the SOC. Other trails indicate an exchange on 25 kg C/ha in living biomass and 11 kg C/ha in SOC for each supplied kg of N/ha. Disadvantages with N fertilizing is that it can cause N leakage from forest ecosystems and that N fertilizing on forest land with high and/or fluctuating ground water level can lead to N_2O emissions

One disadvantage with increased standing volume is that it also increases the risk for disturbances like storms and insects outbreak, disturbances which are supposed to increase with a warmer climate. For example the hurricane Gudrun in southern Sweden 2005 caused net C emissions at 3,5 million ton during 2005, which is approximately 10 % of the Swedish forests gross C uptake (Lindroth, 2007). This can be seen as a proof on that Schlamadinger and Marland (1996) had right then they stated that

"CO_2 emissions avoided by not using fossil fuels are forever and that carbon sequestration in biomass is temporary".

It is also proven that different tree species sequester different amounts of carbon per hectare, depending on the tree species production and different N content in theirs litter. This leads to that it is possible to affect the carbon stock in the same way as fertilizing by changing tree species. For example a mixture between Norway spruce and birch (Betula sp.) on some sites can produce more biomass than a pure Norway spruce stand (Klang & Ekö, 1999). Another example is that Scots pine (Pinus sylvestris) forests has a lower carbon stock compared to Norway spruce or birch forests, because of that their litter has a lower N content compared to spruce or birch (Berg et al., 1996) and the result on the C/N quota will be the same as for N fertilizing.

1.4 Substitution of energy intensive materials

In this part I will also include carbon sequestration in forest products like buildings etc., which is strongly correlated with the substitution of energy intensive materials.

Wood products generally affect the natural carbon cycle between the forest ecosystem and the atmosphere due to that carbon is released during manufacturing and harvesting operations (Hashimato et al., 2002). On the other hand wood products could have a positive affect on the net CO_2 emissions and three main reasons are often given for this; less fossil fuel is needed for manufacturing wood products compared to manufacturing other materials, residuals and by-products of wood processing can substitute fossil energy as bioenergy and wooden materials store carbon. The last reason is insignificant compared to the two first reasons (Sathre & Gustavsson, 2007).

The forest sectors carbon stock and fluxes is often divided into two groups; Forest Product Sector (FPS) and forest ecosystem (Apps et al., 1999). Globally the C pool in living forest biomass is 425 Pg compared to the C pool in FPS that is estimated to 4,2 Pg (Nabuurs & Sikkema, 2001). Currently forest operations lead to an annual carbon loss from forests of approximately 1,1 GtC. The biggest part is quickly released to the atmosphere, but there is a small increase of carbon stored in FPS and globally it increase with 139 MtC/year (Kirschbaum, 2003). This sink corresponds to 14 % of the gross C emission from FPS harvesting and manufacturing, and to 2 % of the fossil fuel emission in 1990 (Hashimato et al., 2002). The European FPS sink was estimated to 29 TgC/year, to compare with the forest biomass sink that was estimated to 101 TgC/year, by Nabuurs et al. (1997).

National analysis of the FPS sink often shows that it is of bigger importance in industrialized and forest rich countries like Finland and Sweden, which is the countries with highest FPS C/emission ratio (Hashimato et al., 2002). For Finland Pingoud et al. (2001) estimated that the total C stock in FPS originated from Finnish forestry (excluding wood waste and paper products, but including exported forest products) might correspond to as much as 7 % of the standing forest biomass in Finland. Apps et al. (1999) did a carbon budget over the Canadian FPS and estimated the amount of carbon in each group 1989. The total carbon stock for the forest sector was calculated to 86,6 PgC, of which 71,3 PgC in the SOC, 14,5 PgC in the living biomass and 0,8 PgC in the FPS. Even if the FPS C stock contains less than 1 % of the total forest sector carbon stock, it was increasing with 25 TgC/year in Canada. Thus they considered it to play a significant role in the net C exchange between the forest sector and the atmosphere for Canada.

Despite that usage of wooden materials in many cases has the possibility to be a net C sink it is not accountable under the Kyoto protocol. It has been discussed for a long time that it should be incorporated under Article 3.4, but if it should be included in post-2012 agreement, a proposal is needed by mid 2009 (Hetsch, 2008). The main reason for this is that the FPS often is seen as a stable pool without any net accumulation and that it should be hard to measure.

Even if FPS could play a significant role in mitigation net CO_2 emissions through substitute more energy intensive materials and fossil fuel, it is not self evident that a substitution always leads to decreased net emissions. Therefore for example Murphy (2004) pointed out the importance of Life Cycle Analysis (LCA) for evaluating the substitution effect and even for rising wood products competitiveness on the market place. The summary of advantages and disadvantages which often is applied in a LCA for timber in comparison to other materials is simplistic clarified in table 1.

Table 1. Advantages and disadvantages for timber in comparison to other building materials, after Murphy, 2004.

LIFE-CYCLE PHASE	*Advantages for timber*	*Disadvantages for timber*
Raw material origin	CO2 removal from atmosphere, provision of ecosystem services, renewable with appropriate management	Extensive land-use
Harvesting/extraction	Relatively low energy and material needs	Ecosystem damage, greenhouse gas emission due to disturbance, transport distances
Processing	Low energy consumption, useful by- and co-products, potential for energy generation	Low recovery rates (tropical), transport distance
Use	High strength to weight, good thermal properties	Additives may be needed to enhance durability
End-of-life	Multiple re-use, recycling and energy recovery options, energy recovery can substitute fossil energy needs	Need to segregate contaminated wood, downgrading in recycling

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Levine et al. (2007) pointed out that if usage of wood for substituting other building materials like steel and concrete often decreases the carbon dioxide net emissions, through requiring less energy for the construction. The most important factor in a LCA perspective in the building sector is the selected materials energy requirements for heating and cooling, and whether the building materials are recycled after its lifetime. They also stated that the energy requirement for heating and cooling during the life-time of modern building is more or less equal for concrete and wood framed buildings.

A Swedish analysis was made where they compared the GHG balance for a multi-stored wood frame house with a similar house built with a concrete frame. The result was that the primary energy needed (mainly fossil fuel) for the concrete frame was 60-80 % higher than for the wood frame building. They also studied how the average GHG mitigation per unit of area was affected if the wood residues and excess biomass was utilized as bioenergy and substituted fossil fuel. The LCA showed that with a 100 year perspective the GHG mitigation efficiency for the wooden framed building was 2-3 times higher per unit of area, than the GHG efficiency for the concrete framed building. Although if the excess forest from the concrete framed building case was used for bioenergy purposes (Börjesson & Gustavsson, 2000). Factors that contributed most significantly to this result, with lower energy and CO_2 balances for wood framed building was; the wood processing residues for substituting fossil fuel and the recovery of demolition (Gustavsson & Sathre, 2006). Perez-Garzia et al. (2005) did a LCA by applying four different management strategies in a Douglas fir (Pseudotsuga meunziesii) stand and then study how different scenarios for the usage of wood materials in residential houses affected the mitigation potential for different management strategies. The applied management strategies were 45, 80, 120 years rotation age and a no harvest scenario, simulations were made for 165 years. The conclusions from the different rotations ages impact showed two main features. The combined carbon pool of forest and forest products increased with longer rotations up to at least 165 years, but when the substitution effect of energy and material were added shorter rotation age led to greater cumulative climate change mitigation effect of the whole.

1.5 Bioenergy

Bioenergy as a part of renewable energy sources is probably most discussed of the three forestry options to mitigate climate change. It has at least been most focus on this issue from politicians and the public in the Nordic countries, who put a lot of reliance on bioenergy.
The reason for this is not only to decrease CO_2 emission, other important advantages is that it leads to higher employment, air quality and especially a higher energy security.
The main difference between carbon in biomass-energy and carbon in fossil fuel is that the carbon from biomass is a part of the present natural carbon cycle. Carbon emissions from biomass was recent absorbed from the atmosphere (some decades ago maybe) and the carbon would return to the atmosphere during the natural decomposition anyway. This means that burning it would only speed up the natural carbon cycle without affecting the atmospheric CO_2 content in a longer term. Carbon from fossil fuel has not been a part of the natural carbon cycle for hundreds of millions years and therefore is it not a part of the natural carbon cycle anymore (Bernes, 2003). The conclusion from this is that bioenergy mitigation is captured as a decrease in fossil fuel consumption and not by the use of bioenergy itself. Therefore the bioenergy carbon pool can be seen as a pool with non combusted fossil fuel that remains in the ground.
There is a conflict between C sequestration in biomass and fossil fuel substitution, due to that when biomass is harvested it always leads to that less carbon is stored in the forests than it would have been under a pure carbon sequestering management. Which strategy that is most preferable from a mitigation point of view often seems to depend on the time-scale. A shorter time horizon often benefits the sequestration option and a longer time-horizon benefits the substitution option. The substitution option also benefits from increasing site fertility and the sequestration option benefits on low fertile sites (IPCC, 2000). Another conflict that often is mentioned is when bio-fuel consumption leads to deforestation, even if it is assumed that only 5-7 % of the total bio-fuel consumption leads to deforestation (Schlamadinger & Marland, 1996).
On the other hand a more recent study pointed out that the production of sugar-cane, soybean and oil-palm often leads to deforestation (GRAIN, 2007). In Indonesia with an oil-palm plantation area at 3,6 million hectares, that annually increases with around 13 %, it is estimated that approximately around 17-27 % of the deforestation is caused by establishment of oil-palm plantations. In Malaysia this number could be up to 80 % (FAO, 2008b). Deforestation has caused large emissions of GHG to the atmosphere, the emissions is special severe when the plantations are located on drained peat lands and 27 % of the plantations are located to these kind of area. In Indonesia the emissions from drained peat land is 2000 $MtCO_2$, which correspond to 8 % of the annual emissions from global fossil fuel burning. This makes Indonesia to the third biggest CO_2 polluter after USA and China (Hooijer et al., 2006).
Even when sustainable managed oil-palm plantations replace secondary forests it will take 50-100 years before the carbon is recaptured (Butler, 2007). This is one of the biggest reasons for that an Fuel-Cycle Analysis (FCA) must be done for each single bio-mass fuel to evaluate how it impact the net GHG emissions. Schlamadinger et al. (1997) proposed that this kind of FCA should handle following issues:

- Time interval analyze and changes of carbon stocks
- Reference energy system
- Energy inputs required to produce, process and transport fuels
- Mass and energy losses along the entire fuel chain
- Energy embodied in facility infrastructure, distribution systems, cogeneration systems
- By-products, waste wood and other biomass waste for energy
- Reference land use and other environmental issues

One example on the importance of a FCA is that 1 t of wood that substitute oil for heating decreases the CO_2 emission with 1,3 t, if it substitutes coal for electricity production the emission decrease with 1,5 t and if it instead would have been used to substitute fossil fuel with a biomass fuel (with efficiency at 55 %) the CO_2 emission decrease would have been 0,8 t (Azar, 2006). This clearly shows how important a FCA is for maximizing the mitigation effect from bioenergy.

In 2004 bioenergy globally contributed to 10,6 % of the energy net supply, to compare with the shares from fossil fuels 80,5 %, nuclear power 6,5 % and hydropower 2,2 % (IEA, 2007a). Biofuels share of the energy net supply vary a lot between developed and industrialized countries and bioenergy stands for more than 90 % of some countries household energy supply. This is very obvious in Africa, where 90 % of the annual harvested volume is utilized for energy purposes (FAO, 2007) and over 2 billion people have bioenergy as their dominant energy source (FAO, 2008a). On a global level the annual fuel wood production is 1,8 billion m^3, of which 13 % are produced in industrialized countries. The amount of fuel wood is bigger than the annual global industrial wood production at 1,7 billion m^3 and 65 % of this is produced in industrialized countries.

Only a few industrialized countries like Sweden, Finland, Austria, Mexico and the United States have a significant production of bioenergy. The bioenergy production in these countries differ a lot from the developing countries due to that the main part of theirs bioenergy originates from indirect industrial sources. Sources like black liquor from pulp mills and other wood residuals from the industry like bark and sawdust etc. and the industrial use of bioenergy stands for more than 50 % of the total use of bioenergy in these countries (FAO, 2008b). Despite this, the industrial biomass use in OECD countries is only 5,6 EJ annually, to compare with the total global biomass energy sources that provides 46 EJ/yr. Including the industrial use in OECD countries, 8,6 EJ/yr is used for heat and power generation in plants and until 2030 the non industrial use is supposed to increase from 3,2 EJ (2002) to 10,8 EJ annually. If this increase would be realized it would double the global share of heat and energy consumption originated from biomass from 2 % to 4 % (Sims et al., 2007).

The global biomass energy mitigation potential varies a lot between different studies and it is often connected with a high degree of uncertainty. In the forestry chapter in the IPCC report "Mitigation of Climate Change" from Working Group III. They estimated that biomass from forestry can contribute to the global energy consumption with 12-74 EJ/yr into 2030. This would give biomass from forestry a mitigation potential that varies between 0,4-4,4 $GtCO_2$/yr, depended on if it substitute gas or coal in power plants (Nabuurs et al., 2007).

The biggest global biomass potential is assumed to be in the agricultural sector, which could contribute to the global energy consumption in a range between 20-400 EJ/yr until 2050. The higher number is only reachable if we succeed to outpace the food demand with higher efficiency in the agricultural sector (Barker et al., 2007).

EU 27 goal is that in 2010 the share of renewable energy should be 12 % of the energy consumption, which will not be reached even if some progresses are made. In 2020 this share should increase to 20 % (Röser et al., 2008).

In 2005 the EU renewable share of the gross energy consumption was 6,7 % and 67 % of the renewable energy originated from biomass and waste. To reach the European commissions roadmap for 2020, EU's Biomass Action Plan suggest that the use of biomass should increase with 80 million ton oil equivalent (mtoe) until 2010, which is a drastic increase compared with the consumption 2006 at 87 mtoe (Eurostat, 2008b). Another important reason for EU to increase the share of biomass energy and other energy sources than fossil fuel is to improve EUs energy security. 2006 EUs energy dependence rate from countries outside EU was 54 % and a lot of the fossil fuel supply originates from unstable regions and unpredictable regimes. Russia was the biggest supplier with a share on 33 % of the oil imports and 40 % of gas imports (Eurostat, 2008a).

Sweden is one of the countries in EU with the highest share of biomass energy supply and 2006 bioenergys share of the annual energy gross supply was 19%, which corresponded to 116 TWh (Energimyndigheten, 2007).

One reason for this except the good natural conditions in Sweden for biomass energy was the international oil crisis during the 1970s. That showed how vulnerable Sweden's economy was for drastic increased oil prices, due to the high dependence on imported energy. This led to that Sweden developed its renewable energy policy under 1970s and 1980s, which focused on technology research and development. During 1990s the market developed subsequent, when taxes and subsidies that favoured investments in renewable energy infrastructure were created.

For example district heating plants shifted from oil-fired boilers to biomass cogeneration in pace with increased carbon taxes and development in biomass extraction followed. This resulted in that the use of forest residues in district heating plants increased from 13 PJ 1990 to 65 PJ in 2001. The Swedish policy implementation since the oil crisis is at the international arena seen as a good example on a successful energy policy (Sims et al., 2007). Since 1970s the oil consumption in Sweden has decreased with 43 % and the bioenergy supply has increased with 170 % (Energiläget, 2007).

The biggest biomass energy consumer in Sweden is the industry sector and when mainly the forest industry sector, that 2006 consumed 58 TWh biomass energy (Anon., 2007b). The biggest part of this is residuals from production of other forest products and 2003, 45 % of the Swedish annual fellings were used for energy purposes. Although the utilizing of biomass in Sweden seems to be high, the current potential is not fully utilized and calculations show that additional 40 TWh could be utilized from the current annual harvesting in form of slash, stumps and small dimensions logs (Börjesson et al., 2007).

Even ENGOs in Sweden would like to increase the biomass harvesting for energy purposes and The Swedish Society for Nature Conservation (SSNC) think that the potential in 2030 will be 200 TWh annually (SSNC., 2005). But they do not mention how this goal should be reached. Börjesson et al. (2007) predicted that in 2100 it is probable that biomass from forestry will contribute with 200 TWh annually. For doing this without harming the forest industry, which in 2006 stood for 11,6 % of the export value and is the absolute biggest net exporting branch in Sweden (Swedish Forest Agency, 2008) the annual increment must increase. This can be done in several ways, better regenerations, improved seeds and seedlings material could lead to increased growth that corresponds to 40 TWh annually in a medium term. Fertilizing at the same level as during 1980s and increasing the area replanted with Lodgepole pine (*Pinus contorta)* instead of Scots pine could lead to additional 15 TWh annually (Börjesson et al., 2007). Even the climate change will have a positive effect on the biomass growth in Sweden and if this increase only is utilized for energy production the potential would be 116 TWh/yr in 2100 (Kellomäki & Leinonen, 2006).

Bioenergy under the Kyoto protocol is a quite complicated story and differs a lot from how forests as a carbon sink and forest management under article 3.4 is handled. The reason for

this is that according to the Kyoto Protocol and the Marrakech Accords biomass for energy is not a land use activity. Instead it is handled through the reduction CO_2 emission that appears when fossil energy is substituted by biomass energy in the energy sector. Which means that where is no land use policy about bioenergy, instead the land use sector can benefit from policies aiming at the energy sector. Under the Clean Development Mechanism (CDM) unsustainable use of bioenergy are not included in the baseline scenario even if it would lead to net emissions. Therefore CDM activities in non Annex-B countries like improving biomass energy efficiency and replacing unsustainable biomass energy with sustainable will not give any credits. This is problematic when many of the non Annex-B countries often rely on biomass energy and improved efficiency in biomass energy use is probably the most significant way to use CDM in this biomass energy relying countries (Schlamadinger et al., 2007). Another complexity which is connected with the biomass energy under the Kyoto protocol is that it can originate from a lot of different sources (Figure 2).
To better understand the global potential for bioenergy originating from forests to replace fossil fuel it is worth to mention that if we would like to substitute the total global oil consumption with biomass from forests. The global annual cuttings would need to increase from 3.4 billion m^3 to 17 billion m^3, which is not reasonable (Swedish ministry of Agriculture 2006).

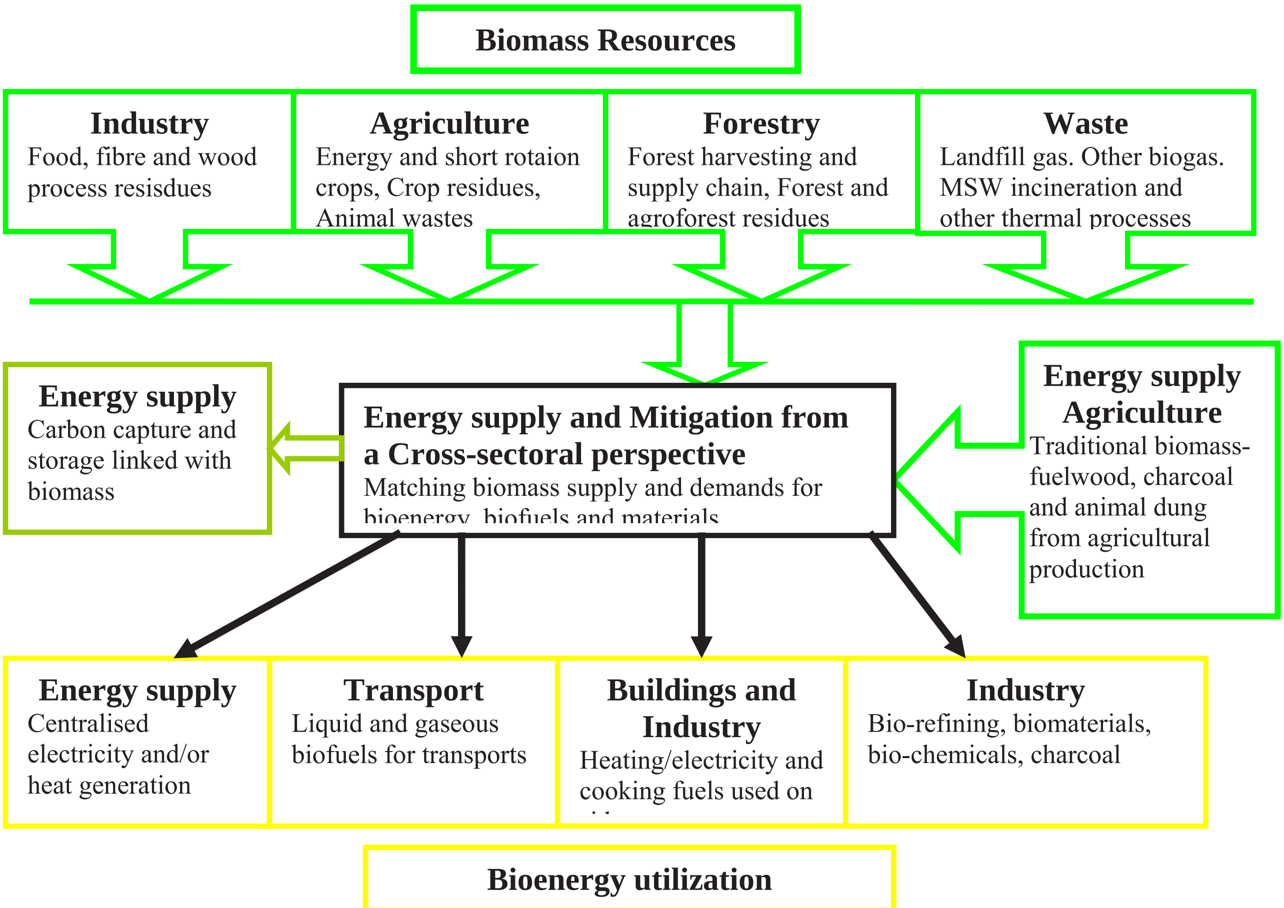


Figure 2: after IPCCs Fourth Assessment Report, Working Group III, “Mitigation of Climate Change” (IPCC, 2007b) shows the complexity and huge variation in origin for the biomass resources.

2. Objectives

There are several written scientific papers about how different forest management strategies could influence the carbon balance and the net CO_2 emissions from forestry. Some examples are Eriksson, 2006; Karjalinen et al., 2002; Pohjola & Valsta, 2007 and Kaipainen et al., 2004. In their studies they focus on how different rotation lengths, thinning regimes etc. affect the carbon flux between forests and the atmosphere, by looking at carbon stock changes and substitution effects. They all have in common that they focus on a time horizon that reach over one or several rotation periods and do not take any or little consideration to a shorter term perspective. This is by tradition the most common approach in the forestry sector with its long term horizon, settled by the trees natural increment rate. Another reason for choosing the long term horizon is that it is easier to implement long-term strategies than short-term strategies that could lead to drastic shifts.

One obstacle that is connected to this long term view is the great complexity of the climate system and that many mechanisms might have a threshold value which could lead to irreversible radical shifts in the climate system (Bernes, 2003). Examples on this mechanisms are the Meridional Overturning Circulation (MOC) that already have started to decline, cloud feedbacks caused by increasing content of water vapour in the atmosphere (Solomon et al., 2007) and that the global warming could be a trigger for large emissions of methane from the tundra soils if the permafrost melts (Bernes, 2003). The big uncertainties connected to the climate mechanism means that the long term view might be connected with high risks when the feedbacks are unknown and they could lead to high costs. Therefore it could be better to study the forests mitigation potential after IPCC:s short and medium term mitigation view (until 2030) to decrease the risks.

