ISSN 1891-2281

Carbon cycle effects of different strategies for utilisation of forest resources - a review

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INA fagrapport 19

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2011

Preface

This study is carried out by researchers at Department of Ecology and Natural Resource Management, Norwegian University of Life Science. The report reviews studies of relevance for the forest carbon cycle and subsequent climate effects with special emphasis on utilization of forest resources in Norway and discusses the potential costs and benefits of forest mitigation efforts.

The study is funded by Ministry of Finance. We appreciate the opportunity to study these important, interesting and challenging issues. The views expressed in the report are the opinion of the authors and do not reflect any official view of the Department of Ecology and Natural Resource Management.

We wish to thank Tron Eid for reviewing the report.

Ås, Norway,

December, 2011

Erik Trømborg

Summary

The objective of this report was to review studies of relevance for the Norwegian forest carbon cycle and on that basis, indicate global warming impacts of possible changes in management and utilization of the Norwegian forest resources. In the photosynthetic process, forests sequester carbon dioxide from the atmosphere. Carbon is stored in living vegetation, dead organic matter, and soil. Intensive planting and afforestation in Norway between 1950 and 1990, in combination with relatively stable harvest levels well below annual growth during the last decades, have resulted in net carbon sequestration in forests equaling more than half the current national annual greenhouse gas (GHG) emissions. The the average forest age is increasing, and the forest growth and carbon accumulation rate is therefore projected to decline in the future given continuation of recent harvest levels.

A range of studies at different scales with a variety of approaches have been carried out to assess the climate change mitigation possibilities in the forest sector. Prolonged rotations, afforestation, intensified planting, improved plant materials, changes of species, more fertilization and less thinning are all changes in the forest management that might enhance carbon sequestration. Use of bioenergy can reduce overall GHG emissions by replacing fossil fuels, and wood materials can substitute GHG-intensive materials such as concrete and steel. Studies of such substitution effects generally find a reduction in the GHG emissions when biomass systems are compared to fossil reference systems, as long as the permanent reductions in terrestrial carbon pools are small. However, the majority of these case studies assume carbon neutrality in the meaning that as new trees grow where the old ones are harvested, an amount of CO_2 similar to the quantity emitted during combustion will be sequestered during the next rotation. This assumption of carbon neutrality is in line with the approach taken by the Kyoto Protocol, i.e. biogenic carbon flows are summarized without regard to the timing of each flow. However, since combustion of wood usually is less energy efficient / more carbon intensive than combustion of oil and natural gas, using wood instead of these fossil fuels for energy will in the short term lead to increased CO_2 concentration in the atmosphere, creating a carbon debt and a corresponding CO_2 pay-back time. If wood energy replaces power produced from coal, the net GHG emissions in the combustion process are approximately zero. The length of the pay-back time from increased harvest in Norway is mainly determined by the following factors: (i) the foregone sequestration in the harvested stand, (ii) how large share of the harvested biomass in the stand is utilized and the substitution effects of this utilization, and (iii) the initial growth of the new stand. With the present biomass utilization, forest growth and management in Norway, the length of this pay-back time is relatively long. A positive carbon price implies longer rotations for forest stands, the more if the sequestration in the existing stand is high, re-growth is slow and substitution effects low. However, at a certain point in time, a forest stand will reach a state of slow and eventually negative growth, and in this situation, harvest to replace fossil fuels followed by regeneration is more likely to improve the GHG balance also in the short run.

Our main conclusions are:

- Domestic and imported wood are to a large extent substitutes and changes in domestic harvesting levels can change harvesting levels elsewhere. Impacts of global GHG emissions of changes in domestic harvest levels require broader analyses than carried out in this study
- Higher demand for biomass from forest in Norway is likely to be covered through a mix of increased harvest, higher harvest residue utilization, reduced wood consumption in the pulp and paper industries and more import.
- With the present forest management and wood utilization, increased harvest in Norway as a result of growing demand for biomass in the energy sector, will in the short to medium term cause an increase in the GHG emissions to the atmosphere. If fossil-fuel based commodities are replaced, increased use of wood products will reduce GHG emissions in the long run.
- Utilization of harvest residue for energy can be increased within the current harvest level and have positive GHG effects also in the short run (5-15 years).
- Forest carbon sequestration can be increased by changing forest management practices: more fertilization, higher densities in planting, improved plant material, changed species, less thinning, and allocation of harvest to stands with current low growth, but with a potential of higher growth. Except for fertilization and allocation of harvest, these measures have limited carbon sequestration impacts in the short run, but considerable impacts in the medium and long run.
- To improve the substitution effects of wood products and thus the GHG impacts of harvesting, it is important that the wood products actually replace fossil-fuel intensive products , that the most GHG-intensive fossil fuels and materials are replaced and that the wood product chain has high GHG efficiency.
- The understanding of the development of old, dense stands is limited, and thus the carbon effects by keeping such stands far beyond regular forest management practices are uncertain, in particular for spruce and birch.
- Impacts of the albedo effect of different forest management regimes are not yet well known, but some studies indicate that that it might be of a magnitude that could change the conclusions drawn when considering GHG only.

If harvest in Norway increases and the use of oil and natural gas is replaced by forest bioenergy, the GHG emissions will increase in the short to medium run. However, given that increased use of biomass substitute fossil fuels or materials, increased use of biomass will reduce GHG emissions in the long run. An important question is therefore what the relevant time horizon for global warming mitigation efforts is. The optimal mitigation strategy will depend upon this chosen time horizon. To assess the pros and cons of short term versus long term emissions, one needs to broaden the scope from pure GHG emission calculations to the entire climate system and include non-GHG effects like reflections from the forest surface (albedo). Albedo effects may imply shorter rotations, more broadleaves and less afforestation compared to what is optimal when considering GHG effects only.

The net wood import accounts for 20-30% of the domestic wood consumption in Norway. Changes in the harvest level will affect wood import since there are few barriers to timber and wood product trade in Europe. Thus, possible leakage effects must be considered if implementing policies to change the harvest level in order to mitigate climate change. More research regarding the growth and mortality of old forest, and substitution effects of present and new wood products, is also needed to estimate more correctly the GHG effects of different forest management strategies in Norway. Finally, efforts to change the management of the forest resources to mitigate global warming should be coupled with considerations on factors such as economic development and biodiversity, in addition to short-run versus long-run global warming impacts in order to achieve the desired outcomes.

