Impacts on carbon budgets of increased use of Norwegian forest resources for energy

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Abstract

When forests are logged for heat and electricity production, emissions from burning of the biomass are not accounted for in national greenhouse gas reporting to the climate convention. This would have been correct if a forest stand did immediately regrow to its initial state, storing the same amount carbon as was logged. In reality, a carbon debt is created after harvest and lasts until a replanted forest stand has grown and absorbed as much carbon as the old one stored. By increasing the harvest rate, logging younger trees in rotational forestry, there is a loss of stored carbon in the forest. This carbon debt could be partly or fully repaid, using the harvested wood. E.g. bioenergy from harvested wood can replace an equivalent amount of fossil energy, and thus avoid the corresponding greenhouse gas emissions from the fossil energy source.

This thesis aims to quantify the temporal imbalance between carbon losses and gains of a permanently increased harvest, using a simplified model of Norwegian forests capturing some of their characteristics. An uneven-aged forest of a constant area is studied, where a share of the biomass is removed by harvest, and a share is left on site decaying. Future harvest conditions which are considered the most realistic and viable give a carbon payback period ranging from 89 to 362 years. This range comes mostly from estimating how much greenhouse gas emissions from fossil fuels that is avoided by replacing it with bioenergy from harvested wood. Using a medium estimate from the literature results in a carbon payback period ranging from 89 to 123 years.

The sensitivity of the carbon debt to using additional trunks and harvest residues is tested and included in these estimates. When a portion of the additional trunks is used in constructions, the carbon payback period is shortened by 1 to 23 years for the chosen forest characteristics depending on harvest condition. Carbon debts from only utilization of existing harvest residues for bioenergy could most probably be repaid within 24 to 86 years.

A brief introduction to global forests and a literature review of national forest dynamics has also been performed to put the study in context and select parameters for modelling. The present state of Norwegian forests is shown to be strongly conditioned by forestry practice the last 100 years. Dynamics not included in the model is discussed, and in what direction related processes probably would influence the results.

Sammendrag

Når skog hugges for energiproduksjon regnes stort sett ikke utslippene med i nasjonale klimagassregnskap. Denne tankegangen baserer seg på at karbonet som frigjøres ved forbrenning absorberes umiddelbart tilbake igjen i ny voksende biomasse. Skog vokser ikke så raskt, så i realiteten bygges det opp en karbongjeld fra hogst og forbrenning som er nedbetalt idet ny skog har vokst til den opprinnelige tilstanden. Dersom hogsten permanent øker i en større skog vil den kontinuerlig lavere alderssammensetningen føre til et permanent lavere karbonlager. Denne karbongjelden kan fortsatt tilbakebetales ved å benytte hogstkvantumet til bioenergi. Dersom det antas at årlig hogst for energi erstatter en tilsvarende menge fossil energi unngår man fossile utslipp som akkumuleres for hvert år.

Denne oppgaven forsøker å kvantifisere den temporale ubalansen mellom tap og gevinst av karbon ved en permanent økt hogst. Det benyttes en forenklet modell av skogen i Norge med noen av dens kjennetegn. Hver teig antas å ha en gjennomsnittlig vekst i skogen med en ujevn alder og et konstant areal, og det gjenværende hogstavfallet begynner å oksidere etter hogst. Fremtidig økt hogst for bioenergi som antas å være realistisk og gjennomførbart resulterer i en karbongjeld som varer fra 89 til 362 år. Denne usikkerheten kommer hovedsakelig av estimater på hvor mye fossile utslipp som unngås ved å erstatte fossil energi med bioenergi. Middelestimatet fra litteraturen gir en karbongjeld som varer fra 89 til 123 år.

Det skilles mellom å øke uttak av både stammevirke og/eller hogstavfall. Karbongjelden ved å benytte en andel av økt stammevirke til bygg beregnes også, hvor det viser seg at denne reduserer tilbakebetalingstiden med 1 til 23 år, avhengig av andre forhold. Karbongjelden ved å bare benytte eksisterende hogstavfall til bioenergi vil mest sannsynlig være tilbakebetalt i fra 24 til 86 år.

Det gjennomgås også relevant litteratur for globale og nasjonale skoger for å sette oppgaven i kontekst. Norske skoger er i dag et resultat bestemt av skogstiltak de siste 100 år. Andre faktorer ikke inkludert i metoden blir diskutert, og i hvilken retning de sannsynligvis vil påvirke resultatene.

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1. Introduction

Forest bioenergy was the major contributor to global primary energy until 1850, from when it gradually was substituted by fossil fuels in forms of coal and later petroleum (Grubler et al., 2012). Increasing use of fossil fuels for energy the last 150 years has in turn lead to a changing climate, with increasing global temperatures among other impacts mainly driven by release of carbon to the atmosphere. In addition to being an energy source, forests are also one of the great carbon reservoirs. Such reservoirs play a vital role in how the climate responds to greenhouse-gas (GHG) emissions, by carbon fluxes of different directions and magnitudes within the lifetime of a tree. The Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) agreed at its 21st meeting in Paris in 2015 to adapt and mitigate GHG emissions. In the long-term, the target is to keep the global average temperature well below 2° C above pre-industrial levels (UNFCCC, 2015). How forests are managed in the future may greatly impact the outcome of this agreement.

Central to the mentioned agreement of UNFCCC is Nationally Determined Contributions (NDCs). This term describes the reduction in GHG emissions for each member state. These reductions are renewed every five years, as they should be in line with the GHG emission trajectories necessary to reach the long-term goal. Even though forest management influences atmospheric concentrations of carbon dioxide (CO_2), there are several concerns related to credible carbon accounting for forests from both a land use sector and an energy sector perspective. The implementation of land use including forests to the NDC of a country has proven to be rather complex, when natural effects on forest carbon dynamics should be separated from anthropogenic effects. Also, there is an uncertainty related to carbon leakage effects, e.g. the GHG-emissions of land-use activities that are displaced due to forest conservation (Grassi et al., 2017).

As for the energy sector, EU still considers emissions from solid and liquid biofuels in use as zero, dating back to the legislative Renewable Energy Directive (RED) from 2009 (European Parliament & Council of the European Union, 2009). This approach to dealing with emissions from burning biofuels, including forest biomass, was recently also adopted by the U.S. Environmental Protection Agency in a statement released in April 2018 (EPA, 2018). EU's formal commitment to the Paris Agreement through a common NDC, which Norway is effectively a part of, initially targeted a 40 % reduction of GHG emissions in 2030 compared to 1990 levels (Klima- og miljødepartementet, 2015). This reduction of GHG emissions automatically increased as the RED was revised in June 2018, when the intended renewable energy as a share of the EU energy mix increased from 27 % to 32 % (European Commission, 2018). This higher target combined with EU's still-existing approach to CO_2 emissions from burning of biofuels, in effect stimulating increased harvest of biomass, can counteract climate change mitigation for decades and set a dangerous global example, according to Searchinger et al. (2018).

Regardless of these concerns and others, bioenergy from forest biomass and other biological sources together with carbon capture and storage (BECCS) is regarded by the Intergovernmental Panel on Climate Change (IPCC) as a very promising technology for carbon dioxide removal (CDR). Implementation of large-scale CDR is necessary at some point under the lower emission scenarios provided by IPCC from studies using integrated assessment models (Clarke et al., 2014). Afforestation and reforestation is another possible CDR technology, but constrained by availability of appropriate land areas. Ultimately, 87 % of the 116 scenarios in the latest assessment report from IPCC that lead to a likely global temperature increase below 2° C in 2100 rely on large-scale deployment of BECCS as CDR technology. The remaining scenarios which do not include BECCS predict that GHG emissions peaked in 2010 (Mander, Anderson, Larkin, Gough, & Vaughan, 2017), and thus show a reduced need of large-scale CDR in the future. However, annual emissions did not peak in 2010 and continue to rise (Mander et al., 2017).

The theoretical benefit of BECCS providing heat and power with negative CO_2 emissions is reflected in Clarke et al. (2014, their fig. 6.20), where model results of primary energy supply from BECCS cluster around 25-30 % as a share of global primary energy supply in 2100, under the mentioned scenario. With respect to the last decades struggle of proving viability of CCS in power production, and the enormous suggested land area required to satisfy the biomass supply in these typical scenarios, Anderson & Peters (2016) argue that BECCS is a political high-stakes gamble which provides a social licence to continue the present combustion of fossil fuels while apparently fulfilling the commitments of the Paris Agreement.

Considering current legislation and future energy and emission evaluations, a possible resurgence of bioenergy from woody biomass together with other types may occur. In that case it would be in stark contrast with the energy transition prior to and in the beginning of the industrial era. Primarily in Great Britain and to some extent also in mainland Europe, intensive logging for centuries had degraded and depleted forests to the extent that coal became essential for further development, even when population and energy consumption was only a small fraction of the present (Sieferie, 2015).

The main motivation for this thesis is to investigate the alleged carbon neutrality of forest bioenergy in Norway by simple calculations on the future forest carbon dynamics. The sensitivity of the carbon budget on what is harvested, how much, and the purpose of harvest is tested, with emphasis on cases with increased harvest from Norwegian forests in the years to come. These calculations are based on a broader overview of the carbon cycle and global land use changes, together with other climatic impacts from forestry. A foundation based on such literature is believed to be helpful if a more comprehensive model for assessing climatic impacts from bioenergy in other regions should be done.

2. Background theory

2.1 Global carbon cycle

Carbon is stored in the earth and the atmosphere in several reservoirs. In between these reservoirs, carbon is exchanged via fluxes from one reservoir to another. Due to the nature of these reservoirs, the cycle can be explained in one geological and one biological category.

2.1.1 Geological carbon cycle

The geological carbon cycle describes carbon movement between the atmosphere, oceans, and the lithosphere. Carbon in the atmosphere slightly acidifies atmospheric water as they combine and creates carbonic acid. This weak acid reaches earth's surface as precipitation. At the surface, the carbonic acid chemically weathers rocks, producing their component ions. Rivers transfer these ions to the ocean, where they precipitate to calcium carbonate. Several marine organisms use calcium carbonate to build hard shells. Such shells sink to the seabed when organisms die, and the carbon eventually gets stored in rocks as limestone through sedimentation. The rocks that engage in subduction zones due to plate tectonics release CO_2 as the rocks go through metamorphism, and CO_2 reaches the atmosphere again through volcanic eruptions (Kump, Brantley, & Arthur, 2000).

The turnover time of the reservoirs in the geological carbon cycle ranges from ten thousand to several hundred million years, so this cycle also is referred to as the slow carbon cycle. Carbon-containing rocks are by far the largest carbon reservoir, where the rocks explained above are approximately 80 % of the total rocks. The remaining rocks contain organic carbon coming from biological decomposition of organic matter. Under certain conditions, these organic sedimentary rocks are buried to later form petroleum as gas, oil and coal (Riebeek, 2011).

2.1.2 Biological carbon cycle

The main component of the biological carbon cycle is the biosphere which contains all life on earth. All life forms contain carbon, as CO_2 is one of the key reactants to perform photosynthesis. The reaction of photosynthesis may be represented as,

$$6CO_2 + 12H_2O + Light + Nutrients \rightarrow C_6H_{12}O_2 + 6O_2 + 6H_2O$$

CO_2 and water (H_2O) are abundant in earth's atmosphere and soil, respectively. The sun emits electromagnetic radiation to the surface of the earth, and the photons in the visible spectrum contains the proper amount of energy so the solar energy is converted to chemical energy. This reaction happens in green plants together with algae and certain microorganisms, as the solar energy synthesizes H_2O and CO_2 into carbohydrate molecules (Narbel, Hansen, & Lien, 2014). The chemical energy is stored in these molecules, such as glucose ($C_6H_{12}O_2$) or sugar. Oxygen (O_2) is a by-product together with water, and atmospheric oxygen became abundant as a result when photosynthetic biomass first evolved.

In a plant, tiny pores on a leave called stomata exchanges the gaseous molecules when CO_2 is absorbed and O_2 is released. The water is mainly absorbed from the soil through the roots and serves two important functions. Water gives access to the uptake of nutrients like nitrogen from the soil, which is needed to sustain plant growth. Water then transpires mainly in the stomata, where liquid water evaporates to the atmosphere. Energy is used by the leaf to evaporate the liquid water, and latent heat is released cooling down the plant. Life functions in photosynthetic biomass are preserved due to respiration. Carbohydrate molecules oxidize in respiration, and energy subsequently releases when molecular bonds break. This energy sustains vitality and growth throughout the lifetime, while the excess carbohydrate molecules are stored for later conversion. Respiration releases water and CO_2 in a reaction that is opposite of the photosynthesis.

In vegetation, photosynthesis absorbs CO_2 from the atmosphere, and respiration oxidizes some of this carbon back to the atmosphere as CO_2. The ocean does not absorb atmospheric carbon only indirectly through photosynthesis in marine organisms, but also directly since atmospheric CO_2 dissolves directly in water and creates carbonic acid. Turnover-times for the reservoirs in the biological carbon cycle ranges from years in the atmosphere up to millennia for the larger reservoirs in terrestrial vegetation and the various ocean zones (Riebeek, 2011). Due to the much shorter turnover-times than the geological cycle, the biological cycle is also called the fast carbon cycle. Carbon fluxes between the biological and geological cycle are very small when the climate system is left unperturbed by orbital changes. Figure 2.1 presents a schematic of the global carbon cycle with a focus on the biological components. Note that the figure does not show the reservoir of carbon-containing rocks in the lithosphere which is estimated to be approximately 100 million gigaton carbon (GtC) (University of New Hampshire, 2009). The units in figure 2.1 is in petagram carbon (PgC) and in PgC per year for reservoirs and fluxes, respectively, where 1 PgC is equivalent to 1 GtC.

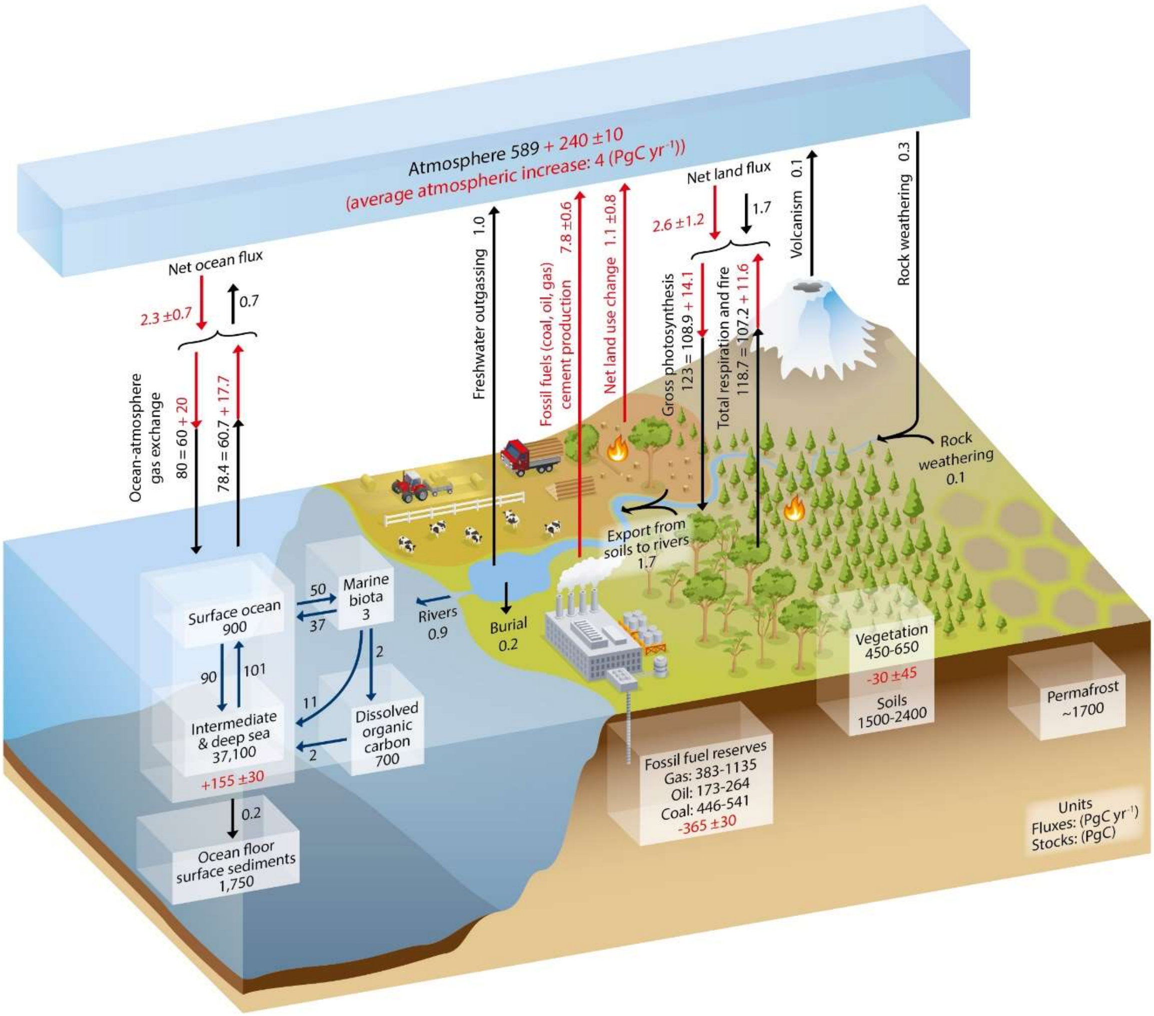

Figure 2.1. Reservoirs and fluxes of the global carbon cycle. Carbon reservoirs and fluxes are represented as boxes and arrows, respectively. The black numbers are estimates prior to 1750. The red numbers in reservoirs are cumulative changes from 1750-2011, while the red numbers in fluxes are mean anthropogenic fluxes over 2000-2009. From Ciais et al. (2014).

2.1.3 Greenhouse-gas effect and anthropogenic perturbation to the carbon cycle

Earth's climate would be inhabitable without the radiative properties of CO_2 and other well-mixed GHGs in the atmosphere. They absorb energy from the earths infrared radiation and re-emits it in all directions including back to the earth's surface. Since the beginning of the industrial revolution and until today, atmospheric CO_2 has increased from approximately 280 parts per million volume (ppm) to 410 ppm. Still, CO_2 is only 0.04 % of the gases in our atmosphere but contributes a significant share to the net GHG effect. The anthropogenic perturbation to the global carbon cycle and the associated climate feedbacks is responsible for most of the global temperature increase that is recorded over the last century, which presently is about 0.8 °C (Hansen, Ruedy, Sato, & Lo, 2010). Carbon in fossil fuel reserves is essentially a part of the slow carbon cycle described in section 2.1.1. As humans extract and burn fossil fuels, carbon is transferred from the slow to the fast carbon cycle. In figure 2.1, the carbon flux from fossil fuels is almost 80 times the natural occurring carbon flux from volcanos to the atmosphere in the slow carbon cycle.

The anthropogenic carbon flux also includes contributions from cement production. Cement is mainly processed by heating of limestone which mostly precipitates through the pathway explained in section 2.1.1. As limestone decomposes, CO_2 becomes one of the products. Additional CO_2 emissions come from burning fossil fuels to produce the heat required to decompose limestone (Andrew, 2017). In the figure, it is estimated that emissions from cement production make up 4 % of the flux of 7.8 ±0.6 GtC per year. The other anthropogenic carbon flux of 1.1 GtC per year comes of net land use change.

The gross atmospheric carbon coming from anthropogenic sources over the period was estimated to be 555 GtC which is more than two times the net atmospheric carbon increase in figure 2.1. Of this gross carbon supply, 180 Gt is estimated to come from land use change, while 375 Gt is estimated from fossil fuels and cement production (Ciais et al., 2014). The deviation between anthropogenic supply and accumulation in the atmosphere is due to the reservoirs in ocean and in vegetation and soil. These reservoirs have acted as carbon sinks and absorbed and stored a roughly equal amount of atmospheric carbon each since 1750. Note that the increase is only written in the ocean in figure 2.1, while the vegetation and soil reservoir have shrunk (-30 ±45 GtC). This means that the land carbon sink has not fully compensated for the emissions from net land use change over the same time. This carbon accumulation on land which has almost compensated the historical carbon emissions from land use change is not well understood (Houghton, 2002; Houghton, Baccini, & Walker, 2018). Since this sink is mainly calculated as the remaining share of the global carbon budget, it is referred to as the residual terrestrial carbon sink. It is believed to be caused by two main mechanisms; enhanced photosynthesis both by increased atmospheric CO_2 concentration and nitrogen deposition, and a warmer and wetter climate extending the growing season in boreal and temperate forests (Le Quéré et al., 2018). This residual land sink together with the other mentioned sinks and sources is shown in figure 2.2.

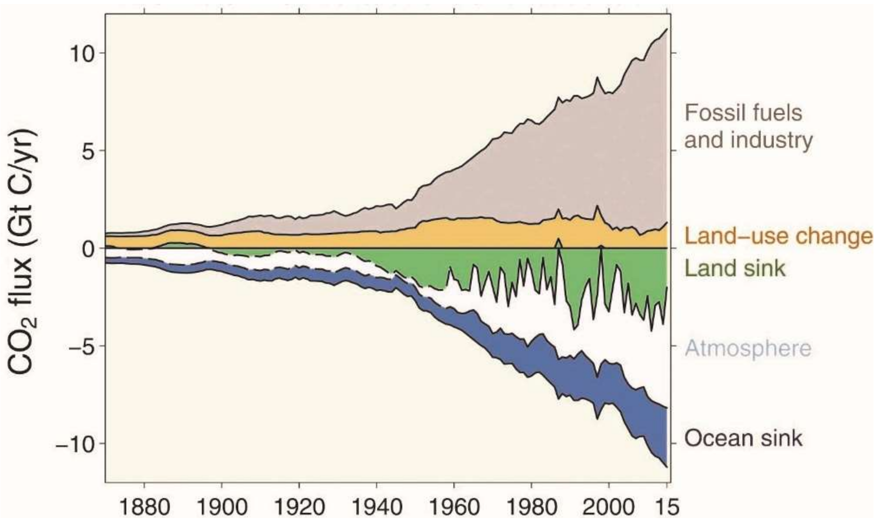

Figure 2.2. The five main global sinks and sources of carbon. The irregular residual terrestrial sink in not well understood. From Candela & Carlson (2017).