The Stern report pointed out that if we want to stabilize the atmosphere CO_2e content at 550 ppm the global emissions of GHGs must peak in the next 20-30 years and after that decrease with 1-3 % annually. The mitigation cost for this is estimated to 1 % of the global GDP and delayed or weak action in the next 10-20 years could make a stabilization level at 550 ppm CO_2e hard to reach and lead to significantly increased risks. The Stern report also point out that even if we can not be 100 % sure on the climate changes negative impact, mitigation actions still can be seen as a relative cheap insurance for unexpected consequences. Nowadays the European Commissions target to stabilize on 450 ppm CO_2e is more or less is out of reach. For reaching this target the global emissions need to peak in the coming 10 years and after that annual decrease with at least 5 % (Stern, 2006).

Therefore my thesis will assume that IPCC and especially the Stern report are correct when they pointed out that action taken in the short and medium term (until 2030) is the most important and cost-effective way to mitigate the climate change, through stabilizing the atmospheric CO_2e content at 550ppm and thereby reducing the risks for unknown climate feedbacks. Especially the risks and uncertainty for climate feedbacks in the climate mechanism is something that Bernes (2003) pointed out when he quote Aristotle when he in the 4th century BC said that:

“It is likely that unlikely things should happen”

Because of this and that very few studies focus on the short and medium term horizon I will focus on that in my thesis.

My main objectives are to compare how different rotation lengths in Norway spruce dominated forests in the region Götaland, Sweden could influence the net CO_2 emission to the atmosphere. I will also study how the different rotation lengths influence the carbon location and distribution in different carbon pools like; biomass, soil, product, bioenergy slashwood mitigation and bioenergy industrial mitigation carbon. The two bioenergy carbon pools will be regarded as a carbon stock relating to non extracted fossil fuel due to that biomass is combusted instead of fossil fuel. Another objective is to study how the mitigation potential for the different scenarios and the importance for the different carbon pools changes, depending on if a long or short term horizon is applied. This will be summarized to a rough analyze for the mitigation potential for spruce dominated forests in region Götaland, Sweden. Also the mitigation potential differences between the different harvest scenarios will be studied.

3. Material and Methods

3.1 Approach

To analyze the effect on net CO_2 emission and carbon location dependence on different rotation lengths for Norway spruce forests in Götaland, a synthetic forest was created. This synthetic forest is a rough simplification of the current state of Norway spruce dominated forests in Götaland. The forests were divided into three yield classes; low, medium and high fertility sites. Each yield class was divided into age-classes with 20 years interval. On each yield class three different rotation lengths was applied and set as scenarios;

1. Business as usual (BAU) scenario, thinnings were made after thinning guidelines (Thinning guidelines, 1985) for each yield class and final-felling occurred 20 years after the lowest allowable cutting age in Sweden (SFS, 1979) for the site-index that correspond to the yield class.

2. Prolonged scenario, rotation age prolonged with 20 years compared to BAU, thinnings were made after thinning guidelines.

3. Shortened scenario, rotation age shortened with 20 years (same as lowest allowable cutting age), thinnings were made after thinning guidelines.

This approach with its simplification due to that the same thinning program is applied independent on which rotation length that is used, leads to that the simulations focus on the harvesting levels influence on net CO_2 emission and carbon allocation in Götaland more than different silvicultural programs influence. For doing this broad analysis on the time horizons influence on carbon fluxes, allocation and mitigation potential for different scenarios simulation was made with 30 and 300 years time-horizon.

3.2 CO2FIX V 3.1

For doing this analysis on different rotations ages and time horizons influence on the amount and allocation of sequestered carbon and shifts in the carbon pools importance in different yield classes the model CO2FIX V 3.1 was used (Schelhaas et al., 2004; Masera et al., 2003). CO2FIX V 3.1 is an ecosystem-level simulation model that quantifies the stocks and fluxes of carbon in the forest ecosystem and the forest product sector. The model also quantifies the substitution effect when wood or wood waste replaces fossil fuel. CO2FIX V 3.1 is applying a full carbon accounting approach, this means that it calculates all changes in carbon stock in all carbon pools with annual steps (see figure 3 for how I applied it).

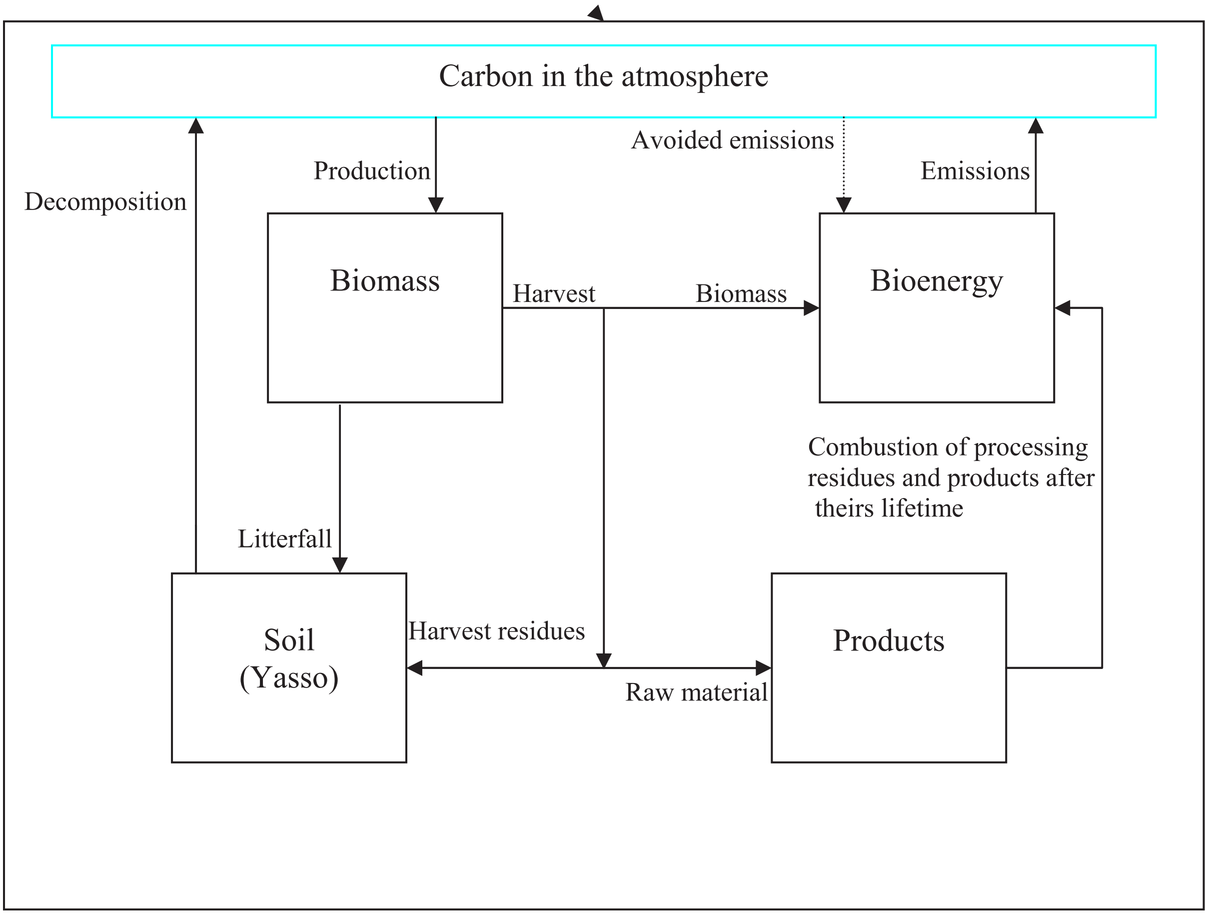


Figure 3: Shows the carbon fluxes in CO2FIX V 3.1 for my simulations (after. Schelhaas et al., 2004)

The following description of CO2FIX V 3.1 and how it is designed around six main modules is based on Schelhaas et al. (2004) and Masera et al. (2003).

- Biomass module
- Soil module
- Products module
- Bioenergy module
- Financial module
- Carbon accounting module

3.2.1 Biomass module

The biomass module distinguishes tree biomass compartments into; stem (including bark), foliage, branches and roots. The needed input is growth rate of stem wood volume, which often can be derived from yield tables. For calculating the growth of biomass compartments i.e. needles, branches and roots, CO2FIX V 3.1 needs their growth relative to the stem wood growth. For calculating the carbon stock and fluxes several coefficients is needed. In addition to carbon content and dry matter density, turnover rate for different compartments is needed for calculating the dynamics of SOC. Harvesting operations are also conducted in the biomass module for calculating how much and which compartments of the biomass that is removed or reallocated. The harvested biomass is divided into logwood, pulpwood and harvest residues (logging slash). These figures will then be allocated to the product, biomass or soil module.

3.2.2 Soil module

CO2FIX V 3.1 uses the dynamic soil carbon model Yasso. This model describes the dynamics and decomposition of soil carbon in well drained soils. The used version of Yasso soil carbon model is calibrated to describe the total stock of soil carbon without dividing it into different soil layers. It consists of three litter compartments; non-woody litter (fine roots & foliage), fine woody litter (branches & coarse roots) and coarse woody litter (stem). The litter compartments is during the decomposition fractionated into five decomposition compartments in the module; Extractives, Cellulose, Lignin-like compounds, Humus 1 and Humus 2. The litter production is derived from the biomass module through the processes harvest residues, natural mortality and biomass turnover. Since no distinction is made between fine and coarse roots in the biomass module, Yasso module uses the proportion between foliage and branches litter to calculate them. Each litter compartment has a fractionation rate determining the proportion of its content that in one time step should be released to the decomposition compartment. The proportion of chemicals in the litter compartment decides its distribution into the different decomposition compartments. Which all has its own specific decomposition rate and a fraction of the losses are transferred to subsequent compartments with slower decomposition rates, the leftover is removed from the system. Both the fractionation and decomposition rate is controlled by temperature and water availability.

3.2.3 Products module

The products module traces the carbon that is reallocated from the biomass module after harvesting as logwood, pulpwood and logging slash. The same years as the harvesting takes place several processing steps reallocate the raw material into sawnwood, boards, paper and firewood. Fractions from process losses in each product category are reallocated to subsequent product categories. The product module differentiates the end products into three life-span categories; long, medium and short term products and each product is distributed over these categories. When products are discarded at the end of their life-time they can be recycled (into the same or lower life-span category), used for bioenergy in the bioenergy module or deposited into a landfill. Carbon is released from the product pool at the end of the life-time either through decomposition in landfills or through the bioenergy module.

3.2.4 Bioenergy module

The bioenergy module calculates the carbon dioxide emission mitigation due to substituting fossil fuel with biomass fuel. It can even calculate the mitigation potential for improving efficiency in biomass combustion. The module derives inputs from the biomass modules “slash firewood” originating from thinning-harvest operations and from the products modules industrial residues firewood and products disposed to energy after theirs life-time. Other inputs needed are the combustion efficiencies and emission factors of both the biomass fuel and the fuel that is supposed to be substituted.

The CO_2 emission from biomass fuel combustion is always kept at zero in the module, where it is assumed that in a sustainable harvesting cycle the net emissions should be zero and if not, it will show up as a decreasing carbon stock in the biomass module. A trustful emission analysis also needs to take into consideration the GHG emissions from non-CO_2 GHG gases which are not absorbed in biomass growth, like methane, nitrous oxide and carbon oxide. Therefore this data is included for the comparative analysis of the difference in emission scenarios for different fuels.

3.2.5 Financial module

The financial module is a simple model for assessing the financial costs and benefits for different scenarios. Different types of costs and benefits need to be specified for each case. Then CO2FIX V 3.1 calculates the current costs and returns, discounted costs and returns and the Net Present Value (NPV). The financial module works like an ordinary forestry model and can only handle the financial situation for forestry operations and does not take any added values into account.

3.2.6 Carbon accounting module

The carbon accounting module in CO2FIX V 3.1 uses the simple stock change approach and temporary and long term credits can be calculated for Clean Development Mechanism – Afforestation Deforestation (CDM-AR) projects. Carbon pools that are eligible under CDM-AR projects are biomass, litter, dead wood and soil organic matter. The carbon accounting module derives this data from the biomass module. All carbon pools are expressed as CO_2e, for making them compatible with all kind of kind of avoided GHG emissions. CO2FIX V 3.1 does not take into account other leakages and GHG emissions than CO_2. For calculating the carbon credit balance for a project, a base-line scenario is needed to be simulated in CO2FIX V 3.1.
I will not use the financial or the carbon accounting modules in my thesis.

3.3 Simulations

3.3.1 Location, species and yield classes.

Norway spruce forests in the region Götaland, Sweden, was chosen to represent forest and forestry condition in southern Sweden and to represent a starting state for the synthetic forest. Norway spruce was chosen since it is the dominating and economically most important tree species in Götaland with 39 % of the forest area and 47 % of the standing volume. The Norway spruce forest was divided into three different yield classes after mean annual increment (MAI) data from Swedish National Forest Inventory (SNFI, 2008.) see Table 2, each yield class was divided into age classes, with 20 years interval.

Table 2. Area Norway spruce forests in Götaland (100. hectare,), divided into yield and age classes, national parks and nature reserves excluded. (SNFI, 2008a)

Yield class	*MAI (m^3 ha^{-1}/yr)*	*1-20yr (100.ha)*	*21-40yr (100.ha)*	*41-60yr (100.ha)*	*61-80yr (100.ha)*	*81-100yr (100.ha)*	*101yr- (100.ha)*	*Total (100.ha)*
Low (2-7 m^3 ha^{-1}/yr)	5.9	373	229	155	136	123	113	1129
Medium (7-9 m^3 ha^{-1}/yr)	8.8	801	913	434	457	512	380	3497
High (10< m^3 ha^{-1}/yr)	11.2	4372	4030	2859	2010	1016	389	14676
							Total,	19302

3.3.2 Biomass parameters

Yield classes for each yield class was assessed by simulations with the stand growth model ProdMod2 (Ekö, 1999; Ekö, 1985), see appendix for start values apprehended from Elfving and Hägglund (1975). Site index were chosen to correspond to the average MAI in each yield class, the low yield class corresponding to site index Spruce 22, medium yield class to site index Spruce 28 (27,5) and the high yield class to site index Spruce 32. Coefficients for wood density (MgDM/m^3) were set to 0,4 MgDM/m^3 (Andersson, 1996) and carbon content was assumed to be 0,5 MgC/MgDM in all biomass compartments. The relative growth of biomass compartment i.e. needles, branches and roots compared to stemwood growth was derived by biomass equations from Marklund (1988) and data from yield tables after Eriksson (1976). Then the relative compartment growth was calculated by comparing the periodic growth of biomass compartments with the periodic stemwood growth. The turnover coefficients for foliage were derived from Kellomäki et al. (1992) and for branches and roots from Liski et al. (2002). Parameter for mortality was derived from simulation with ProdMod2 and mortality due to forest management was neglected. Thinning was done after Swedish national thinning guidelines for Southern Sweden, for more information about the thinnings see appendix 1. Final harvesting in the BAU scenario took place 20 years (see table 3) after the lowest allowable cutting age for each yield class according to the national Swedish forestry act (SFS, 1979). In the short scenario the rotation age was shortened with 20 years and for the long scenario it was prolonged with 20 years compared to the BAU scenario. The harvested stem volume was divided into logwood, pulpwood and harvest residues (slash) and allocation for each assortment was derived from Ollas (1980) functions for estimating assortment exchange for trees and stands. The minimal diameter for logwood was set to 14 cm and the pulpwood was assumed to be cut into falling lengths with a minimal diameter at 5 cm. In final felling 70 % of the slash were assumed to be utilized as biomass fuel. See table 3 for more information.

3.3.3 Soil parameters

General Yasso soil parameters for litter composition, temperature sensitivity for humus decomposition and initial decomposition rate for soluble compounds for coniferous forest were used (Nabuurs & Schelhaas, 2002). To derive the initial carbon stock, preparation simulations for one rotation period was needed for each yield class for calculating the mean annual carbon input to the forest. No slash was assumed to be utilized in the preparation simulations. Growth season were assumed to start when the monthly mean temperature reaches five degree (˚C). Climate data for monthly mean temperature (˚C) and mean month precipitation was derived from a global climate dataset (World climate, 2008). The derived data were mean values for four locations in the region Götaland (Halmstad, Växjö, Landvetter and Jönköping), for mean values see table 3 and 4.

Table 3. Main parameters used in the biomass and soil module

	Low	*Medium*	*High*	*General*
Mean annual temperature (˚C)				6,6
Degree day above zero (˚C)				2563
Preciption in growing season (mm)				430
Turnover rates (1/yr)				
Foliage	0,16	0,16	0,16	
Branches	0,027	0,027	0,027	
Roots	0,027	0,027	0,027	
Rotation length (yr) BAU	85	80	70	
Initial SOC (MgC/ha)	26	44	60	
Wood density ($MgDM/m^3$)				0,4
Carbon content (MgC/MgDM)				0,5
Fraction removed at final felling	0,95	0,95	0,95	

Table 4. Monthly mean temperature (˚C) and perception (mm) for the chosen locations

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
˚C	-2,2	-2,0	0,6	4,9	10,6	14,4	16,1	15,3	11,5	7,7	2,8	-0,5	6,6
mm	60	40	42	39	47	62	82	88	76	75	66	59	737

3.3.4 Products parameters

The product module input quantities for logwood and pulpwood were derived from the biomass module. These were allocated into four product categories: sawnwood, boards, paper and firewood, the board category was neglected. After their life-time the products were reallocated to recycling or energy purposes, no products were assumed to end up in land fills. All yield classes were assumed to have the same product parameters (Table 5.), these parameters were derived from Kaipainen (2004) for Norway spruce in Finland, but the parameter for fraction lost in process was adjusted for paper after the high amount of chemical pulp mills in Götaland.

Table 5. Parameters used in the product module

	Raw material allocation		
	Fraction to production line		
Raw material	Sawnwood	Paper	Firewood
Logwood	0,79	0,21	
Pulpwood		0,95	0,05
Production line	*Fraction lost in process reallocated to*		
Sawnwood		0,44	0,12
Paper			0,4
	Products average life span (yr)		
	Long term	Medium term	Short term
Average life span (yr)	50	15	1

Products allocation	Fraction allocated to		
Production line	Long term	Medium term	Short term
Sawnwood	0,35	0,45	0,20
Paper			1
Products allocation end of life	*Fraction disposed to*		
	Recycling	Energy	Landfill
Long term	0,30	0,70	
Medium term	0,25	0,75	
Short term	0,70	0,30	
Production type	*Fraction recycled as*		
	Long term	Medium term	Short term
Long term		0,50	0,50
Medium term		0	1

3.3.5 Bioenergy parameters

GWP index for each GHG were derived from IPCC (table 6) Heating value was set to 15 MJ/kg for both slash and industrial residues. Coal combusted in a cookstove was chosen to be substituted by slash wood combusted with the technology stoker boiler. Industrial residues fuelwood was combusted in a stoker boiler with adjusted efficiency according to the substituted fossil fuel, which was oil combusted in a combustion plant. These alternatives and combinations were chosen due to that they have the same combustion efficiency and I wanted to compare the substitution effect independently from the combustion technology. See table 7 for these parameters, which are basic parameters in CO2FIX V 3.1.

Table 6. Parameters applied in the biomass module.

Global warming potential (GWP)				
CO_2	CH_4	N_2O	CO	TNMOC
1	23	296	2	12

Table 7. Bioenergy parameters.

		Technology emission factors (g/Kg fuel)						
Fuel	*Technolgy*	*CO_2*	*CH_4*	*N_2O*	*CO*	*TNMOC*	*Heating value (MJ/kg)*	*Efficiency (%)*
Fuelwood from slash	Stoker Boiler	0	0,225	0	8,85	0	15	24
Coal	Cookstove	2550	7,98	0,037	66,2	0,02	28	24
Industrial residues Fuelwood	Stoker Boiler	0	0,225	0	8,85	0	15	33
Oil	Combustion plant	3134,82	0,121	0,08	0,603	0,1206	40,19	33

4. Result

4.1 High yield class

4.1.1 High yield class, 30 years perspective

The simulations in the high yield class clearly showed that even a modest change in rotation age with 20 years affects the carbon allocation and the amount of carbon stored significantly (Table 8). Prolonged scenario increased the biomass carbon pool with 17 % and the carbon soil pool with 5 %, compared to the business as usual scenario (BAU). In absolute values this corresponds to an increase of the biomass and soil carbon pool with almost 22 TgC in the high yield class. It means that during the period the biomass and soil carbon sink that is eligible under Kyoto article 3.4. annually increased with 0,78 TgC compared to the BAU scenario on the high yield class forest area. The main reason for the increase in the biomass pool was that the prolonged rotation led to a decrease in harvested volume with 26 % (Figure 4). This decrease in harvested volume led to that the biomass energy mitigation carbon pool decreased with 21 % and that the product pool decreased with 23 % (Table 8). In absolute values it means that the substitution effect from bioenergy carbon pools decreased with roughly 13 TgC and the product pool with 3 TgC in Götaland for the prolonged scenario compared to BAU. (Figure 6). Measured over all carbon pools the prolonged scenario led to a total increase in carbon sequestration with 2 % or 5,7 TgC for the 30 years period, compared to the BAU scenario.

Table 8. Carbon allocation and sequestered amount (TgC), in High yield class after 30 years.

30 year	*Biomass*	*Soil*	*Products*	*Bioenergy*	*Bioenergy*	*Bioenergy*	*Total*
				Slashwood Mitigation	**Industrial Mitigation**	**Total**	
BAU	**100,74**	**109,17**	**13,67**	**3,99**	**59,40**	**63,39**	**286,97**
Long	**117,71**	**114,17**	**10,59**	**1,87**	**48,37**	**50,24**	**292,71**
Short	**84,50**	**104,16**	**14,21**	**7,59**	**67,05**	**74,65**	**277,52**

The carbon sequestration pattern for shortened rotation with 20 years is contrary compared to the prolonged rotation. It resulted in that the biomass carbon pool decreased with 16 % and the soil carbon with 5 % compared to BAU. In absolute values it means that the biomass and soil carbon pool decreased with 21 TgC. The harvesting volume for the shortened scenario was 17 % higher compared to BAU. This is the main reason for the decrease in the biomass and soil carbon pool. Another consequence due to this is that the bioenergy slashwood mitigation carbon pool increased with 90 % and the industrial mitigation carbon pool increased with 13 %. In absolute values the biggest increase at 7,66 TgC occurred in the industrial mitigation pool, in the slashwood mitigation pool the increase was 3,60 TgC. The huge relative increase for the slashwood mitigation pool was due to the high amount of final fellings in the shortened scenario (Figure 5). The product pool increased with 4 % or 0,54 TgC. Totally the shortened scenario led to a decrease in carbon sequestration over all pools with 3 % or 9,45 TgC compared to BAU scenario. Compared to the prolonged scenario the carbon sequestration decreased with 5 % or 15,19 TgC. The pattern for bioenergy was the opposite compared to the prolonged scenario (Figure 6).