Sammendrag

Formålet med denne rapporten er å gjennomgå studier som er relevante for karbonkretsløpet i skog og på dette grunnlaget vurdere hvordan endringer i skogbehandling og bruk av skogressursene påvirker utslipp av klimagasser. Gjennom fotosyntesen binder skogen karbondioksid fra atmosfæren. Karbonet blir så lagret i levende vegetasjon, dødt organisk materiale og i jordsmonnet. Omfattende planting og skogreising i Norge mellom 1950 og 1990 i kombinasjon med et relativt stabilt avvirkningsnivå de siste tiårene har resultert i en nettobinding av karbon i norske skoger som tilsvarer mer enn halvparten av de nasjonale klimagassutslippene. Reduserte investeringer i skogkultur og stabil avvirkning har resultert i høyere gjennomsnittsalder på skogen. Tilveksten og dermed opptaket av karbondioksid vil derfor reduseres i fremtiden dersom avvirkningen holdes på dagens nivå.

Det har blitt gjort en rekke studier på ulike geografiske nivåer og med ulike tilnærminger av mulighetene for å utføre klimagasstiltak i skogsektoren. Økt hogstalder, skogreising, tettere plantinger, forbedret plantemateriale, bytte av treslag, mer gjødsling og mindre tynning er eksempler på tiltak som kan øke karbonopptaket i skog. Bruk av bioenergi kan redusere klimagassutslippene ved at biomassen erstatter bruk av fossile energiressurser. Trematerialer kan erstatte mer klimagassintensive materialer som sement og stål. Studier av slike substitusjonseffekter viser generelt en reduksjon i klimagassutslippene når biomassesystemer sammenlignes med referansesystemer basert på fossile energiressurser. Dette er forutsatt at de permanente reduksjonene i de terrestriske karbonlagrene er små. Det er imidlertid slik at de fleste av disse studiene forutsetter at bruk av biomasse er karbonnøytralt fordi nye trær vil vokse opp etter hogst og karbondioksidet som slippes ut gjennom forbrenningen vil tas opp av det nye skogbestandet. Denne forutsetningen om karbonnøytralitet er i samsvar med bestemmelsene i Kyoto-protokollen og innebærer at de biotiske karbonstrømmene blir summert uavhengig av tidspunktet for utslipp og opptak. Forbrenning av biomasse er imidlertid som regel mindre energieffektive/mer karbonintensive enn forbrenning av olje og naturgass. Bruk av trevirke istedenfor disse fossile energiressursene vil derfor på kort sikt føre til økt konsentrasjon av karbondioksid i atmosfæren, som resulterer i en karbongjeld med tilhørende tilbakebetalingstid for karbondioksidet. Når trevirke erstatter kull er netto klimagassutslipp i selve forbrenningen omtrent null.

Tilbakebetalingstiden ved økt avvirkning i Norge bestemmes i hovedsak av følgende faktorer: (i) Tap av binding i bestandet som avvirkes, (ii) hvor stor andel av den avvirkede biomassen som utnyttes og substitusjonseffekten av denne biomassen, og (iii) tilveksten i det nye bestandet. Med dagens utnyttelse av biomasse, vekstforhold og skogbehandling i Norge er tilbakebetalingstiden relativt lang. En reduksjon i de samlede klimagassutslippene innebærer som oftest lengre omløpstider for skog. Omløpstiden øker hvis den tapte bindingen i eksisterende bestand er høy, tilveksten i det nye bestandet lav og substitusjonseffektene små. På et gitt tidspunkt vil imidlertid bestandet få en lav og etter hvert også negative tilvekst og avvirkning vil da kunne forbedre klimagassregnskapet også på kort sikt.

Våre hovedkonklusjoner er:

- Innenlandsk og importert trevirke er i stor grad substitutter, og endringer i innenlands avvirkning kan endre avvirkningen utenlands. Vurderinger av endringer i globale klimagassutslipp som følge av endringer i innenlandsk avvirkning krever bredere analyser enn det som er gjort i denne studien.

- Økt etterspørsel etter biomasse fra skog i Norge vil sannsynligvis bli dekket gjennom en blanding av økt avvirkning, større utnyttelse av greiner, rot og topp, redusert bruk i øvrig skogindustri og mer import.

- Med dagens skogbehandling og utnyttelse av biomasseressursene vil økt avvirkning som resultat av økt etterspørsel etter biomasse i energisektoren på kort og mellomlang sikt resultere i økte klimagassutslipp til atmosfæren. Dersom biomasse erstatter produkter produsert av fossile råvarer, vil økt bruk av treprodukter føre til lavere klimagassutslipp på lang sikt.

- Økt utnyttelse av greiner, rot og topp til energiproduksjon innenfor dagens avvirkningsnivå vil ha positiv effekt på klimagassutslippene også på kort sikt.

- Karbonopptaket i skog kan økes ved å endre skogbehandlingen. Økt gjødsling, høyere plantetetthet, forbedret plantemateriale, mindre tynning og allokering av avvirkningen til bestand med lav vekst og potensial for høyere vekst etter hogst er eksempler på tiltak med positive klimagasseffekter. Bortsett fra gjødsling og allokering av avvirkningen har disse tiltakene en begrenset klimagasseffekt på kort sikt, men kan gi betydelige effekter på mellomlang og lang sikt.

- For å bedre substitusjonseffektene og dermed klimagasseffektene ved bruk av treprodukter, er det viktig at treproduktene faktisk erstatter produkter basert på fossile ressurser og ikke kommer i tillegg. Videre er det viktig at de mest klimagassintensive produktene blir erstattet og at produksjonskjedene for treproduktene har en høy klimagasseffektivitet.

- Kunnskapen om hvordan eldre og tette skogbestand utvikler seg og dermed karboneffektene av å overholde slike bestand langt utenfor dagens praksis er usikker. Spesielt gjelder dette for gran og bjørk.