2.1.4 Land use changes and soil organic carbon

The net land use change flux to the atmosphere has been and is at present mainly driven by deforestation. A similar estimate as that to figure 2.1 is shown in figure 2.3, where the net land use change flux is compared to its attributional components.

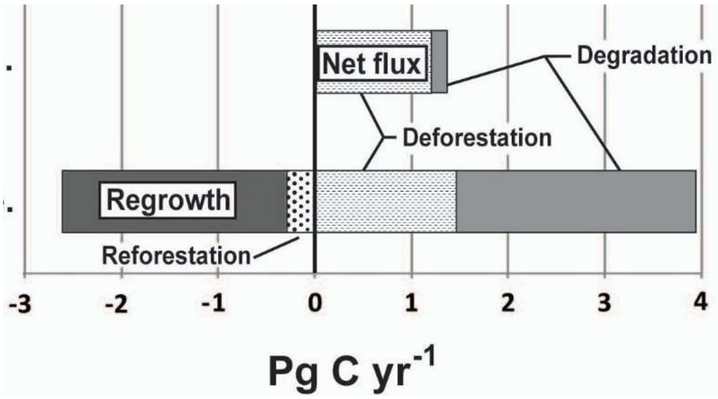

Figure 2.3. Carbon sinks and sources contributing to net flux averaged over 2000-2009. Top bar shows net flux (source), bottom bar shows gross sink and gross source. Unit is PgC per year equivalent to GtC per year. Adapted from Houghton et al. (2012).

By the top bar in figure 2.3, only a minor fraction of the net flux is attributed to forest degradation. Forest degradation is a broad term that includes both anthropogenic and natural changes that affects the forest's productivity and capacity negatively, e.g. a lower carbon stock per hectare (FAO, 2011). Degradation and regrowth which both may occur in a logged forest nearly cancel each other. Reforestation share of the gross sink is much smaller than regrowth and refers to expanding forest area on earlier agricultural land (Houghton et al., 2012).

When considering different types of land use changes, figure 2.4 shows that conversion to forest for wood harvest has not been the major carbon source from land during the industrial era. The main culprit has rather been land conversion for agricultural land use, especially from forest land. Goldewijk (2001) estimated that combined land area for cropland and pasture expanded almost 4000 million hectare (Mha) from 1750 to 1990, compared to a total area just above 1000 Mha in 1750. Even though pasture area was more than twice the cropland area in 1750, and responsible for 70 % of the agricultural land expansion towards 1990, the largest CO_2 emissions has come from conversion to cropland.

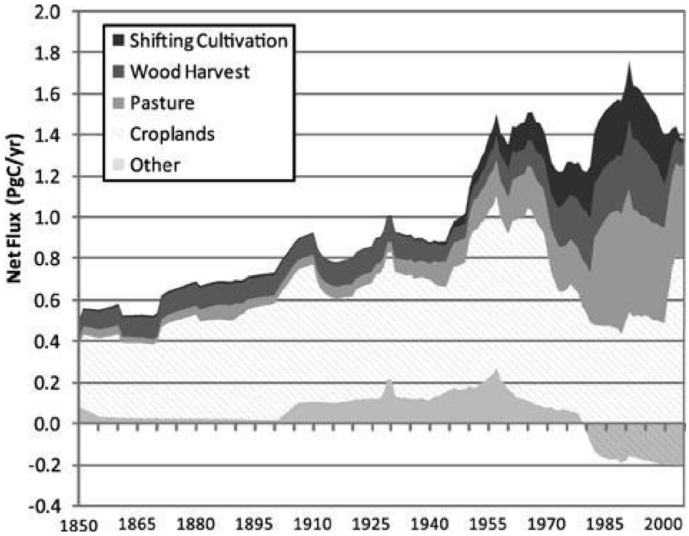

Figure 2.4. Net land use change flux from 1850-2005 represented by different types of land uses. Unit is PgC per year equivalent to GtC per year. Description of the categories follows below the figure. From Houghton (2010).

All five types of land use change in figure 2.4 are net fluxes, which mean they contain different components as in figure 2.3. Conversion to croplands tends to change the aboveground carbon stock more compared to conversion to pasture, since pasture often expands into natural grasslands with a subsequent smaller change in aboveground carbon stock (Houghton, 2010). Based on the partial cancelling out of forest degradation and regrowth in figure 2.3, you may assume that the net flux from wood harvest would be close to zero if there was a constant area of logging and regrowth. The net wood harvest flux in figure 2.4 therefore suggests a steady increase in area for wood harvest. Areas in shifting cultivation change between cropland and forest recovery. At first, a forest area is cleared by logging or with fire. After establishment of cropland, cropping is maintained until the soil loses a critical amount of nutrients resulting in low soil fertility. Later, the soil would have recovered, resulting in a new forest establishment. Increased population densities with higher food demand in especially low-income countries have shortened these periods of recovery, leading to a permanent forest damage or deforestation (Ickowitz, 2006). Shifting cultivation has existed for a long time but was severely intensified in the decades prior to 2000. The land use change named Other is an estimate of the remainder land use changes, that is deforestation and degradation prior to 1980 and afforestation post 1980 not to the expense of other land uses.

The soil's performance as a carbon sink or source is complex but important to the net land use change flux. Estimates of the global soil carbon reservoir range widely. Around two thirds are soil organic carbon (SOC). The remainder inorganic carbon has a high stability with a low rate of formation compared to SOC and will not be described further (Lal, 2008). SOC is in the organic matter which are living and dead organisms in various stages of decomposition. These stages are everything from fresh residues as litterfall to the more resistant humus with its possible turnover time of thousands of years in certain climates (Paul, 2016). The main control of SOC formation is possibly root biomass, which transfers carbon to soils both from dying roots and indirectly through soil microbes feeding on roots which provides nutrients in return (Ontl & Schulte, 2012). The SOC reservoir has thus built up as the productivity of photosynthesis minus respiration has exceeded decomposition. Present estimates of SOC show considerable range. The median of 27 studies estimating the global SOC reservoir in Scharlemann et al. (2014) was almost 1500 GtC. Estimates of historical SOC losses have ranged from 40-500 GtC as noted in Lal (2004). A recent study estimated SOC losses from land use change over the last 12000 years (Sanderman, Hengl, & Fiske, 2018). The cumulative SOC losses in this study is 133 GtC. The annual rate or flux of SOC increased sharply from < 0.05 GtC per year prior to 1800 to around 0.22 GtC per year after 1800 which is comparable to the numbers in figure 2.4.

Changes in SOC depend on the climate where the land is converted, and on the specific land conversion (Post & Kwon, 2000). In general, croplands are cultivated more extensively than pasture which affects the SOC. This is also an important factor in figure 2.4 where the net flux from croplands are larger than from pasture, even though pasture dominates in area. If cropland is established on the expense of either forest or pasture, SOC may decrease around 50 % whereas the SOC change could be slightly positive if forest converts to pasture (Guo & Gifford, 2002). In the latter study reviewing hundreds of studies on SOC and land use change, one of the conversions is from natural forest to forest plantation. Coniferous forest tends towards the greatest SOC loss of around 20 %, where the effect is strongest when measured up to 40 years, and in areas with precipitation above 1500 mm per year. Results of SOC observations more than 40 years after the conversion shows nearly no change in measured SOC.

2.2 World's forests

2.2.1 Development and use

Forest land is defined by the Food and Agriculture Organization of the United Nations (FAO, 2012). as land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover larger than 10 %. At present, forest land covers around 4000 Mha or about 27 % of the global land area. Most of the area are natural forest as only 7 % are planted. Between 1990 and 2015 according to FAO, the annual net loss or deforestation was 8.6 Mha/year corresponding to a net loss rate of 0.13 % (FAO, 2016b). This last decade's decline is however asserted as wrong in a study where it is shown that global forest land have increased almost 6.6 Mha/year between 1982 to 2016 (Song et al., 2018). Common to both contradictory studies are that the net loss of forest happens in the tropics, while the latter shows that this loss is outweighed by a net gain of forest in the extratropics. Both also credit China as the most important country for the net gain of forest land.

Chinas several extensive forest programmes since 1990s began as an initial response to environmental concerns of flooding and soil erosion, since forests may serve the important function to stabilize the soil and therefore both directly and indirectly absorb waterfall and prevent flooding (Rodríguez et al., 2016). The land use change category called Other in figure 2.4 after 1980 acts as a carbon sink, and is credited mainly to afforestation in China together with agricultural abandonment in Europe and in the US (Houghton, 2010). The strategy in China is however controversial since natural forests provide important ecosystem services. If land areas are exposed to non-native trees, as in China, the afforestation may damage these vulnerable ecosystems (Xu, 2011). As the previous studies measured tree canopy cover, you may also measure global leaf area of all vegetation using satellite data to estimate forest land. This is done in a recently published study concluding that the earth is getting greener since 2000, and the greening is most prominent in China and India (Chen et al., 2019). Forests contribute however only 4 % of the greening in India compared to 42 % in China, while two-thirds of the overall greening is shared about equally between increase of forests and cropland. Direct effects as anthropogenic land use management is pointed out as the major driver of the overall greening, in opposite to e.g. Zhu et al. (2016) which states that 70 % of the greening comes of CO_2 fertilisation and only 4 % from human land use change.

The global annual harvest of roughly 3600 million m^3 (Mm^3) roundwood is distributed equally between industrial roundwood production and wood fuels, but with distinctive differences between parts of the world. Wood fuels accounts for over 90 % of roundwood production in Africa, while the share in North America and Europe corresponds to 10 and 20 %, respectively (FAO, 2016a). These shares have been relatively stable in the years prior to 2016. Traditional usage of wood fuels for heating, cooking and light are related to health risks. Such inefficient use of wood are one of the main sources of indoor air pollution which causes an annual 4.3 million prematurely deaths (Barría, 2016).

2.2.2 Carbon fluxes

Despite some uncertainties of how much and why the earths forests are increasing, there is less doubt of the forests potential to sequester carbon and thus mitigate climate change. This potential was recently analysed and quantified by ecologists at the Crowther lab in the Swiss Federal Institute of Technology in Zurich (Crowther, 2019; Vandette, 2019). Their result is that available degraded and abandoned land could host an additional 1.2 trillion trees, increasing their estimated number of trees from 2015 by 40 % (Crowther et al., 2015). Since the available land is presently unused, this could absorb atmospheric CO_2 equal to at least a decade of anthropogenic emissions without large biodiversity losses. The residual terrestrial carbon sink mentioned in section 2.1.3 is at present compensating the net land use change flux resulting in a global net sink from 2000-2009 at approximately 1.5 GtC/year based on figure 2.1. The global residual sink for the same period was 2.6 GtC/year, and probably higher the most recent years (Keenan et al., 2016). Magnitude and direction of these carbon fluxes differ between forest biomes. The residual sink is larger than the source from land use change in both boreal and temperate forests, in opposite to tropical forests (Houghton et al., 2018). Deforestation and forest degradation in the tropics emit around 0.86 GtC/year which is twice the amount of carbon sequestered in tropical regrowth, resulting in a net source of carbon from the tropics (Baccini, Walker, Carvalho, Farina, & Houghton, 2017). There are also essential differences in how much and where the carbon is stored between the three major forest biomes. An overview follows in table 2.1 including above- and below-ground biomass, deadwood, litter and soil carbon to 1 m depth (Pan et al., 2011).

Table 2.1. Carbon stored in the three forest biomes and in the main domains. The remaining domains are deadwood (8 %) and litter (5 %). The numbers are obtained from Pan et al. (2011).

Forest biome	Area [Mha]	Carbon [Gt]	C density [t/ha]	Biomass C [%]	Soil C [%]
Boreal	1135	272 ± 23	240	20	60
Temperate	767	119 ± 6	155	38	58
Tropical	1949	471 ± 93	242	56	32

The carbon density in temperate forests constitutes only 60 % of the density in the other forest biomes. Boreal and tropical forests have a comparable carbon density, but the vertical distribution within each zone is very different. Soil carbon to 1 m depth accounts for 60 % of the total carbon in boreal forests, whereas only 20 % is stored in above- and below-ground biomass. The distribution in the tropics is almost opposite. The main reason for this difference is the continuously high temperatures in the tropics which ensure fast decomposition of organic matter and consequently recycling of nutrients leading to faster growth of living biomass. In boreal forests, the lower temperature results in a higher rate of formation of soil organic matter and a higher level of SOC equilibrium (Malhi, Baldocchi, & Jarvis, 1999).

2.3 Forests of Norway

This chapter presents characteristics of forests in Norway with a particular emphasis on carbon fluxes, and explanations of present conditions. The assumptions stated in the later method of this thesis are based on most of these characteristics.

2.3.1 History

The national forest inventory of Norway was the first of its kind when it started in 1919 to assure sustainable forest resources from an ever-smaller standing stock. Forest management based on systematic data collection the past 100 years has at present tripled the growing stock volume compared to 1925. Forest area covered in 2014 slightly above 12.1 Mha, equivalent to almost 38 % of total land area (Tomter & Dalen, 2018c). Area change over the last decades is very small, as forest land area have decreased around 0.006 % since 1990 (Norwegian Environment Agency, 2018). About 8.3 Mha of this forest land is productive forest not limited by protection or other uses, whereas its share in wood volume accounts close to 90 % of total wood volume in Norwegian forests (Tomter & Dalen, 2018d). Productive forest is a forest site yielding on average at least 1 m^3 roundwood per ha and year, and 8.3 Mha can therefore be considered as the theoretical potential area for harvesting (Bækkelund, 2018a). The development between 1919 to 2014 of total wood volume, annual increment of wood volume, and annual harvest is presented in figure 2.5.

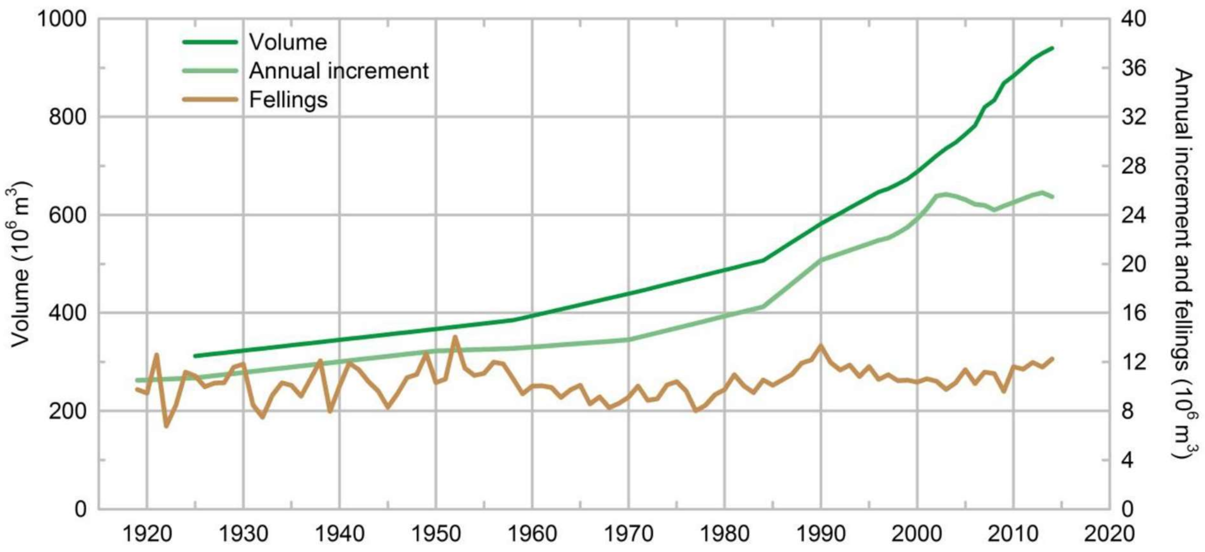

Figure 2.5. Volume, annual increment, and annual harvest without bark (fellings) between 1919-2014. The left-sided y-axis is wood volume in Mm^3. The right-sided y-axis is annual increment and harvest in Mm^3. Note that annual increment contains harvested wood, so net annual increment equals annual increment minus annual harvest. From chapter 6.1.1 in Norwegian Environment Agency (2018).

The wood volume has accelerated in growth towards the 2000s since the deviation between annual increment and harvest have increased during the same period. Harvest has stabilized at below half of the increment since 2000, even though this level of harvest has been near constant since 1919 when the volume was around a third of the present volume. There are several factors explaining the growth and present volume in Norwegian forests. The most significant factor is probably modernisation in forestry throughout the century, where selective logging was replaced with systematic clear-cutting and subsequently replanting of the same species resulting in denser forests (Bækkelund, 2019). Another important reason is afforestation in mainly western and northern parts of Norway starting in the 1950s. This afforestation was heavily subsidised with the intention to grow forests on new areas or replace native tree species with native or non-native species with a higher wood productivity (Tomter & Dalen, 2018a). Figure 2.6 presents such afforestation in selected years between 1952-2010 in Western and Northern Norway. Summing the whole period gives 0.39 Mha new forests. Fewer livestock leading to overgrown land areas together with an ever higher tree line due to a warmer climate is also contributing to the forest growth (Steinset, 2015).

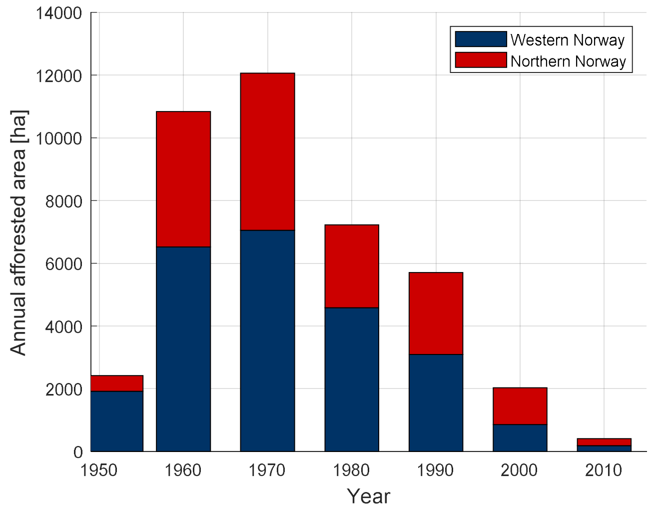

Figure 2.6. Afforestation from 1952 to 2010 in western and northern parts of Norway. Data are obtained from Tomter & Dalen (2018a).

Most of the forest in Norway is boreal, characterized by a relative slow growth and other characteristics mentioned in section 2.3.2. The extensive areas afforested in the 1960s and 70s suggests a large annual increment today as sees in figure 2.5 due to growth dynamics which will be clarified in the next section.

2.3.2 Forest properties

The volume growth of a productive forest stand is categorised in site indices, which is the ability of the forest floor to produce wood products depending on climatic factors and supply of water and nutrition. A site index states the mean height of the 10 trees with largest diameter per decare (da) of 40 years since the tree reached 1.3 m above the ground, and varies between tree species (Bækkelund, 2018b). The previous and current dominating tree species in Norway is spruce, pine and birch. Of the approximate 965 Mm^3 of wood in the latest year in figure 2.5, these three tree species are responsible for almost 90 %, with spruce as the most common at 43 % (Tomter & Dalen, 2018f). Native and non-native spruce were also the most common species afforested related to figure 2.6. Site indices are normally ranged from 6 to 26. The productivity in the classes of site indices from 6 to 8, 11 to 14, and 17 to 26 are defined as low, medium and high, respectively. A spatial distribution of site indices for the period 2005-2009 follows in figure 2.7.

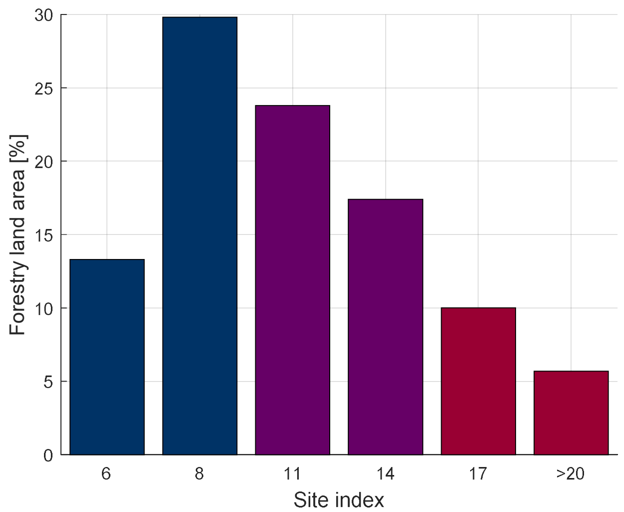

Figure 2.7. Forestry land sorted by site index classes. Blue bars are low productive, purple bars are medium productive, and red bars are high productive. Site index >20 in the figure contains also the classes of 23 and 26. In addition to 23 and 26, all existing site index classes which are used in classification are included in the figure. The total area is 7.94 Mha, smaller than 8.3 due to the use of older data obtained from Granhus, Hylen, & Nilsen (2012).

Low and medium producing sites cover 43 and 41 %, respectively, while the most productive sites cover only 16 % of the forestry land. The difference in growth is significant between the different sites. An example is shown in figure 2.8 which considers forest stand ages and standing stock of spruce at site indices 8 and 14. This figure implies the two growth rates as the wood volume is plotted against forest stand ages.