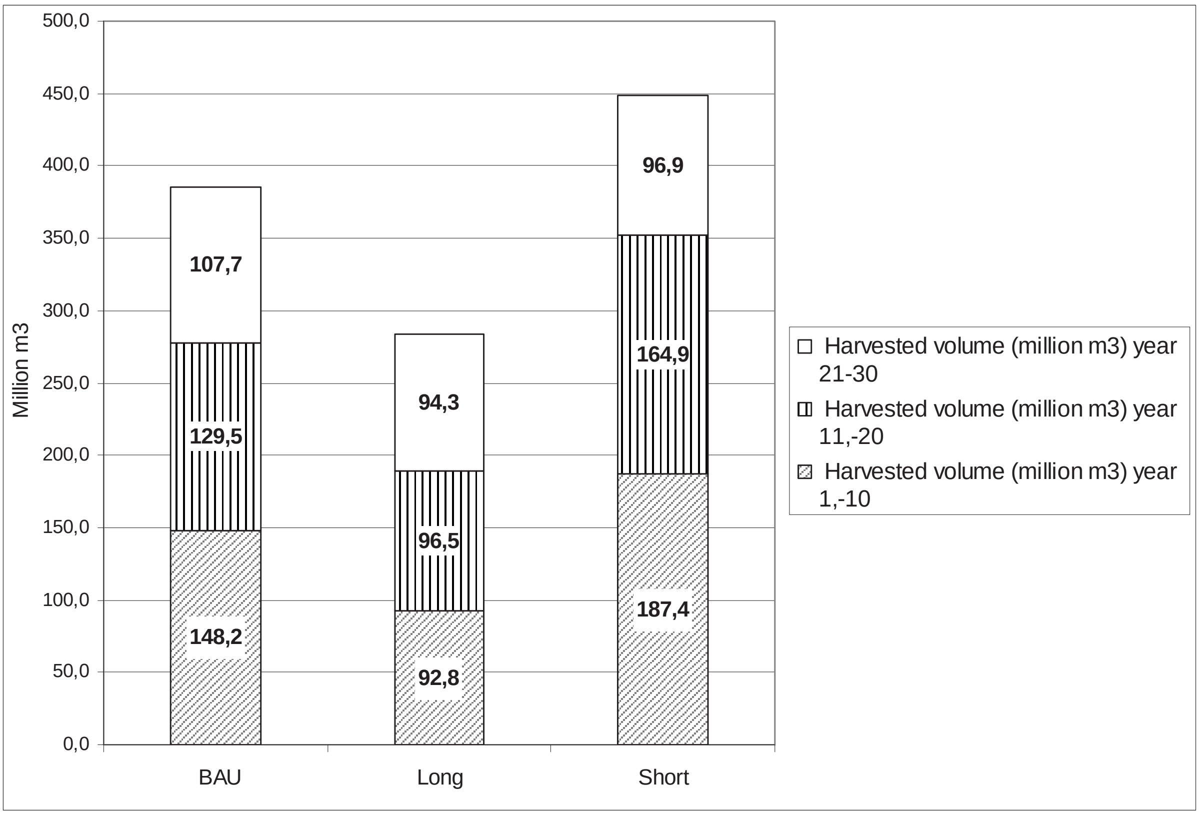


Figure 4. Harvested volume per scenario during the period (million m^3), divided into 10 years interval.

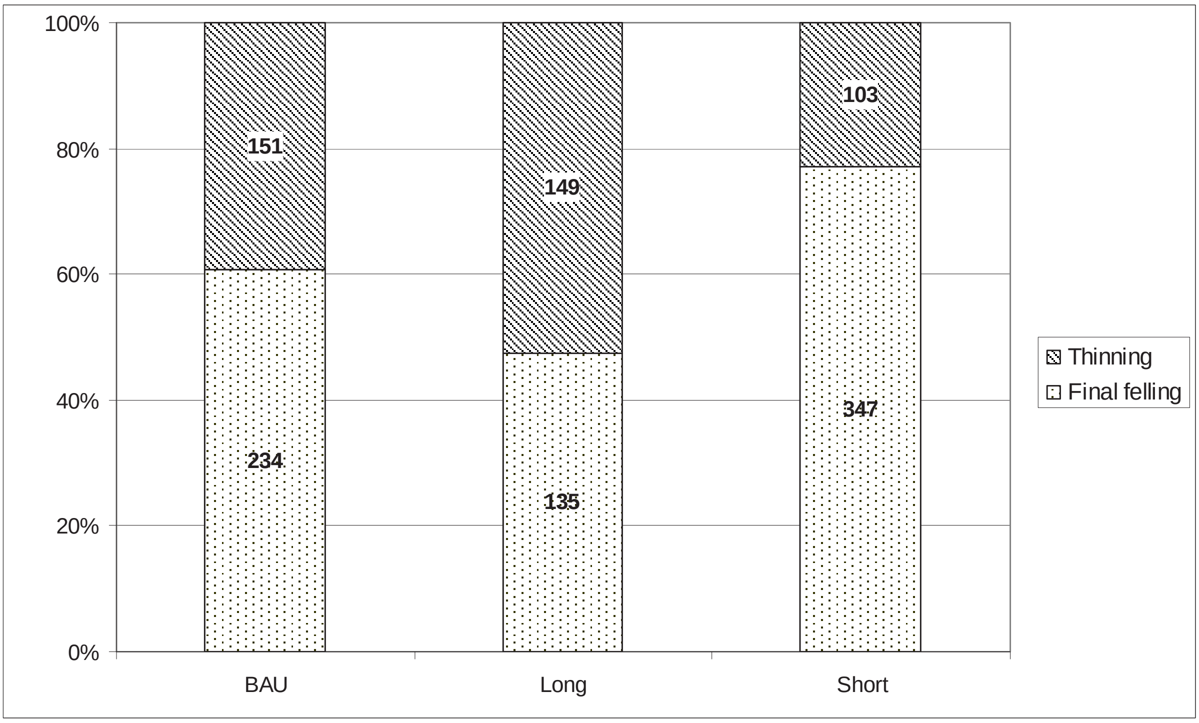


Figure 5. Dividing of harvested volume between final felled and thinned volume per scenario during the 30 years period. Values in bars in million m^3

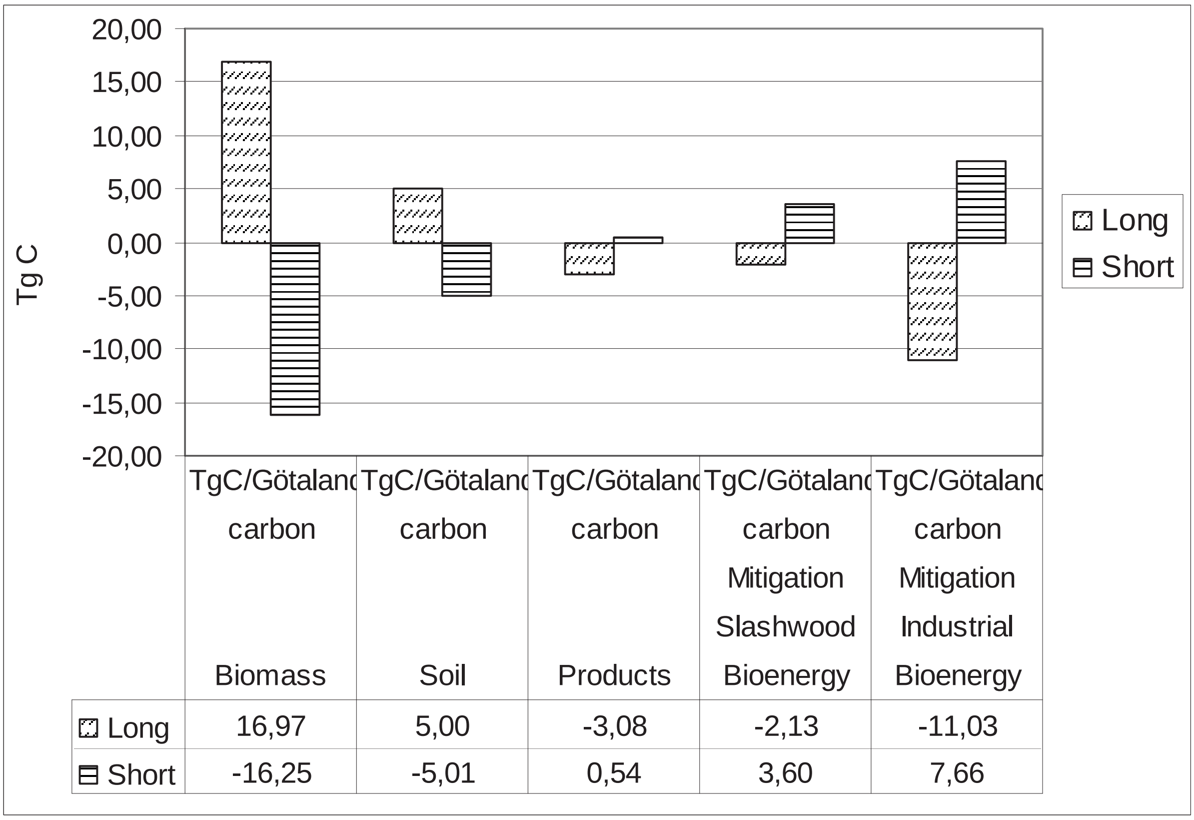


Figure 6. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 30 year time horizon.

4.1.2 High yield class 300 years perspective

In these simulations the BAU, prolonged and shortened rotation age was studied on a 300 years time-scale instead of the 30 years time-scale. This led to drastic shifts in the mitigation potential ranking for the different rotation age scenarios (Table 9).

In this case the prolonged scenario increased the biomass carbon pool with 13 % and the soil carbon pool with 7 %. This corresponds to an increase in the biomass carbon with 13,03 TgC and with 8,09 TgC for the soil carbon pool over the 300 years period compared to BAU. This means that the mean annual forest ecosystem sink eligible under Kyoto 3.4 would be 0,07 TgC in the long term scenario. The harvested volume for the prolonged scenario was 17 % lower compared to the BAU scenario over the 300 years period. Also for the long term scenario the main reason for the higher sink in the forest ecosystem was the decreased harvested volume. Which also led to that the bioenergy mitigation carbon pool was 17 % lower for the prolonged scenario, which in absolute value led to that 90,36 TgC more is emitted to the atmosphere during the 300 year period compared to the BAU scenario. The lower harvest level also led to that the product pool decreased with 12 % (2,68 TgC). Summarizing the changes in all carbon pools 9 % (71,93 TgC) more carbon was emitted to the atmosphere for the prolonged rotation scenario compared to the BAU scenario.

Table 9. Carbon allocation (TgC) in High yield class after 300 years.

300 year	*Biomass*	*Soil*	*Products*	*Bioenergy* Slashwood Mitigation	*Bioenergy* Industrial Mitigation	*Bioenergy* Total	*Total* carbon
BAU	**101,69**	**119,95**	**22,39**	**43,50**	**477,75**	**521,25**	**765,28**
Long	**114,71**	**128,04**	**19,71**	**42,75**	**402,67**	**430,89**	**693,35**
Short	**83,56**	**112,27**	**20,62**	**74,72**	**504,75**	**579,47**	**795,92**

When the shortened rotation age was studied over a 300 years period, it led to a drastic shift in the mitigation potential for this strategy compared to the 30 years period.
The biomass carbon pool decreased with 18 % (18,13 TgC) and the soil carbon pool with 6 % (7,68 TgC) in relation to the BAU scenario. The biggest advantage for the shortened scenario originates from the harvested volume and especially the high amount of final fellings, which during the 300 year period was 18 % higher for the shortened scenario compared to BAU (Figure 7). This resulted in that the bioenergy slashwood mitigation carbon pool was 72 % (31,22 TgC) bigger and that the industrial mitigation carbon pool increased with 6 % (27,01 TgC). The increase in the industrial mitigation pool corresponds well with the increase in total harvested volume at 7 %. The shortened rotation led to that the harvested timber had a smaller dimension which led to that the product carbon pool decreased with 8 % (1,78 TgC) compared to BAU. The carbon allocation for the different management alternatives shows similar patterns with the 30 years horizon, but the importance of bioenergy increases and plays a major role for the outcome when 300 years is applied (Figure 8). Summarizing all carbon pools the total carbon sequestration increased with 4 % (30,64 TgC) over the 300 year period applying the shortened scenario compared to the BAU scenario. The main reason for this is as mentioned before the accumulating characteristics for the mitigation pools.

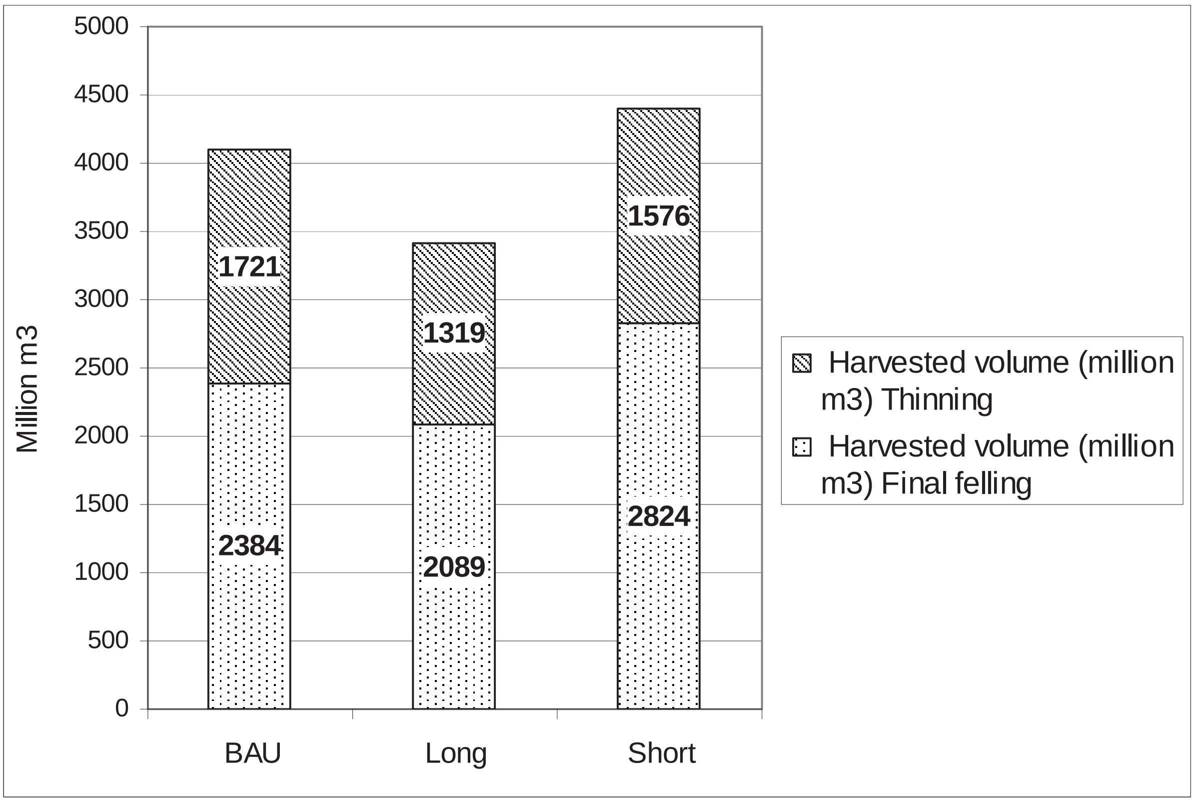


Figure 7. The figure shows the total felled volume in million m^3 during the 300 years period, divided into volume from thinnings and final fellings for each scenario.

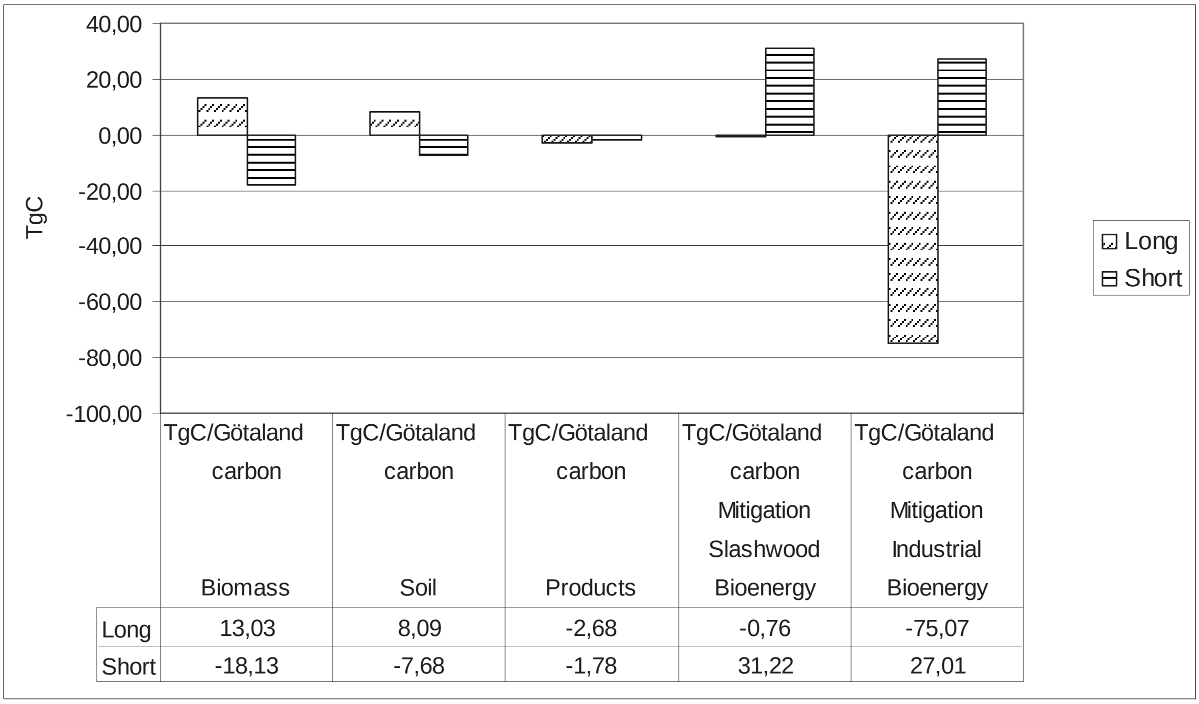


Figure 8. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 300 year time horizon.

4.1.3 High yield class, comparison between 30 years and 300 years time horizon.

The result from the simulations for the high yield class shows clearly that the different strategies carbon sequestration potential is correlated and highly depends on which timescale that is applied. For the 30 years time horizon the prolonged rotation age will result in the highest carbon sequestration. The main reason for this is the larger carbon stock in biomass, due to the lower harvest level that already has been mentioned. Another reason connected with the previous is that such a short time horizon as 30 years is not enough for the regenerated areas to become a true carbon sink due to the increased rate of decomposition that the final felling leads to. By shifting to the long term horizon the mitigation potential for the prolonged scenario changed drastically (Figure 9) and the result for the high yield class in a 300 years horizon clearly shows the opposite result. In this case the shortened rotation age sequester more carbon than the other alternatives. In the long term horizon the substitution pool had a major impact, the main reason for this is that it do not get saturated and continue to grow with the same pace during the whole period. In figure 10 it is obvious that the difference in biomass sequestration is evening out in a longer time perspective. This is very obvious for the biomass pool, where the carbon pool differences between the prolonged and shortened rotation age decreased with 2,06 TgC in the 300 year horizon compared to the 30 year horizon. Another example on this shifts is that the difference in the bioenergy mitigation pool increased with 124,17 TgC between the different time horizons. Similar pattern can be seen in figure 11 where the size of each carbon pool and how their importance changes depended on which time horizon that is applied. The figures also show that the differences will even out in a longer time perspective.

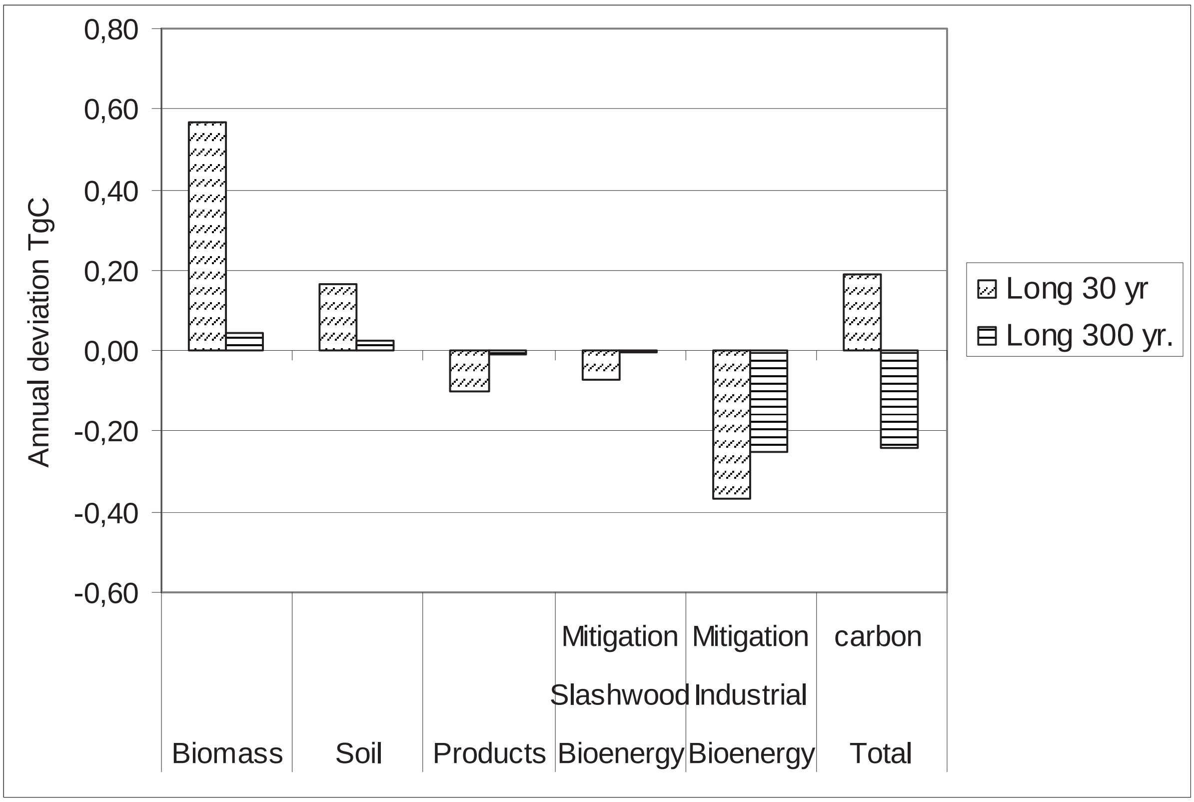


Figure 9. Shows the mean annual sequestration difference for the prolonged (Long) scenario, compared to BAU for 30 and 300 years time horizon.