- Størrelsen på albedoeffekter av ulike skogbehandlingsregimer er fortsatt ikke god kjent, men det finnes studier som indikerer at dette kan være av en slik betydning at det endrer konklusjoner som baserer seg utelukkende på klimagasseffekter.

Hvis avvirkningen i Norge økes for å erstatte bruk av olje og gass med skogbasert bioenergi, vil klimagassutslippene øke på kort og mellomlang sikt. Gitt at biomassen erstatter bruken av fossile ressurser vil økt bruk av biomasse redusere klimagassutslippene på lengre sikt. Et sentralt spørsmål er dermed hva som skal anses å være en relevant tidshorisont for klimatiltak fordi valget av optimal strategi i stor grad vil være avhengig av den valgte tidshorisonten. For å vurdere fordeler og ulemper ved kortsiktige og langsiktige tiltak, er det behov for å utvide perspektivet fra rene klimagassregnskap til hele klimasystemet og også inkludere albedoeffektene av endringer i skogbehandlingen. Albedo effekter (refleksjon fra skogarealet) kan tilsi kortere omløpstider, mer lauvskog og mindre skogreising enn hva som er optimalt når bare klimagasseffektene inkluderes i analysene. Nettoimporten av trevirke utgjør 20-30% av virkeforbruket i Norge og endringer i innenlands avvirkning vil endre tømmerimporten i og med at det er få restriksjoner på handel med trevirke i Europa. Dette innbærer at effekter av endringer i internasjonal handel (”leakage”) bør vurderes dersom det skal innføres tiltak for å påvirke nasjonal avvirkning. Mer forsking om utviklingen for tilvekst og mortalitet i gammel skog og substitusjonseffekter for dagens og fremtidens skogprodukter er også nødvendig for bedre beregninger av klimagasseffekter av ulike strategier for skogbehandling i Norge. I tillegg til å vurdere klimagasseffekter på kort og lang sikt må tiltak for å endre forvaltingen av skogressursene for å redusere klimaendringene vurderes sammen med andre viktige faktorer som økonomisk utvikling og biodiversitet.

Contents

1. INTRODUCTION

Climate change caused by the accumulation of GHGs (green house gases) in the atmosphere is an important topic. As forests are important in the carbon cycle, they may present possibilities for mitigation of climate change. Vegetation sequesters carbon dioxide from the atmosphere through the process of photosynthetic assimilation. Over a certain period of time plant growth coupled with the production of biomass accumulates and stores carbon in living vegetation, dead organic matter, and soil. The ability to remove carbon dioxide from the atmosphere and store the carbon in biomass provides climate mitigation benefits. The natural carbon flux between the terrestrial systems and the atmosphere is almost six times the emissions from fossil fuel combustion and cement production (Watson et al., 2000), and 90% of this flux is within forests (Winjum et al., 1993). The contribution from land use change to total global GHG emissions varies from 5-18% (Harris et al., 2010; Denman et al., 2007). Recent estimates of GHG emissions from deforestation and land degradation include 1.6 Pg/year in the 1990s (Denman et al., 2007), and 1.5 Pg C/year (Houghton, 2008) and 0.4-1 Pg C/year (Harris et al., 2010) for the years 2000-2005. However, in total, the world's forests are carbon sinks with a positive net accumulation of carbon, with almost one-third of global GHG emissions ending up in terrestrial systems (Nabuurs et al., 2007). An important part of this accumulation takes place in boreal forests (Sarmiento et al., 2010), which is the biome with the largest carbon storage in the world (Watson et al., 2000).

The Marrakesh meeting in 2001 decided that emissions from deforestation and land degradation should be implemented in the Kyoto Protocol. Moreover, Annex I countries[1] could choose whether to include forest management as an offset, but only up to 3% of national emissions for the first commitment period, which in Norway's case means 1.5 million tonnes CO_2/year (UNFCCC, 2002). Annex I countries also have the option to include afforestation sinks for areas which were not forested in 1990 but afforested later. The estimated total potential for the afforestation option in Annex I countries is 150-180 million tonnes CO_2/year, although only about 10% of the potential is actually used (Chopra et al., 2005).

In Norway, intensive planting and afforestation between 1950 and 1990, in combination with relatively stable harvest levels over the last decades, have resulted in net carbon sequestration in forests equaling more than half of the current national annual GHG emissions. With a continuation of recent harvest levels, the accumulation rate is projected to decline due to reduced growth in old, dense stands and low investments in silviculture. The Norwegian government decided in 2007 to aim for an increase in the national production of bioenergy of 14 TWh within 2020.close to a doubling of the current production. A strategy plan from the Ministry of Petroleum and Energy, which outlines and coordinates necessary measures in order to reach the bioenergy target, was published in April 2008 (Norwegian Ministry of Petroleum and Energy, 2008). The main strategy for the fulfillment of

[1] Annex I countries include European countries, the U.S., Canada, Australia, New Zealand and Japan (UNFCCC, s.a.).

the bioenergy target is to increase the use of bioenergy for heating followed by a balanced increase in the supply of wood based fuels.

Forests and use of forest products are complex systems. A range of studies on different scales with a variety of different approaches have been carried out to assess the potentials and costs of climate change mitigation in the forest sector (forestry and forest industries combined). Prolonged rotations, afforestation, intensified planting and other changes in forest management can increase carbon sequestration (Nabuurs et al., 2007a). Use of bioenergy can reduce overall GHG emissions by replacing fossil fuels (Sims et al., 2007) and wood materials by substituting non-renewable materials such as concrete and steel (Gustavsson et al., 2006). However, the majority of case studies ignore the CO_2 flux within a bioenergy system, (e.g. Korpilahti, 1998; Raymer, 2005; Wahlund et al., 2004; Bright & Strømman, 2009).This assumption of carbon neutrality is in line with the approach taken by the Kyoto Protocol. Biogenic carbon flows are summarized without regard to the timing of each flow. As new trees grow where the old ones are harvested, an amount similar to the CO_2 emitted during combustion will be sequestered during the next rotation.