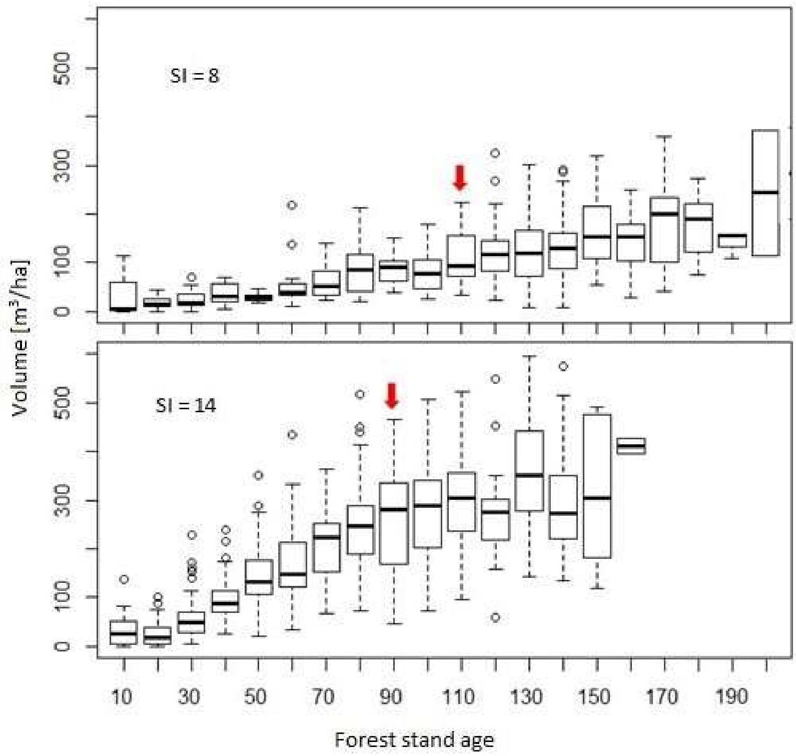

Figure 2.8. Box plots of wood volume at forest stand ages from 10 to 190 years of spruce on site index 8 (top) and 14 (bottom) from the national forest inventory over the period 2008-2012. The red arrows indicate usual stand age of felling. Adapted from Dalsgaard et al. (2015).

Common to both sites is that the volume is low the first 30 years and steadily increases later. On site index 14, the volume increases less from around 100 years and possibly flattens out at older stand ages. The lower site index indicates that the wood volume continues to increase at a higher rate after 100 years, but still only reaches around 50 % of the volume at a 100-year-old stand of site index 14. The optimal stand ages of felling or the rotation age giving the highest return are based on biological and economic factors. From a purely biological perspective, this age should be when the mean wood production per year reaches maximum. Even though the volume continues increasing, it decelerates leading to a smaller mean wood production. The optimal rotation age is therefore negatively correlated with site index, since better sites grow faster and hence produce a larger volume per year. Since a forest stand can be considered as a long-term investment, the rotation age is usually dependent on economic factors such as costs, future timber price and discount rates (Płotkowski et al., 2016). More productive spruce stands than the two in figure 2.8 can be harvested after around 70 years, yielding up to ~ 400 m^3/ha (Gizachew, Brunner, & Øyen, 2012).

When considering the afforestation in figure 2.6, this implies a large forest area with trees at an age around 40 to 60 years today. At these ages, the growth rate is high according to figure 2.8, indicating the high and steady annual increment since the 2000s in figure 2.5. An estimate of age classes of the unprotected productive forest at 8.3 Mha follows in figure 2.9.

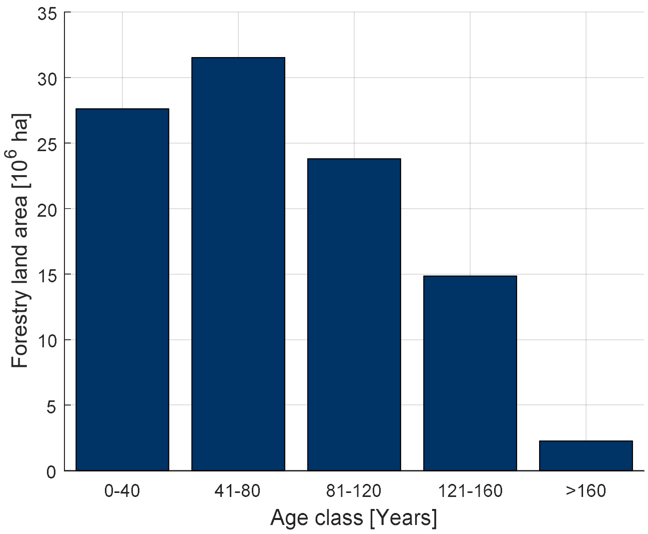

Figure 2.9. Forestry land divided by age classes. Total area is 8.296 Mha. Age 0 is stands not immediately replanted after harvest, or with a too modest planting to be considered as a forest stand and make up only 6 % of the age class 0-40 years. Numbers applies to 2014 and are from Tomter & Dalen (2018b).

These ages do also imply a large growing tree stock at present due to large areas of forest at ages where the volume increases rapidly. 31 % of the area is between 41-80 years, while the adjacent age classes cover around 25 % of the total forestry land.

2.3.3 Harvest quantity and products

The harvest levels in figure 2.5 consist mostly of industrial roundwood and traditional wood fuels. The harvest of such wood fuels between 2007-2017 fluctuated between 2-3 Mm^3, with an average harvest level of almost 2.5 Mm^3 dominated by broadleaved species as birch (Statistics Norway, 2017). The total harvest from 2014 in figure 2.5 was 12.5 Mm^3, and almost 11 Mm^3 of this bulk was fellings for industrial roundwood. Traditional wood fuel is thus the largest source to bioenergy from the forest in Norway, which scope and potential is further discussed in section 2.5. The wood fuel share of total harvest is very similar the equivalent share in Europe discussed in section 2.3.1. Industrial roundwood is distinguished between saw logs and pulpwood, depending on quality of the trunk. Saw logs are typically utilized in sawmills for building materials or furniture, while pulpwood is often used for pulp and paper industries. More than 75 % of the industrial roundwood comes from spruce stands, while the remaining share is mostly trunks from pine stands. Harvested roundwood in Norway have historically been distributed approximately equal between saw logs and pulpwood, but the trend in the years beyond figure 2.5 is a larger share of saw logs than pulpwood (Norwegian Agriculture Agency, 2019).

Annual harvest of roundwood including fuelwood is expected to increase. The European Parliament and the Council of the European Union adopted a legislative regulation in June 2018 under its targets mentioned in chapter 1, the 2030 climate and energy framework. This regulation implements GHG emissions and removals from land use, land use change, and forestry (LULUCF) to the 2030 targets (European Parliament & Council of the European Union, 2018). For member states including Norway, this ensures that GHG emissions from LULUCF are accounted in a framework similar to other sectors by the forest reference level approach (FRL). The FRL approach projects GHG emissions and removal in LULUCF between 2021-2030 based on a continuation of forest management practises from a chosen reference period of 2000-2009. This does not set a target of a larger carbon sink in LULUCF, but rather penalizes a member state if the source offsets the sink, forcing it to cut emissions in other sectors (Nabuurs, Arets, & Schelhaas, 2018). Conversely, a lower harvest resulting in a larger sink can be accounted as a reduction in GHG emissions. Emissions and removals in a FRL is thus a result of both historic forest management and the developing age classes, as a member state may increase or must decrease harvest in the FRL period. The proposed FRL for Norway was recently chosen and is expected to be approved as it lies within the regulations. Given that certain terms are met, this FRL may allow Norway to increase harvest of roundwood and fuelwood to 16.5 Mm^3 (Ministry of Climate and Environment, 2019; Norwegian Environment Agency, 2019).

What type of products the raw material becomes is important for the temporal distribution of emissions from the products, due to various time-scales of decomposition or carbon oxidation from the harvested wood products. A recent study (Iordan, Hu, Arvesen, Kauppi, & Cherubini, 2018) quantified net CO_2 emissions from forest products in Norway, Sweden and Finland between 1960 to 2015, where figure 2.10 shows the result for Norway.

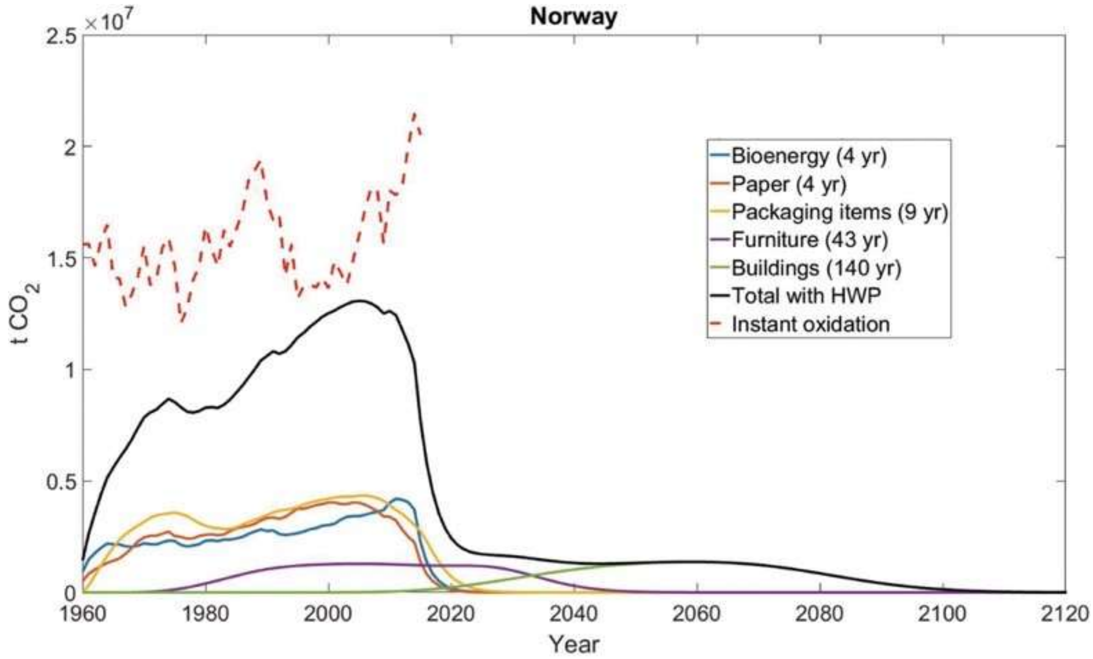

Figure 2.10. Total CO_2 emissions and emissions split in selected categories of harvested wood products (HWP) from 1960 to 2015 in Norway. Emissions after 2015 is legacy emissions of HWPs prior to 2015. Red dashed line are emissions if all products instantly oxidized to atmospheric CO_2. Numbers in parenthesis in the legend are average lifetime in the anthroposphere for each category. Adapted from Iordan et al. (2018).

The figure above points out the significance of wood products in the context of temporal distribution of emissions. Buildings represented in the green line is the category with longest average life-time at 140 years. Net emissions from this category is thus 0 in the period towards 2015, since the forest can regrow over the time that carbon in buildings oxides to atmospheric CO_2. The trend of more saw logs than pulpwood previously mentioned therefore has a positive impact on climate. Emissions from short-lived products of bioenergy, paper and packaging items happens more instantly after harvest, and these emissions declines rapidly after 2015. The total legacy emissions some years after 2015 consists only of buildings which oxides carbon up to 100 years after 2015.

2.3.4 Carbon reservoirs and fluxes

The key property of boreal carbon distribution in table 2.1 is recognized in Norwegian forests where at least 60 % of the carbon is stored in the soil. When including below-ground carbon in roots and partly stumps, the share is maybe 80 %. The trend in SOC since 1980 is declining attributed by among other things a warmer climate and hence a faster decomposition, leading to a negative feedback for the climate (Bjune, Lee, & Lange, 2018). A completely different situation is registered when focusing on the carbon in trees, due to extensive growth explained in section 2.4.1. Estimates from the Norwegian Environment Agency of carbon stored in forest biomass are shown in figure 2.11.

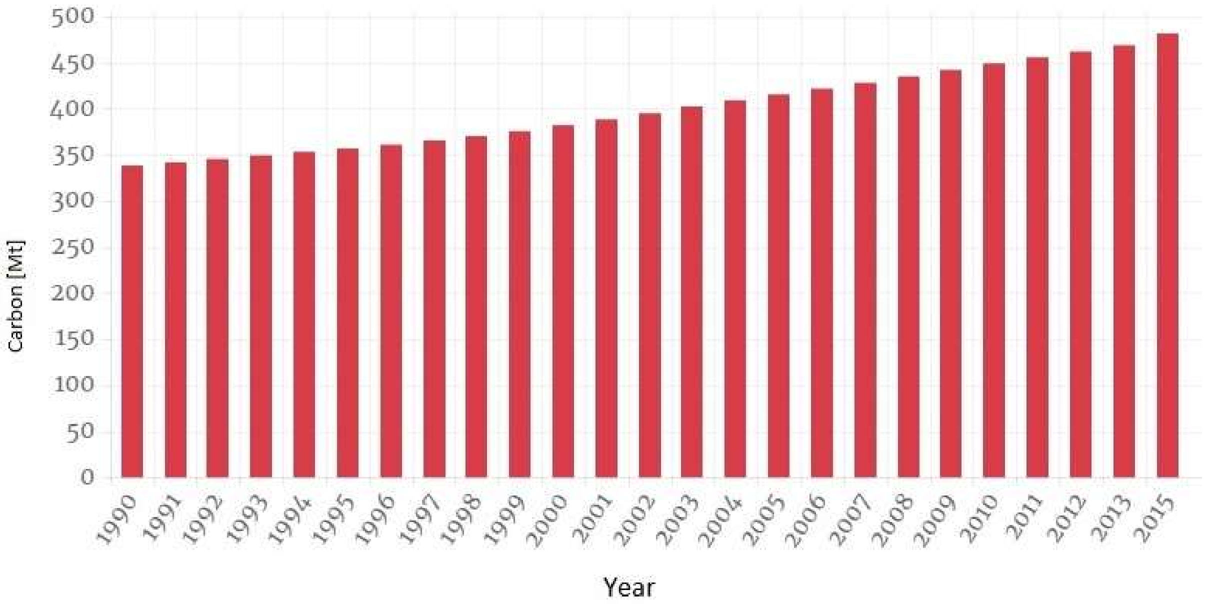

Figure 2.11. Carbon stored in tree biomass from 1990 to 2015. Adapted from Tomter & Dalen (2018e).

Since 1990, carbon stored in forest biomass has increased by more than 43 % to 477 MtC in 2015. Almost 80 % of this reservoir in above-ground biomass is in trunks and branches, while the remainder carbon is in roots and parts of the stump. The forest sequestration of atmospheric carbon sharply increased prior 2000 and has been around 7-8 MtC per year the last decades. This number equals approximately half of the national GHG-emissions in all sectors. Hence the growing forest is a major contributor to mitigating climate change (Tomter & Dalen, 2018e).

Forestry in Norway is mainly driven by price and demand of the trunk which constitutes less than half of the total biomass of a tree (Løken, Eriksen, Astrup, & Eid, 2012; Melbye & Killingland, 2013). This means that a significant amount of biomass is left on the site as branches, tops, stumps and roots. To discuss carbon neutrality of forest bioenergy, it is thus not enough to focus on the carbon which is harvested and regrown since a larger share than extracted carbon is normally left on site as other biomass. Such harvest residues decompose in the years after harvest, gradually emitting CO_2 to the atmosphere. The rate of decay strongly depends on specific climate and soil conditions, together with the size or diameter of the residues. A study from 2012 modelled a spruce forest grown in Norway with different levels of utilizing residues. The global warming potential evaluated over a time horizon of 100 years ranged from 0.44 with 100 % utilization to 0.62 with no utilization, compared to fossil CO_2 emissions at 1 (Guest, Cherubini, & Strømman, 2012). Another study modelling Finnish forest, which has comparable climate to Norway, points out the significance of harvesting residues (Repo et al., 2012). Including shorter time effects than the Norwegian study, the latter study modelled substitution effects down to 20 years after replacing fossil fuels with different residue categories for energy production. Results are shown in figure 2.12, where all direct and indirect GHG emissions are included.

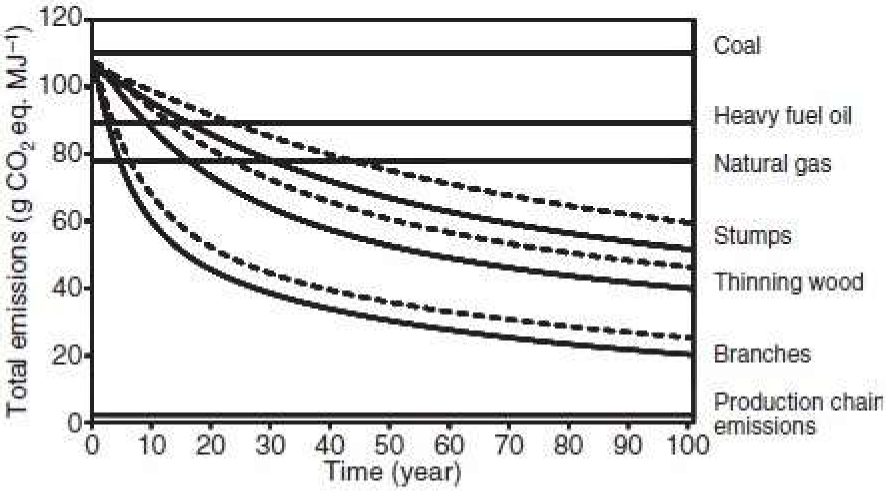

Figure 2.12. Total GHG emissions per MJ of selected fossil fuels (horizontal lines) and biomass residue categories collected in Northern Finland (dashed lines) and Southern Finland (solid lines) from 1 to 100 years after harvest. The production chain emissions belong to the biomass emissions. Note that this does not only show the decaying residues, since the bioenergy production chain emissions are included. From Repo et al. (2012).

The extreme cases of replacing coal with branches and natural gas with stumps reduced cumulative emissions with 62 % and 7 % after 20 years, respectively. Equivalent numbers for a 100-year time scale was 77 % for coal/branches and 21 % for gas/stumps. Similar results were obtained in Repo, Tuomi, & Liski (2011), where they conclude that such indirect emissions from residues increases with a decreasing residue decay rate, as e.g. coarse stumps decompose slower than fine branches. These studies are however more relevant to Finland than Norway, since the market for utilizing harvest residues in large scale is mature in Finland and Sweden of the Nordic countries (Asikainen, Björheden, & Laitila, 2014). It is also worth noticing that Finland's energy consumption in 2017 included 27 % forest derived bioenergy (Statistics Finland, 2018).

In general, not all the available harvest residues should be utilized. Too intensive additional harvest could decrease the carbon in both above-ground biomass and the soil. A large share of the nutrients in a tree is being contained in branches and needles. When harvest residues as these types are left on the forest floor, they add nutrients to the soil and thereby increases the soil productivity (Nilsen, Hobbelstad, & Clarke, 2008). Removing these residues and potential effects on the soil productivity could decrease biomass production for the future rotations leading to a smaller stock of stored carbon in both trees and soil since the trees transfer carbon to the soil through e.g. litterfall and roots as mentioned in section 2.1.4. An assessment from 2014 assumes that the theoretical maximum residues which could be extracted is 63 m^3/m^3 trunk or roundwood. However, due to effects mentioned above just below 70 % of that again is used to simulate a non-perturbed soil fertility (Norwegian Environment Agency, 2011).

Figure 2.13 illustrates the most important aspects of the dynamics of carbon stock of a typical forest stand in Norway.

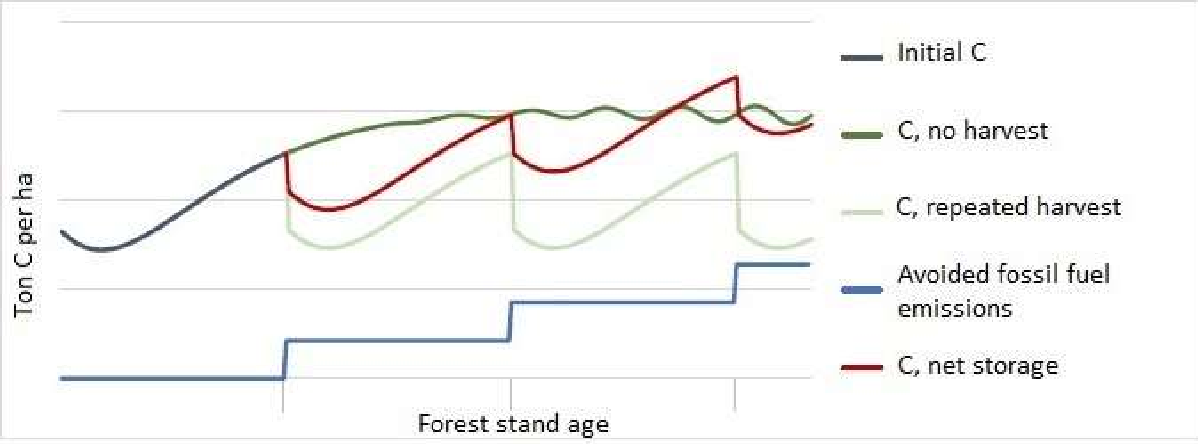

Figure 2.13. Carbon (C) stock in an exemplified forest stand under conventional harvest and no-harvest regimes, assuming that forest bioenergy replaces fossil fuels in the harvest regime. The stand age reaches rotation age at the grey vertical lines. Adapted from Norwegian Environment Agency (2016).