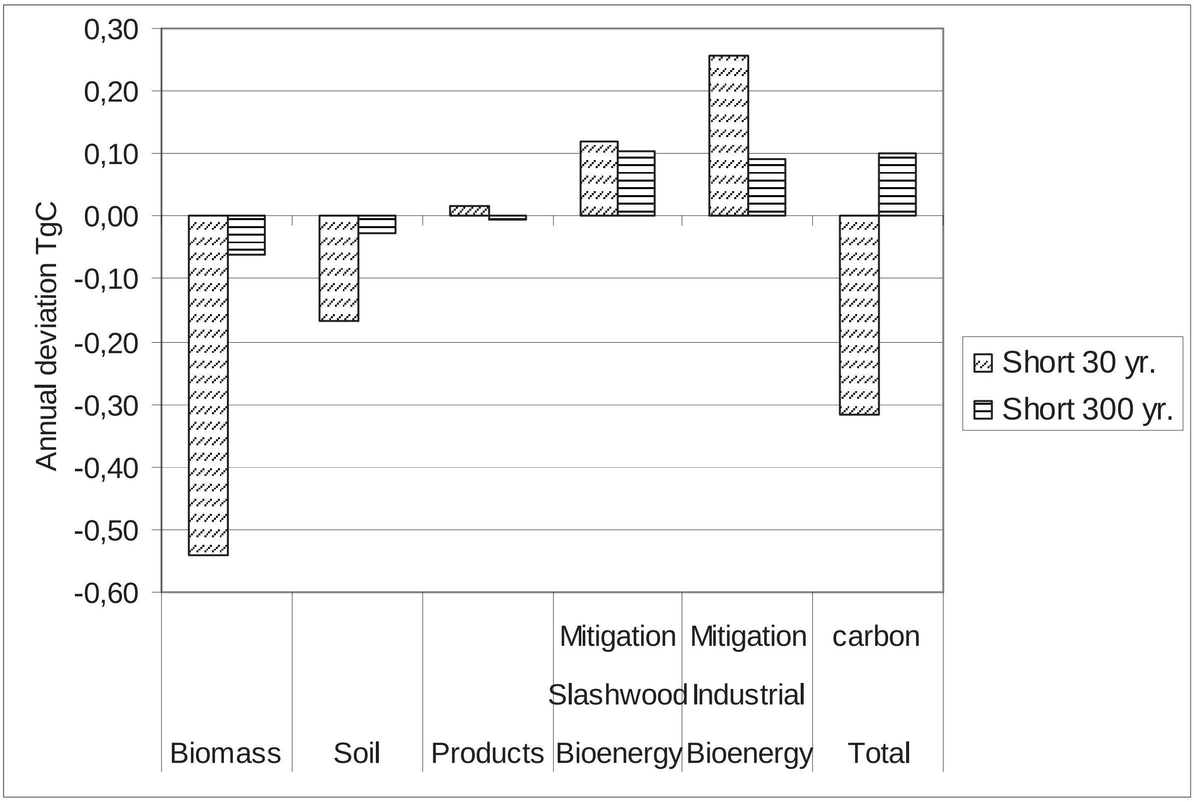
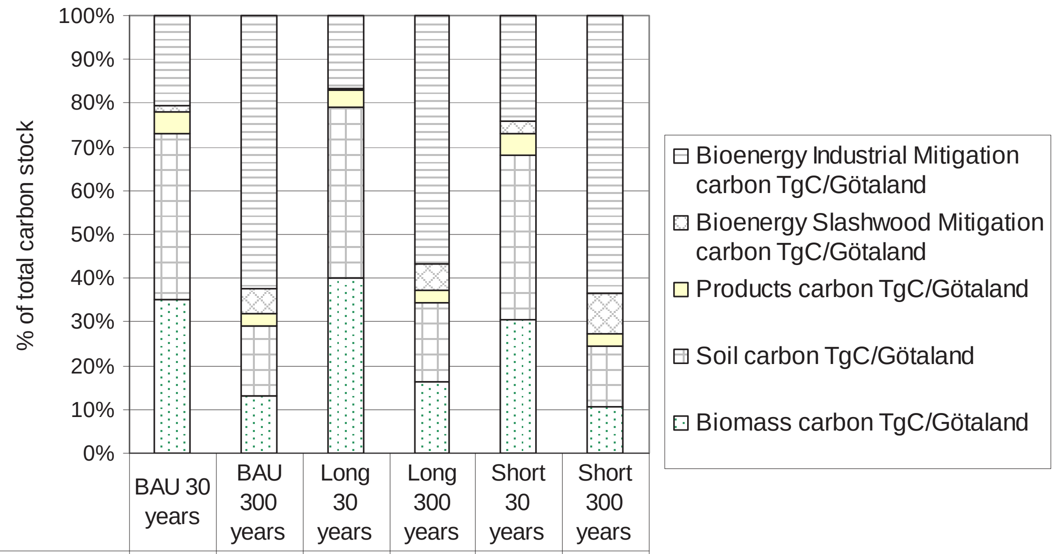


Figure 10. Shows the mean annual sequestration difference for the shortened (Short) scenario, compared to BAU for 30 and 300 years time horizon



	BAU 30 years	BAU 300 years	Long 30 years	Long 300 years	Short 30 years	Short 300 years
Bioenergy Industrial Mitigation carbon TgC/Götaland	59,40	477,75	48,37	402,67	67,05	504,75
Bioenergy Slashwood Mitigation carbon TgC/Götaland	3,99	43,50	1,87	42,75	7,59	74,72
Products carbon TgC/Götaland	13,67	22,39	10,59	19,71	14,21	20,62
Soil carbon TgC/Götaland	109,17	119,95	114,17	128,04	104,16	112,27
Biomass carbon	100,74	101,69	117,71	114,71	84,50	83,56

Figure 11. Show the carbon allocation for the different scenarios and time horizons and how the importance carbon pools that do not get saturated increases when a longer time horizon is applied.

4.2 Medium yield class

4.2.1 Medium yield class, 30 years perspective

The simulations for the medium yield class showed similar pattern as the high yield class. Even if the divergence between the different rotation lengths were of slightly smaller magnitudes compared to the high yield class, they still had a clear impact on the sequestration of carbon (Table 10). The prolonged scenario where the rotation age was prolonged from 80 years to 100 years, the carbon stock in the biomass pool increased with 11 % (2,26 TgC) and the soil carbon pool with 5 % (0,96 TgC). This would give an annual increase of the carbon sink in biomass and soil with 0,12 TgC compared to the 80 years rotation in BAU scenario. This increase is eligible under Kyoto protocol article 3.4 as an alternative forest management regime applied on the medium yield class Norway spruce forest area. The main reason for the increase in the biomass carbon pool was that the prolonged scenario led to a 13 % decrease in harvest level compared to BAU under the 30 years period (Figure 12). The decrease in the harvested volume had negative impact on the bioenergy and product carbon pool. The mitigation effect from slashwood decreased with 35 % (0,25 TgC), industrial mitigation pool with 14 % (1,73 TgC) and the product pool with 8 % (0,20 TgC) compared to BAU (Table 10). The outcome on the net carbon sequestration for the prolonged scenario is that it increased the carbon sequestration compared to the BAU scenario with 2 %. Which led to that the carbon sink over the 349 700 hectares of medium yield class Norway spruce forest in Götaland would increase with 1,97 TgC in the 30 year period.

Table 10. Carbon location (TgC) in Medium yield class after 30 years.

30 year	*Biomass*	*Soil*	*Products*	*Bioenergy Slashwood Mitigation*	*Bioenergy Industrial Mitigation*	*Bioenergy Total*	*Total carbon*
BAU	**19,95**	**20,53**	**2,39**	**0,71**	**11,90**	**12,61**	**55,48**
Long	**22,21**	**21,50**	**2,19**	**0,46**	**10,18**	**10,64**	**56,53**
Short	**16,39**	**19,70**	**2,76**	**1,18**	**12,93**	**14,11**	**52,96**

Even for the medium yield class the carbon sequestration and location pattern for the shortened scenario is contrary compared the scenario with prolonged rotation age.
The simulations showed that shortened rotation with 20 years led to a decrease in the biomass carbon pool with 18 % (3,56 TgC) and in the soil carbon pool with 4 % (0,84 TgC) compared to BAU. The main reason for this drastic decrease was that the total harvested volume increased with 13 % and it gets even more obvious since the volume from final felling were 40 % higher compared to BAU (Figure 13). The high amount of final felling led to that the mitigation effect from slashwood was 65 % higher (0,48 TgC), the bioenergy industrial mitigation was 9 % bigger (1,02 TgC) and the product carbon pool increased with 16 % (0,37 TgC). Also the result from the simulations for the medium yield class clearly shows that the total carbon stock decreases when the rotation age is shortened and in this case the decrease from 80 years to 60 years led to a decrease at 5 % (1,5 TgC). This means that the result from the shortened scenario compared to the prolonged scenario shows that the total carbon sequestration measured over all pools decreased with roughly 7 % (3,57 TgC) over the 30 years period. This means that the impact from the different pools shows a similar pattern with the high yield class (Figure 14).

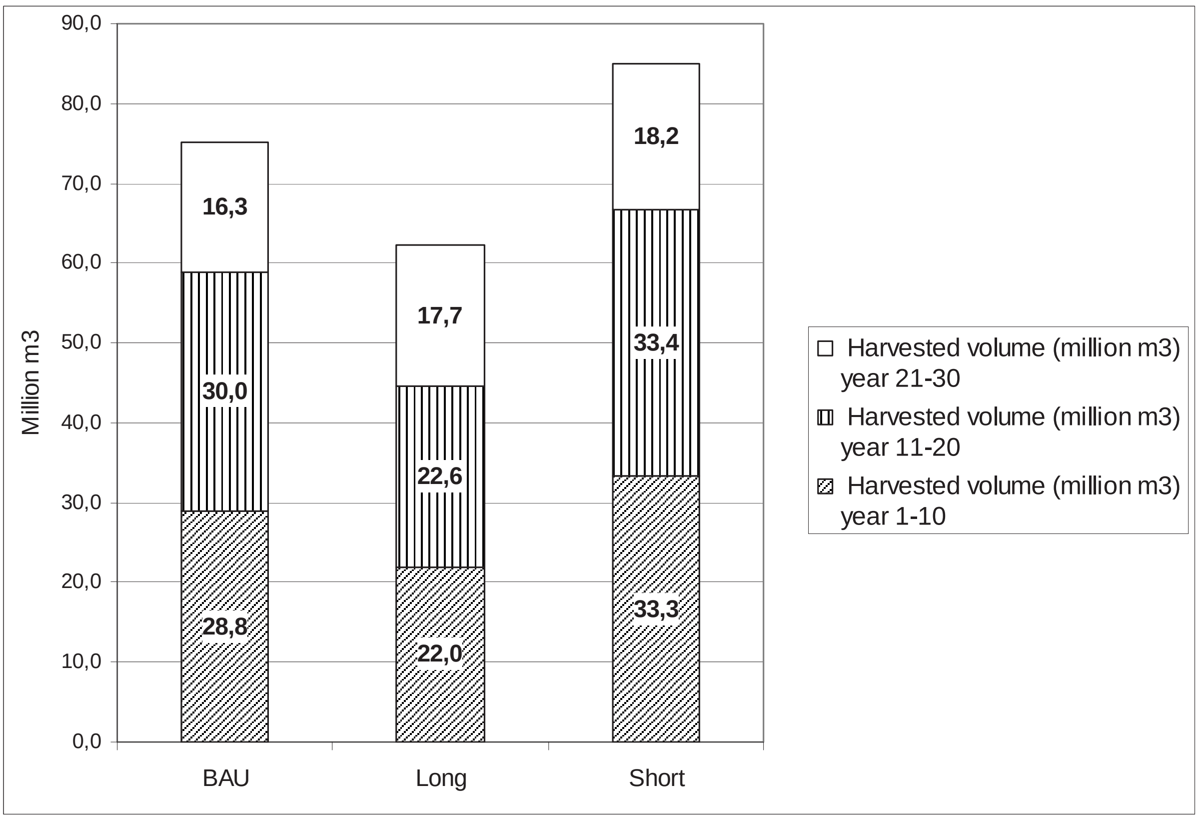


Figure 12. Harvested volume per scenario during the period, divided into 10 years interval.

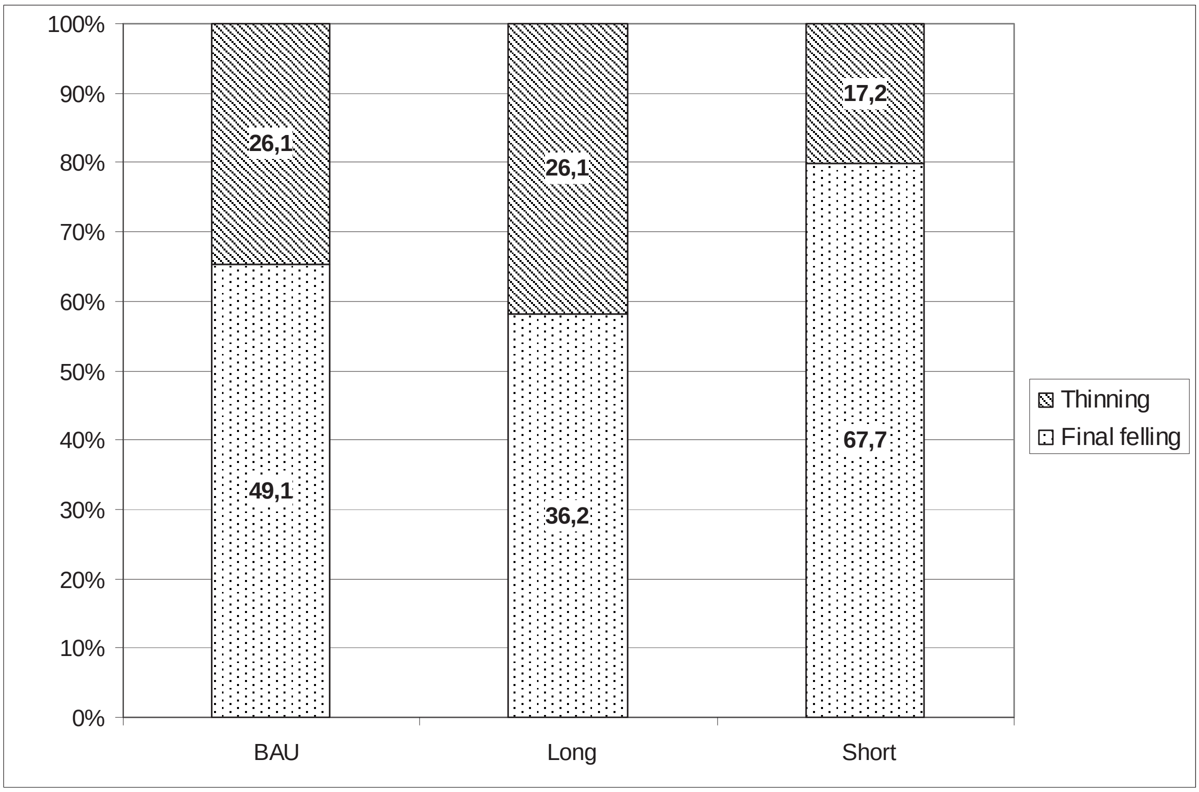
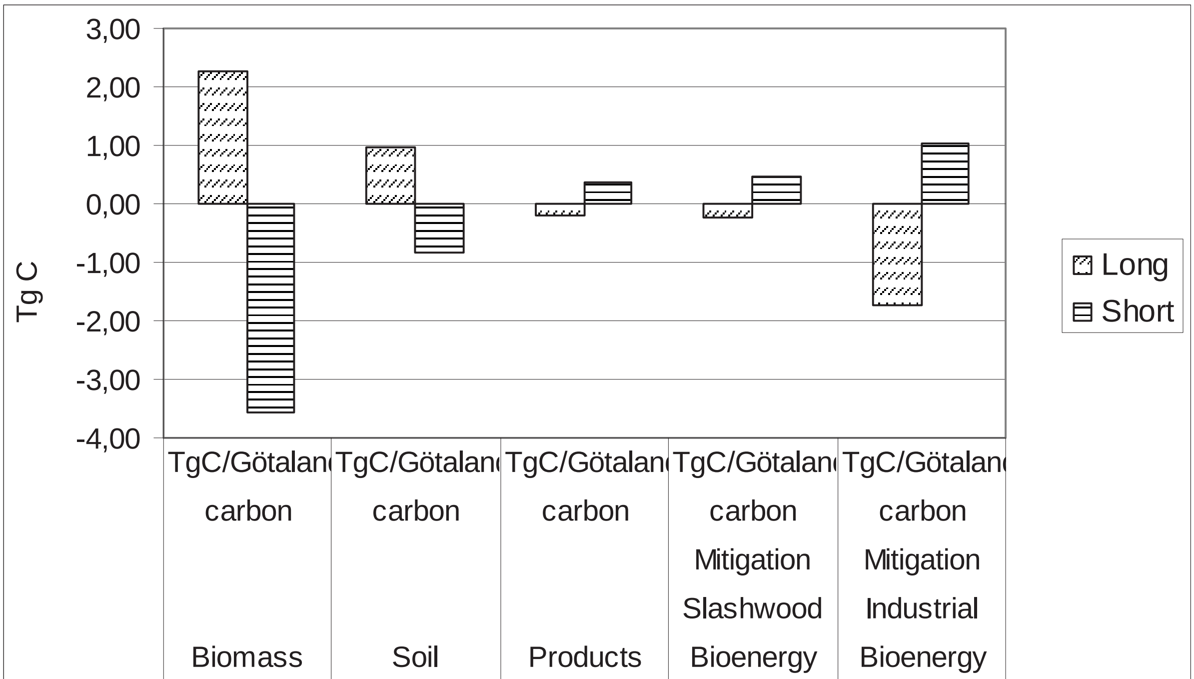


Figure 13. Dividing of harvested volume between final felled and thinned volume per scenario during the 30 years period. Values in bars in million m^3



	TgC/Götalan carbon Biomass	TgC/Götalan carbon Soil	TgC/Götalan carbon Products	TgC/Götalan carbon Mitigation Slashwood Bioenergy	TgC/Götalan carbon Mitigation Industrial Bioenergy
Long	2,26	0,96	-0,20	-0,25	-1,73
Short	-3,56	-0,84	0,37	0,48	1,02

Figure 14. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 30 year time horizon.

4.2.2 Medium yield class, 300 years perspective

Also in the medium yield class simulations were made to see how the time perspective affected the influence on carbon sequestration for different rotations lengths. The patterns were similar to the pattern for the high yield class, but it was some differences in the magnitudes from BAU between the yield classes. The time horizon change led to drastically changes in the ranking of the best carbon sequestration scenario (Table 11).
The prolonged scenario led to that the biomass and soil carbon stock increased with 16 % (3,15 TgC) respectively 5 % (1,19 TgC) over the 300 year period. This resulted in that the size of the annual forest ecosystem sink eligible under Kyoto protocol article 3.4 would be 0,015 TgC, which is 8 times less compared to the 30 years time horizon. The reason for the increased forest ecosystem carbon sink compared to the BAU is that the prolonged scenario led to a 20 % decrease in harvested volume over the period (Figure 15). The 20 % decrease in harvested level also led to that the bioenergy slashwood carbon pool decreased with 32 % (2,19 TgC) and that the bioenergy industrial carbon pool decreased with 19 % (16,28 TgC). The harvest level even influenced the product carbon pool by decreasing it with 13 % (0,56 TgC). Summarizing the changes over all carbon pools in the 300 years time horizon is that the prolonged scenario led to that the total carbon stock decreased with 11 %. As a result from this 14,69 TgC more carbon would be emitted to the atmosphere by prolonging the rotation age from 80 years to 100 years in the 300 years time horizon.

Table 11. Carbon allocation (TgC) in Medium yield class after 300 years.

300 year	*Biomass*	*Soil*	*Products*	*Bioenergy Slashwood Mitigation*	*Bioenergy Industrial Mitigation*	*Bioenergy Total*	*Total carbon*
BAU	**19,21**	**23,35**	**4,19**	**6,78**	**85,28**	**92,06**	**138,81**
Long	**22,36**	**24,55**	**3,63**	**4,60**	**69,00**	**73,59**	**124,13**
Short	**16,55**	**19,25**	**3,91**	**11,55**	**86,91**	**98,46**	**140,65**

When the shortened scenario which decreased the rotation age from 80 years to 60 years was applied, it drastically shifted the sequestration potential for the shortened rotation compared to the other scenarios, even if it had the same effect on the biomass and soil carbon stock, which initial decreased with 16 %. This decrease was distributed as following: the biomass carbon pool 14 % (2,66 TgC) and the soil carbon pool 18 % (4,10 TgC). Even here the reason is that the shortened rotation age led to that the harvested volume and especially the final felling frequency increased (Figure 15). The final felling frequence mainly affects the bioenergy slashwood mitigation that increased with 70 % (4,77 TgC) compared to the BAU scenario. It is a big increase compared to the bioenergy industrial carbon pool that only increased with 2 % (1,63 TgC). The product carbon pool decreased with 7 % (0,28 TgC) during the period, due to the smaller dimensions of the harvested timber that led to that the amount of timber allocated to sawn wood decreased. Finally the increased bioenergy carbon more than well corresponded to the decreases in the other pools, which led to that the shortened scenario in the 300 year perspective increased the carbon sequestration with 2 % (1,84 TgC) compared to the BAU scenario. The relationship between the different scenarios influence on the different pools compared to BAU can be seen in figure 16.