The absence in GHG balances of the climate impact of CO_2 from biomass combustion imply that most of the studies generally find a reduction in the contribution to climate change when biomass systems are compared to fossil reference systems, provided that permanent changes in terrestrial carbon pools are minimized (Searcy & Flynn, 2008). Harvesting highly productive wood for the efficient substitution of carbon and energy intensive products (preferably through cascading chains) is in many studies regarded as feasible climate mitigation means (Werner, 2010; Dornburg et al., 2010, Marland2010, Marland & Schlamadinger 1997).

However, since combustion of wood is slightly less energy efficient /more carbon intensive than most fossil fuels, using biomass for bioenergy purposes may on a short term lead to increased CO_2 concentration in the atmosphere (McKechnie et al., 2011; Marland, 2010) compared to a fossil alternative. The payback time for the initial carbon debt depend on which product is substituted and the physical condition of the forest, especially growth rate as well as anticipated mean occupation time for the carbon in the atmosphere. Carbon leakage from the soil will also have an influence on the net effects of forest activities. While there is little disagreement on the long term climate change benefits of using renewable forest biomass, the short term benefits are less certain, since the payback time may exceed the timeframe for climate mitigation goals (Cherubini, 2011). The short term carbon neutrality assumption or GHG-effects of forest biomass use is therefore challenged (Johnson et al., 2010; Guinée et al., 2009).

As forest management and especially harvest operations alter the vegetation and snow cover in boreal forests, an additional factor in climate accounting in forestry is the albedo effect. The albedo, or reflection coefficient, is the share of short wave incoming radiation that is reflected back to the atmosphere by the surface. Depending on its colour and brightness, a change in land surface can have a positive (cooling) or negative (warming) effect on climate change. Planting coniferous trees as a climate mitigation measure has been questioned in areas with snow since the darkening of the surface (decrease in albedo) may contribute to warming. And vice versa, the albedo effect may lower or even completely offset the lost carbon sinks following expanded timber harvesting. Recent research suggests that forest management strategies for climate change mitigation should focus on more than just GHG reduction, and that the albedo effect should be among the most important considerations for forest management (see for example Arora & Montenegro, 2011; Bala et al., 2007; Betts, 2000; Betts et al., 2007; Bonan, 2008; Gibbard et al., 2005; Schwaiger and Bird, 2010; Thompson et al., 2009). The albedo effect may be of particular interest in boreal forests like in Norway which normally is covered by snow in the spring months. Here, from a climate mitigation point of view, the albedo effect may imply shorter rotations, more mixed or broadleaved forests and less afforestation than what is optimal when only considering carbon sequestration.

Forest management also influences evaporation and plant transpiration (evapotranspiration). Higher evapotranspiration promotes low-level cloud cover increasing top-of-atmosphere (TOA) albedo. Through emissions of biogenic volatile organic compounds forming secondary organic aerosols (SOA) forests influence the TOA albedo itself through increased cloud condensation and droplet number concentrations (CDNC) which increase albedo and life time of clouds. Schwaiger & Bird (2010) point out that these non-GHG effects should be included in studies of global warning impacts of land use systems and use of biogenic products.

A recent study by Bright et al. (2011) suggests that the albedo effect offsets the negative GHG effect from increased harvest over a century. Unarguably, as long as there is snow cover in late winter and spring, increase in clear cut will have a cooling effect, but more research is needed before definite conclusions can be drawn.

The objective of this report is to review studies of relevance for the forest carbon cycle and subsequent climate effects with special emphasis on utilization of forest resources in Norway. What do we know about the different factors that affects this carbon cycle? What are the possible implications of non-GHG effects of use of forest products? Where do we lack knowledge, and what is the possible impact of uncertain factors? What are the possible economic and environmental impacts of efforts to increase carbon mitigation in the forest sector?

The report is a review of available studies of relevant carbon flows in the forest ecosystem (Chapter 2) and impacts of forest management on these carbon flows (Chapter 3), and of substitution effects when forest products including bioenergy replaces materials and energy produced from other resources (Chapter 4). Chapter 5 discusses the potential costs and benefits of forest mitigation efforts, and summarizes conclusions and main uncertainties. Due to lack of data and analyses related to Nordic forestry, non-GHG effects are not specifically analyzed in this report.

2. THE FOREST CARBON CYCLE

2.1 Forest and the global carbon cycle

The carbon flux between the biosphere and the atmosphere (gross primary production - net primary production) amounts to roughly 60 Pg C (220 billion tonnes CO_2) per year, compared to annual emissions from the use of fossil fuels and the production of cement of 6.3 Pg C (Watson et al., 2000). 90% of the global carbon flux between terrestrial systems and the atmosphere occurs in forests (Winjum et al., 1993).

Between 5 and 18% of the anthropogenic global GHG emissions are estimated to be from the forest sector (Harris et al., 2010; Houghton, 2008; Nabuurs et al., 2007a), almost all of which are from land degradation and deforestation in tropical areas (FAO, 2010). CO_2 emissions from fossil fuel combustion, cement production and deforestation end up in three pools; approximately 42% are estimated as being placed as higher atmospheric CO_2 concentration, while oceans and terrestrial ecosystems each absorb about 29% of the emissions (Watson et al., 2000). However, there is a high degree of uncertainty in these figures (Denman et al., 2007).

The carbon sequestration in the world's terrestrial ecosystems is assumed to more than offset the CO_2 emissions from land use. As displayed in Figure 1, deforestation is calculated to emit totally 1.6 Pg C, while the terrestrial ecosystems are assumed to totally sequester about 2.3 Pg C, i.e. the net sequestration is 0.7 Pg. About 0.5 Pg C/year is estimated to be absorbed in temperate and boreal zones in each of the Eurasian and North American continents (Sarmiento et al., 2010). The net carbon accumulation in the European forest sector was in the early 1990s estimated to 0.14 Pg, of which 64% was added to living vegetation, 14% to soil and 7% to each of the three pools of dead wood, the forest floor and forest products (Goodale et al., 2002). There may be several reasons for this relatively large forest sink in Europe. During the last two decades Europe's (excluding Russia) forest area has expanded by 700,000 - 850,000 ha/year (FAO, 2010). Furthermore, as shown by Spiecker (1999), numerous studies have found increased productivity in many European forest sites, particularly in central Europe. In some sites, productivity in terms of wood volume per hectare has increased by more than 50% over the last decades. Likely reasons for this shift in forest growth include forest management and altered species composition, in addition to a higher atmospheric concentration of CO_2 and nitrogen deposition via precipitation. Indications of longer growing season in Europe, attributed to a warmer climate, have also been found (Myneni et al., 1997; Menzel & Fabian, 1999).