The dark grey line in the first period shows the initial carbon after one harvest. The carbon decline after harvest is mainly due to the mentioned decomposition of residues, but also temporary SOC losses for some years after logging as noted in the end of section 2.1.4. If the forest stand becomes protected, the stock of carbon follows the green curve which gradually flattens out. A share of natural dead wood makes up a portion of this stock as the trees are getting older. The fluctuations represent natural disturbances as e.g. fire, drought or damage from pests (Norwegian Environment Agency, 2016). If the stand is continuously harvested, the isolated forest carbon stock repeats itself after each rotation period and follows the bright green curve. However, when bioenergy from the harvested products replaces an amount of fossil-derived fuels, an amount of fossil fuel emissions is not emitted to the atmosphere for each rotation. The result by adding these avoided fossil fuel emissions to the forest carbon budget is a net loss of atmospheric CO_2 after a longer period.

2.4 Bioenergy from harvested products

2.4.1 Overview of technologies

There are several ways to utilize the energy potential from forests. Most of the bioenergy products discussed throughout chapter 2 are woody or solid fuels, which differs from the other pathways due to their limited need of processing. Figure 2.14 shows a schematic of the other bioenergy conversion processes which are biochemical, thermochemical and chemical conversion, together with selected products and byproducts.

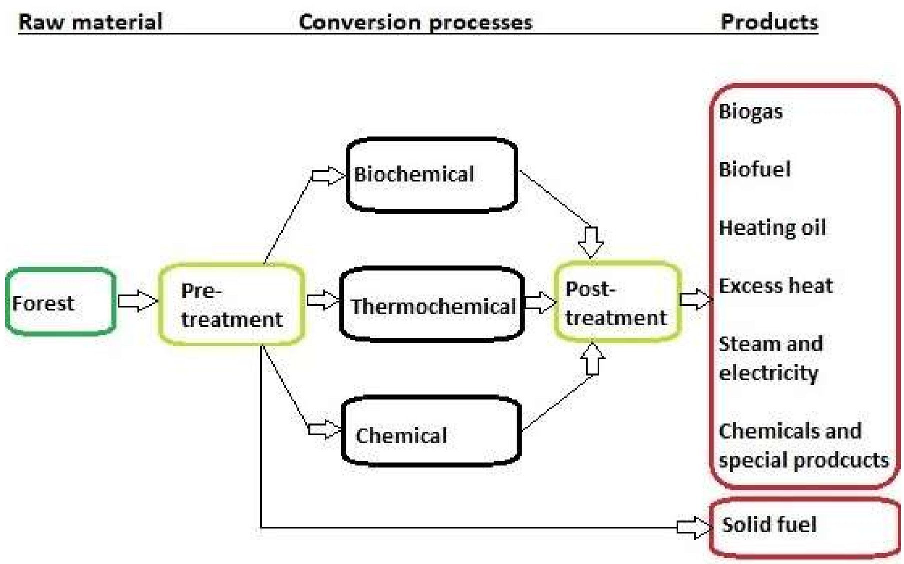

Figure 2.14. Forest biomass conversion processes together with selected products and byproducts. Adapted from chapter three in Melbye & Killingland (2013).

Biochemical biomass conversion is a mature technology in especially Brazil and USA. The two countries produce more than 80 % of the global bioethanol, and they have implemented bioethanol at large scale in their domestic transportation (Gallo, Bueno, & Schuchardt, 2014). This biofuel is however mainly 1st generation, or produced from edible biomass as corn and sugarcane. Lignocellulosic biomass from forests requires more extensive pre-treatment and processing to deliver the same amount bioethanol compared with bioethanol from starches. The main difference comes of lignin which makes up a considerable amount of a tree together with cellulose and hemicellulose. Pre-treatment of lignocellulosic bioethanol separates the in-fermentable lignin, followed by hydrolysis of complex carbohydrates within the cellulosic material before the free sugars could be fermented (Nanda, Mohammad, & Reddy, 2014). Biochemical conversion is relevant for Norway where Borregaard now becomes the world's largest producer of lignocellulosic bioethanol from forest biomass. The feasibility of tripling their production lies in a near total utilization of the raw materials, producing other chemicals and special products as included in figure 2.14 (Martiniussen, 2019).

Thermochemical conversion depends on heat to produce bioenergy and is a less commercially mature conversion than biochemical conversion. The main processes are pyrolysis and gasification of biomass, where gasification is also a pyrolysis with the purpose of producing flammable gases. The high stability of biochar produced by pyrolysis could mean a huge climate change mitigation potential of biochar, especially if it is derived from harvest residues which eventually decays and emit CO_2 to the atmosphere. As a soil amendment, biochar could also increase fertility and thus carbon sequestration (Steen, 2017). The liquid product of heating oil in figure 2.14 is produced at the same time, and can further be upgraded to biofuels in transportation or to obtain heat and electricity production (Tanger et al., 2013). Merely chemical conversion of biomass is similar to biochemical conversions but without the living organisms in the process of e.g. fermentation (Melbye & Killingland, 2013). Bioenergy from forests through the three conversion processes is modest in scope when compared to solid fuels on a global scale. Relevance of such solid biomass is discussed in the next section.

2.4.2 Global scope and implications

Most of the global renewable energy supply comes of biomass at 70 % due to the previously mentioned extensive usage of traditional wood fuels in developing countries. In 2016, direct heat accounted for 75 % of the biomass primary energy supply dominated by Asian and African countries. However, the largest share of heat derived from renewables which has more than doubled since 2000 is in Europe at 88 %, where 96 % of this amount comes from biomass. A considerable amount of renewable electricity is also produced in Europe, as Europe is also the largest producer of biomass-derived electricity (WBA, 2018). About 42 % of harvested wood in Europe was used for energy in 2013, where firewood, wood chips and in particular pellets dominate. Europe is also the largest consumer of heat and power from biomass which accounts for around 10 % of the gross final energy consumption, whereas around three quarters of this share is derived from solid biomass as wood. Pellets is now the major commodity in this market due to advances in energy density and costs of transport and production (Brack, 2017). The extensive growth of energy from biomass is tightly connected with the GHG targets discussed in chapter 1. There is a significantly higher demand than supply of pellets in Europe, even though almost half of the global pellets production happens here. Figure 2.15 shows the global tradeflow of pellet in 2016.

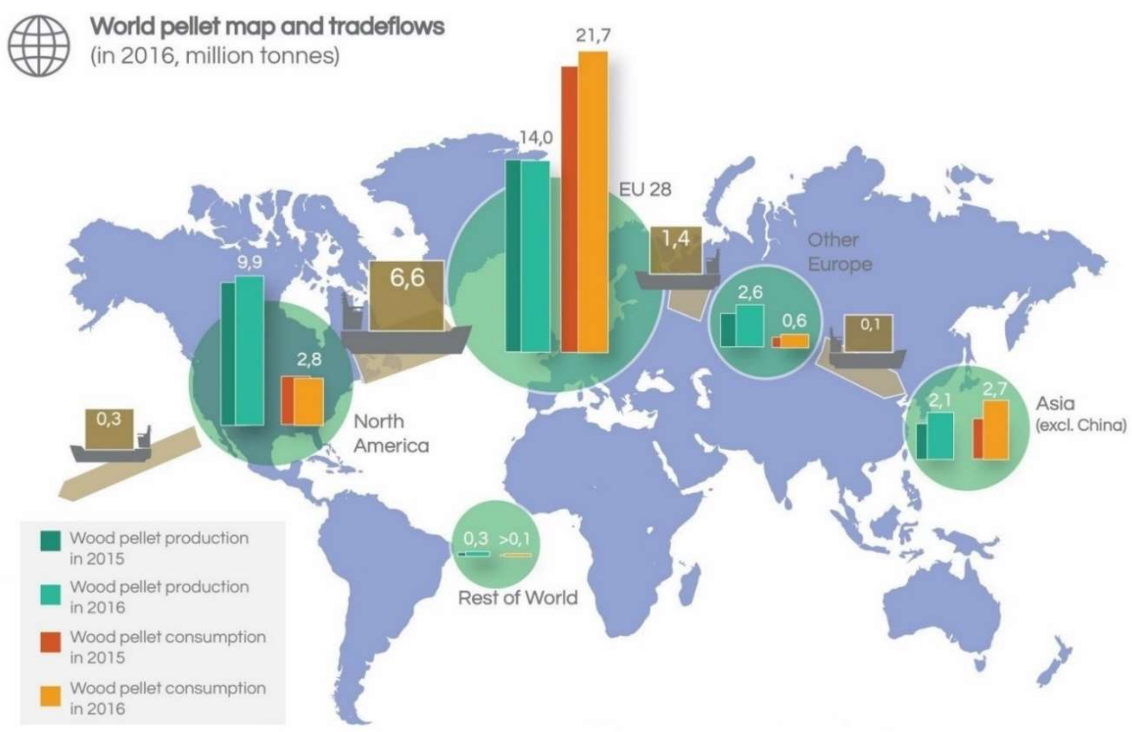

Figure 2.15. Global tradeflow of pellet in 2016. Production and consumption from 2015 are also included. From European Pellet Council (2017).

As shown in figure 2.15, the US is a major supplier of pellet to Europe and especially the UK where pellet burning is strongly subsidised. This trade of American trees to European alleged renewable energy have received heavy criticism. The criticism concerns both degradation and biodiversity of US forests, and that the carbon debt may counteract climate change mitigation for many decades (Biofuelwatch, 2018; Elbein, 2019; Fernandez, 2019; Timperley, 2017; Zeller, 2015).

2.5 Other climatic impacts of forestry

In addition to altering carbon fluxes, there are other climate forcings of relevance from forest activities. The next section discusses albedo, which is perhaps the most important.

2.5.1 Albedo

Reflectivity of a surface or the albedo determines how much solar radiation is being absorbed, and thus affects the global surface energy budget. The albedo of forest canopies is in general lower than open land, whereas the change strongly depends on latitude and tree species. The latitudinal dependency is of particular interest since a snow covered ground on high latitudes amplifies the effect due to the high albedo of snow. Net effect of a forest activity is thus influenced by changes in surface albedo in addition to the discussed biogeochemical effects. Other more uncertain effects are briefly discussed in the next section. Afforestation and reduced deforestation is regarded as the most cost effective technology to mitigate climate change (Smith et al., 2014). However, a study quantifying the trade-of between carbon sequestration and albedo changes from afforestation in mid- and high-latitude North American forests found a latitudinal boundary of the net effect (Mykleby, Snyder, & Twine, 2017). Effects from the lower albedo of afforestation north of this boundary outweighed the additional carbon sequestration resulting in a net warming effect. The opposite happened south of this boundary, where the smaller decrease in albedo was outweighed by the additional carbon sequestration. The forest productivity was also important of this result, since productivity mainly declines at higher latitudes, consequently absorbing less carbon.

Similar issues of albedo changes should conversely be accounted for when biomass is harvested for energy production. Recent findings on bioenergy from forests in Norway suggests that changes in albedo contributes to partially offset the gross warming effect including warming from CO_2 emissions (Arvesen et al., 2018). This study also differentiated on forest biomass productivity. Cooling effect from changes in albedo were found to be larger if biomass is harvested from a low productive forest stand. The reasoning is that slower regrowing sustains the higher albedo over a longer period, compared to a high productive stand. Furthermore, harvest of residues could reduce the cooling effect from albedo changes in a harvested stand for bioenergy. Less snow is required to generate a homogenous reflectivity of solar radiation if more residues is extracted, increasing the cooling. This increased effect is however outweighed by the additional biomass yield, which reduces the required area harvested and the corresponding albedo cooling (Cherubini, Bright, & Strømman, 2012).

Harvesting of residues thus decreases the warming effect from CO_2 emissions as discussed in chapter 2.3.4, but also may decrease the cooling effect from changes in albedo. However, the net effect of extracting residues when including albedo is still dominated by smaller emissions of CO_2. The net effect of harvesting wood for bioenergy when including albedo is also probably dominated by combustion emissions, whereas relative contributions are more uncertain and strongly depends on the complexity of the applied model (Holtsmark, 2015).

2.5.2 Other climate forcings

A range of additional climate forcings are shown in figure 2.16. The numbers are from Arvesen et al. (2018) and shows the global warming potential (GWP) evaluated over a time horizon of 100 years for different climate forcers. Two examples are used, burning biomass in stoves and district heating, to highlight the inequalities in two different uses of forest bioenergy.

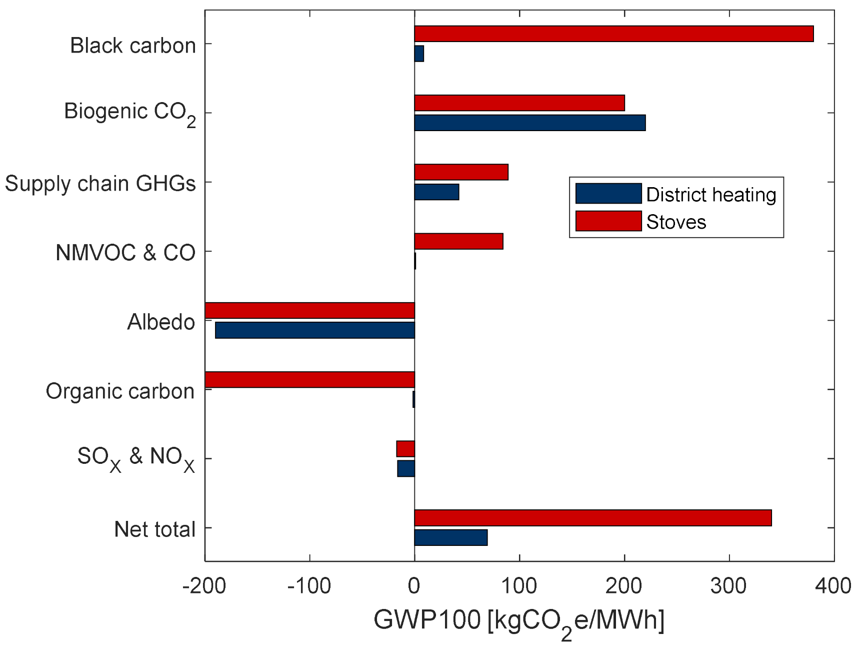

Figure 2.16. Global warming potential (TH = 100) for different climate forcings from forest bioenergy to stoves and district heating. NMVOC is non-methane volatile organic compounds. Numbers are from Arvesen et al. (2018)

Black carbon and organic carbon are primary aerosols which contributes in different directions to the GWP due to their radiative properties. Effect from these are however much smaller in district heating, due to emission abatements in this more advanced bioenergy technology. SO_X and NO_X are precursors to aerosols, while NMVOC and CO are precursors to form tropospheric ozone, a strong GHG. There is in other words many complex processes in different climate forcings from forest bioenergy, resulting in a considerable uncertainty when the processes are modelled. Except biogenic CO_2 emissions and supply chain GHGs, the remainder climate forcers from figure 2.16 is neglected in the method of this thesis, but rather briefly discussed in relation to the results.

3. Methodology

3.1 Data and forest growth assumptions

To represent a common growth curve of forest biomass in Norwegian forests, I have followed the assumption of Holtsmark (2012) where it was used data from a growth model for a spruce stand on a medium site index in Norway given the dominance of spruce in Norwegian forests. The ability of the forest floor to produce wood products determines the site indices, where 14 in the Norwegian classification system is the medium site index which will be used in the following. The growth data from Braastad (1975) is from a forest stand with no active thinning and a small fraction natural thinning as stand age and volume increases. To simulate forest biomass growth, the same assumption as in Ni, Eskeland, Giske, & Hansen (2016) is made that it follows a logistic growth function merely dependent on forest stand age. Ni et al. (2016) and Holtsmark (2012) stand out in the literature with a relative simple way of forecasting global and national forest development, respectively. The logistic function is written as,

$$V(t) = \frac{K}{(1 + e^{-r(t-t0)})}$$

where the output $V(t)$ is volume [m^3/ha], K is the stand's carrying capacity or maximum volume [m^3/ha], r is the logistic growth rate, $t0$ is the point of inflection and t is the forest stand age. The spruce stand's carrying capacity K or the upper asymptote of the logistic growth function is determined by regression models of site indices (SI) and maximum volume (Gizachew et al., 2012). This is found to be,

$$K = 829.1434\left[1 - e^{(-0.2074\,SI)}\right]^{3.9178}$$

where $SI = 14$ further in this thesis. Figure 3.1 shows the logistic function with its chosen values together with the data from Braastad (1975) at a forest stand age from 0 to 200 years.

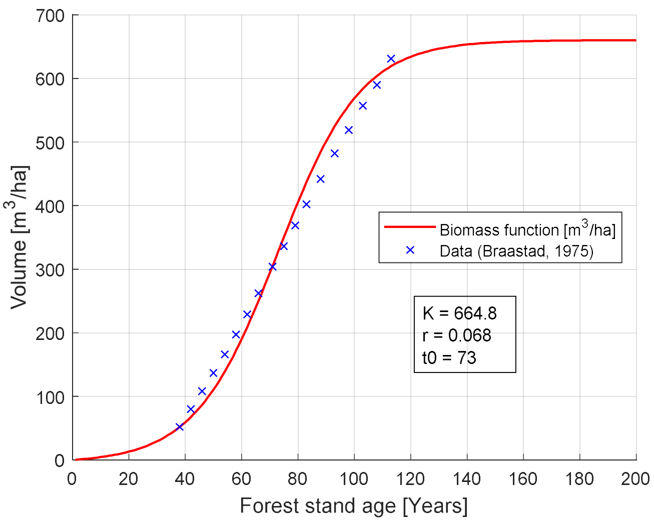

Figure 3.1. Logistic growth function and the data from Braastad (1975).

As a forest stand follows the common growth path in figure 3.1, you would like to know at what stand age you may clear-cut the stand to optimize production of wood per time unit. When not considering economics and other factors, the optimal rotation age is calculated from the logistic growth function. This rotation age is obtained from the mean annual increment (MAI) and the current annual increment (CAI) which is written as,

$$MAI = \frac{V(t_n)}{t_n}, \qquad CAI = \frac{V(t_n) - V(t_{n-1})}{t_n - t_{n-1}}$$

where $V(t_n)$ is the yield at age t_n, and $V(t_{n-1})$ is the yield at age t_{n-1}. When relating the terms to figure 3.1, the units of both is [m^3/ha/year]. The optimal rotation age is where MAI and CAI intersect and is shown in figure 3.2.

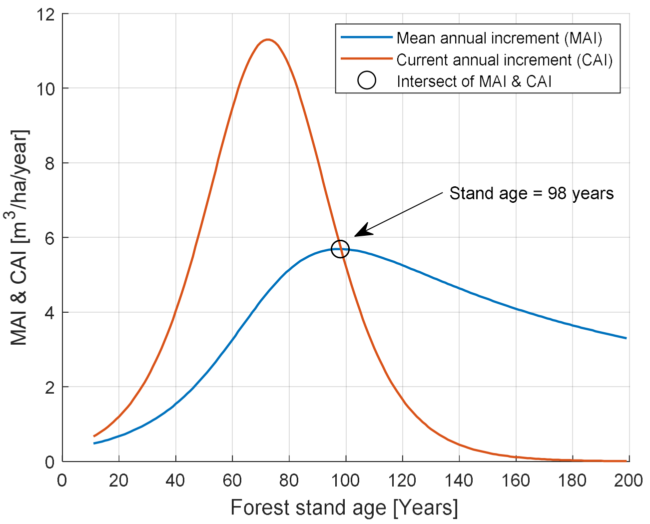

Figure 3.2. MAI and CAI. Maximum CAI is the point of inflection $t0$ from figure 3.1 while MAI and CAI intersect at stand age = 98 years where MAI ≈ 5 m^3/ha/year.

The optimal rotation age varies across different species over different site indices, as spruce may vary from 70 years on very productive sites, to 130 years on weaker sites. On the given site in this thesis, mean productivity decreases about 20 % as the rotation age increases to 130 years or decreases to 70 years.

To estimate the dry weight of biomass, I have used the weighted average density of the eight most common tree species in Norway which constitute over 96 % of the total volume of trunks in 2014. The densities are given as dry-raw densities which relates the biomass dry weight with the moist volume. These properties are sketched in table 3.1.

Table 3.1. Properties of selected species and weighted average density. Tree species and volume are obtained from Tomter & Dalen (2018f), dry-raw densities are obtained from Norwegian Institute of Wood Technology (2003).

Tree species	Volume [1000 m^3]	Volume [%]	Density [kg/m^3]	Weighted density [kg/m^3]
Spruce	472,190	44.26	380	168.19
Pine	332,577	31.17	440	137.15
Birch	199,475	18.70	500	93.50
Grey alder	20,488	1.92	360	6.91
Aspen	20,178	1.89	380	7.18
Sallow	11,179	1.05	430	4.52
Rowan	10,877	1.01	520	5.25
Sum	1,066,964	100	Average density = 422.7 kg/m^3	

When the average dry weight density is established at 422.7 kg/m^3, I further assume that carbon content is 50 % of biomass dry weight (Ecometrica, 2011). This gives 211.35 kgC/m^3 or 0.21135 tC/m^3.

When clear-cutting the forest stand however, not all the biomass is trunks which is mostly utilized in Norway today. Since the biomass growth function is representing all living biomass, the tables in Løken et al. (2012) are used to estimate different parts of a tree. When not including trees with a smaller diameter than 5 cm at 1.3 m height, the living biomass is divided in three mass fractions. Trunks without bark at 47.7 %, stumps and roots at 25.4 %, and tops and branches at 26.9 %. The average density is assumed to be uniform over all fractions. Using these assumptions and equations, calculated evolution of carbon in biomass and volume of trunks and the other biomass is shown in figure 3.3.