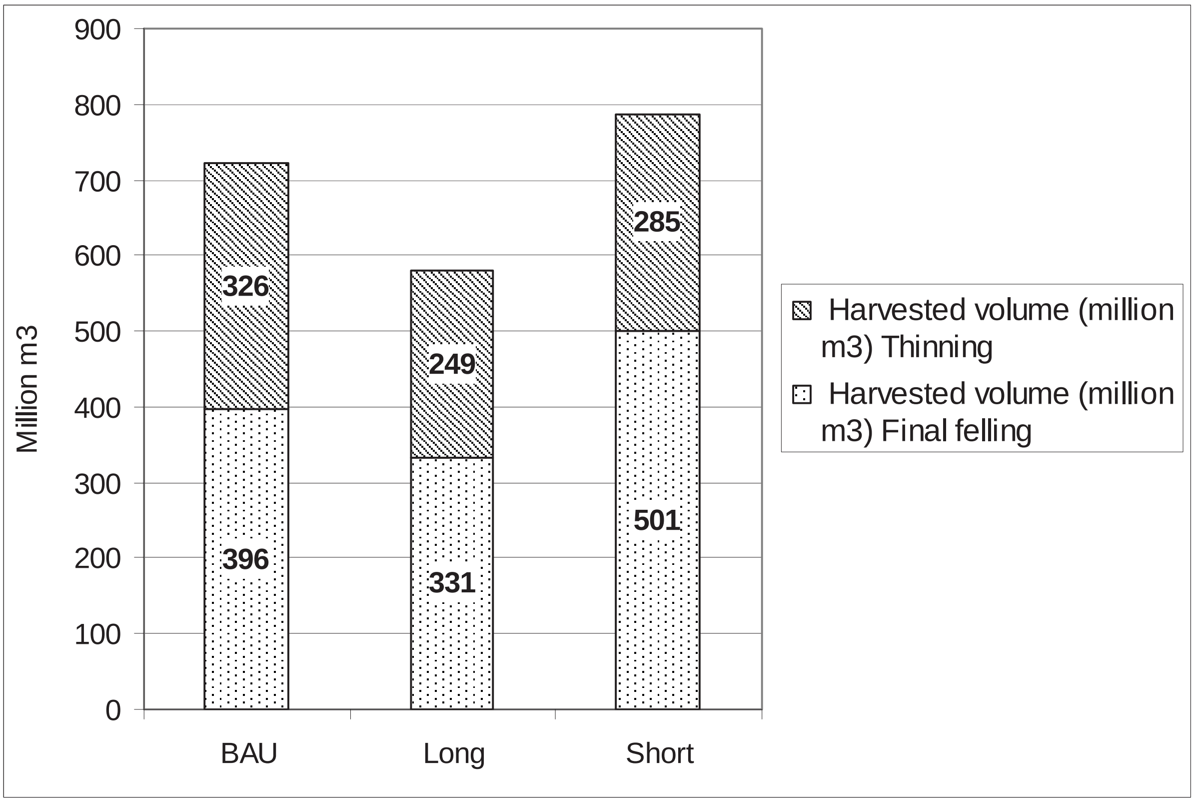
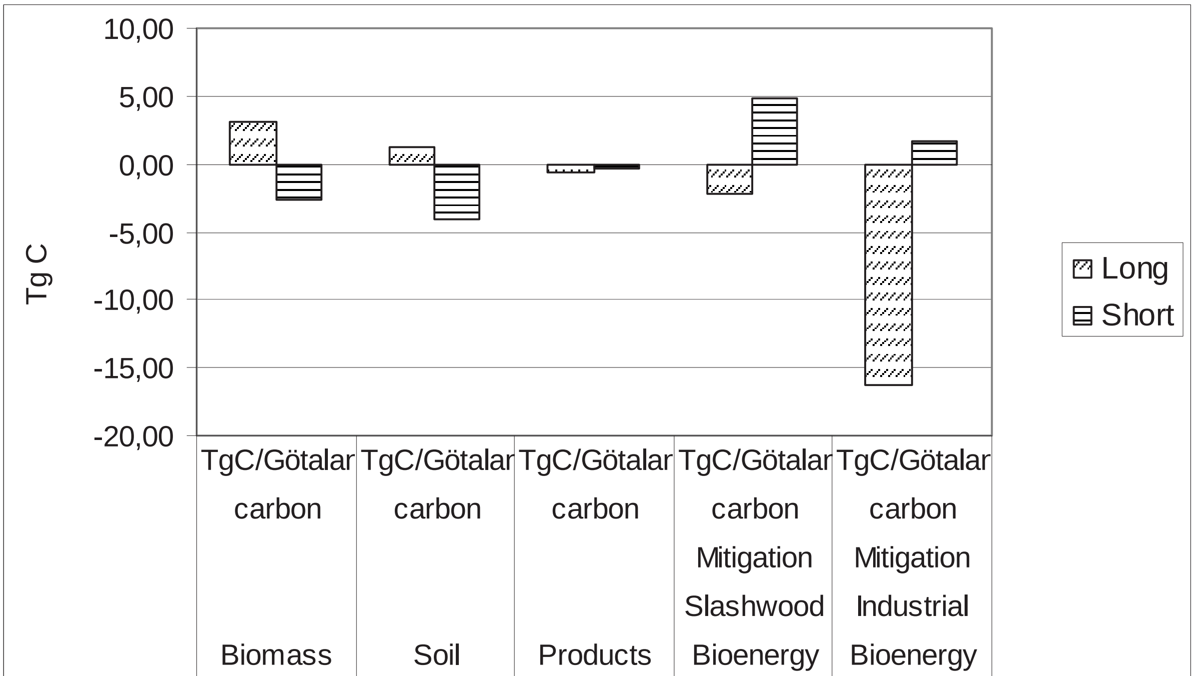


Figure 15. The figure shows the total felled volume in million m^3 during the 300 years period, divided into volume from thinnings and final fellings for each scenario. Value in bars in million m^3



	TgC/Götalar carbon Biomass	TgC/Götalar carbon Soil	TgC/Götalar carbon Products	TgC/Götalar carbon Mitigation Slashwood Bioenergy	TgC/Götalar carbon Mitigation Industrial Bioenergy
Long	3,15	1,19	-0,56	-2,19	-16,28
Short	-2,66	-4,10	-0,28	4,77	1,63

Figure 16. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 300 year time horizon in the medium yield class.

4.2.3 Medium yield class, comparison between 30 years and 300 years time horizon

The result from the simulations with changed rotation ages showed that even a modest change with 20 years affects the amount of carbon sequestered in the medium yield class Norway spruce forests in Götaland. The most important result follows the same pattern as for the high yield class. That one of the most important factors to take into consideration when it comes to changing forest management for reducing the net carbon emissions to the atmosphere is the time horizon. If the aim is to decrease the net carbon emissions in a 30 years period the prolonged scenario with decreased harvest levels fulfil this aim best. Even here the main reason for this is the decrease in final fellings, which leads to that more carbon are stored in the biomass and soil pool. This is connected with that a lot of carbon is emitted to the atmosphere after a final felling due to decomposition of harvest residues left at site, increased soil respiration and that the initial biomass increment does not correspond to this carbon emissions. But the decrease in bioenergy leads to that it only is 2 % better than BAU from a carbon sequestration point of view. In the 300 year horizon the result is the opposite and the shortened scenario slightly will outcompete the prolonged and the BAU scenario, due to that the bioenergy pool will not become saturated compared to the biomass and soil pool. Instead the increased harvested volume will be accumulated in the bioenergy pools and over a longer time period these pools will be much bigger than the biomass and soil carbon pool, this pattern is obviously for all scenarios (Figure 19). It can also be seen in figure 17 for the prolonged scenario and in figure 18 for the shortened scenario. It is also very obvious that the annual differences decrease when a longer time horizon is applied.

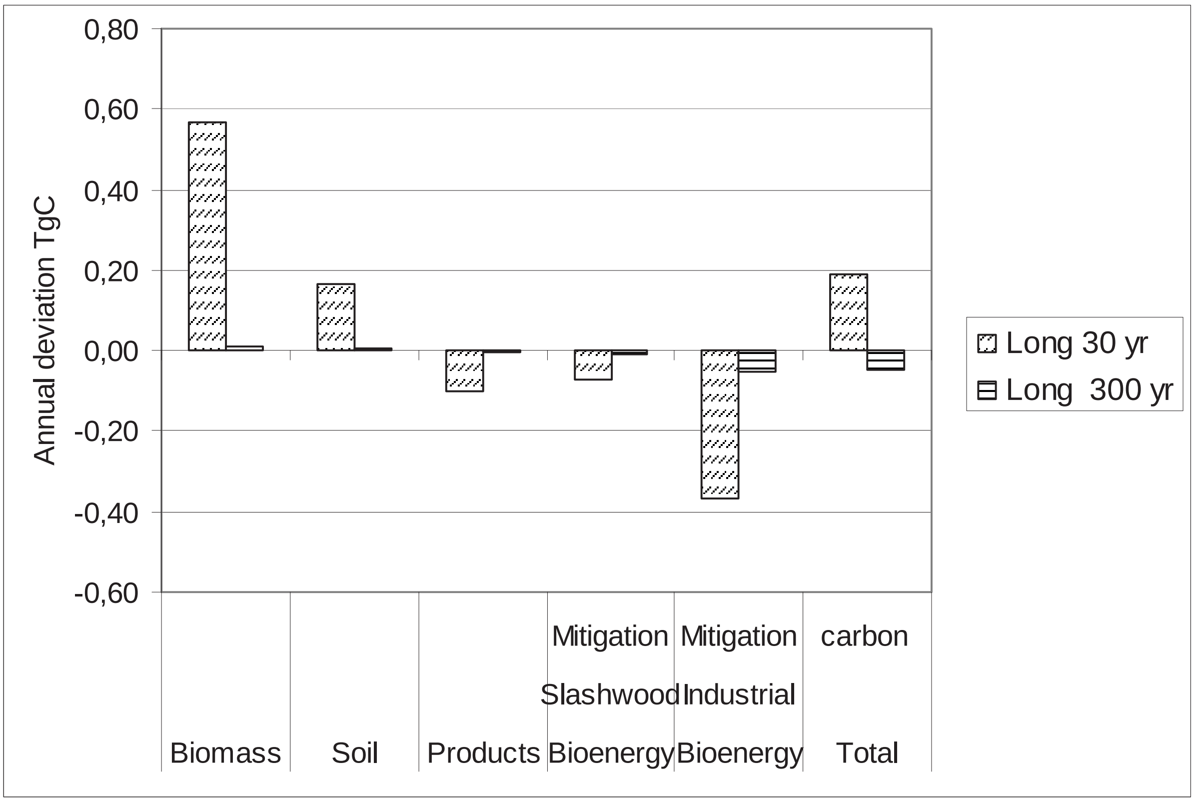


Figure 17. Shows the mean annual sequestration difference for the prolonged, compared to BAU scenario for 30 and 300 years time horizon in medium yield class.

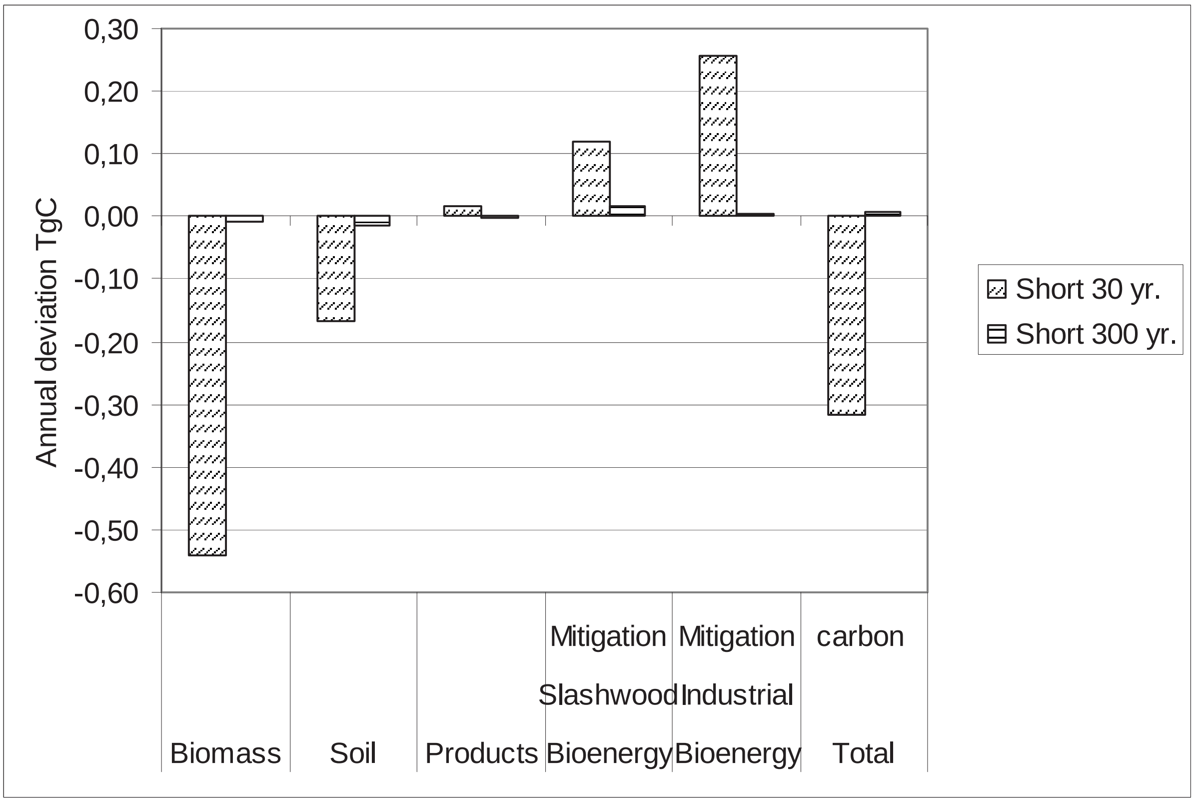
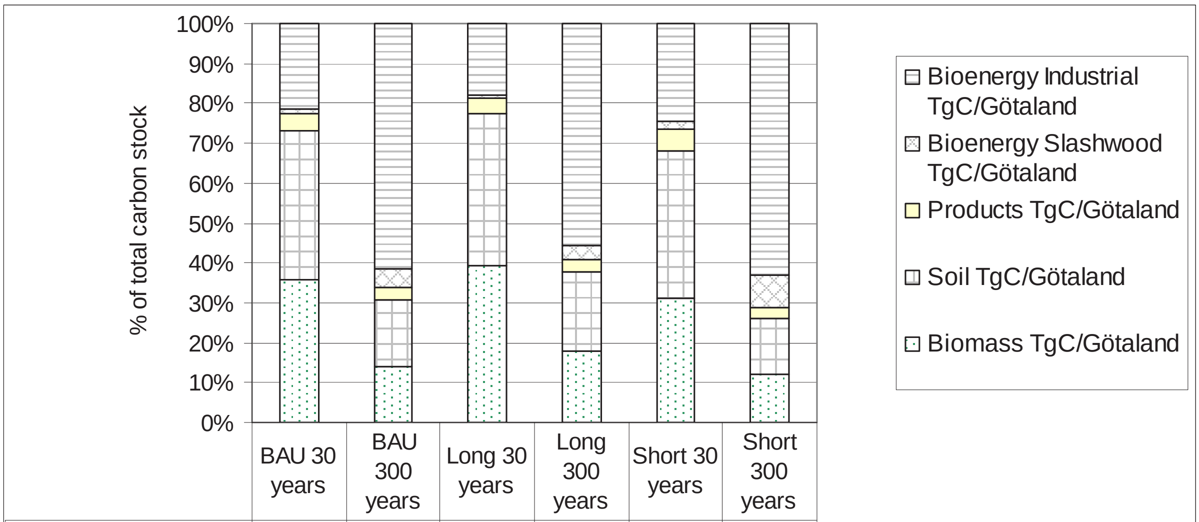


Figure 18. Shows the mean annual sequestration difference for the shortened scenario, compared to BAU scenario for 30 and 300 years time horizon in medium yield class.



	BAU 30 years	BAU 300 years	Long 30 years	Long 300 years	Short 30 years	Short 300 years
Bioenergy Industrial TgC/Götaland	11,90	85,28	10,18	69,00	12,93	86,91
Bioenergy Slashwood TgC/Götaland	0,71	6,78	0,46	4,60	1,18	11,55
Products TgC/Götaland	2,39	4,19	2,19	3,63	2,76	3,91
Soil TgC/Götaland	20,53	23,35	21,50	24,55	19,70	19,25
Biomass TgC/Götaland	19,95	19,21	22,21	22,36	16,39	16,55

Figure 19. The figure shows the importance of each carbon pool for different scenarios and especially how the importance of carbon pools that do not get saturated increases when a longer time horizon is applied.

4.3 Low yield class

4.3.1 Low yield class, 30 years perspective

Also the low fertile yield class with 85 years rotation age in the BAU scenario showed similar patterns with the simulations for the both higher yield classes. Even if the relation between the carbon pools showed some differences for the low yield class compared to the two higher yield classes (Table 12). In the prolonged scenario the biomass carbon pool increased with 15 % (0,69 TgC) and the soil carbon pool with 5 % (0,20 TgC). Over the 30 years period this means that the annual net sink eligible under article 3.4 for the prolonged scenario compared to the BAU scenario would be 0,03 TgC in the low yield class. Also in the low yield class the main reason for this is that a prolonged scenario led to a decrease in total harvested volume with 20 % and for final fellings with 30 %. This decrease in harvest level led to a decrease in the carbon pools which is direct correlated to the harvested volume, the product carbon pool decreased with 19 % (0,04 TgC), the bioenergy slashwood mitigation carbon pool with 39 % (0,07 TgC) and the bioenergy industrial mitigation pool with 14 % (0,32 TgC) compared to BAU scenario. Summarizing all changes, the prolonged scenario resulted in that 4 % (0,40 TgC) more carbon was sequestered compared to the BAU scenario over the 30 years period.

Table 12. Carbon allocation (TgC) in Low yield class after 30 years.

30 year	*Biomass*	*Soil*	*Products*	*Bioenergy Slashwood Mitigation*	*Bioenergy Industrial Mitigation*	*Bioenergy Total*	*Total carbon*
BAU	**4,60**	**4,06**	**0,49**	**0,18**	**2,30**	**2,48**	**11,63**
Long	**5,29**	**4,26**	**0,45**	**0,11**	**1,97**	**2,08**	**12,08**
Short	**3,86**	**3,85**	**0,50**	**0,30**	**2,51**	**2,81**	**11,02**

When the rotation age was shortened with 20 years it led to a contrary result also in the low yield class compared to the prolonged scenario. In the low yield class the simulations showed that the shortened scenario led to that the biomass carbon pool decreased with 16 % (0,74 TgC) and the soil carbon pool with 5 % (0,21 TgC) compared to BAU scenario. On the other hand the shortened scenario led to that the product carbon pool increased with 2 % (0,01 TgC). This relative small increase was mainly due to that the harvest level for the last ten years during the 30 year period was 20 % lower for the shortened scenario, compared to the BAU scenario (Figure 20). Measured over the entire 30 years period the harvest level was 12 % higher for the shortened scenario compared to BAU scenario and looking only at final fellings the increase was 40 % (Figure 21). This could be seen both in the decrease in the biomass and soil carbon pool and in the increase in the bioenergy carbon pools. The bioenergy slashwood mitigation pool increased with 65 % (0,12 TgC) and the bioenergy industrial mitigation pool with 9 % (0,21 TgC) compared to the BAU scenario. Summarizing the carbon sequestration differences measured over all carbon pools when the shortened scenario was applied clearly shows that it led to a decrease in carbon sequestration compared to the BAU scenario. In absolute values the decrease was 0,60 TgC (5 %). The pattern for the carbon sequestration differences for the different carbon pools is obvious in figure 22.

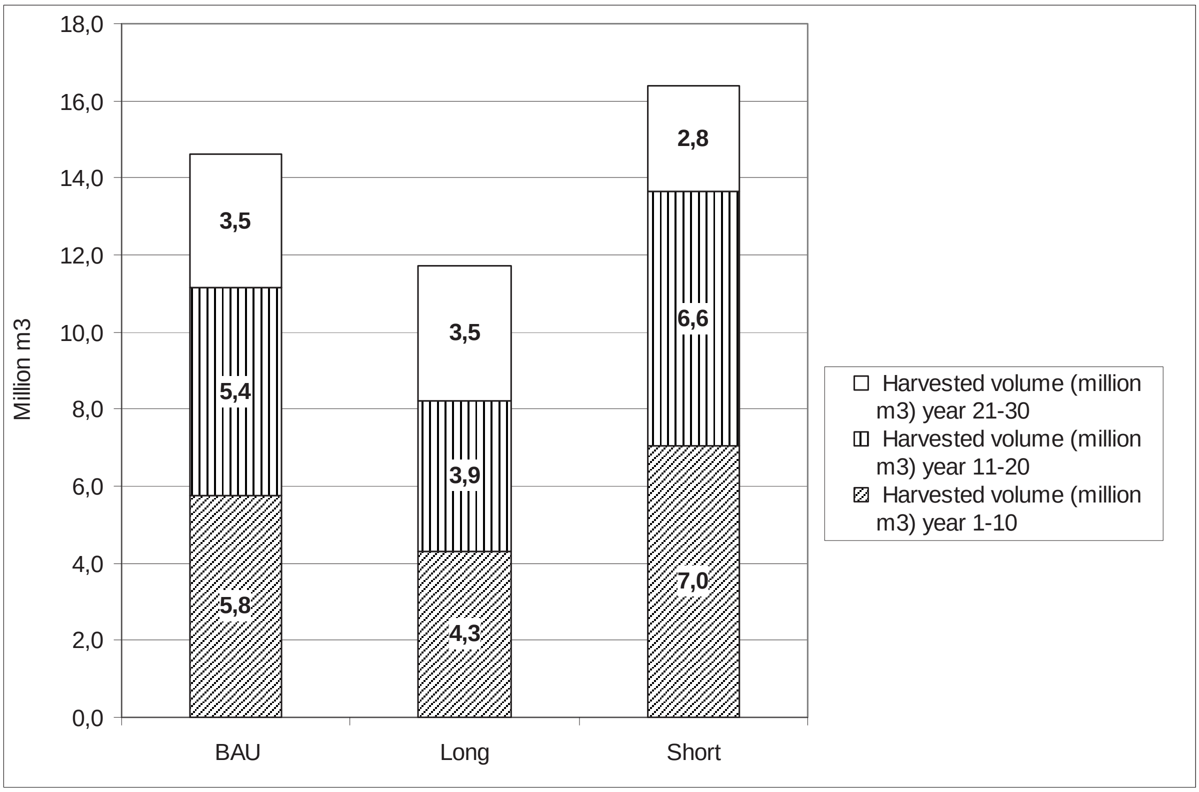


Figure 20. Harvested volume per scenario in the low yield class during the period, divided into 10 years interval.