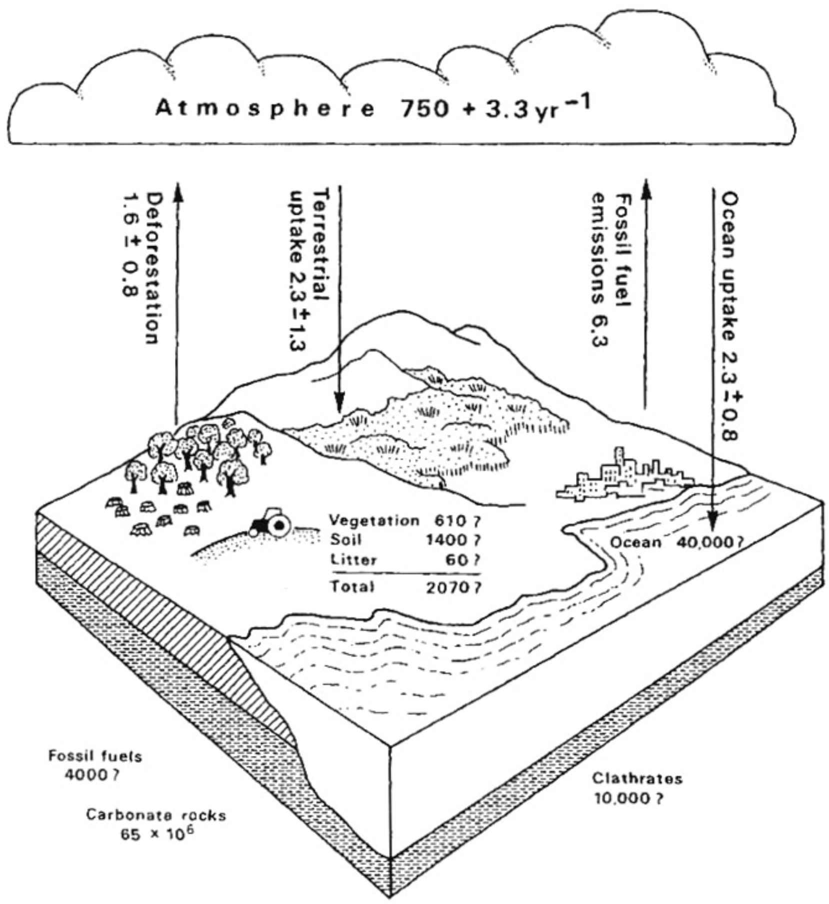

Figure 1: Carbon stocks (Pg) and fluxes (Pg /yr). Fluxes are indicated with arrows. Source: Grace (2004).

2.2 Carbon dynamics in the Norwegian forest sector

About 120,000 km^2 or 37% of the total area in Norway is covered by forest. Of this about 76,000 km^2 is productive forest (Climate and Pollution Agency, 2010). In Norway, the organic soil carbon pool in forests is estimated to 77 % of the total forest carbon pool (Grønlund et al., 2010). The total carbon pool in forests is estimated to 2 Gt C, of which approximately 1.55 Gt C is in soils, i.e. about three quarters of the carbon in Norwegian forests is stored in the soil.

Over the last century the standing stock has increased dramatically. Standing stock is now about 850 million m^3 – almost three times the stock in the early 20th century. This is mainly due to the post World War II forest policy with emphasis on forest tree planting in new areas (mainly on the western coast) and replanting on clearfelled areas after harvest. In the period from 1955 to 1992 more than 60 million plants were on average planted annually (Climate and Pollution Agency, 2011b). These investments have lead to an increase in annual growth. And most importantly, the rather stable harvest (about 10 million m^3 per year) well below growth during the last 60 years has resulted in a steady increase in standing stock.

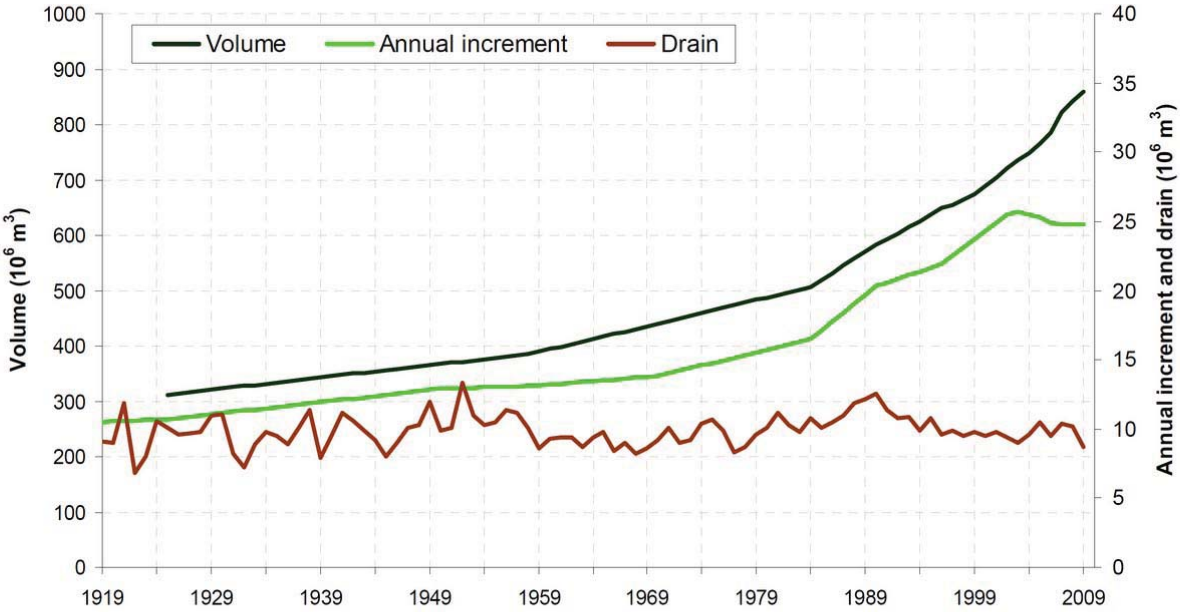

Figure 2. Development of standing stock (volume), annual growth and harvested volume (drain) in Norwegian forests. Data from Statistics Norway (2011)

The net increase in forest carbon storage in 2009 is estimated to be 7.5 Tg C (27.6 million tonnes CO_2) of which about 1,3 Tg C (4.6 million tonnes CO_2) comes from increased carbon stock in forest soils (Climate and Pollution Agency, 2011b). Thus, roughly 50% of the current total Norwegian GHG emissions are sequestered in the forest system.