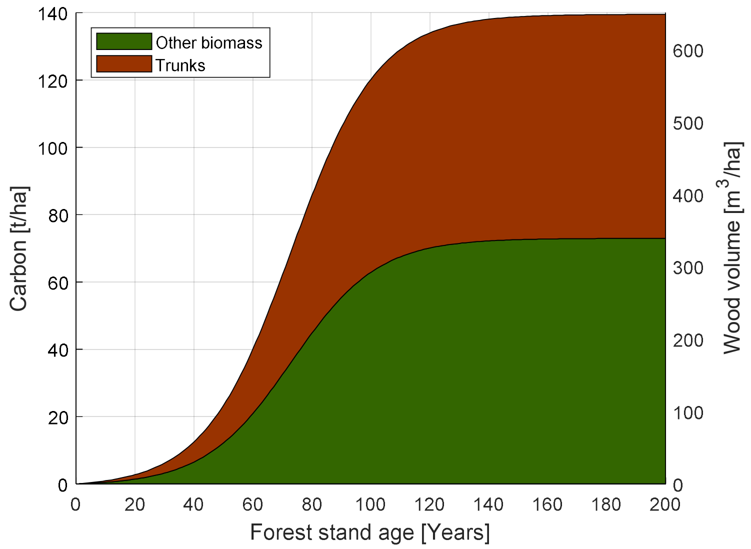

Figure 3.3. Trunk share of total biomass on one stand over 200 years of growth including total volume and biomass carbon.

Only the trunks are assumed to be removed from the stand at conventional logging. The remaining biomass is subsequently assumed to be left at the logging site. This biomass of branches and tops together with stumps and roots will begin to decompose as logging takes place. The decomposition rate is set to 3.33 % as this was the average decomposition rate constant found in Næsset (1999) over the different biomass components, even though the decomposition rate strongly depends on the specific microclimate and the properties and size of the biomass. However, this rate is for simplicity acting to 70 years after logging where 90 % of the biomass has decomposed. The decomposition from 70 years after clear-cut is set to decrease linearly towards 100 years where all biomass has decomposed. The remaining share of biomass after each harvest is shown in figure 3.4.

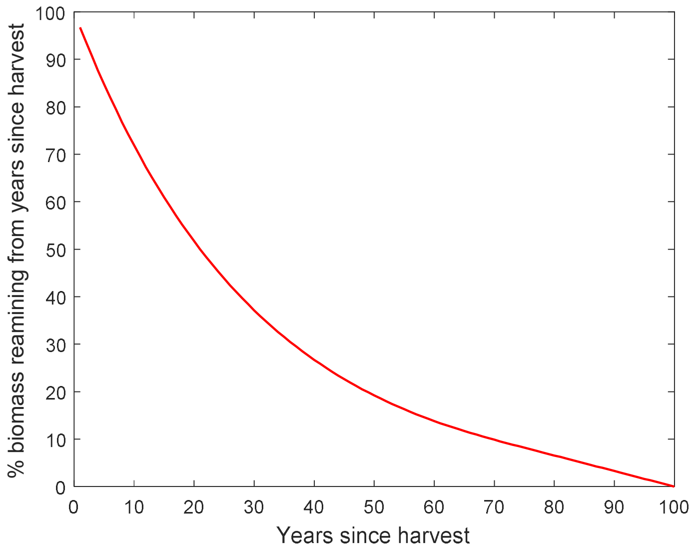

Figure 3.4. Remaining biomass in year 1 to 100 after harvest. The decay is exponential the first 70 years after harvest at a rate of 3.33 %.

3.2 Forest dynamics

Before studying Norwegian forests as a whole with relevant parameters and cases in section 3.3, the present section explores aspects of forest dynamics through idealized examples. A common assumption of all further estimates in this thesis is the immediate replanting of the harvested forest stands after logging. Figure 3.5 shows what happens when 1 ha is afforested, harvested, and subsequently replanted. In the years of logging, the trunks are removed from the site, and the other biomass begins to decompose. Removing trunks from the stand therefore emits a given amount of CO_2 to the atmosphere following the mentioned decomposition rate. In addition is the potential direct emissions from trunks, depending on the purpose of felling.

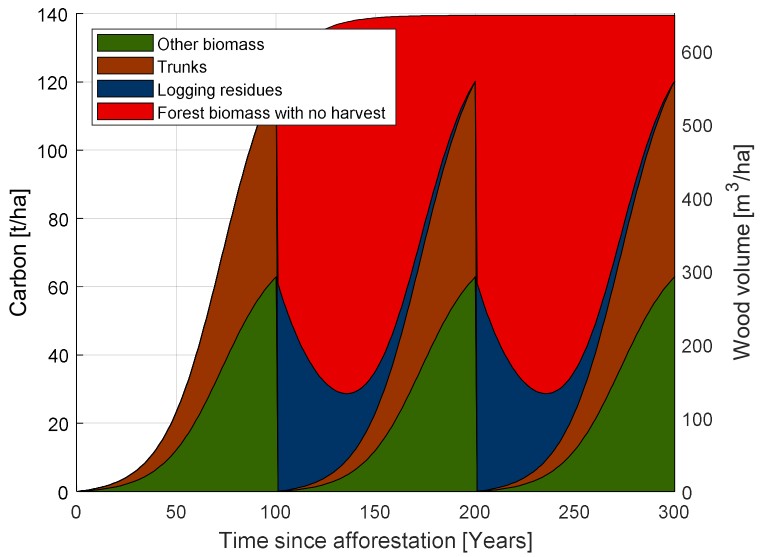

Figure 3.5. Carbon and wood volume in a forest stand which is afforested and harvested at a rotation age of 100 years compared to total biomass if no harvest The left-sided y-axis is carbon in tC/ha, while the right-sided y-axis is the corresponding volume of all biomass.

To get a better picture of a forest containing several areas as that in figure 3.5, another example of the total stock of wood is shown in figure 3.6. The case is a 1000 ha large forest which has been logged and regrown for some time so that the forest stock is in equilibrium. Only 500 ha of the forest have been logged or managed towards 2020, while the other 500 ha have been unmanaged. Five ha of the managed part is thought to have been logged and replanted every year with a rotation age of 100 years, resulting in a harvest of 1357 m^3/year.

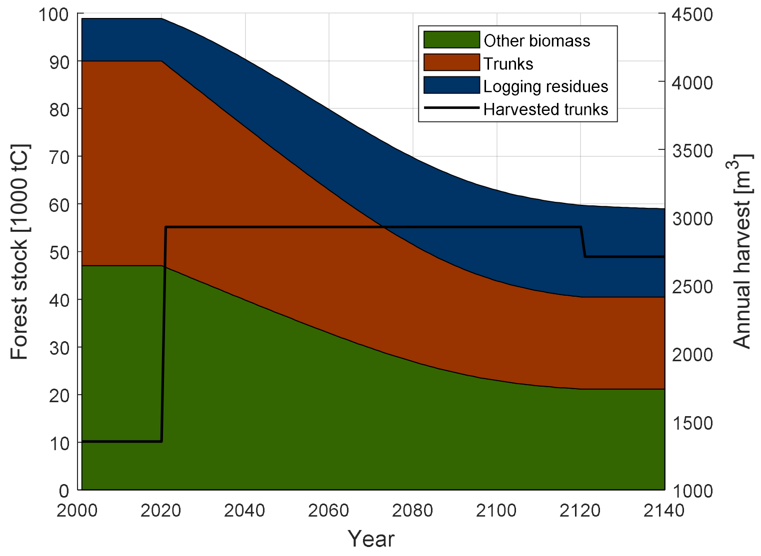

Figure 3.6. Carbon stock and annual harvest of the unmanaged and managed forest between two equilibria at the same rotation age. All unmanaged forest in 2020 is converted to plantation within 2120.

From 2020, the forest owner decides to increase harvest by including the additional 500 ha unmanaged forest into the rotational forest. This is done by clear-cutting five additional ha each year from 2020. In 2119, the last area of five ha is added from the unmanaged forest to the managed forest and the stock reaches a lower equilibrium with ten ha of forest at each stand age from 1 to 100 year. Given that the unmanaged forest was mature and older than 150 years, annual harvest increases to 2931 m^3 from 2020 to 2119. Annual harvest would then decrease to the double of the initial harvest from 2120 and onwards, or 2714 m^3/year. The stock of logging residues will still after 2120 slowly decrease towards a new equilibrium 100 years later, due to the time of decomposition.

The forest owner could still increase productivity by decreasing rotation age to 98 years which is found to be optimal rotation age for wood harvest according to figure 3.2. The effect of decreasing the rotation age on the carbon stock and yield is explained in the following example which considers a 1500 ha large forest. Unlike the forest in figure 3.6, this one is completely managed and has been so for a long time with a relatively long rotation period of 150 years where 10 ha is clear-cut each year yielding 3132 m^3/year. From 2021, an additional 5 ha is logged on top of the 10 ha. Since there is only 10 ha of forest at 150 years in 2021, the additional ha are logged from the now oldest stand at 149 years. The next year, only 5 ha have now grown to an age of 150 years and are logged, while the remainder 10 ha are logged at a stand age of 149 years.

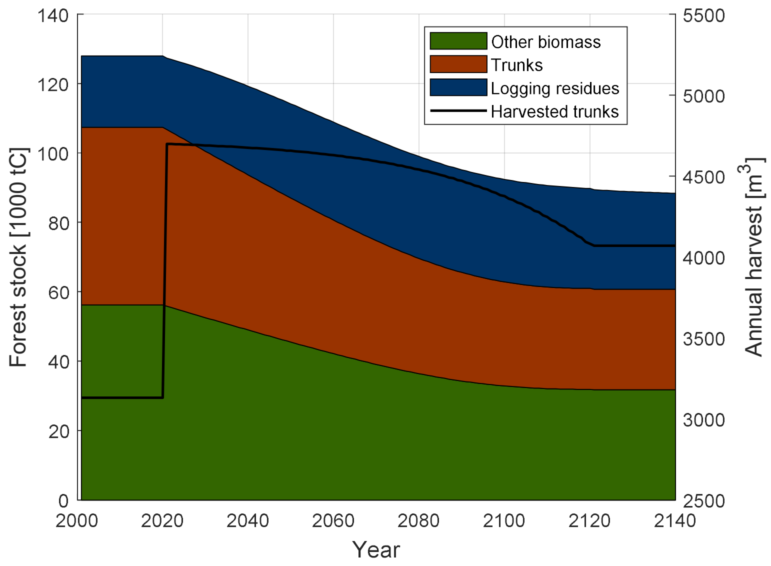

Figure 3.7. Carbon stock of the forest between two equilibriums of living biomass where the whole forest is managed. Rotation age decreases from 150 to 100 years within 2020-2120.

This strategy of harvest continues for the next 100 years, as the rotation age decreases year by year. Annual harvest is high the first 50 years where the now oldest part would be around 125 years. The next 50 years, annual harvest decreases faster in parallel with the steepness from a 125-year-old stand and younger in figure 3.3. As 2120 turns to 2121, the same stands of 15 ha logged in 2021 have now became 100 years old. The stock of trunks and other biomass have consequently reached a new equilibrium, with an annual harvest of 4070 m^3/year. The stock of residues would in the same manner as in figure 3.6 still decrease a bit the next 100 years.

The purpose of the examples in figure 3.6 and figure 3.7 is to show the abrupt changes in the forest's carbon stock as the harvest strategies changes. Both examples are showing the annual harvest as a result of the specific changes of the forest composition and stand ages. This would be a rather unconventional harvest strategy in the real world. Normally, annual harvest is the factor controlling the resulting forest composition and carbon dynamics. This is visualised in figure 3.8, where the initial forest is equivalent to that of figure 3.7, with 10 ha of each forest stand age from 1 to 150 years. From 2021, annual harvest is set to approximate as closely as possible the annual harvest after the forest reaches a new equilibrium in figure 3.7. The resolution is therefore increased from ha to da as 1 ha equals 10 da. Unlike the previous figure where 15 ha was harvested each year from 2020, annual area harvested from 2020 in figure 3.8 is 13 ha the next 7 years, 13.1 ha the following 38 years, and 13.2 ha the following 16 years. Except the first 7 years after increased harvest, the trend of shorter periods of equal area harvested after 2020 continues to about 2130. Just after 2130, the stand age of felling has decreased rapidly to about 110 years, meaning that there are several forest stands or da available at each stand age since it has been approximately 110 years since the first area larger than 10 ha was felled.

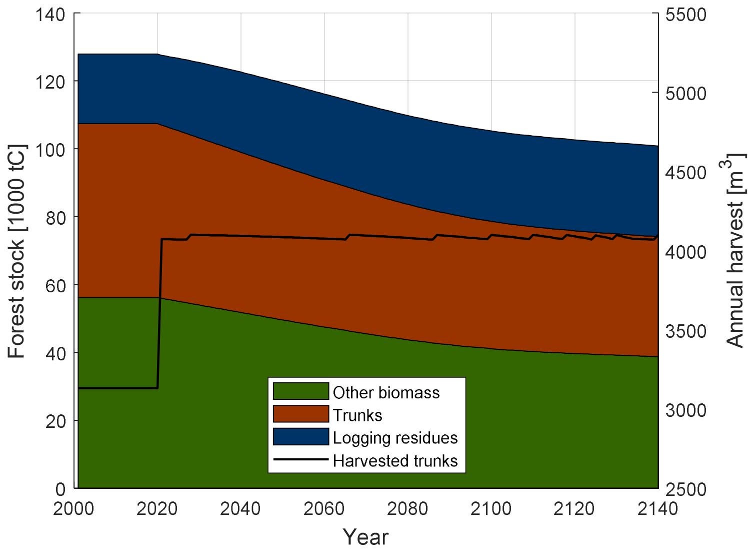

Figure 3.8. Carbon stock of the same forest as in figure 3.6, with a common harvest strategy. The fluctuations of annual harvest are small due to imperfect resolution, and they reflect the mentioning above the figure of periods of same area felled. The forest stock does not reach equilibrium within 2140.

The mean annual harvest from 2021 towards 2140 is around 4080 m^3/year which is a few m^3 above the annual harvest after a new equilibrium in figure 3.6. The less extensive adjustments to the forest stock with this more common harvest strategy strongly affects the period of dynamics until the forest stock reaches a new equilibrium. However, the stock of logging residues reaches an approximate equilibrium in 2120, since there has been a near constant annual harvest the prior 100 years. The stock of trunks and other biomass would eventually reach the same equilibrium as in figure 3.6 several hundred years later, although the rate of change is very low the next centuries.

3.3 A Norwegian forest

This section presents growth and carbon dynamics of the Norwegian forest as one managed unit, given certain assumptions.

3.3.1 Initial conditions and age of harvest.

To represent the whole forest based on mentioned dynamics, an initial age distribution is provided in figure 3.9. The resolution for the remainder part of this thesis is set to 1 km^2, where 1 km^2 equals 100 ha. This distribution is partly based on the coarse estimate in figure 2.8, and partly determined to fit the amounts of initial carbon and standing stock to the corresponding values of 2015 which is defined as the starting year further in this thesis.

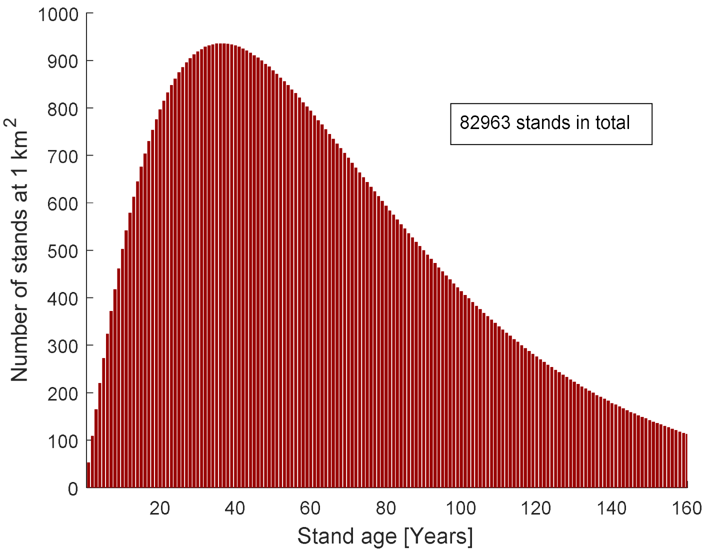

Figure 3.9. Initial age-distribution of the whole forest as a gamma probability density function.

Based on the annual wood harvest in figure 2.4, I assume that the average annual harvest from 1919 to 2015 was 10 Mm^3 as an approximation, where only the trunks were utilized. The remaining residues which begin decaying each year following figure 3.4 gives an initial amount of carbon in harvest residues at 65.5 MtC. The initial carbon in living trees becomes 433.8 MtC according to figure 3.9, as the total initial carbon is 499.3 MtC. The initial standing stock of trunks is corresponding to 979.1 Mm^3.

The stand age of felling is for simplicity always set to the oldest available forest stand to maximize the stock of carbon. The reasoning behind this follows in an example where annual harvest is 17.315 Mm^3, and the forest has reached equilibrium. This could be achieved in e.g. two ways with described details in table 3.2.

Table 3.2. Example of two strategies of same annual harvest and different ages of felling.

Option	Annual harvest [Mm^3]	Stand age of felling	Area harvested annually [km^2]	Managed area [%]	Unmanaged area [%]	Forest stock [MtC]
A	17.315	150	553	100.0	0.0	706.7
B	17.315	100	640	77.1	22.9	636.0

All available area is incorporated in a cycle and felled every 150 years in option A. If the trunks are harvested at a rotation of 100 years, the annual harvested area must increase since a stand contains more biomass at 150 years than 100 years. However, only 77.1 % of the area are sufficient if age of felling is 100 years. The result of harvesting at oldest stand ages is a total forest stock of carbon including residues which is more than 11 % higher than option B. It is also worth noticing that the maximum sustainable conventional harvest is 22.5 Mm^3 where 846.5 km^2 is felled each year at a rotation age of 98 years according to figure 3.2, resulting in a modest forest stock of 383 MtC.

3.3.2 Reference scenario and purpose of harvested wood products

The reference scenario for further comparisons is provided in figure 3.10. Annual harvest is set to 12 Mm^3 which is a reasonable number given annual harvest in 2015 and later years. The harvested share of available biomass is 47.7 %, meaning that only trunks are harvested as this mostly reflects the situation today.

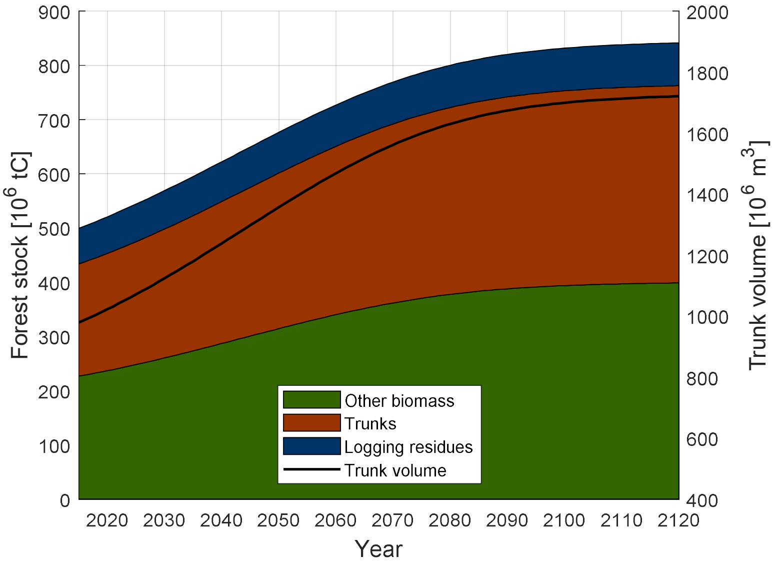

Figure 3.10. Reference scenario of the isolated forest stock development from 2015. Annual harvest is constant at 12 Mm^3 and no residues are harvested.

The harvested wood products could either be used for energy purposes, or in constructions. The possibility of utilizing wood products in buildings is important to simulate a more realistic net carbon budget, where not all available biomass is used for energy products and instantly oxidized. Parts of a trunk with the highest quality will always be used in building to sustain profitability of wood harvest. Considering figure 2.9, carbon is stored in buildings for a long period compared with the other wood products, before it oxidizes to the atmosphere. To simulate the effect of harvested wood in building, I use the same method as in Iordan et al. (2018). This method is merely depending on the average lifetime seen in figure 2.9, where carbon oxidation is distributed symmetrically. The distribution is a chi-square distribution which is shown in figure 3.11.

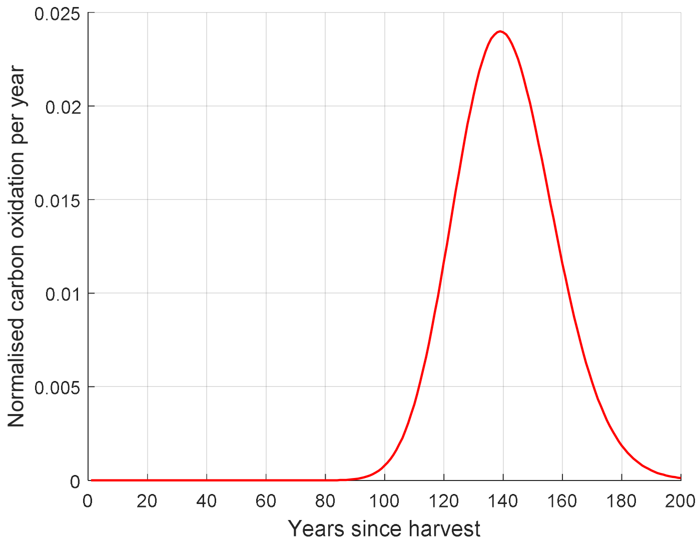

Figure 3.11. Normalised carbon oxidation from buildings according to the method in Iordan et al. (2018). Average lifetime of buildings is 140 years.