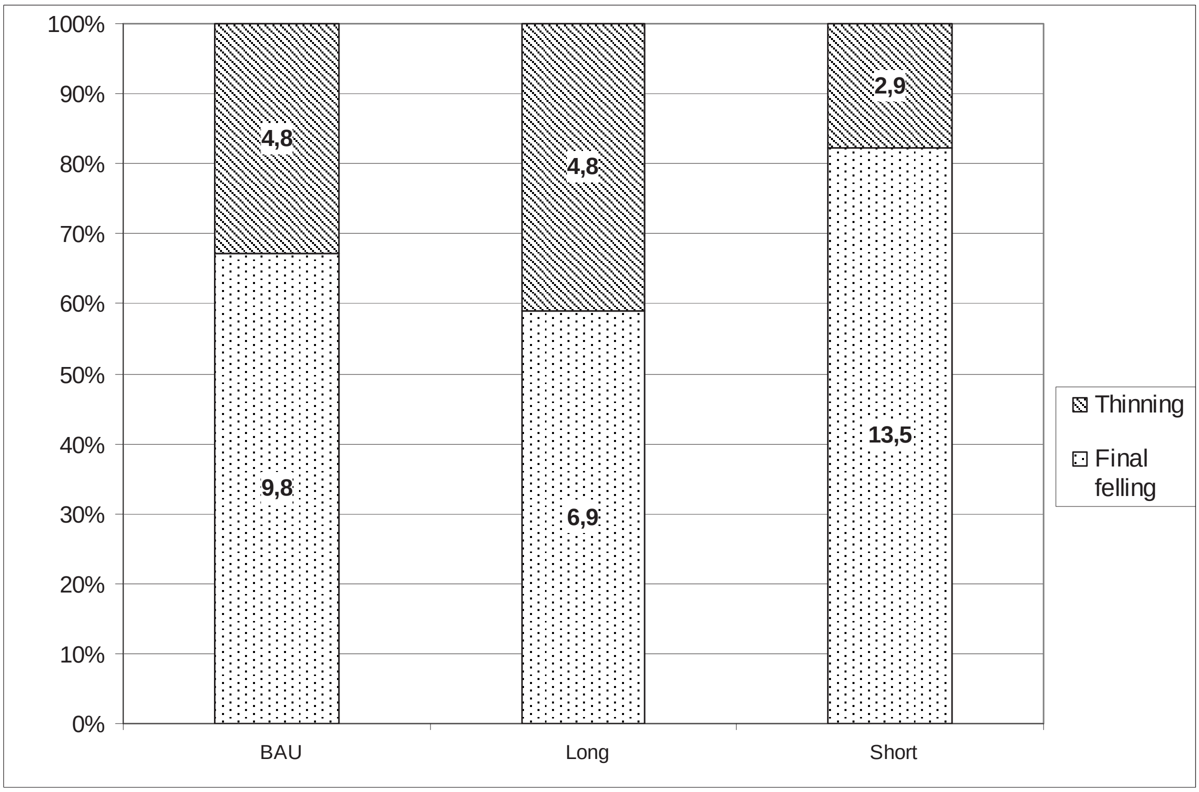
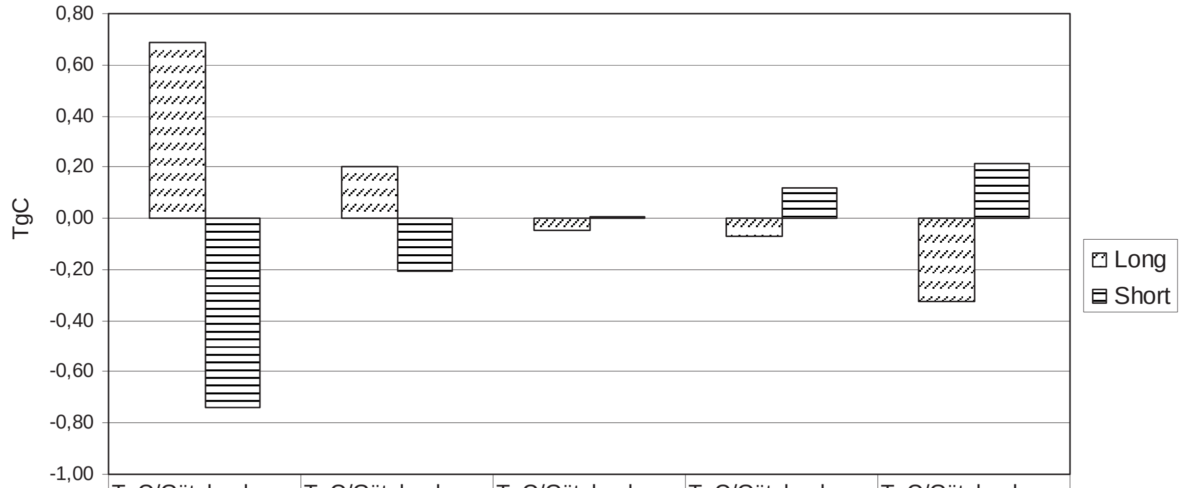


Figure 21. Dividing of harvested volume between final felled and thinned volume per scenario during the 30 years period in the low yield class, values in bars in million m^3.



	TgC/Götaland carbon Biomass	TgC/Götaland carbon Soil	TgC/Götaland carbon Products	TgC/Götaland carbon Mitigation Slashwood Bioenergy	TgC/Götaland carbon Mitigation Industrial Bioenergy
Long	0,69	0,20	-0,04	-0,07	-0,32
Short	-0,74	-0,21	0,01	0,12	0,21

Figure 22. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 30 year time horizon in the low yield class.

4.3.2 Low yield class, 300 years perspective

The low yield class simulations in the 300 years horizon showed similar pattern with the simulations for the two higher yield classes, but the result actually showed a shift on the throne for having the highest carbon sequestration potential compared to the two higher yield classes (Table 13). The prolonged scenario led to a marginal increase with 1 % (0,05 TgC) in the biomass carbon pool and the soil carbon pool actually decreased, even if it was at a insignificant level, less than < 1 % (0,01 TgC) compared to the BAU scenario. This means that the prolonged scenario in a 300 years horizon would lead to an insignificantly annual eligible net sink under article 3.4. In the prolonged scenario the harvested volume decreased with 17 % compared with BAU scenario and 12 % occurred in the final felled volume (Figure 23).

The 12 % decrease in final felled volume led to a decrease in the bioenergy slashwood mitigation carbon pool with 29 % (0,54 TgC) and the 17 % decrease in total harvested volume led to that the bioenergy mitigation carbon pool decreased with 13 % (2,47 TgC) compared to BAU scenario. The harvest level in the prolonged scenario also led to that the product pool decreased with 13 % (0,12 TgC). Summarizing the changes over all carbon pools the prolonged scenario in the 300 years horizon led to a decrease in total carbon sequestration with 11 % (3,5 TgC) compared to the BAU scenario. The carbon allocation for the different scenarios compared to BAU in the 300 years time horizon is showed in figure 24.

Table 13. Carbon allocation (TgC) in Low yield class after 300 years.

300 year	*Biomass*	*Soil*	*Products*	*Bioenergy Slashwood Mitigation*	*Bioenergy Industrial Mitigation*	*Bioenergy Total*	*Total carbon*
BAU	**4,76**	**5,07**	**0,95**	**1,89**	**19,18**	**21,06**	**31,85**
Long	**4,81**	**5,06**	**0,83**	**1,35**	**16,70**	**18,05**	**28,35**
Short	**3,79**	**4,61**	**0,89**	**3,05**	**19,32**	**22,36**	**31,65**

When the shortened scenario was applied in the 300 years horizon the carbon sequestration potential increased compared to the other scenarios, even if it did not led to any drastic shifts as for the two higher yield classes. The affect on the biomass and soil carbon pool eligible under article 3.4 was that they totally decreased with 15 % (1,44 TgC). The biomass carbon pool decreased with 21 % (0,98 TgC) and the soil carbon pool with 9 % (0,46 TgC) compared to BAU scenario. Despite this also the total harvested volume decreased with total 2 %, but the final felled volume increased as expected and in this case with 10 % compared to BAU scenario. This led to that the bioenergy slashwood mitigation carbon pool increased with 62 % (1,16 TgC) and bioenergy industry carbon with nearly 1 % (0,14 TgC) compared to BAU scenario. On the other hand the decreased total harvested volume and the shortened rotation age, led to that the harvested trees held a smaller average diameter, which resulted in that the product carbon pool decreased with 7 % (0,07 TgC) compared to BAU scenario. Calculated over all carbon pools the shortened scenario in the 300 years time horizon led to a marginal decrease in carbon sequestration at < 1 % (0,20 TgC) compared to the BAU scenario, which is a result that really differ from the result for the two higher yield classes. The relationship between the different rotation lengths impact on the size of the different carbon pools compared to BAU is shown in figure 24.

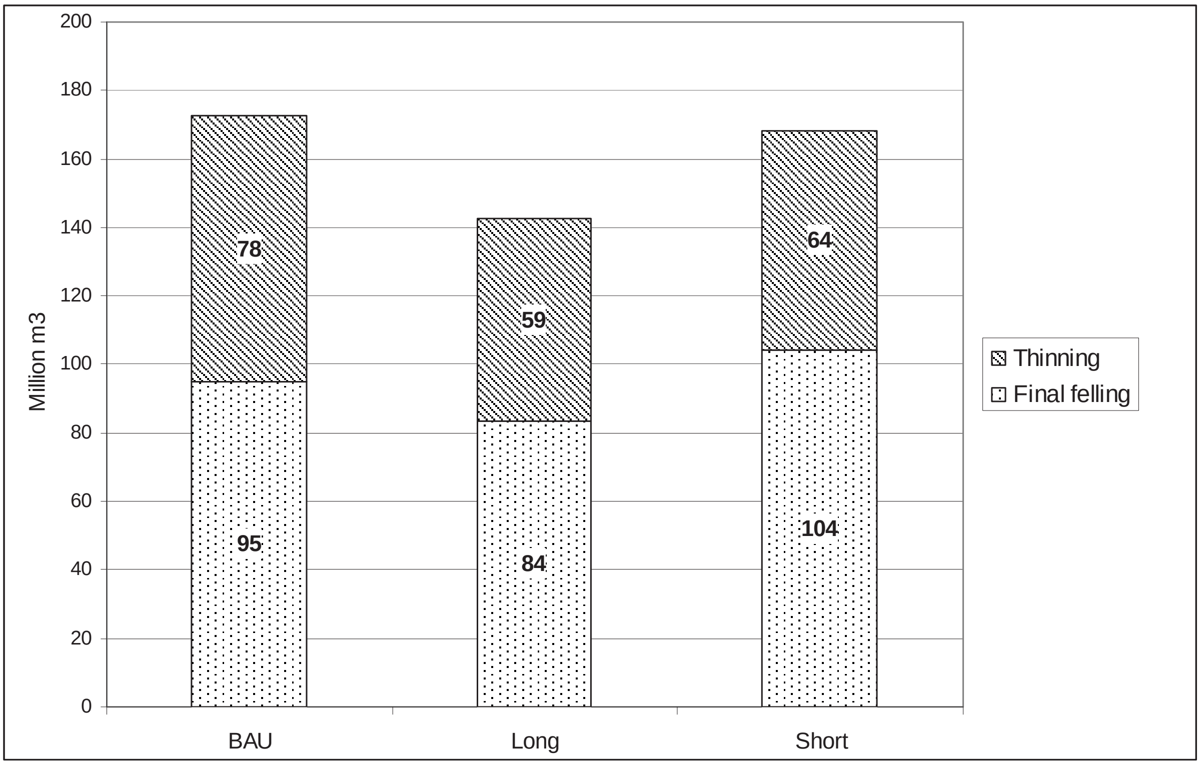


Figure 23. The figure shows the total felled volume in million m^3 during the 300 years period, divided into volume from thinnings and final fellings for each scenario in the low yield class, value in bars in million m^3

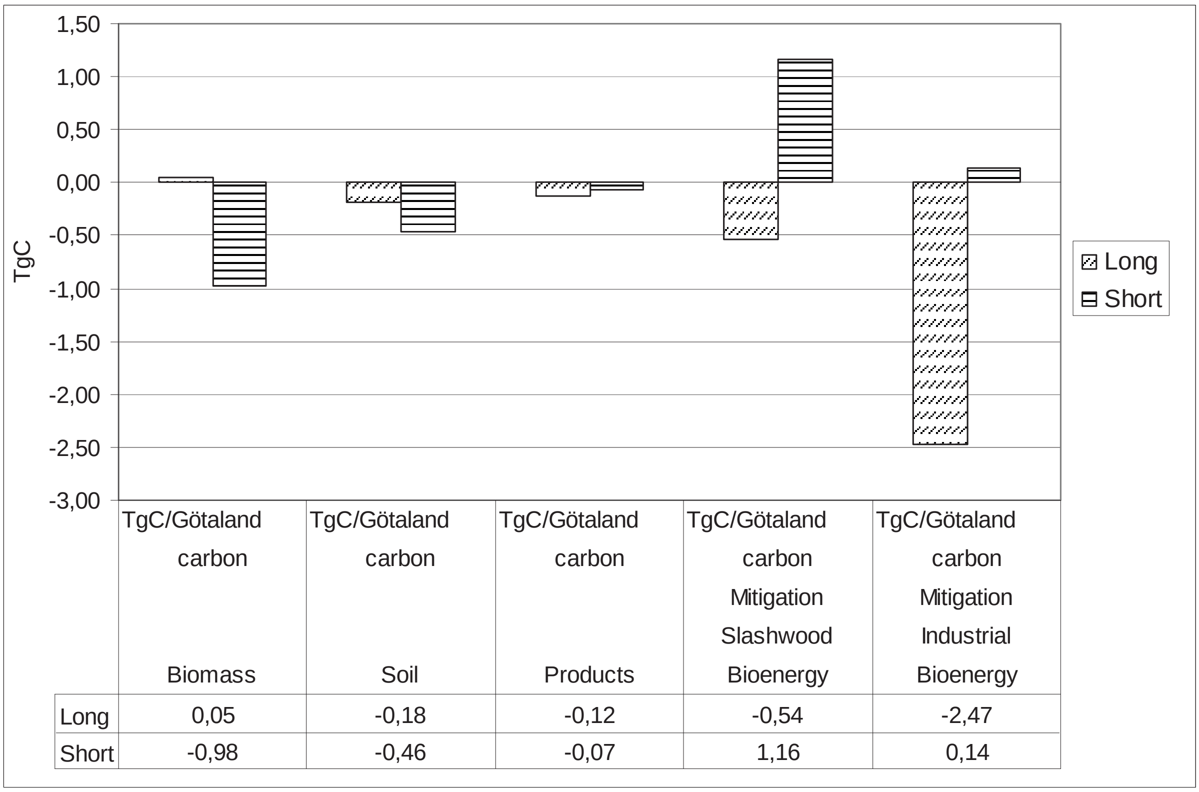


Figure 24. Comparison between carbon sequestrations in different pools for prolonged (Long) and shortened (Short) scenario compared to BAU scenario for the 300 year time horizon in the low yield class.

4.3.3 Low yield class, comparison between 30 years and 300 years time horizon

Also the result from the simulations in the low yield class shows that the best strategy to sequester carbon from forests highly depends on the applied time horizon. When a 30 years time horizon was applied the prolonged scenario led to the highest total carbon sequestration. The reason for this was that the decreased harvested volume in the prolonged scenario compared to the other two scenarios led to that the biomass and soil carbon pool was bigger for the prolonged scenario. One reason for this is as mentioned before that 30 years is too short for the regenerated areas to start to be a significant net carbon sink. It is also a too short time for that the saturated characteristics of the biomass and soil carbon pool will be obvious. When the time horizon changed to 300 years it resulted in a drastic shift for the mitigation potential for the prolonged scenario as well as for the influence of the different carbon pools, which can be seen in figure 25. It resulted in that the bioenergy carbon pools characteristics get dominant. Therefore the higher harvest level in the shortened scenario gained its carbon sequestration potential in the 300 years horizon, compared to the 30 years horizon (figure 27). Even if a big improvement in mitigation potential was seen for the shortened rotation when 300 years horizon was applied, the BAU scenario actual sequestered slightly more carbon than the shortened scenario in the low yield class (Figure 26). The higher harvest level in the BAU scenario (Figure 23) led to a higher accumulation in the bioenergy carbon pool the most important factor for the higher carbon sequestration potential for BAU compared to the prolonged scenario. Comparing the BAU scenario with the shortened scenario showed that in the low yield class the BAU scenario actually competed out the shortened scenario as well. Which is a result that differs from the two higher yield classes, due to that with 300 years time horizon applied the harvest level is more or less equal for the shortened and the BAU scenario. Even if the higher amount of final fellings in the shortened scenario led to that more carbon is accumulated in the bioenergy slashwood carbon pool, this increase does not correspond to the decrease in the biomass and soil carbon pool that the shortened rotation led to. Therefore the BAU scenario has the highest carbon sequestration potential in the low yield class with 300 years horizon applied. Another important feature for the 300 years horizon compared to the 30 years horizon is that the more even harvest level and age class distribution leads to that the differences in carbon sequestration will even out, which is very obvious in figure 25 and 26.

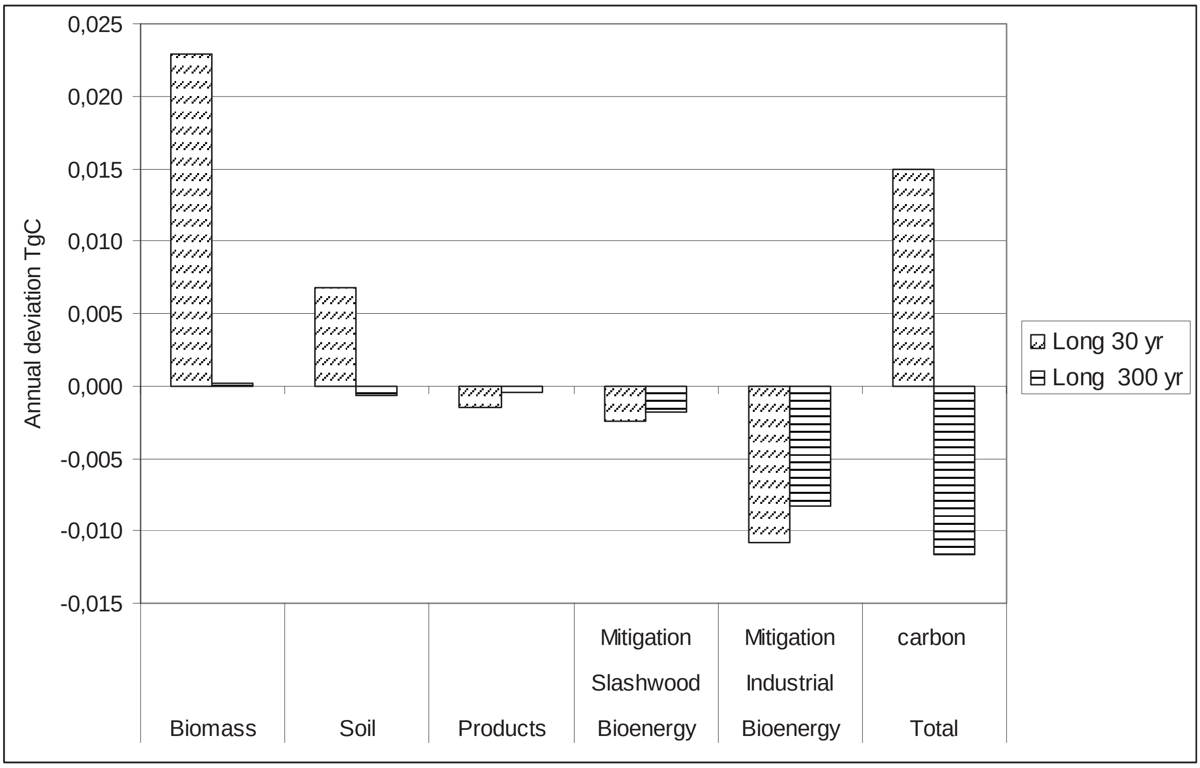


Figure 25. Shows the mean annual sequestration difference for the prolonged, compared to BAU scenario for 30 and 300 years time horizon in low yield class.

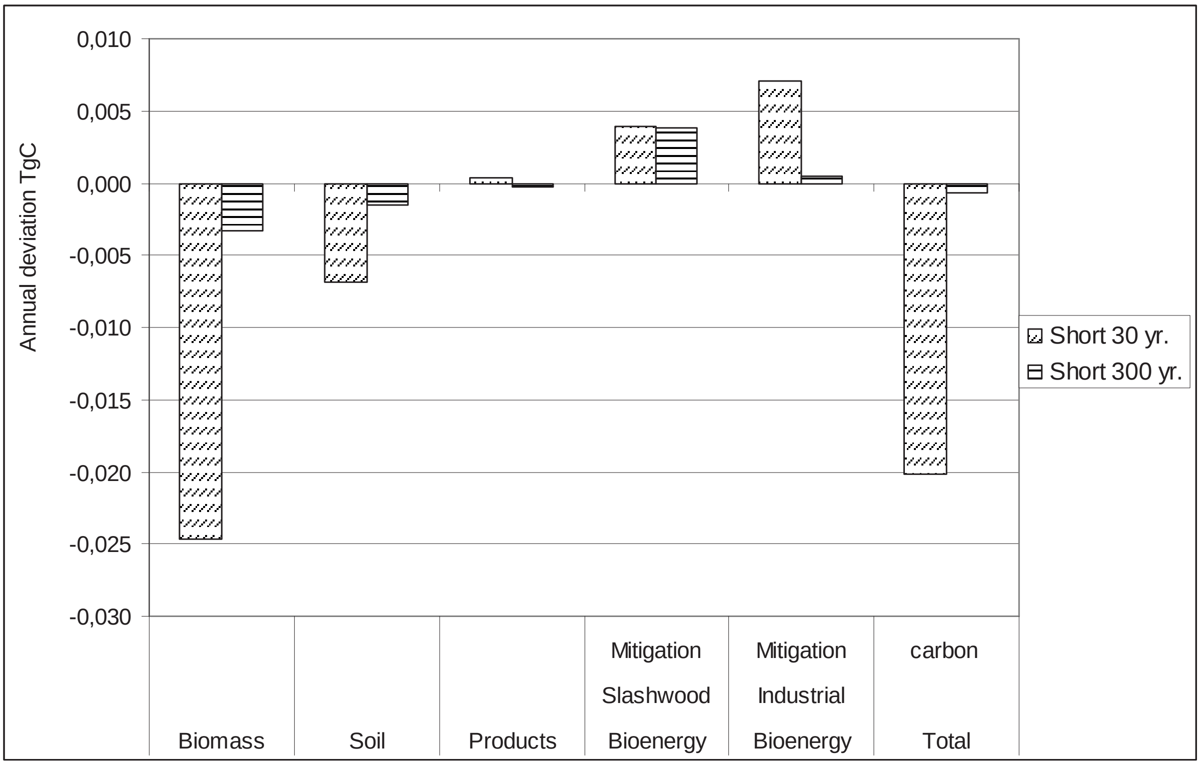
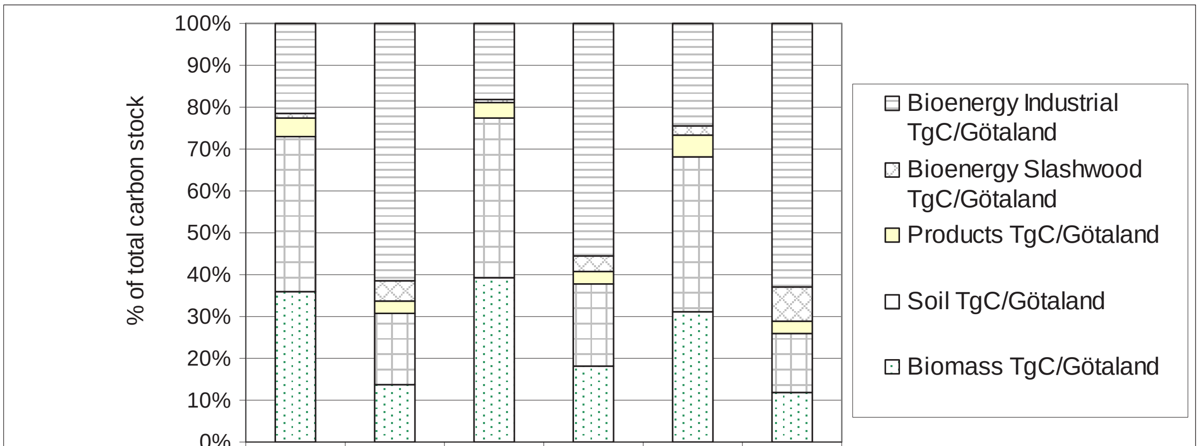


Figure 26. Shows the mean annual sequestration difference for the shortened scenario, compared to BAU for 30 and 300 years time horizon in the low yield class.