As will briefly be discussed below, annual tree growth is at its peak at an age in the interval 50 – 90 years (depending on the productivity). Given the age structure of the Norwegian forests, this means that gross growth will decrease. If harvests are held constant – e.g. at the current level – stock will grow at a slower pace, see e.g. Climate and Pollution Agency (2010).

In the figure above, we see that the annual growth has been roughly 2 – 2.5 times the harvest the last couple of decades. However, it is important to bear in mind that the annual growth does not represent the potential for harvest. Maximum non-decreasing harvest has been estimated to be in the range 12 – 15 million m^3 per year, see e.g. Vennesland et al. (2006).

Carbon in tree biomass (stems, branches, roots, etc)

Above we have considered biomass in trees as one homogenous pool, but biomass is distributed in different parts of trees. Stems, i.e. timber, normally constitute roughly 50% of total biomass of trees. Other parts of the tree have traditionally not been harvested, but are to an increasing degree harvested in the Nordic countries. In Sweden and Finland this is an established industry, but in Norway the use of harvest residues is limited. Utilization of different parts of trees will affect the carbon balance in two ways. Increased removal of biomass will reduce the amount stored in forest, but at the same time increased utilization of forest biomass may reduce the emission of fossil carbon through substitution. Therefore, we will take a look at the distribution of biomass and to what degree biomass may be removed from the forest.

Figure 3 shows the distribution of biomass in ton dry matter per hectare for Norway spruce (1 ton d.m. is equivalent to about 1.8 ton CO_2).

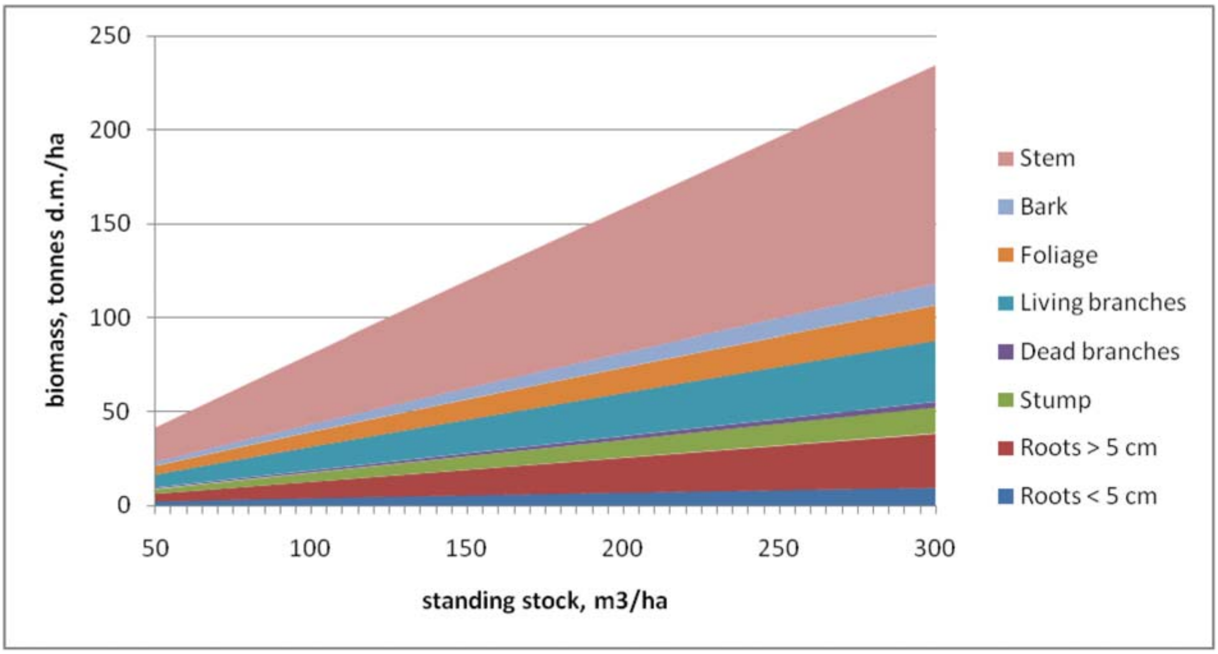

Figure 3. Biomass development in Norway spruce as a function of forest volume (standing stock). Calculations are based on Lehtonen et al. (2004).

The other main forest tree species show similar distributions, but the total level of biomass is lower. According to Gjølsjø & Hobbelstad (2009) the average shares of total tree biomass for the main species are: branches 15%, foliage 5%, bark 5%, stem 53%, stump 6% and roots 14%.

In "normal" harvest operations in Norway about 90% of the stem volume is removed in a spruce stand. Thus, about 60% of the tree biomass is left in the forest. If 60% of these harvest residues (tops, branches and logs not suitable for industrial processing) are also harvested, about 65% of the biomass will be removed. It is probably technically possible to remove more than 80% of the biomass in trees. However, this will be expensive and is not likely to happen.

Biomass decay

Dead biomass – for example harvest residues – will be exposed to natural, biological processes and decay over time. The carbon that was captured in the biomass will again end up in the atmosphere – mainly in the form of CO_2. The speed of these processes depend on micro climate and properties of the biomass (e.g. size of tree parts and chemical composition) (Næsset, 1999). The availability of water is important for the processes. Under anaerobic conditions the main output is methane (CH_4). This is a more potent GHG than CO_2. However, it is unlikely that a substantial share of the biomass is decomposed under anaerobic conditions.