I further ignore eventual substitution effects of using wood construction to replace e.g. steel or concrete, as such substitutions currently have a great uncertainty (Leskinen et al., 2018). Even though around 50 % of a trunk is used as saw logs, only 40 % of saw logs is assumed as available end product in buildings. An overview of assumed maximum available products for use in energy production and in buildings follows in figure 3.12.

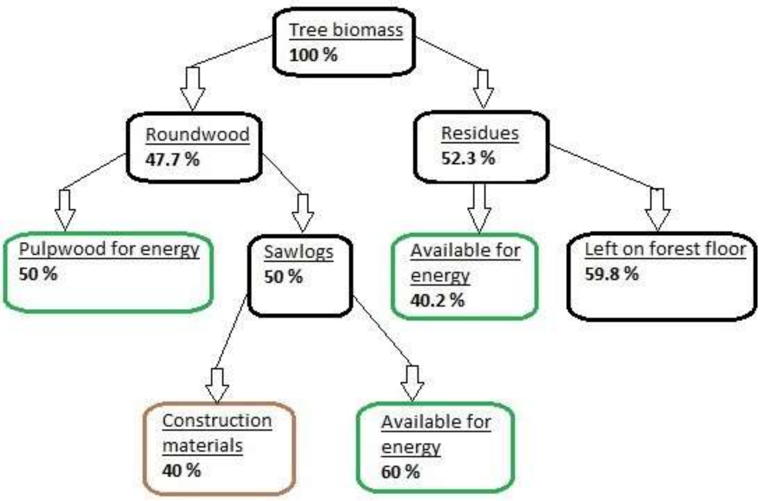

Figure 3.12. Available products of one unit forest biomass. Green boxes are biomass for energy purposes, the brown box is wood for buildings. The potential is based on Norwegian Environment Agency (2011).

By figure 3.12, the maximum harvest of residues equals 0.44 m^3/m^3 roundwood or trunk. Equivalent to the reference scenario in figure 3.10, another reference scenario is used when assuming that a share of saw logs are used in buildings. This other reference includes both development of forest carbon and accumulated carbon in buildings and follows in the figure below.

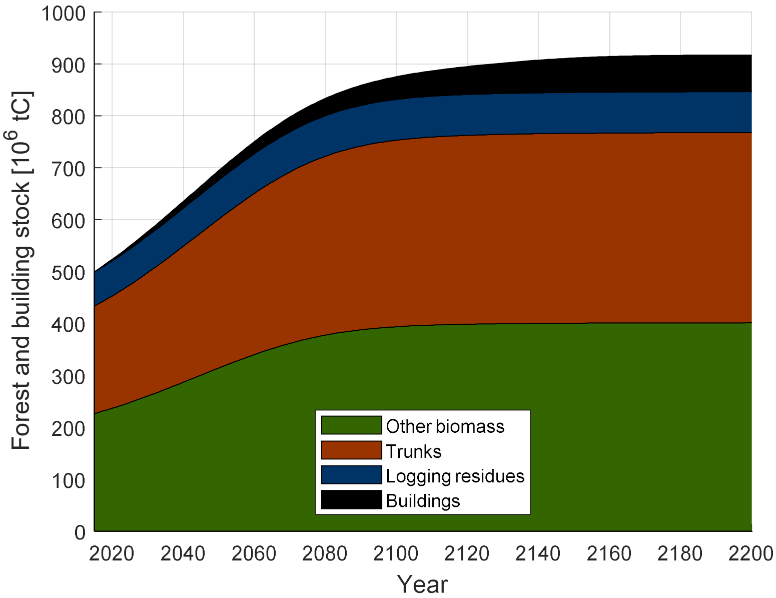

Figure 3.13. Reference scenario when including 20 % of harvested trunks is stored in buildings. This figure is identical with figure 3.10, except that the black area of carbon in buildings is included. Note that the time-scale is 80 years longer than figure 3.10.

The effect from carbon oxidation in buildings in figure 3.11 are clear in the figure above. Accumulation of harvested carbon continues for approximately 200 years, from where it reaches an equilibrium. The difference between these two scenarios when in balance is 71 MtC. Note that the stock of carbon begins at 0 in the starting year of 2015. This means that the amount of carbon in buildings does not start at a realistic level as the other reservoirs. However, this is not relevant since I will only compare different harvests and stocks. The difference of carbon in buildings will be the same regardless of starting level, as it will only be determined by the developments which again is dependent on change of harvest.

All available products for bioenergy are assumed to replace an equivalent amount of fossil energy, and thus accumulate avoided fossil CO_2 emissions. Such substitution factors depend on specific type of bioenergy, process efficiencies, and what type of fossil energy source which is replaced. I will use three different substitution factors for comparison between high, medium and low substitution, which also are obtained from Norwegian Environment Agency (2011). These are presented in table 3.3. The medium and low factors are however considered as the most viable options.

Table 3.3. Avoided fossil CO_2 emissions per m^3 wood burned for bioenergy, with three different efficiencies of carbon intensity. Numbers are from (Norwegian Environment Agency, 2011)

Efficiency	High	Medium	Low
Substitution factor [tCO_2/m^3]	0.714	0.525	0.252

3.3.3 Alternative harvest levels

The alternative harvest of trunks is an increase of 10, 20 and 30 %, while the alternative harvest of residues is 33.3, 66.6 and 100 % of the maximum level which is 0.44 m^3/m^3 trunk as mentioned in the previous section. All possible levels are given in the table below. The alternative harvest of trunks is considered with respect to the FRL explained in section 2.3.3.

Table 3.4. Possible harvest strategies of trunks and residues.

Only trunks [Mm^3]	Trunks + 33.3 % residues [Mm^3]	Trunks + 66.6 % residues [Mm^3]	Trunks + 100 % residues [Mm^3]	Available for buildings [Mm^3]
12.0	13.76	15.52	17.28	2.40
13.2	15.14	17.07	19.01	2.64
14.4	16.51	18.62	20.74	2.88
15.6	17.89	20.18	22.46	3.12

Matlab is used for calculating the developing forest scenarios, where the script for simulating the reference scenarios is included in the appendix. The script accounts for every scenario by changing harvest level and harvested share if residues are extracted.

In the next chapter, the decline in the stock of carbon is compared with the accumulated avoided fossil CO_2 emissions, depending on harvest strategy and purpose. The scenarios in the table above are directly compared by using the carbon payback period. This period is the number of years until when the accumulated avoided fossil emissions offset the carbon debt caused by a reduction in the carbon stock.

4. Results and discussion

This chapter firstly provides selected results from the cases in table 3.4. The second part is a general discussion of the results, while the last two parts discusses the method and how the results may vary if other parameters would be included. Given the many assumptions, basic calculations and the temporal scale, all results should be interpreted with caution. The scenarios which are considered most viable are highlighted.

4.1 Response of carbon stock on selected scenarios

4.1.1 Increasing harvest of trunks for energy

This section gives results of the developing carbon stock when only trunks are harvested, with no storage in buildings. Figure 4.1 provides developing carbon stocks of increasing harvest with, 10, 20 and 30 %, respectively.

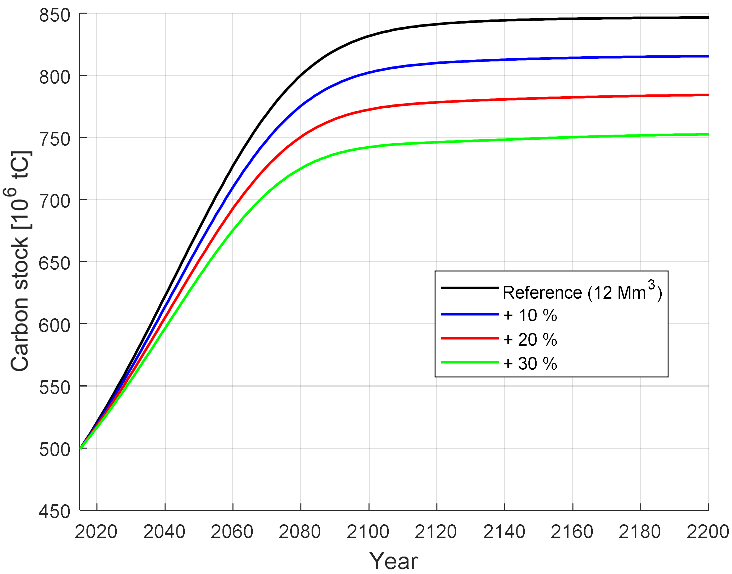

Figure 4.1. Developing carbon stock when increasing only harvest of trunks. Black line is for reference, blue line, red line, and green line shows stock when increasing harvest by 10, 20 and 30 %, respectively. No harvested products in constructions.

The effect of permanently increased harvest is the vertical distance between the increases and the reference scenario at any point in time. In year 2200, the stock when largest harvest is 94 MtC lower than the reference. The smaller stock at larger harvest is partly counteracted by a larger reservoir of harvest residues, as the highest harvest scenario contains 22.6 MtC more as residues in 2200 than the reference scenario. The change in carbon stocks relative to the reference scenario is shown in figure 4.2.

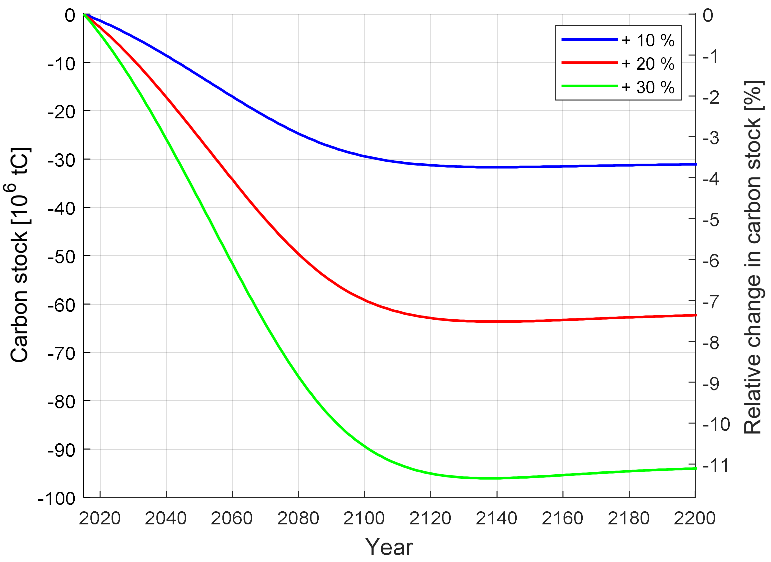

Figure 4.2. Change in forest carbon stock after three different increases of annual harvest. Left y-axis is the absolute change in carbon while right y-axis is the relative change.

By assuming the medium substitution factor, the three additional harvests from smallest to largest eliminate approximately 0.17, 0.34 and 0.51 MtC per year. The net carbon debt of each scenario for a medium substitution factor is plotted in figure 4.3. The carbon payback period proves to be the same for each of the harvest scenarios.

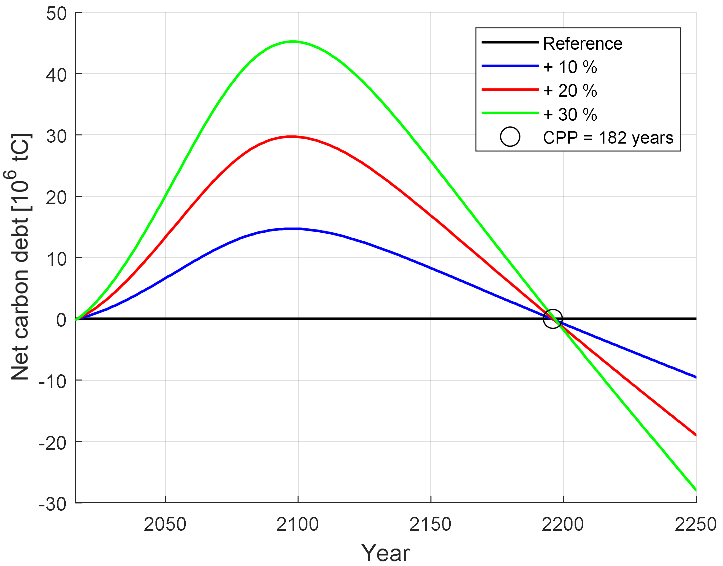

Figure 4.3. Net carbon debt of each harvest scenario given a medium bioenergy substitution factor at 0.525 tCO_2/m^3. Carbon payback period (CPP) is the same in all scenarios at 182 years.

The period until the decrease in stored carbon is offset by avoided fossil emissions extends over 182 years. The next figure shows the effect of how much fossil CO_2 that is avoided per amount of harvested wood. The applied harvest increase is 20 %, as the carbon payback periods on every increase is the same, also on different substitution factors.

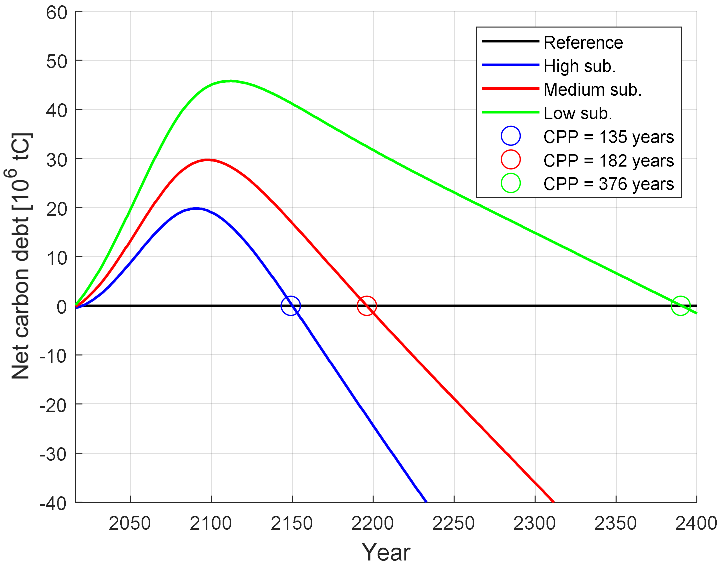

Figure 4.4. Net carbon debt by 20 % increased harvest with different amounts of eliminated fossil emissions per amount harvested wood. High, medium and low substitution (sub.) eliminates 0.714, 0.525 and 0.252 $tCO2/m^3$, respectively.

The lowest substitution factors result in a carbon debt period of 376 years, while the highest gives a period of 135 years, suggesting that only increased harvest of trunks for energy compares very poor for near-term climate change mitigation.

4.1.2 Increasing harvest of trunks for buildings in addition to energy

This section provides isolated results of using 20 % of the harvested trunks in buildings and the remainder for bioenergy. The effect on the developing carbon stock including a portion stored in buildings is shown in figure 4.2.

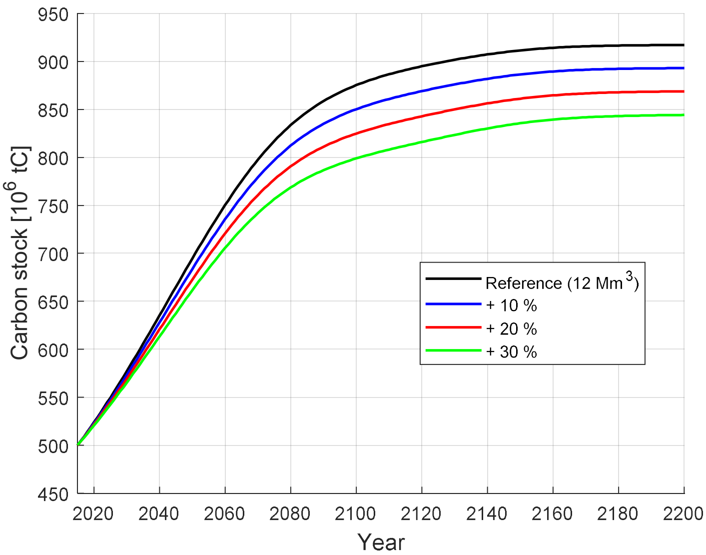

Figure 4.5. Developing carbon stocks when increasing only harvest of trunks with 20 % of the harvested trunks in buildings.

The accumulation of stored carbon lasts over a longer time compared to figure 4.1 due to the assumed lifetime and slow oxidation of carbon in buildings. The total stocks are consequently considerably higher, as the equivalent black area from figure 3.13 is added to each of the scenarios. The spread between the scenarios looks smaller compared to the carbon stocks in the previous section, at least when considering that the y-axis in figure 4.5 goes further. The reason for this is that the carbon share stored in buildings increases as harvest increases. Effects of increasing harvest are shown in the next figure.

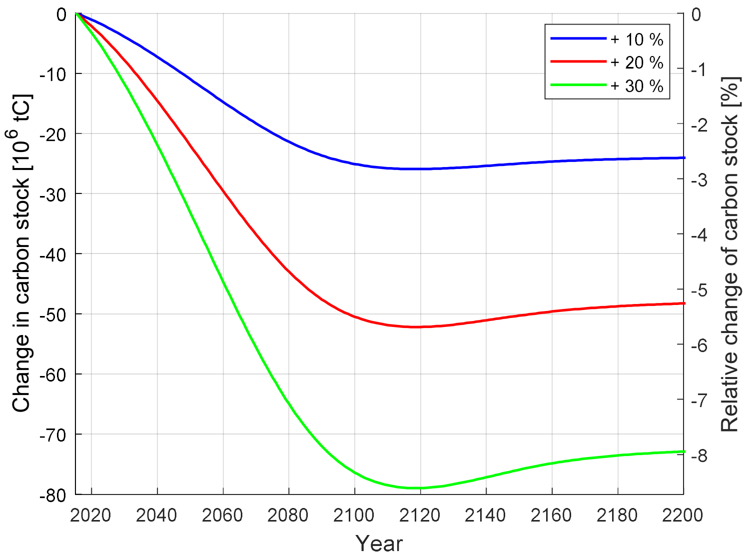

Figure 4.6. Change in forest and building carbon stock with three different harvest increases. Left y-axis is the absolute change, right y-axis is the relative change.

The smaller reduction is confirmed when looking at the relative change in figure 4.6 compared to figure 4.2. The relative change is 2-3 % smaller when additional harvested trunks are stored in buildings. The additional carbon in buildings thus compensate a portion of the loss in forest carbon when increasing harvest. Figure 4.7 shows the net carbon debt of each scenarios, using the medium bioenergy substitution factor.

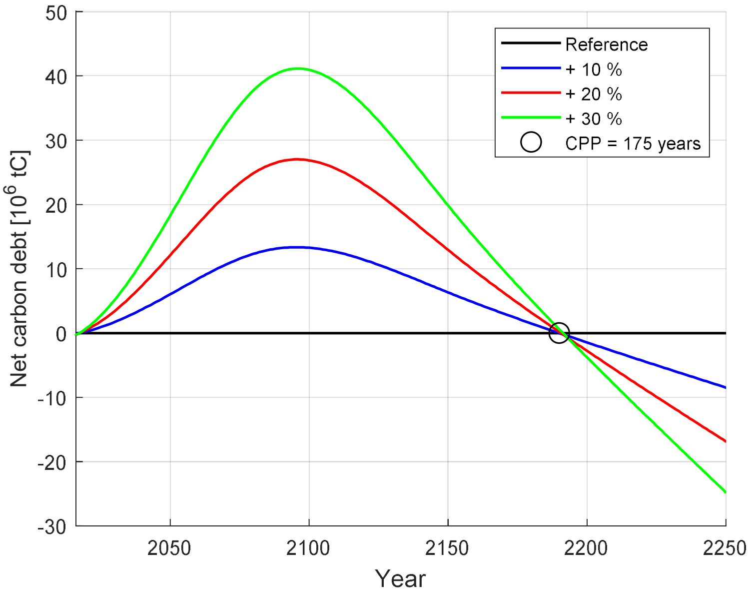

Figure 4.7. Net carbon debt of each scenario given a medium bioenergy substitution factor, 20 % trunks used in buildings and the remainder for energy purposes. Carbon payback period (CPP) is near 175 years on low and medium increase, while the highest increase is closer to 176 years.

The time until forest bioenergy offsets a smaller carbon stock is 175 years, which is 7 years shorter than the equivalent period when all wood harvest is used for energy purposes. The share of wood harvest available for buildings or the lifetime of a building is thus not enough to significantly reduce this period. Note that eliminated fossil CO_2 emissions is now 80 % of the eliminated emissions when all wood harvest is burned as bioenergy. A comparison of the different bioenergy substitution factors when increasing harvest by 20 % is shown below.

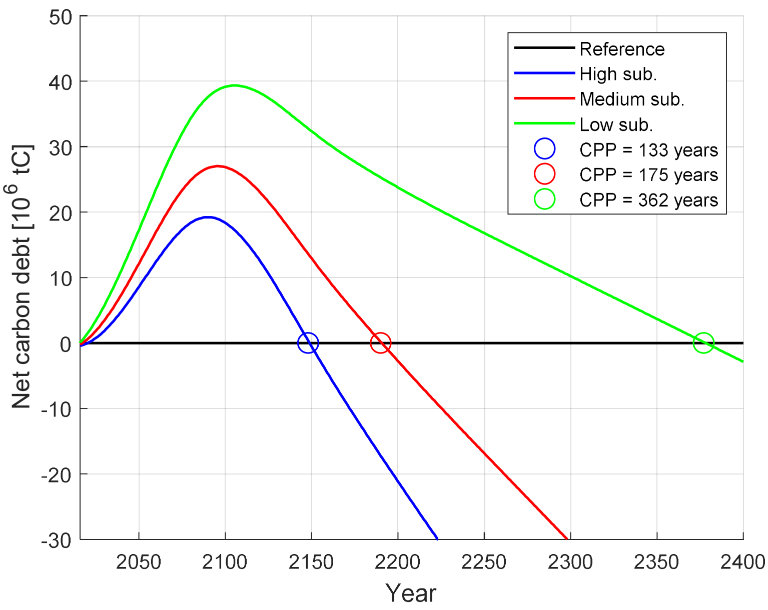

Figure 4.8. Net carbon debt with 20 % increased harvest given different bioenergy substitution factors, where 80 % of harvested wood is used in energy production.