	BAU 30 years	BAU 300 years	Long 30 years	Long 300 years	Short 30 years	Short 300 years
Bioenergy Industrial TgC/Götaland	11,90	85,28	10,18	69,00	12,93	86,91
Bioenergy Slashwood TgC/Götaland	0,71	6,78	0,46	4,60	1,18	11,55
Products TgC/Götaland	2,39	4,19	2,19	3,63	2,76	3,91
Soil TgC/Götaland	20,53	23,35	21,50	24,55	19,70	19,25
Biomass TgC/Götaland	19,95	19,21	22,21	22,36	16,39	16,55

Figure 27. The figure shows the importance of each carbon pool for different scenarios and especially how the importance of carbon pools that do not get saturated increases when a longer time horizon is applied.

4.4 Comparison between different yield classes BAU scenario

4.4.1 Comparison between different yield classes BAU scenario with 30 years time horizon

The simulations in the BAU scenario showed that there is a big difference in carbon sequestration capacity between the different yield classes. The result showed, as expected, that the highest carbon sequestration potential was in the high yield class and the lowest in the low yield class. The total carbon sequestration was 88% (96,17 MgC/ha) higher in the high yield class compared to the low yield class and 28 % (44,76 MgC/ha) higher than the medium yield class, which was 47 % (51,50 MgC/ha) higher than the low yield class. The carbon pools that showed the biggest differences in carbon sequestration between the yield classes were the biomass and soil carbon pool. In the biomass carbon pool the high yield class sequestered 76 % (27,22 MgC/ha) more than the low yield class and 22 % (11,54 MgC/ha) more than the medium yield class which sequestered 44 % (15,67 MgC/ha) more than the low yield class. In the soil carbon pool the high yield class sequestered 105 % (38,67 MgC/ha) more than the low yield class and 28 % (16,74 MgC/ha) more than the medium yield class, which sequestered 59 % (21,92 MgC/ha) more than the low yield class. The harvest level was 103 % (4,5 m^3/ha/yr) higher in the high yield class compared to the low yield class and 22 % (1,6 m^3/ha/yr) higher compared to the medium yield class (Figure 28). This difference in harvest level led for example to that the total bioenergy carbon pool was 82 % (25,42 MgC/ha) higher in the high yield class compared to the low yield class.
The pattern in carbon sequestration potential showed an expected pattern where the difference in carbon sequestration corresponded well to the difference in increment between the different yield classes.

Table 15. Shows the average carbon sequestration in different carbon pools in the different yield classes (MgC/ha), 30 years time horizon applied.

30 yr	*Biomass*	*Soil*	*Products*	*Bioenergy*	*Bioenergy*	*Bioenergy*	*Total*
Yield class				*Slashwood Mitigation*	*Industrial Mitigation*	*Total*	
Low	**35,95**	**36,98**	**5,40**	**2,38**	**28,57**	**30,95**	**109,27**
Medium	**51,62**	**58,90**	**7,68**	**2,62**	**39,95**	**42,56**	**160,77**
High	**63,16**	**75,64**	**10,26**	**3,78**	**52,59**	**56,37**	**205,44**

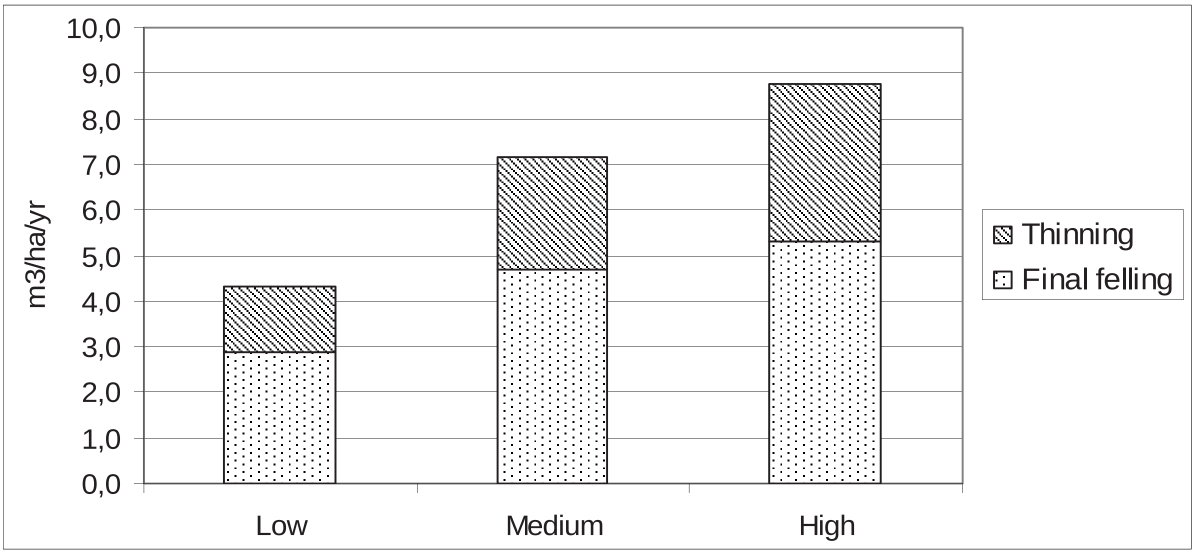


Figure 28. Shows the average annually harvested volume per hectare for the different yield classes in BAU scenario, with 30 years horizon.

4.4.2 Comparison between different yield classes carbon sequestration in BAU scenario with 300 years time horizon

The 300 years time horizon showed some deviant result compared to the simulations with 30 years time horizon. Comparing the two higher yield classes with the low yield class showed that the difference in the biomass and soil carbon pool had decreased compared to the 30 years horizon (Table 16). With 300 years horizon the differences between low and high yield class was 64 % (27,09 MgC/ha) in the biomass and 82 % (36,81 MgC/ha) in the soil carbon pool. Between the low and medium yield class the difference was 30% (12,73 MgC/ha) in the biomass pool and 49 % (21,86 MgC/ha) in the soil carbon pool. Between the medium and high yield class the difference was 26 % (14,37 MgC/ha) in the biomass carbon pool and 22 % (14,95 MgC/ha) in the soil carbon pool. This difference shows very obvious the site fertilities impact on carbon sequestration capacity. The harvest level was 84 % higher in the high yield class compared to the low yield class and 36 % higher than in the medium yield class (Figure 29) This led to that the difference in the product carbon pool was 80 % (6,8 MgC/ha) between the low and high yield class, 42 % (3,53 MgC/ha) between the low and medium yield class and 27 % (3,3 MgC/ha) between the medium and high yield class. The difference in the bioenergy total carbon pool with its accumulating characteristic was 90 % (168,61 MgC/ha) between the low and high yield class, 41 % (76,69 MgC/ha) between the low and medium yield class and finally between the medium and high yield class the difference was 35 % (91,91 MgC/ha). Measured over all carbon pools with 300 years time horizon applied the carbon sequestration difference was 85 % (239,31 MgC/ha) between the low and high yield class, 41 % (114,80 MgC/ha) between the low and medium yield class and 31 % (124,51 MgC/ha) between the medium and the high yield class.

Table 16. Shows the average carbon sequestration in different carbon pools in the different yield classes (MgC/ha), 300 years time horizon applied.

300 yr	*Biomass*	*Soil*	*Products*	*Bioenergy*	*Bioenergy*	*Bioenergy*	*Total*
Yield class				**Slashwood Mitigation**	**Industrial Mitigation**	**Total**	
Low	**42,2**	**44,9**	**8,5**	**16,7**	**169,9**	**186,6**	**282,1**
Medium	**54,9**	**66,8**	**12,0**	**19,4**	**243,9**	**263,3**	**396,9**
High	**69,3**	**81,7**	**15,3**	**29,6**	**325,5**	**355,2**	**521,4**

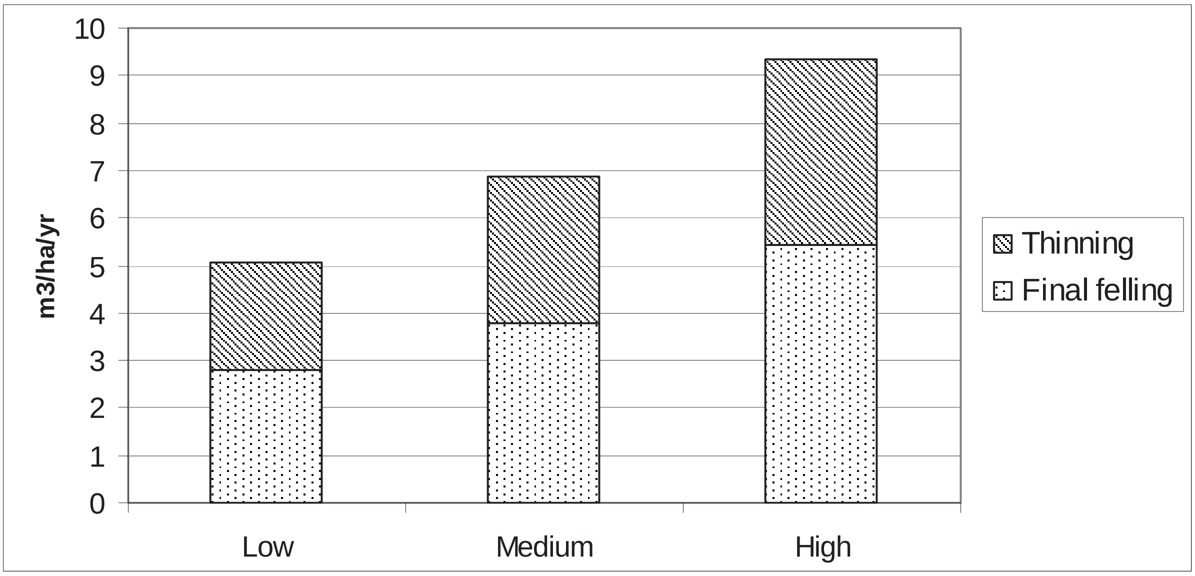


Figure 29. Shows the average annually harvested volume per hectare for the different yield classes in BAU scenario, with 300 years horizon.

4.4.3 The time horizons impact and carbon sequestration potential differences between the yield classes in BAU scenario.

The result from the simulations showed that the carbon sequestration capacity difference was huge between the yield classes, but their relationship in carbon sequestration potential differed only with a few percent depended on if the applied time horizon was 30 or 300 years. Comparing the influence of different carbon pools showed that when the 30 years horizon was applied the biggest difference occurred in the biomass and soil carbon pool, both in percent and absolute value. When 300 years time horizon was applied it was a total shift both in percent and in absolute value for the different carbon pools importance. This means that the bioenergy carbon pools importance increased and the carbon pools originated from harvested biomass became the most important carbon pools. Except for the product carbon pool which importance remained more or less the same due to the quite short life span in its different compartments. The pattern for how the "forest ecosystem" carbon pool decreased between the low and the two higher yield classes when a longer time horizon was applied can be seen in figure 30 and this magnitude was insignificant compared to the increase in the bioenergy carbon pool with the 300 years time horizon applied. This means that in absolute values the differences decreased in the biomass and soil carbon pool between the two higher yield classes and the low yield class. The differences between the medium and high yield class showed a different pattern in the biomass carbon pool, where the difference increased to 26 % (14,37 MgC/ha) from 22 % (11,55 MgC/ha), but the difference in the soil carbon pool decreased also here. In figure 31 is the difference in all carbon pool with 300 years horizon obvious.

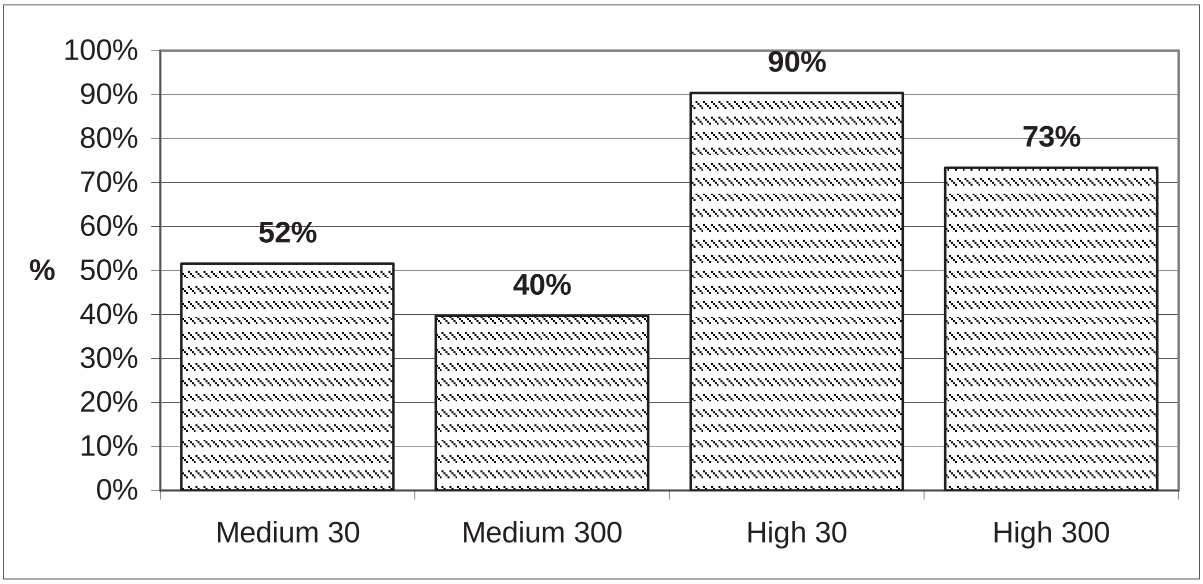


Figure 30. Show how much more carbon (%) per hectare that is stored in the "forest ecosystem" pool in the medium and high yield class compared to the low yield class for the different time horizons.

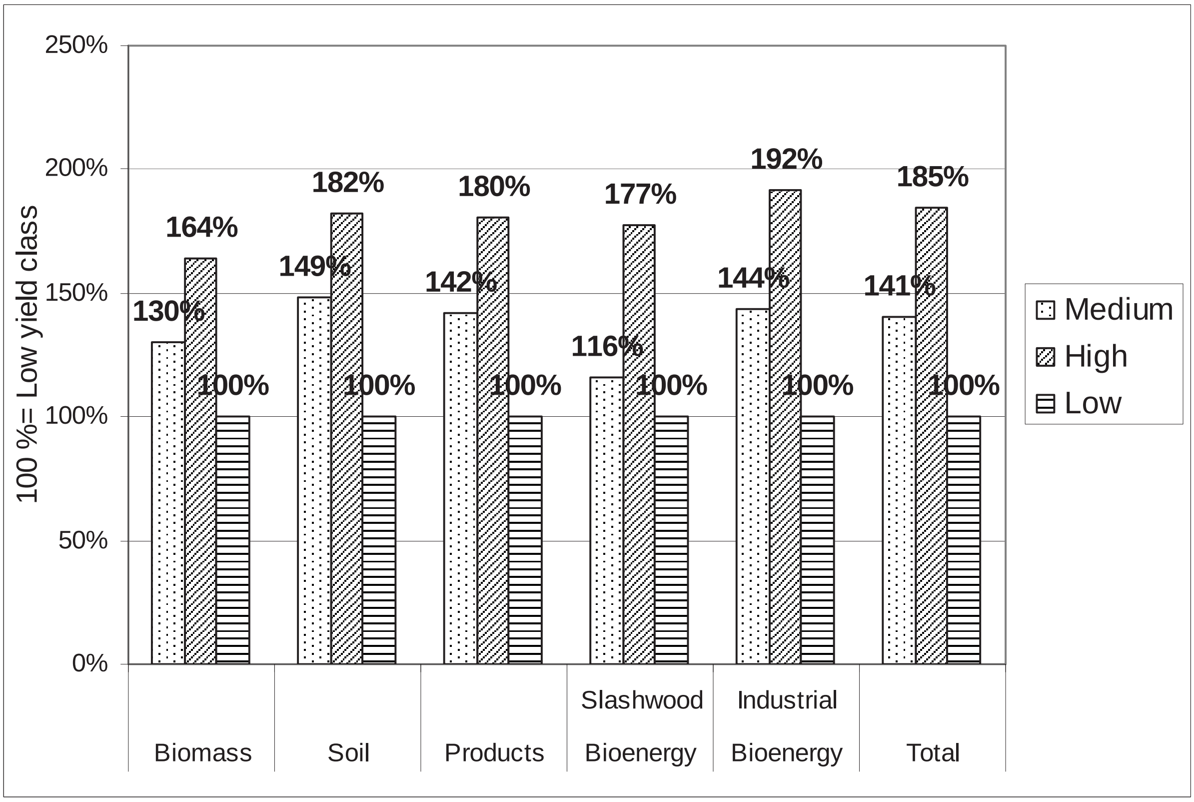


Figure 31. Shows the difference in carbon sequestration between the different yield classes in the 300 years horizon, the low yield class is set to 100 %.

5. Discussion

5.1 Reliability of the result

The reliability of the results when it comes to the time-horizons impact on the carbon sequestration pattern for the different management scenarios can be considered as trustworthy. The reliability when it comes to the different management scenarios outcome in carbon allocation and the amount of sequestered carbon is connected to more uncertainty. Firstly it depends on the reliability of different modules in CO2FIX V 3.1 and on the applied values on the required parameters. For the carbon sequestration capacity for Norway spruce forests in the entire region of Götaland the assumed simplifications and parameters in synthetic forest played a major role for this uncertainty.

ProdMod 2 that was used for deriving the yield tables, is regarded as a stable stand level growth model built on historical statistical data. This means that it does not take into account that the growth and forestry condition is not constant and as mentioned in the introduction the forest increment rate is in reality assumed to increase, due to climate change and better genetic material. If this is true it would lead to that the carbon sequestration is underestimated, especially in the long term horizon. Also where is a simplification in the synthetic forest, where it was assumed that in each yield class the same thinning regime is applied over the whole area and that it is independent on the rotation length. There could also be some uncertainties with the parameters for biomass compartments assessed by Marklunds (1988) biomass equations, especially on the high yield class. Kaipainen (2004) mentioned that in Norway spruce stands in Central Europe, Marklunds biomass equations slightly underestimated branch biomass but overestimated biomass of needles and roots with 25 %. On the other hand Nabuurs et al. (2008) concluded that the parameter of the stem influenced the result with CO2FIX V 3.1 most significant. Comparisons between data from my CO2FIX V 3.1 simulations with statistical data for Norway spruce forests in Götaland (SNFI, 2009), regarding average standing volume/hectare showed that CO2FIX V 3.1 overestimated the average standing volume with 11 % with BAU scenario applied in the long term horizon.

From another point of view the soil organic carbon pool probably was underestimated in my simulations. The comparison between average values for all forest land in Sweden (Morén, 2005) with the mean value from the simulations for region Götaland indicates this. The soil organic carbon pool in my simulations was 15% lower than the average value for whole Sweden, when it actually should have been the opposite when the average site fertility is taken into account. The main reason for this assumed underestimation was probably the initial soil carbon stock that was derived from one rotation period simulations in CO2FIX V 3.1 on a site without any initial soil carbon. Other factors could have been the density of the wood and simulations in high yield class BAU scenario showed that if the density increased with 20 % from 0,4 to 0,48 $MgDM/m^3$ the soil carbon pool increased with almost 20 % as well. This is of course a factor that significantly affects all carbon pools in a similar way. These factors probably influenced the result more significant than the Yasso soil module, which is seen as a robust soil model (Nabuurs et al., 2008), due to few parameters and the temperature sensitivity functions in the model.

Concerning my result in the product carbon pool it is important not to forget that the module does not take into account the substitution effect, depending on that no LCA is made and the product carbon pool is strictly handled like the biomass and soil carbon pools. Another factor that contributed to that a small amount of carbon was accumulated in the product pool was that no products were assumed to end up in land-fills, which are considered as a more stabile

carbon pool than living biomass, if the land-fill is in an anaerobe environment (Apps et al, 1999).
The input to the bioenergy slashwood mitigation carbon pool is overestimated due to that it was assumed that 70 % of the slashwood was utilized for energy purposes, which probably is a too high amount according to the high variability in site conditions. Other assumptions and simplifications that could have contributed to overestimations that CO2FIX V 3.1 assumes that all carbon that passes the product carbon pool will be utilized as bioenergy, without any losses in the supply chain. In addition to this the technical parameters might have been simplified too much and therefore contributed to a loss in accuracy. The main example on this is that the combustion efficiency was assumed to be equal. Even if the largest disadvantages with the bioenergy and product carbon pool for really evaluating the substitution effect, is the lack of a LCA and FCA. On the other hand it would been to put too high demand on a simple carbon bookkeeping model as CO2FIX V 3.1 and especially it would have increased my workload far out of reach for a master thesis just to derive the parameters that such a model would require.
The conclusion from this is that the accuracy for the absolute value of total carbon sequestration in the Norway spruce forests in region Götaland should be handled carefully, but this value was not the main objective for my simulations. Even if the of total carbon level might be insecure the accuracy for the differences between the applied scenarios should be acceptable and fulfil the requirements for my master thesis. The result from my simulations concerning the main question, about the time horizons impact on carbon sequestration potential can be seen as reliable due to the expected result and that CO2FIX V 3.1 is seen as stable and rough model.

5.2 Changing forest management: The time horizons impact on; carbon density at plot and landscape level

The result from my simulations clearly showed the time horizons impact on the importance at increased carbon density at plot and landscape as a climate change mitigation strategy. With 30 years horizon the prolonged scenario, with decreased harvest levels compared to BAU had the highest mitigation potential. In this case the rotation period was prolonged only with 20 years, which must be seen as a quite modest and realistic change. This can indicate that for example Greenpeace is on the right track in their report "Turning up the heat, Global Warming and the Degradation of Canada's Boreal Forest" (Anon., 2008), where they promote a conservation strategy for the Canadian boreal forest. It is also in line with Luyssaert et al. (2008) result, that a lot of carbon would return to the atmosphere if these old-growth forests were disturbed, which on the other hand is quite logical. This is also supported by my simulations where 30 years time horizon was applied. These result showed that the importance of the forest ecosystem carbon pool was higher than the bioenergy and product carbon pool with this time horizon. It means that shortened rotation lengths led to negative mitigation potential compared to prolonged rotation lengths. This pattern supports that a pure conservation scenario probably would have sequestered even more carbon and led to an even higher carbon sink in forests, due to forest management or lack of forest management. My simulations with 300 years time horizon applied showed contradictory results compared to the 30 years horizon. They showed that a conservation strategy or decreased harvest intensity through prolonging the rotation age in a longer term leads to that the Net Ecosystem Exchange (NEE) reach a steady state, when Gross Primary Production (GPP) equals the respiration and the carbon sequestration is equal to zero. This led to that in the 300 years horizon the importance of the forest ecosystem carbon pools decreased drastically and were completely out competed by the bioenergy carbon pools. Depending on that these substitution pools never reach a steady state as the forest ecosystem carbon pools do and therefore can accumulate an unlimited amount of carbon. This is also strengthening by the simulations with ProdMod2 (Figure 32), that showed that a steady state will occur quite near the prolonged scenarios applied rotation ages in my simulations. Even if this pattern to some extent is strengthened of that no late thinnings are applied, on the other hand late thinnings is connected with increasing risk for wind damages and other calamities that leads to carbon emission.