A literature study of decay rates was conducted in the early 1990s at UMB (Lunnan et al., 1991). The main objective was to find the time until 90% of the biomass was decayed. The following intervals were found: for wood (branches, stumps, etc) 75 – 150 years and for foliage and roots 8 – 15 years. If we assume a constant decay rate, i.e. a constant share of the remaining biomass is decomposed each year, the corresponding rates are 1.5 – 3% for wood and 14 – 25% for foliage and roots. Næsset (1999) found an average decay rate of spruce logs of 3.3%.

Figure 4 shows estimated decay rates represented as remaining biomass for branches and stumps of different diameters. As can be seen from the figure, decay rate reduces as the diameter of the wood part increases.

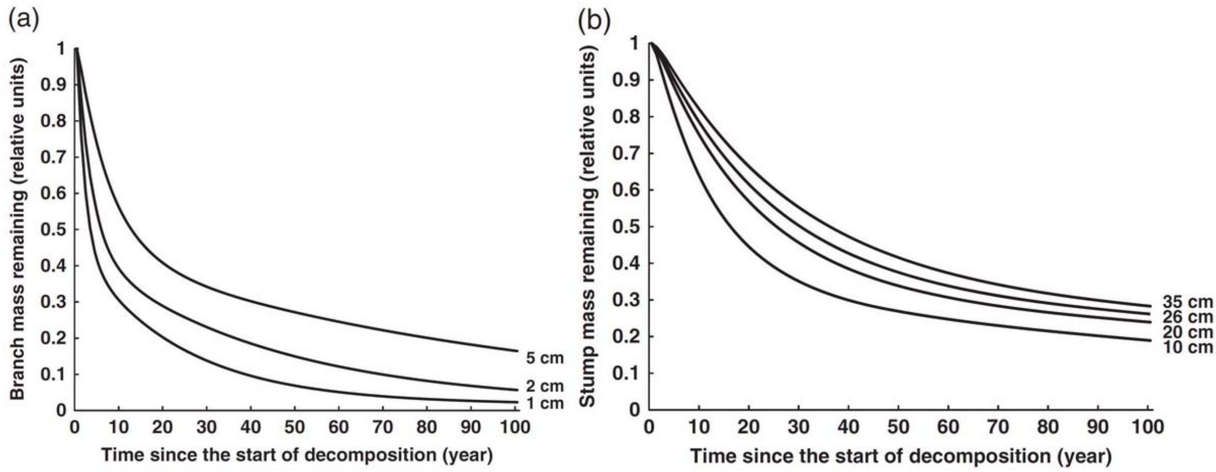

Figure 4. Mass remaining of decomposing Norway spruce branches (diameter 1–5 cm) and stumps (diameter 10–35 cm) over a 100-year period after the start of decomposition. Source: Repo et al. (2011).

Utilization of dead biomass – for example harvest residues – implies a shift in time of carbon emission. If wood is used for energy purposes, all carbon is emitted during combustion instead of decaying over time. Utilization of harvest residues may give a net reduction in climate gas emissions within 15 – 25 years (Climate and Pollution Agency, 2011a) depending on the assumed substitution effect and biomass decay rate.

2.3 Carbon sequestration in soil in boreal forests

Carbon sequestration in soil in boreal forests

Soil holds carbon in the form of organic matter (soil organic carbon, SOC). Carbon input to soils mainly happens through litter fall from plants, either by natural senescence, mechanical forcing such as wind and fire or by plant infestation such as insects or plant diseases. It is believed that litter from root turnover is more important than that from aboveground turnover (Lorenz & Lal, 2010). In general, litter fall deposition declines with increasing latitude and is thus smaller in boreal than tropical forests. However, the same pattern exists for decomposition and in general soil carbon content increases with decreasing temperature (Post et al., 1982), implying that boreal forests will hold more soil carbon than temperate and tropical forests.

The formation and stabilization of the carbon pool in soil is a long term process, taking hundreds and even thousands of years. Accumulation of carbon in soils is believed to continue also at late successional stages in forests (cf. e.g., Zhou et al., 2006; Sebastiaan Luyssaert et al., 2008). Organic matter is normally concentrated to the upper soil layers, with some 50% of total SOC down to 1 m depth being concentrated in the upper 20 cm (Jobbágy & Jackson, 2000). The first meter soil contains approximately 66% of the total carbon pool down to 3 m depth (Jobbágy & Jackson, 2000:430).

The boreal forest biome (950 to 1570 million hectares) contains approximately 78-143 Pg C in the vegetation layer and 338 Pg C in soils (to 1m depth). The temperate forest biome (920 to 1600 million hectares) contains some 73-159 Pg C in the vegetation layer and 153-195 Pg C in soils (to 1m depth), while tropical forests (1450 to 2200 million hectares) is estimated to have 206-389 Pg C in the vegetation layer and 214-435Pg C in soils (to 1m depth) (Lorenz & Lal, 2010). Thus, except for tropical forests, most carbon is stored in soils.

Luyssaert et a.l (2008) estimate that boreal and temperate forests which are 200 years old and above sequester on average 2.4 ± 0.8 t C/ha/yr, distributed on 0.4 ± 0.1 t C/ha/yr in stem biomass, 0.7 ± 0.2 t C/ha/yr in coarse woody debris and 1.3 ± 0.8 t C/ha/yr in roots and soil organic matter. According to Luyssaert et al. (2010), the net primary production (NPP) of forests within the European Union is 520 ± 75 g C/m^2/yr over a forest area of 1.32 to 1.55*10^6 km^2 (EU-25). The corresponding carbon sink is 75 ± 20 g C/m^2/yr. They further suggest that 29 ± 15% of the NBP (i.e., 22 g C/m^2/yr) is sequestered in the forest soil.