Compared to the scenarios in section 4.1.1, the carbon payback periods when a harvested wood share is stored in buildings only decrease with 2, 7 and 14 years, if applying high, medium and low substitution efficiency, respectively.

4.1.3 Extracting existing harvest residues

This section deals with the carbon budgets resulting from assuming no increase of conventional harvest, but rather collecting the harvest residues to utilize as bioenergy. Numerical effects of storing wood in buildings cannot be quantified in this scenario, since there in no increase of harvested roundwood. The additional collected residues are shown in of table 3.4, where the maximum sustainable extraction is 0.44 m^3/m^3 roundwood according to figure 3.12. Figure 4.9 shows the developing carbon stocks, and the difference between the three levels of harvesting residues vs the reference harvest.

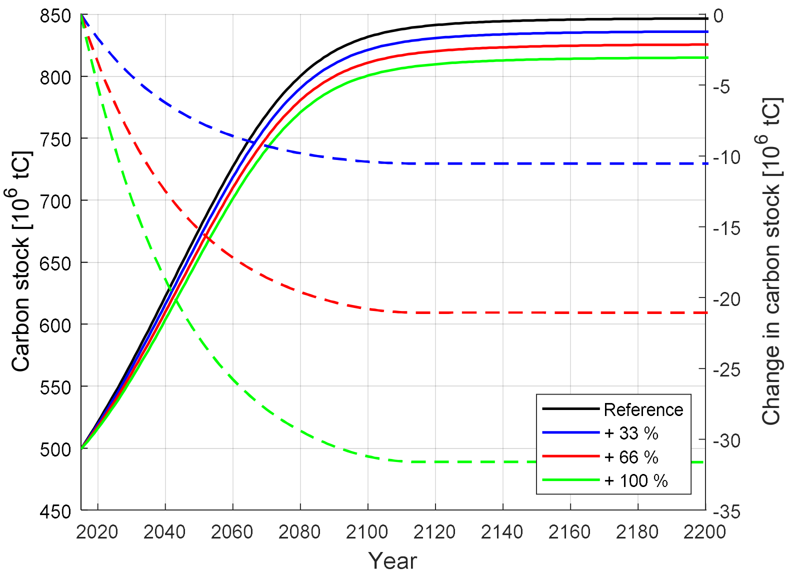

Figure 4.9. Developing carbon stocks and the difference between the reference scenario and the three levels of collecting residues. Left y-axis shows total carbon stock (solid lines), right y-axis shows the change in carbon stock (dashed lines).

The rate of carbon loss in each scenario continues the next 100 years after 2015 due to the chosen residue decay rate which lasts 100 years. The decline of carbon losses is steepest the first year, and gradually flattens out. This is different from the curves in figure 4.2 and 4.6, where the decline increases for a further 70-80 years. The reason is that the additional harvested carbon decays later anyway, and the effect of avoided emissions from decaying residues gets larger for each year. This can be directly compared when considering additional harvest divided on the resulting lower balanced forest stock of carbon. If 38 700 additional m^3 trunks are harvested, the forest carbon loss equals 1 MtC in 2200. To obtain the same carbon loss when only residues are extracted, you must harvest an additional 167 000 m^3, more than four times the amount as trunks.

The carbon payback period given a medium substitution factor is shown in figure 4.10, depending on the different levels of additional extracted residues.

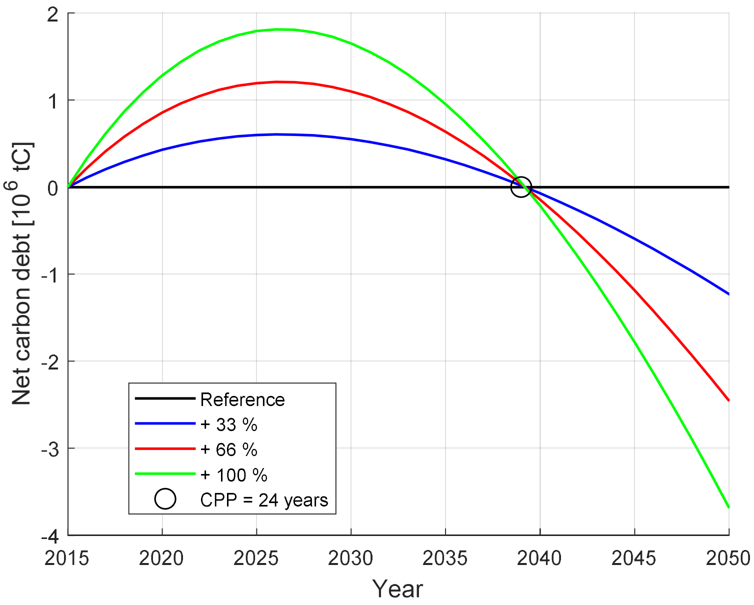

Figure 4.10. Net carbon debt with only increased harvest of residues at 33, 66 and 100 % of maximum available wood given a medium substitution factor. Carbon payback periods are all the same at 24 years.

Similarly to the previous sections, the payback period is also the same at different harvest levels when only more residues are extracted. The period is however significantly reduced, from 182 years to 24 years with medium substitution efficiency. Figure 4.11 includes all three bioenergy substitution factors on 66 % additional extraction of harvest residues.

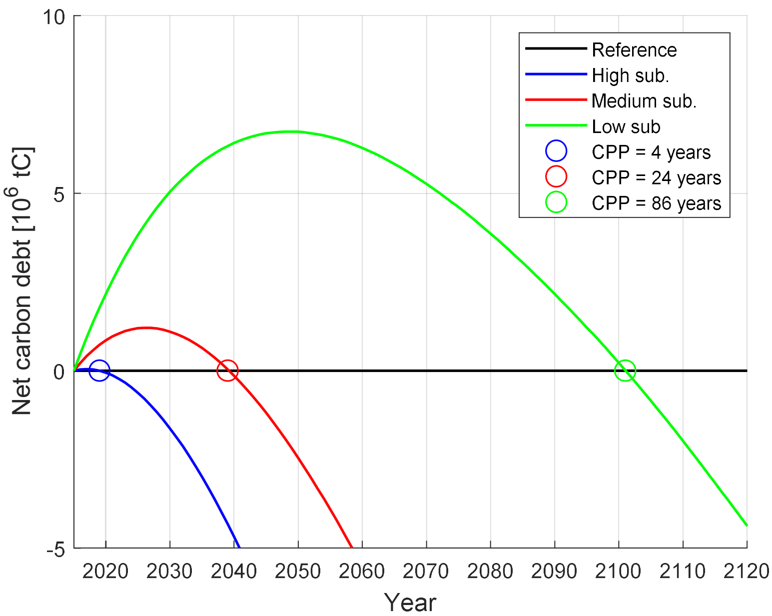

Figure 4.11. Net carbon debt when only increasing harvest of residues with 66 % of the available residues, given a high, medium, and a low bioenergy substitution factor.

The payback period if applying a high bioenergy substitution is not clear from figure 4.11 due to the scale, but it turns out to be 4 years. Expectations of utilizing harvest residues were met, as there is a theoretical potential to avoid fossil emissions without gaining a carbon debt over many decades. However, if the bioenergy products compare poorly to an original source in terms of emissions and efficiency, the net carbon debt could extend over 86 years.

4.1.4 Combination of increasing harvest of trunks and residues, with and without carbon storage in buildings

This section provides the sensitivity on carbon debt by combining the scenarios in the three previous sections. The two cases shown in figure 4.12 and 4.13 use a medium bioenergy substitution factor, while table 4.1 presents the results for each substitution efficiency with and without carbon storage in buildings.

Figure 4.12 shows the carbon payback period when increasing harvest of trunks with 10 and 30 %, both with a harvest residues extraction at 33 % of available residues and no carbon stored in buildings.

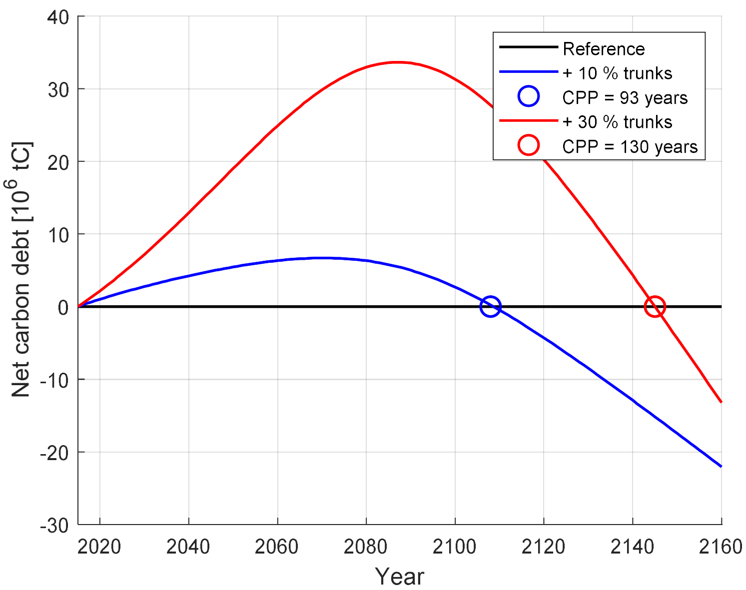

Figure 4.12. Carbon paybacks period with 33.3 % extraction of harvest residues, by 10 % (blue line) and 30 % (red line) increase of harvested trunks. All harvested wood is for energy purposes.

Figure 4.12 shows that the payback period changes with harvest rate when a portion of the harvest residues are extracted. This is different from the results in figure 4.3 and 4.7, where only trunks are removed. The carbon payback period of increasing conventional harvest with 30 % is 37 years longer compared to an increase of 10 %, when a modest share of residues is extracted. A similar result is shown in figure 4.13, where now all the available residues are extracted at the same increases of harvested trunks.

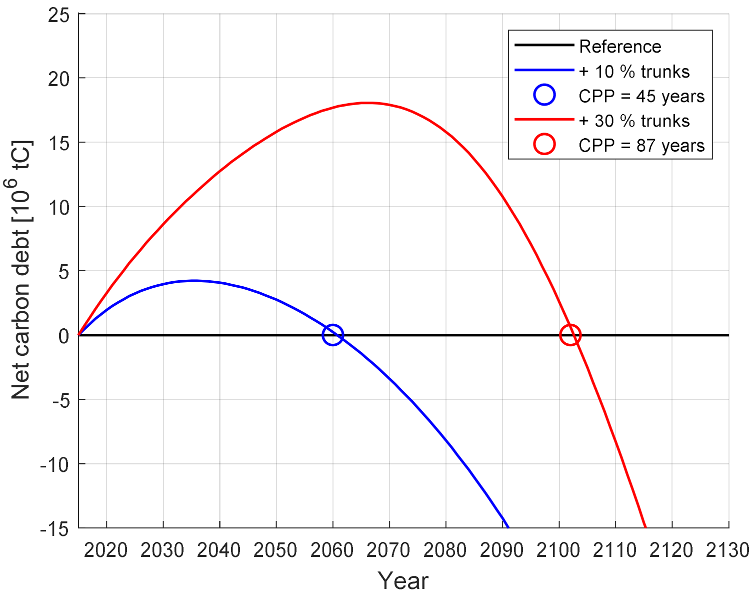

Figure 4.13. Carbon payback periods with 100 % extraction of harvest residues, by 10 % (blue line) and 30 % (red line) increase of harvested trunks. All harvested wood is for energy purposes.

The payback periods decrease further when all available residues are burned for bioenergy. The periods do not significantly change when assuming that a share of the harvested wood is stored in buildings as in section 4.1.2. Table 4.1 follows below, where all carbon payback periods by increasing harvested trunks with 10 and 30 %, extraction of none, 33 % and 100 % available residues, and with and without carbon stored in buildings, is included.

Table 4.1. Carbon payback periods depending on purpose of harvested wood and increase of harvested trunks and residues (res.).

No carbon stored in buildings				**Carbon stored in buildings**			
Substitution:	Low	Medium	High	**Substitution:**	Low	Medium	High
+10 % trunks	376	182	135	**+10 % trunks**	362	175	133
+ 33 % res.	197	93	30	+ 33 % res.	179	89	26
+ 100 % res.	137	45	7	+ 100 % res.	129	43	6
+30 % trunks	376	182	135	**+30 % trunks**	362	175	133
+ 33 % res.	265	130	92	+ 33 % res	242	123	91
+ 100 % res.	187	87	20	+ 100 % res	171	83	17

The largest difference in payback periods between otherwise equal scenarios by storing carbon in buildings is 23 years, when harvested trunks increase with 30 %, 33 % residues are extracted, and the low bioenergy substitution factor is assumed. The lowest difference ranges from 1-3 years, all when the high bioenergy substitution factor is assumed. In other words, storing carbon in buildings at a constant rate seems to have a very small effect on the net carbon budget compared to substituting fossil energy. Nearly all of the net carbon debts when applying a high substitution factor and residues is harvested peaks below 1 MtC, as these scenarios are close to carbon neutral the whole carbon payback period. Common for scenarios where residues are extracted is that the carbon payback period increases as harvested trunks increases from 10 % to 30 %.

4.2 Discussion of scenarios

4.2.1 Increasing harvest of trunks for energy and for buildings in addition to energy

Carbon payback periods remain the same with equal substitution factors, regardless of harvest level and purpose when no residues are extracted. These periods range from 135 to 376 years depending on avoided fossil emissions. Hence, such scenarios of increasing harvest of only trunks for bioenergy should be avoided. However, other important information can be discerned by figure 4.3 and 4.7 depending on timing of the emissions. If the priority is to reduce emissions on a short time-scale, this is best achieved by increasing harvest with 10 % as the net carbon debt reaches only one third of the equivalent carbon debt when increasing harvest with 30 %. Such a priority can be defended when considering feedback mechanisms in climate change, as more emissions today makes climate change mitigation more difficult in the future. On the other hand, one may consider the effects past the carbon payback period. Choosing the highest level of harvest today would eliminate around two thirds more fossil CO_2 emissions each year later compared with the lowest increase of harvest. The latter is however less likely to be motivation for action today.

Increasing harvest of trunks from 10 % to 30 % assures that a larger biomass share is left on the ground oxidizing. This additional emissions from decaying residues could be expected to increase the carbon payback periods at increased harvest. The difference in oxidizing carbon is however very small. Comparing an increasing harvest of trunks from 12 to 13.2 Mm^3 and 12 to 15.6 Mm^3 gives about 2.63 Mm^3 more residues in the year of harvest. This gives an additional annual average emission of 0.006 MtC per year from decomposing residues which is small compared to the magnitude of the carbon sequestered by the growing forest independent of harvest level. The carbon sequestration decreases towards 1 MtC per year at maximum sequestration when comparing a harvest increase of 13.2 and 15.6 Mm^3. This loss is however offset by avoided emissions from fossil fuels, hence the increased emissions from harvest residues is not important due to the ever-growing forest stock.

For clarity, by applying a harvest of only trunks for bioenergy close to the sustainable maximum harvest at 22.5 Mm^3 as noted in the end of section 3.3.1, the stock of carbon and stand ages of felling decreases the next centuries similar to the example in figure 3.8. The resulting carbon debt lasts over 213 years with a medium bioenergy substitution factor, compared to the periods of only increasing trunks for bioenergy in table 4.1 at 182 years with the same substitution factor. Stand ages of felling and number of stands felled with 12 and 22.5 Mm^3 harvest is shown in figure 4.14. This shows that the payback period increases, if increased harvest strongly affect stand ages.

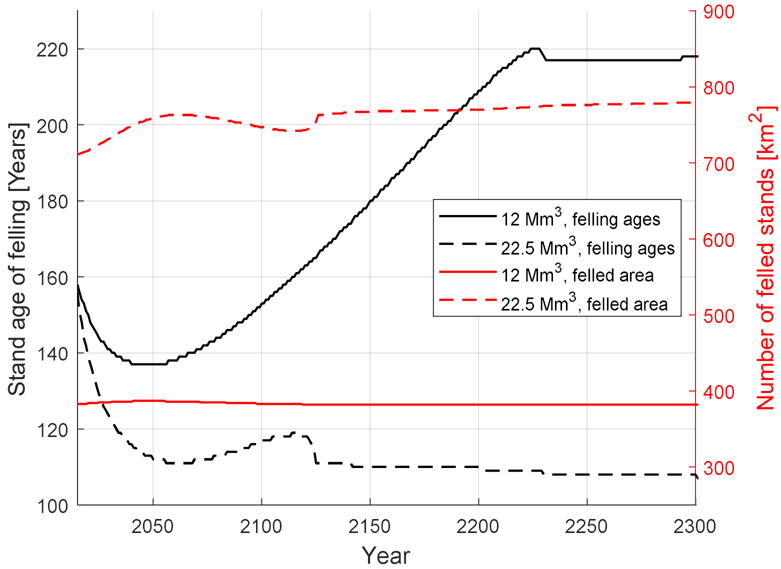

Figure 4.14. Number of stands felled annually (red lines) and felling ages (black lines) in reference scenarios (solid lines) and maximum sustainable harvest (dashed lines). Left y-axis is stand ages when felled, while the right y-axis is annual area felled.

Just below 400 km^2 is sufficient area in the reference harvest. At maximum sustainable harvest, this area nearly doubles, pushing the forest's age composition lower towards 98 years according to figure 3.2.

The payback periods crucially depend on how much fossil CO_2 emissions which is avoided per amount of wood burned as bioenergy. There is a clear disproportionality between substitution and carbon payback period. The three substitution factors are too a much larger degree linearly spaced than the carbon payback periods. This is due to the fact that the bioenergy substitution factor increases by 100 % from 0.2 to 0.4 tCO_2/m^3 vs 50 % if it develops from 0.4 to 0.6 tCO_2/m^3. The effect would hence be much larger by increasing the substitution factor by the same amount when starting with a low factor compared to a higher factor. This effect is shown in figure 4.15.

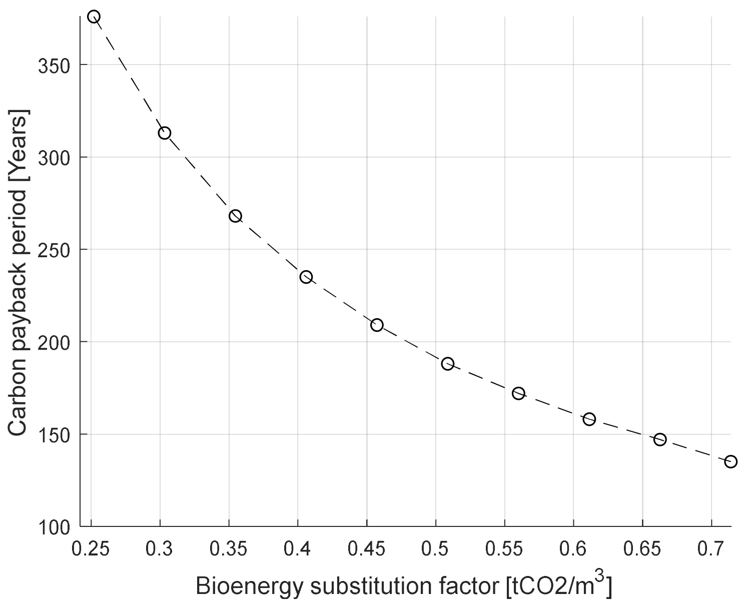

Figure 4.15. Carbon payback period plotted against bioenergy substitution factors ranged from low to high at any of the three increases of only harvested trunks.

Direct emissions from bioenergy would almost certainly be larger than emissions from an equivalent amount fossil derived energy, due to a higher energy content in fossil fuels than biomass. The high bioenergy substitution factor used in this thesis eliminates almost fossil emissions equal to the assumed carbon content of 1 m^3 wood which is 0.211 tC or 0.774 t CO_2, and it is believed to not be a very realistic result of substituting fossil fuels with bioenergy. For a high substitution, the produced bioenergy depends on small indirect emission of processing which may be possible. It also depends on replacing a fossil energy source with high emissions, whereas the future energy system is believed to be partly decarbonized.

The effect of utilizing and storing wood in buildings on the net carbon budget seems to be very small. Peak carbon debts related to the consequences of emissions today vs the future is at least damped. The same goes for accumulated reduction past the payback period. The reduction of payback periods does however increase as the substitution factor decreases. This makes sense since there should be a larger effect of storing carbon when the climatic effect of substituting forest bioenergy with fossil energy is small. According to this, there is a larger advantage in utilizing wood for buildings in a low-carbon economy, where the bioenergy substitution effects would be lower than in a less decarbonised economy. Due to the assumed lifetime and oxidation profile of carbon stored in buildings, increasing the harvested share used in buildings to more than 20 % which could be possible does not significantly decrease the carbon payback period.

The effect on the carbon debt by assuming that wood constructions replaces e.g. steel and concrete is expected to further decrease the carbon payback period. This is tested as Leskinen et al. (2018) reviewed 51 studies and found an average substitution factor by using wood in constructions at 1.2

tC/tC wood. Converted to m^3, this means that harvested wood in this thesis avoids 0.254 tC/m^3 or 0.930 tCO_2/m^3 for comparison with the factors in table 3.3. The resulting payback period can then be obtained by ignoring that the stock of carbon contains stored carbon in buildings, but rather by applying a bioenergy substitution factor on 80 % of harvested trunks as before and this other substitution factor on the 20 % harvested wood for buildings. When using a medium bioenergy substitution factor, this period turns out to be 159 years, compared to the period in figure 4.7 of 175 years. Hence the carbon debt period is still significant when assuming that harvested wood in constructions avoids fossil emissions from the lifetime of a steel or concrete construction.