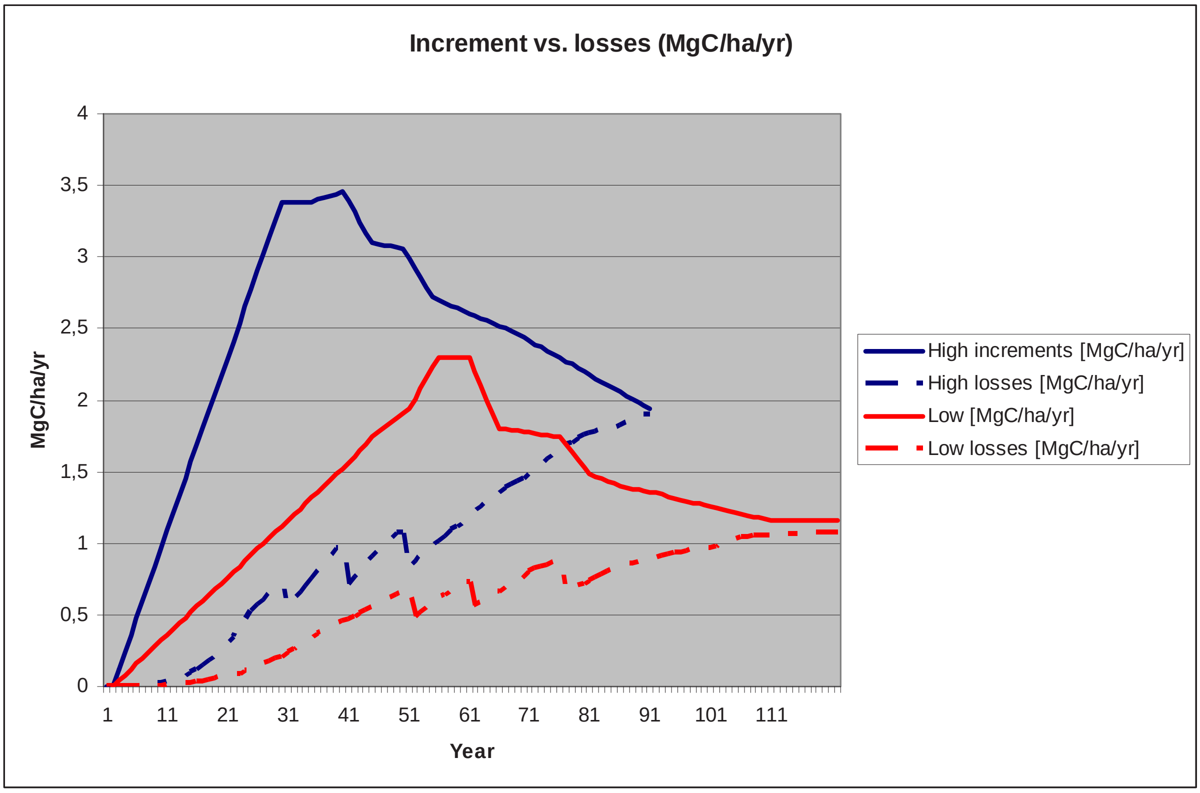


Figure 32. Show how stem biomass development, when the self - thinning rate approaches the annual increment, a steady state seem to appear.

The pattern in figure 31 corresponds well to the measurements from Fiby natural forest outside Uppsala, Sweden that showed that it actually was a carbon source (Grelle, 2006). One conclusion from this steady state characteristic is that the prolonged scenario could be considered as a joint-production between harvesting and increasing carbon density. Joint-production probably has a higher carbon sequestration capacity measured over all carbon pools than pure conservation strategies even in a short term as 30 years. In addition to this the decreased risk and forecasted increase in production that new established forests are assumed to strengthens this theory even more.

A prolonged rotation age with 20 years would also be more than enough to reach the highest eligible carbon sink in article 3.4 in the Kyoto protocol. For reaching the maximum eligible sink it would have been enough to apply the prolonged scenario at 67 % of the studied area, to increase the annual sink with 0,6 MgC/ha in the 30 year horizon. These figures agree well with Kaipainen et al. (2004), where a prolonged rotation age with 20 years in Norway spruce forests in Finland and Germany led to that the annual sink increased with 0,5 respectively 0,7 MgC/ha. This resulted in that the studied countries maximum eligible sink under article 3.4 in the Kyoto protocol easily was reached.

The influence from prolonged rotation age on the forest ecosystem carbon sink decreased when the time horizon shifted to 300 years, even if prolonged rotation still had a positive impact on the eligible sink under article 3.4 compared to BAU and the shortened scenario. This levelling could also be seen in the annual sink, which during the 300 years horizon in average was far below the maximum eligible sink, as well as the annual sink with 30 years horizon. The factor that played the most important role for the carbon density was as expected the site fertility and the MAI differences. Between the low and high yield class the difference in MAI at 90 % influenced the carbon stock in the forest ecosystem with 90 % in the 30 years horizon and with 73 % in the 300 years horizon. This clearly shows that the most significant factor to take into account when it comes to forest management and carbon sequestration are forest management measurements that increases the increment and that changed rotation ages only affected mitigation potential with a few percent. The conclusion is that increased increment combined with joint-production of other goods such as energy, construction timber is the best mitigation strategy both in a short and a longer term. Important mitigation measurements in the short term are them who increases the biomass and soil carbon pool, e.g. fertilizing, drainage on suitable stands (not cause GHG net emissions), speed up the regeneration phase or to summarize it; apply intensive sustainable forest management in a broader scale.

In a longer time horizon the forest management toolbox is enlarged which will lead to even more alternatives such as changing tree species, choose improved seedlings, species composition etc (Klang & Ekö, 1999; Berg et al., 1996). Even if it seem to be a lot of advantages with prolonged rotation age, especially in the short term there is disadvantages that is needed to be taken into consideration and these are often connected with increased risk. Mainly due to that a higher carbon stock in biomass and soil leads to that the C emissions from a disturbance will be much bigger than if a lower amount of carbon would have been stocked in the disturbed ecosystem. One example on this is the storm damages in Sweden from two storms of similar magnitude in wind speed, the storms -69 and the storm Gudrun 2005. The storm Gudrun almost caused twice as much damage than the -69 storms due to that the average standing volume per hectare has increased drastically since 1969. As mentioned before storm Gudrun caused big C net emissions during 2005 due to the large disturbance (Lindroth, 2007). Other disadvantages with prolonged rotations and particularly with conservation strategies, are that they lead towards older and unhealthier trees compared to a managed forest, a disadvantage that probably will be even strengthen when the climate change starts to be appreciable in the Northern Hemisphere.

This is very obvious in Canada, where they have more extensive forest management than we have in the Nordic forestry. Apps et al. (1999) mentioned that Canada's forest ecosystem 1985-1989 was a carbon source at 69 TgC annually due to increased disturbances. Forest operations only played a minor role in this and a factor that actually settles if the forest in Canada should be a C source or sink is the fire frequency and magnitude (EOS, 2008) and the current annual value is calculated to be similar as during the 1980s (Clayton, 2009). Another example on risks is the increased vulnerability for insect outbreak that benefits from disturbances and a warmer climate that leads towards more stressed trees. This problem can be seen in Sweden after the storm Gudrun combined with dry periods, but particularly in Canada with the mountain pine beetle, that so far has killed 620 million m^3 of trees only in British Columbia, which have caused big C emissions and a negative impact in the forestry sector in the affected territory (Pyhtila, 2009).

5.3 Substitution of energy intensive materials

The results from my simulations do not show the substitution effect like a full LCA would have done. Therefore it is only possible to study the carbon sequestration in the forest product carbon pool, which is a temporar carbon pool. Which often is considered to have an insignificant mitigation potential compared to the substitution effect, that occur when residues and by-products is utilized as bioenergy. In CO2FIX V 3.1 this substitution effect will be counted in the bioenergy industrial mitigation carbon pool. That wooden material often requires less fossil fuel for manufacturing compared to other materials (i.e. concrete, steel etc.) is not taken into account.

The influence of sustainable forest management at the forest product carbon pool is obvious in the comparison between the amounts of carbon stored in forests products (FPS) with the carbon stored in the forest ecosystem. At a global level the carbon stock in the FPS is 1 % compared to the forest ecosystem carbon pool (Nabuurs & Sikkema, 2001). In my study the same figure was 6 % (10-13% FPS/Biomass) in the 30 years horizon and 10 % (20-22% FPS/Biomass) in the 300 years horizon. These figures correspond quite well with Pussinen et al. (1997) study on the Finnish forest sectors carbon sequestration. Where 12 % of the carbon sequestered in the forest sector 1990 was allocated to the FPS carbon pool and until year 2100, that share would increase to 24 % according to their simulations. This difference can to a large extent be explained with that one third of the carbon in the FPS was allocated into landfills, which is a pool with a very long life-span (Apps et al., 1999). On the other hand my value is much higher than Pingoud et al. (2001) figures, especially in the 300 years horizon. In their calculations for carbon sequestered in the FPS originating from Finland, 7 % of the total forest carbon was assumed to be stocked in the FPS carbon pool.

Apps et al. (1999) did a carbon budget over the FPS in Canada that showed 1 % (5-6 % FPS/Biomass) of the total forest sector carbon in Canada was allocated to the FPS carbon pool.

The reason for that I have a much higher share of carbon in the FPS sector than these studies, is probably due to that my study only handled productive areas where strict forest management strategies were applied. The other mentioned studies show mean values over all sort of forest area in the studied countries.

Also the product parameters could influence the divergence but probably of a smaller magnitude, the Finnish study applied similar product life-span parameters as I did. In addition to this, one third of the sawn wood in the medium and long term product life-span ended up into landfills, just as in the Canadian study. As mentioned before this is seen as the most stable FPS carbon pool, with a very long life-span compared to the other FPS carbon pools (Apps et al., 1999). The conclusion from this is that the factor behind this difference is that the average forest management intensity on my studied area is much higher than the general average forest management on a country or region level.

On the other hand Nabuurs et al. (1997) did a study where they estimated the annual FPS carbon sink and the annual forest biomass carbon sink in Europe. Their result showed that the amount carbon stored in the FPS was 29 % of the carbon sequestered in the forest biomass. This figure correspond quite well to my result in the 30 years horizon, where the size of the FPS carbon pool varied between 16, 21 and 32 % respectively for the low, medium and high yield class in the BAU scenario. The total size of the annual carbon sink in the FPS sink was 0,23 TgC over the 30 years period. In the living biomass carbon pool it was 0,77 TgC in the BAU scenario compared to the initial state. Over the 300 years horizon the annual FPS sink was 0,17 TgC, which actual is higher than the annual forest biomass sink at 0,08 TgC for the same time horizon. Even this result to a high extent depends on the widespread forest management in my study. On the other hand it can be seen as an argument for that it is a bit contradictory to claim that the product carbon pool should not be taken into consideration in the international climate change framework. Especially when the main argument often is the FPS pools unstable and temporal characteristics, which is a bit contradictory when the biomass and soil carbon pool showed similar characteristics in my simulations. The product carbon pool increased even relatively more than the forest ecosystem carbon pools over the 300 years horizon. Furthermore if it would bin eligible as a sink in the Kyoto protocol, the FPS life-span might increase or at least it would have been one incitement towards this. Just as it is possible to change forest management towards a higher carbon sequestration management for increasing the C sink. Even if also the FPS pool probably would have been more or less saturated in a longer term and that a market aspect must be taken into consideration, it still could have a role to play in shorter term. Another frequent used argument is that it would be hard to measure the FPS C pool, which might be true, but it should not be harder to measure that pool with accuracy compared to the forest ecosystem carbon pools. Instead my result can be seen as an argument for that FPS sink should be accountable in the post-2012 agreement as a carbon sink under article 3.4. If it would be accountable as a sink it also would promote usage of wooden products which could have a much bigger mitigation effect through substitution effects (Sathre & Gustavsson, 2007). CO2FIX V 3.1 does not take into account this positive side-effects or substitution effects. That wooden material often requires less energy than they are processed and manufactured compared to other building materials. Concrete framed houses for example require 60-80 % more primary energy than similar wood framed houses (Börjesson & Gustavsson, 2000). On the other hand the bioenergy industry mitigation carbon pool that originates from the product carbon pool is overestimated, compared to if a traditional LCA would have been conducted (Murphy, 2004). This is due to that the carbon from the product carbon pool is directly transferred to the bioenergy carbon pool, without any emissions or other losses during the transaction. For these reasons it is impossible to evaluate the substitution effect according to a traditional LCA and to trace from which sector (Figure 2) the bioenergy carbon originates from.

5.4 Mitigation through fossil fuel substitution

The bioenergy carbon pools importance was influenced drastically by the time horizon and it was the main factor behind the shift that occurred in mitigation potential for the different scenarios, when the time horizon shifted from 30 to 300 year. This result supports the earlier mentioned statement:

"carbon sequestered in biomass is temporary but saved fossil C emissions are forever and decreases in C emissions when biomass substitute fossil fuel is forever"
(Schlamadinger & Marland, 1996).

Even if this statement is true it does not mean that it necessarily must be the best mitigation option over all time horizons and this was obvious in my simulations.
With 30 years horizon the shortened scenario with decreased rotation length with 20 years compared to BAU scenario the bioenergy carbon pool annual increased with 0,95 TgC in the Norway spruce forests in Götaland. If the whole 54 % increase in harvested volume in the shortened scenario compared to the best carbon sequestration scenario (prolonged) would have been utilized for bioenergy purposes the annually energy gross supply from stemwood would have increased with 10 TWh. This increase correspond to 8,5 % of the total gross energy supply from biomass in Sweden 2006 (Energimyndigheten, 2007) or to 58 % of the

forest residues combusted in district heating plants in Sweden 2001 (Sims et al., 2007). It would stand for 25 % of the increase in renewable energy in the net supply that is necessary for fulfilling EUs Renewable Energy Sources (RES)-directivs target for 2020 (COM, 2008). If this amount would be utilized for substituting fossil fuel it would lead to a accountable sink under the Kyoto protocol at 0,95 TgC/yr. The conclusion from this is that increased harvest intensity through shortened rotation lengths leads to a considerable increase in bioenergy supply in the 30 years horizon, which could be used to substitute fossil fuel.
On the other hand the shortened scenario led to that the carbon sequestration in the forest biomass and soil carbon pool decreased. The outcome from this would be that increased bioenergy utilizing leads to increased net CO_2 emissions in the 30 years horizon and the bioenergy use would backfire on its original purpose. This result points out that if the aim is to decrease the net CO_2 emissions in a short term, like the Stern report points out (Stern, 2006) the harvest levels should decrease and more carbon should be stored in the forest ecosystem instead of being utilized as bioenergy. This result supports that even biomass utilizing in Sweden requires a LCA analysis due to that my study that shows that it could have a negative a negative impact in the 30 years horizon. On the other hand even the BAU and shortened scenario showed a positive mitigation effect and the mitigation potential difference was only a few percent for these scenarios compared to the prolonged scenario. Adding to this that my simulations do not take any risk into account, which is a factor that would promote shorter rotation lengths. As well as that the carbon that is released from sustainable managed forests would have been recaptured much faster than the 50-100 year that is valid for managed oil-palm plantations (Butler, 2007). My simulation with 300 years horizon supports this and even that bioenergy is the best mitigation option in a longer term even if the annual amount of extra gross bioenergy supply for the shortened scenario compared to the prolonged scenario decreased to 6,8 TWh/yr. Although the accumulation characteristics in the bioenergy carbon pools did that the amount of carbon stored in bioenergy compared to the forest ecosystem raised from 16 % (38 TgC) initial to 244% (817 TgC) in the 300 years horizon, which is a increase at 2150 %. In the long term the difference in the biomass and soil carbon pool between the management scenarios were levelling and this support that in a longer term a set-a-side strategy would lead to increased emissions compared to active forest management. Even if the different management scenarios differed in mitigation potential through the bioenergy carbon pool, this difference was just as for biomass and soil carbon pool negligible, compared to the yield class influence on carbon sequestration and climate change mitigation potential.

6. Conclusions/Reflections

My result supports them who in the actual debate argue that in a short horizon as 30 year; the amount of carbon emitted is more important than which source it originates from (fossil fuel or biomass). On the other hand this must be seen as a very simplistic and theoretical point of view, with negative impact in a longer term towards a more sustainable society. Therefore I argue that the mitigation strategy must be seen in a longer term than 30 years, even if the Stern report mentions that actions taken now are the most important. Adding to this the current and coming policies on renewable energy sources and the importance of renewable resources in general that is taken more and more into account that we must change the development towards a more sustainable way.

This altogether and that biomass energy currently have the biggest potential among the renewable energy sources, as an example for reaching the RES-directive target until 2020 on 20% renewables, 2/3 must be biomass based energy (IEE, 2009).

From the environmental non-governmental-organisations you often hear the argument that the forest in Europe mainly should play a role as carbon storage; argument for this is often that final harvested stands in Europe recapture carbon in a too low pace for being defendable in the context of climate change mitigation measurement and that undisturbed ecosystems are most resilience and adaptable for the climate change. This must be seen as an opinion that essentially is value-based and that it misses a holistic view, especially taking the current state in Canada's forests into consideration. Furthermore the climate change can not just be seen at European level and if we in Europe would go for a low intensive management that would decrease our utilization of the forest increment from currently 60% to an even lower level (COM, 2005) and still aiming at reaching the EU targets for renewable energy for example, it would lead to "leakage" effects to other parts of the world. Parts that are not designated to sustainable forest management and with corrupt regime, those who have nothing to gain from long term sustainable solutions, this is also true for poor people that of course must prioritize food. Altogether decreased supply from European sustainable managed forest would not lead to that the demand decreased, therefore the amount of woody biomass from unsustainable sources would increase drastically and such a policy would lead to severe backfire for the aim, a more sustainable development.

These contradictory arguments and lack of holistic view are also obvious in the argument that regenerated forests recapture carbon in a too low pace, 30 years is often mentioned. Which of course make sense in a national or stand level but taking into account that it would not decrease the global demand for biomass, instead it would gain other biomass sources such as palm-oil; that is seen to have at least a three time longer carbon recapture periods, or that more biomass for energy purposes would originate from agricultural land. A development like this would lead to drastic increased foods prices, which would make the situation even worse for them who already are forecasted to face the worst consequences from the climate change, inhabitants in the third world.

In addition to that bioenergy have positive impact on climate change mitigation, it also have positive side-effects such as rural development, energy security etc. Although bioenergys impact is highly correlated to how it is utilized. Currently the main policy interest has been to substitute liquid fuels such as petrol and diesel, even if for example Azar 2006 mention that it is an inefficient way to reduce the CO_2 emissions. This is also the conclusion in a Swedish report concerning biofuels from forest (Anon, 2002). The report conclude that the most cost efficient mitigation option, is obtained when bioenergy replaces electricity produced by coal firing condensed power in neighbouring countries, in some cases there is no additional cost, in most other cases it is estimated to 60 SEK/t reduced CO_2 emission. Replacement of petrol and diesel with woody biomass fuel was given an additional cost at 900 SEK/t CO_2 reduced emissions, which correspond to more than 2,20 SEK/litre. The reduction in CO_2 emissions would be 0,2 Mt/TWh from woody biomass compared to that other options have a reduction capacity up to 2 Mt/TWh when it replaces coal. This can be connected with the actual debate in Sweden, about improving the electricity infrastructure in Europe, to facilitate electricity trade in Europe.

Summarizing the result from my simulations, that a decreased harvest level is to prefer in a 30 years period with what is mentioned above, but when I lift my view from Götaland and taking side effects into account on a global scale, my recommendation from a climate change mitigation point must be that:

- “Leakage” effects must be taken into account

- Measurements that increase the increment in a sustainable manner is more important than prolonged rotation ages

- Recommended rotation length is when mean annual increment peaks, which means that the biomass production is maximized and it should be considered as the best option for joint-production, taking all carbon pools and time horizons into account

- Woody biomass should be used as efficient as possible and it shall originate from a sustainable source that leads to decreased net CO_2 emissions within an reasonable time. It should not interference with food security and do not lead to deforestation or degradation of land.

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9. Appendix

General start data for all ProdMod2 simulations

Latitud	*Altitude m*	*Area*	*Climat zone*	*Unthinned*	*Soil moisture*	*Forest type*
56	100	South	No	Yes	Fresh	Other

Start values for ProdMod2 Simulations

Yield class	*Low*	*Medium*	*High*
Site index (dm)	220	275	320
Age at breast height (yr)	25	17	16
Basal area (m^2/ha.)	13	14	19
Number of stems/ha.	1700	2300	2500

Growth pattern per yield class, derived from ProdMod2

Low yield class			*Medium yield class*			*High yield class*		
Total age (yr)	CAI (m^3/ha/yr)	MAI (m^3/ha/yr)	Total age (yr)	CAI (m^3/ha/yr)	MAI (m^3/ha/yr)	Total age (yr)	CAI (m^3/ha/yr)	MAI (m^3/ha/yr)
39	7,8	2,7	30	12,5	4,4	28	16,9	6,7
44	8,9	3,4	35	14,6	5,9	33	16,9	8,2
49	9,7	4,1	40	13,8	6,9	38	17,3	9,4
49	9,7	4,1	45	13,9	7,7	43	15,5	10,1
54	11,5	4,8	50	11,8	8,1	48	15,3	10,6
59	11,5	5,3	55	11,8	8,4	53	13,6	10,9
59	11,5	5,3	60	11,8	8,7	58	13,1	11,1
64	9,0	5,6	65	10,3	8,8	63	12,7	11,2
69	8,9	5,8	70	9,9	8,9	68	12,2	11,3
74	8,7	6,0	75	9,7	9,0	73	11,6	11,3
74	8,7	6,0	80	9,5	9,0	78	11,0	11,3
79	7,4	6,1	85	9,1	9,0	83	10,4	11,3
84	7,0	6,2	90	8,8	9,0	88	9,8	11,2
89	6,8	6,2	95	8,5	9,0	93	9,3	11,1
94	6,5	6,2	100	8,1	8,9	98	8,8	11
99	6,3	6,2	105	7,9	8,9	103	8,3	10,8
104	6,0	6,2	110	7,6	8,8	108	8,0	10,7
109	5,8	6,2	115	7,3	8,8	113	7,7	10,6
			120	7,1	8,7	118	7,4	10,4

Thinning programs

	Low yield class			*Medium yield class*			*High yield class*		
Thinning	*year*	*Fraction removed (%)*	*Harvested volume m^3/ha*	*year*	*Fraction removed (%)*	*Harvested volume m^3/ha*	*year*	*Fraction removed (%)*	*Harvested volume m^3/ha*
1st	49	32	61	35	31	61	28	31	57
2nd	59	26	63	45	32	84	38	31	90
3rd*	74	22	63	60	27	90	48	27	91

* Not applied in Shortened scenarios