4.2.2 Increasing harvest of only residues, and in combination with trunks for any purposes

The net carbon debt reduces significantly when the increasing harvest comes only from harvest residues. Such a scenario is however more uncertain given the expected allowed harvesting of trunks at perhaps 16.5 Mm^3 as discussed in section 2.4.3. Furthermore, harvest residues are almost not utilized for energy today. Another way of interpreting emissions from harvest residues is used by Repo et al. (2012) in figure 2.11, where the basis is a single harvest, opposite to this thesis which provides carbon budgets based on a permanent harvest. A similar figure to that of (Repo et al., 2012) follows below, which considers a single harvest.

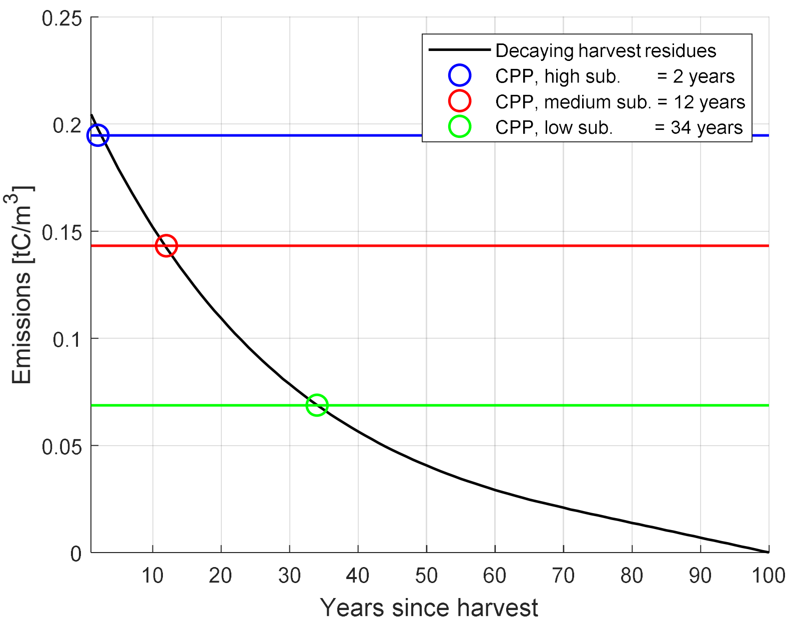

Figure 4.16. Carbon emissions per m^3 wood after a single harvest. Emissions from residues for bioenergy vs the avoided fossil emissions for the three substitutions, and corresponding carbon payback periods. For comparison with figure 2.11, note that this figure does not contain bioenergy production chain emissions as the CPPs are probably a few years longer.

The payback periods of a single harvest in figure 4.16 are considerably shorter than the periods when applying a permanent harvest scenario as in figure 4.11. This is in line with Norwegian Environment Agency (2011) which also calculates emissions of a single harvest and assumes that the payback period could be approximately twice as long when considering a permanent harvest. The longer periods in a permanent harvest scenario is due to the accumulation of bioenergy emissions, compared to a single pulse in figure 4.16 and 2.11.

Storing wood in buildings has much of the previously effect when harvesting trunks and residues increases. It does not have any significant effect on the carbon payback period, whereas the effect is strongest when the low bioenergy substitution factor is applied. The sensitivity of the carbon debt when only focusing on changes in extraction of residues also is the same. Common for all scenarios in table 4.1 is that the carbon payback period decreases when 100 % of the available residues are collected compared to the carbon debt when 33 % of the available residues are collected. This makes sense given the decay rate of harvest residues.

The most interesting result displayed in table 4.1 is perhaps that the payback period is shorter with a small increase of harvested trunks than with a larger increase, assuming the same share of extracted residues. Especially when considering that the harvested amount of only trunks has no effect on the payback period as long as the forest stock becomes larger anyway, according to the discussion of figure 4.3 in the previous section. Also, 33 % extraction of residues equals 1.934 Mm^3 when increasing conventional harvest to 13.2 Mm^3 vs 2.288 Mm^3 when increasing conventional harvest to 15.6 Mm^3. A larger amount of residues are thus harvested as more trunks are harvested, but the payback period is still shorter when the increase of harvested trunks is smaller. This is explained by the relative increase of harvest. When trunks increase with 1.2 and 3.6 Mm^3 on the same share of collected residues at 33 %, harvest residues consist of 61 % of the increased harvest at a small increase, and 39 % of the increased harvest at a large increase of harvested trunks. Utilization of a modest (33 %) share of harvest residues together with trunks for bioenergy is considered most viable with respect to the near absent of harvest residues for bioenergy at present.

4.3 Discussion of methodology

The method in this thesis is similar to that in Holtsmark (2012), capturing some of its assumptions on growth and carbon dynamics. However, more systematic overview of harvested trunks, residues, and comparing harvested wood for bioenergy and for storage in buildings is accomplished in this thesis.

Using one tree species at one specific site index is a major simplification, given the Norwegian forest composition described throughout chapter 2.3. Also, the growth model from (Braastad, 1975) seems to be linear and continue to increase past stand ages of 110 years. The function for the upper asymptote is however derived from regression analysis from plots in the national forest inventory between site indices and maximum volume ($R^2 = 0.99$) (Gizachew et al., 2012).

Biomass growth also depends on the climate, which is changing at present, and will most likely lead to more biomass growth through different mechanisms as previously mentioned. Figure 4.17 (Søgaard et al., 2015) shows several projected pathways of carbon in forest biomass in Norway, depending on the atmospheric concentration of GHGs. This figure is also provided for a realistic comparison with the projected carbon development in this thesis.

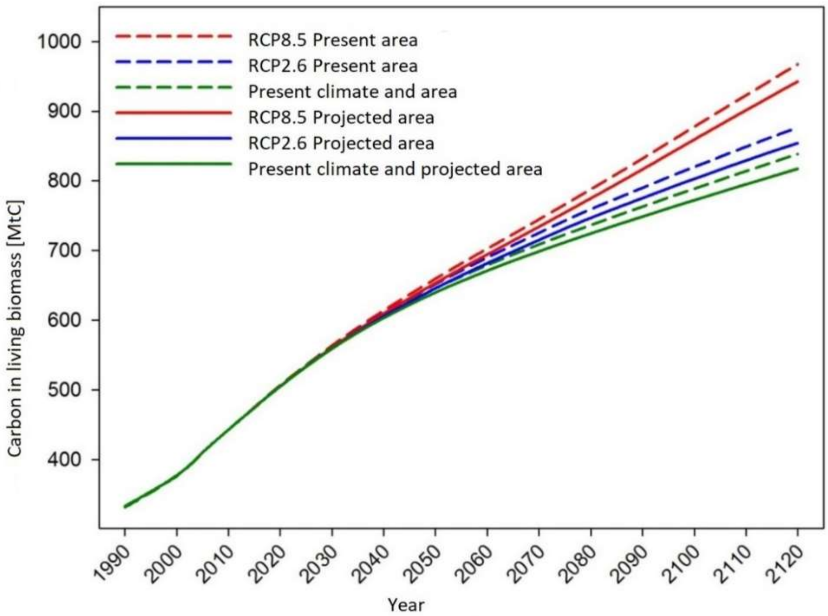

Figure 4.17. Development of carbon in biomass at present climate, and in two representative concentration pathways (RCP), RCP2.6 and RCP8.5. Solid lines assume constant area, dashed lines assume continuation of the decreased area briefly mentioned in section 2.3.1. Adapted from Søgaard et al. (2015).

The coherent harvest levels to the developing stocks in figure 4.17 are highest at RCP8.5 and lowest at the present climate. In the present study, the carbon stock at present climate and area steadily increases harvested trunks to levels comparable to an increase of 20 %. This suggests that despite the major simplifications in this thesis, the simulated carbon stocks are comparable to the much more extensive modelled carbon stocks in Søgaard et al. (2015) from the Norwegian Institute of Bioeconomy.

Annual area felled is also comparable to the actual area. In the reference scenario in this thesis, this area lies between 382 and 387 km^2 which is shown in figure 4.14. The equivalent actual area in 2016 was ~ 449 km^2, where spruce and site index 14 was most common (Granhus & Eriksen, 2017). Note that these areas only consider clear-cutting, which is the only harvest type throughout this thesis. The total area including e.g. selective thinning was just above 500 km^2 the same period, according to figure 3 in Søgaard et al. (2015). The smaller area harvested could be explained by the applied harvest strategy of continuously felling the oldest forest stands. In the reference scenario, the rotation age stabilizes at near 220 years as seen in figure 4.14, something which is unrealistic. A stand contains more biomass at these ages than more realistic rotation ages around 100 years, thus the required area becomes smaller. The largest conventional harvest at 15.6 Mm^3 results in a rotation age around 165 years, where between 497 and 509 km^2 are felled each year.

The chosen decay rate of harvest residues impacts mainly the carbon payback period when residues are collected. When considering the years after harvest, not all remaining biomass decomposes within

100 years as assumed in this thesis. Figure 4.18 shows a similar figure as figure 2.12, whereas this figure only contains the remaining biomass without the related supply chain emissions for bioenergy.

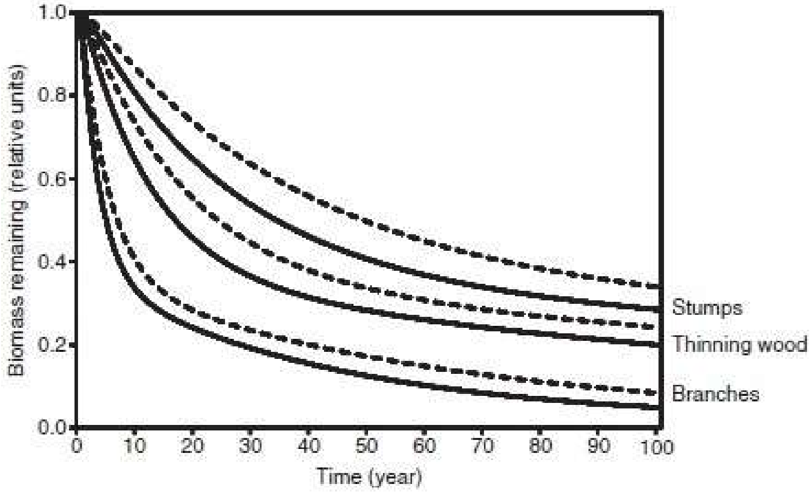

Figure 4.18. Remaining biomass after a single harvest in Northern Finland (dashed lines) and Southern Finland (solid lines) as branches, thinning wood and stumps. The climate is considered similar to that in Norway. From Repo et al. (2012).

By only choosing a longer lifetime of harvest residues, the payback period would probably be longer. On the other hand, the decay rates on specific parts from a tree is very different, compared to the average decay rate which is used in this method. The decay of branches in figure 4.18 is considerably faster than the decay in figure 3.4. The maximum assumed generated residues at 0.44 m^3/m^3 trunk could be covered only by tops and branches, as tops and branches are on average 25.9 % of tree biomass as mentioned in section 3.1. Hence, a faster decay could be assumed, resulting in a larger advantage of harvesting residues.

The bioenergy substitution factors have not been subject to any technical reasoning in the methodology but are simply obtained from a report of the Norwegian Environment Agency. The highest substitution factor is however not assumed to be very realistic, as it assumes very efficiently derived bioenergy from the harvest and substitution of very dirty and inefficient fossil fuels for a long period. Scenarios with high fossil substitution and a maximum share of harvested residues are especially not considered to be realistic. Harvest residues mostly contain more moisture and are related to other disadvantages compared to the more homogenous roundwood, resulting in e.g. more inefficient transport and processing. Furthermore, the payback period only slightly decreases when 20 % wood is stored in buildings. This does not mean that more wood in building constructions is not positive for the climate. It rather states that the effect is very small when harvest increases for mainly heat and energy production, with a realistic share stored in buildings. Carbon budgets of a complete product flow could be assessed based on figure 2.10. However, the sensitivity of only buildings was tested as this would be the most influential product category with its long average lifetime at 140 years.

4.4 Other factors not modelled

Of the range of other climatic factors mentioned throughout this thesis, the effects from soil organic carbon and albedo is further discussed in relation to the results.

Based on the discussion in the last part of section 2.1.4, losses of SOC are believed to be considerable, especially over a short time-scale. As previously stated, the present method mostly increases rotation age when increasing harvest. In reality, increased harvest is most common by extending the harvested area on the same rotation ages as before. As an example, 442.3 km^2 has to be harvested in the reference area with a rotation age of 100 years. If harvest increases to 15.6 Mm^3, the annual harvested area expands another 93 km^2, and natural forests are converted to forest plantations in large scale. SOC loss is greatest in wet climates, which applies for several regions in Norway. Furthermore, conversion of natural forests to rotational coniferous forests have the greatest losses, compared with broadleaved forests. The dependency on species is mostly due to properties of the organic carbon input to the soil, briefly discussed in section 2.1.4. In addition to the reduction of organic carbon input after harvest, light infiltration increases after harvest and further influences microbial activity and carbon emissions.

Long-term effects on SOC by converting natural boreal forest to a rotation forest is more uncertain. Johnson, Scatena, & Pan (2010) simulated SOC long-term responses of harvesting in a northern hardwood forest using two common soil carbon models. In this study, the loss depended strongly on percentage removal of aboveground biomass as discussed in section 2.3.4, together with the applied rotation age. The long-term loss reached only 5 % when rotation age was 120 years and no more than 60 % of the aboveground biomass was removed. Conversely, larger losses of >10 % happened when rotation age was 60 years or 90 years with 90 % removal of aboveground biomass. As this study considered a hardwood forest, the corresponding losses in the Norwegian boreal forest is believed to be somewhat higher, but although with a very low certainty due to the complexity of SOC responses to forest management.

When harvest is permanently increased, more recently cleared land subsequently lead to a higher albedo as mentioned in section 2.1.2 However, increasing harvest rates in Norway with the same management practises, i.e. replanting of the same species, does perhaps only have a minor effect. This was one of the scenarios modelled in Bright et al. (2014) to assess climatic impacts from albedo changes and two other proven less important biophysical factors within future shifting forest managements. The increased harvest was ~ 30 %, approximately the same which is used in this thesis. At the same forest management, i.e. logging and replanting of conifers, the gross albedo cooling the next 100 years was very small and thus resulted in a considerable net warming dominated by a smaller forest carbon sink. A similar scenario to the previous, only with naturally regrowing of birch at the most productive sites instead of replanting conifers resulted in a gross albedo cooling almost outweighing the gross warming from a smaller carbon sink.

The reason is mainly due to the properties of coniferous trees as spruce compared to deciduous trees as birch. Birch shed its leaves during winter, and thus reduces snow masking canopy. Furthermore, deciduous species have a higher albedo during summer than coniferous species. Hence, the cooling effect from albedo through increasing harvest is perhaps only significant if a larger share of forests in Norway becomes populated by deciduous trees. It is difficult to precisely estimate effects of albedo when harvest increases in this thesis. Anyhow, the assumed albedo cooling is not believed to significantly reduce the warming from the simulated decreasing forest carbon sinks.

5. Conclusion and suggestions for further work

The main objective for this thesis was to quantify the temporal imbalance between carbon losses and gains when the harvest rate increases for bioenergy production. The objective was approached by creating a simplified model of Norwegian forests including some of its characteristics. The sensitivity of the carbon debt on how much and what type of biomass harvested have been tested. Main findings are presented in the next paragraph.

Despite the uncertainties in the method, the results imply that bioenergy as an incentive for increasing harvest of industrial roundwood generates a higher atmospheric CO_2 concentration for centuries. Such an incentive should thus be avoided as a strategy for mitigating climate change, also when the highest quality roundwood is used in building constructions. The effort should rather be directed towards utilization of already existing harvest residues for bioenergy. Accumulation of avoided fossil emissions can at best offset forest carbon losses within a couple of years, but more realistically within 24 years, if only this low-quality biomass is burned as bioenergy. The carbon payback period strongly decreases when residues are used for bioenergy, in addition to increased harvest of roundwood. The shortest carbon payback periods considered viable when both these resources are used for bioenergy and buildings would still last between 89 to 123 years, depending on future harvest rates of roundwood. Other climatic impacts from forest management changes are difficult to estimate, but not believed to significant shift the main findings in this thesis.

CDR as BECCS is still an unproven technology. If this further continues, the demand for short-term major emission cuts increases if the set targets at the 21st meeting of COP in 2015 is to be met. Impacts of increasing harvest rates for bioenergy production under certain forest management practices in any country depends strongly on discussed dynamics as shown in this thesis, and should be properly accounted for. A neglection as today of the emissions from burning biomass could thus have dangerous effects on the climate, especially when considering the fulfilment of legislative targets of increasing renewable energy production.

The simple framework in the appendix created for this thesis is transferable to assessing growth dynamics in any other forests. A natural step further from this thesis should therefore include e.g. several species on different site indices to cope with a much more extensive forest, and in other words remove many of the simplifications used here. Adjusting the rotation age to more realistic ages should also be done, whereas different forest plots should contain parameters related to emissions from felling and transportation. The last point is relevant for estimating how much fossil emissions that is avoided when replacing fossil fuel with bioenergy, as the actual bioenergy substitution factor needs to be determined with a much larger degree of certainty. It exists well-established models to investigate changes in soil organic carbon in the literature. Albedo responses on a changing forest management seems to be much less investigated and should be the motivation in future studies.

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Appendix

```
% Matlab script; Forest development in the reference case
% Other cases are run by altering parameter values


% Logistic growth function:
SI = 14;                                  % Site index
K = 829.1434*(1-exp(-0.2074*SI))^3.9178;  % Upper asymptote
t0 = 73;                                  % Chosen inflection point
r = 0.068;                                % Growth rate
t = 1:400;                                % Time and stand ages
VB = K./(1+exp(-r*(t-t0)))*100;           % Biomass volume [m^3/km^2]
VB = VB-VB(1);
VB = (VB-(VB(1)-diff(VB(1:2))));
cs = 0.5;                                 % Carbon in biomass [%]
rho = 422.7;                              % Density [kg/m^3]
CB = VB.*rho.*cs./10^3;                   % Biomass carbon [tC/km^2]

% Initial age distribution:
area1 = 8.296*10^4;                       % Area [km^2]
alpha = 2.1;                              % Parameter in gamma PDF
beta = 33;                                % Parameter in gamme PDF
init_ages = round((area1.*gampdf(t(1:160)....
    ,alpha,beta))*(area1/sum(area1.*gampdf(t(1:160),alpha,beta))));

% Initial trunk volume and carbon in trees and residues:
hi = 10*10^6;                             % Historic harvest [m^3]
hs = 0.477;                               % Harvested share (no residues)
ts = 0.477;                               % Trunk share
k = 0.033;                                % Exp. decay rate
f = [(1*exp(-t(1:70).*k))....             % Vector of remaining residues
    linspace(0.095,0,30)];
init_VT = sum(VB(1:160).*init_ages)....   % Standing stock [Mm^3]
    *ts/10^6;
init_VB = sum(VB(1:160).*init_ages);      % Initial volume [m^3]
init_CB = sum(CB(1:160).*init_ages)/10^6; % Tree carbon [MtC]
init_CBr = sum(((1-ts)/ts).*f)*rho*cs*hi/10^9; % Residues, carbon [MtC]




% Forest development:
h_m = 12*10^6;                            % Lower harvest limit [m^3]
age_max = 225;                            % Mus be higher than maximum
                                          % age at this annual harvest
                                          % (decreases at more harvest)
f_f = ones(max(init_ages),age_max).*....
    [VB(1:size(init_ages,2)) zeros(1,age_max-160)];
for i = 1:size(init_ages,2)
    f_f(init_ages(i)+1:end,i) = 0;
end
f_M = zeros(max(init_ages),age_max,1);
f_M(:,:,1) = f_f;
```

```
for i = 1:401
    f_M(:,:,i+1) = f_M(:,:,i);
    f_M(:,:,i) = f_f;
    for j = size(f_f,1)*size(f_f,2):-1:1
        h(i) = sum(f_f(end:-1:j)*hs);       % Annual harvest [m^3]
        nh(i) = nnz(f_f(end:-1:j));         % Annual n of stands felled
        if h(i) > h_m
            f_f(end:-1:j) = 0;
            for k = age_max:-1:1
                f_f(f_f==VB(k)) = VB(k+1);
            end
            f_f = circshift(f_f,1,2);
            f_f(1:nh(i),1) = VB(1);
            break
        end
    end
end

f_M(:,:,1) = [];
f_M(:,:,end) = [];

% Biomass volume and stand age of felling:
for i = 1:400
    f_V(i) = sum(sum(f_M(:,:,i)));            % Living biomass volume [m^3]
end
for i = 1:400
    [row(i),col(i)] = find(f_M(:,:,i),1,'last'); % Col = age of felling
end

% Harvest residues:
f_Vrr = [ones(1,100).*hi./ts h(1:400)./hs]-[ones(1,100)....
    .*hi h(1:400)];
for i = 1:401
    f_Vr(i) = sum(f_Vrr(i:i+99).*fliplr(f));
end

% Carbon in biomass:
f_t = [init_VB f_V(1:399)].*(rho*cs/10^9).*ts;    % Carbon in trunks
f_o = [init_VB f_V(1:399)].*(rho*cs/10^9).*(1-ts);% Carbon in other biomass
f_r = f_Vr(1:400).*(rho*cs/10^9);                 % Carbon in residues
C = f_t+f_o+f_r;                                  % Total carbon [10^6 tC]

% Additional carbon stored in buildings:
m = 140;                                          % Mean life-time
b_s = 0.2;                                        % Share of ONLY trunks in
                                                  % buildings

% Total stock:
C_b = C + cumsum(h(1:400).*b_s.*rho.*cs./10^9)....
    - cumsum(cumsum((chi2pdf(t,m)).*h(1:400).*b_s.*rho.*cs./10^9));
```