In Norway, the organic soil carbon pool in forests is estimated to 77 % of the total forest carbon pool (Grønlund et al., 2010). The total carbon pool in forests is estimated to 2 Gt C, of which approximately 1.55 Gt C is in soils. Eldhuset & Nilsen (2005) found that the amount of carbon in forest soil at Nordmoen varied from 80 to 140 Mg C/ha – with the smallest amount in 30 year old stands and largest in 120 year old forest. Strand and de Wit (2006) estimated an average of 140 Mg C/ha in mineral forest soils down to 1 m depth based on a soil inventory including 1000 soil profiles from the whole of Norway. Obviously there are large variations in such stocks dependent on the soil type, but these figures give an indication of the level in Norway. Eldhuset & Nilsen (2005) indicated that total amount of carbon in Norwegian forest varies from 200 to 400 Mg C/ha.

Although annual rates of change in the soil carbon pool are small, potential CO_2 emissions from soil may be large and are thus important in the climate system.

Carbon sequestration in soil under forest management

In addition to removing living, and possibly dead, biomass from the forest, harvest operations will affect the remaining carbon pools of the forest ecosystem. When aboveground biomass is removed, an important source of litter fall is removed and thus stops further supply of organic matter to the soil. Harvest operations also lead to altered soil climate by allowing greater light filtration, thus influencing microbial activity and CO_2 release (Bekele et al., 2007). Furthermore, harvesting leads to increased physical mixing processes that break down aggregates containing carbon, which promotes the biodegradation and consequent loss of SOC through respiration (Besnard et al., 1996; Balesdent et al., 2000).

The overall effect on soil carbon pools is uncertain, but attempts have been made at quantification. Following Covington (1981), who analyzed carbon storage in the forest floor mass, it is generally believed that an initial decrease in stand carbon follows harvesting. In Figure 5, the Covington curve is compared with results from Diochon et al. (2009), who found that post-harvest soil carbon storage (in Red spruce stands) was significantly lower than pre-harvest before returning to the original level after approximately one rotation. Norris et al. (2009) found the same pattern for jack pine.

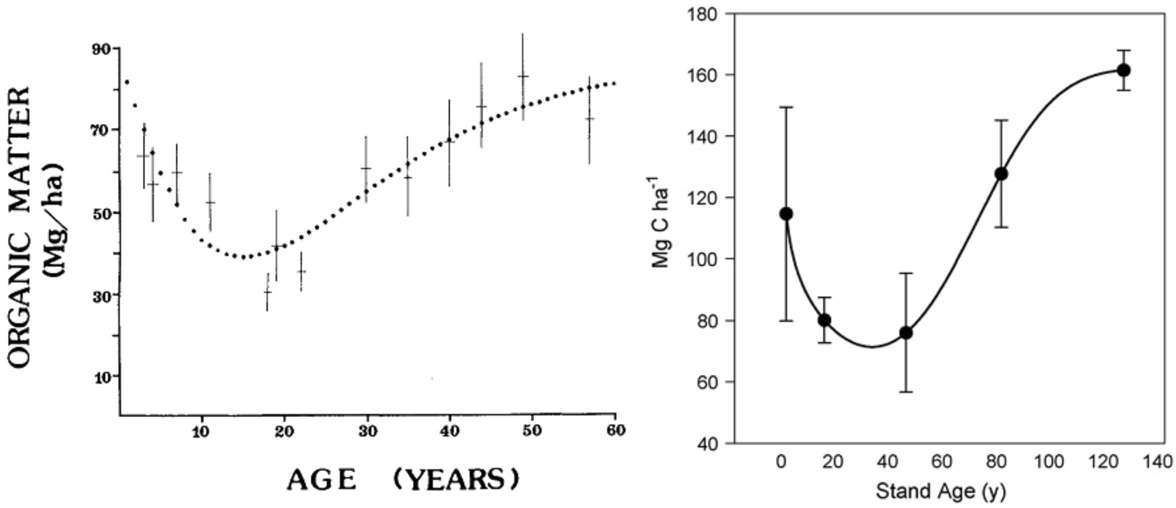

Figure 5. The Covington curve (Covington, 1981) in the left panel and similar curve from Diochon et al. (2009) in the right panel. Both curves show carbon storage as a function of time after harvest.

Zummo and Friedland (2011) showed that the depletion in soil organic carbon after harvest operations increases with the level of disturbance, while Chatterjee et al. (2009) found no differences in soil carbon pools between unmanaged and managed stands of ponderosa and lodgepole pine.

In a northern hardwood forest, YASSO and Century models predict a 5-6% long term (several rotations) decrease in soil carbon as an effect of subsequent stand rotations with harvesting (90 year rotations and 40% biomass removal), with the decrease in soil organic carbon (SOC) increasing with shortened rotations and increased biomass removal (Johnson et al., 2010). This is verified by measurements in both Red pine and Northern hardwood stands in the US, where stands undergone different thinning treatments were all found to have less soil carbon than unmanaged stands (Powers et al., 2011).

However, as Yanai et al. (2003) points out, the Covington curve has been extrapolated and too widely applied and they could not find support for the Covington curve in their modeling efforts.

Meta-analysis of the literature covering effects of forest management on soil carbon and nitrogen storage shows that forest harvesting has no overall effect on carbon storage in soils, but there seems to be effects of harvesting method with sawlog harvesting causing significant increases in soil C and N and whole-tree harvesting causing slight decreases (Johnson & Curtis, 2001:231).

In a meta-analysis, Nave et al. (2010) conclude that in temperate forests harvesting has short-term negative effects on soil carbon pools in the forest floor, while carbon pools in mineral soils seem unaffected. Coniferous/mixed stands experienced less change than hardwood stands.

3. DIRECT GHG EFFECTS OF FOREST MANAGEMENT STRATEGIES

3.1 Timber harvesting and forest carbon dynamics - the single stand perspective

In order to analyze the effects of different strategies in forestry, we need to go beyond the static perspectives described in Chapter 2. In the following section, we use the same point of departure as in Climate and Pollution Agency (2011a): a typical Norway spruce stand (G14) where timber is harvested at age 90 and regenerated with normal plant density. For simplicity we only consider biomass in the two broad carbon pools soil and trees (including all parts). The development in stored biomass (measured in terms of ton CO_2/ha) in soil and trees are shown in Figure 6.

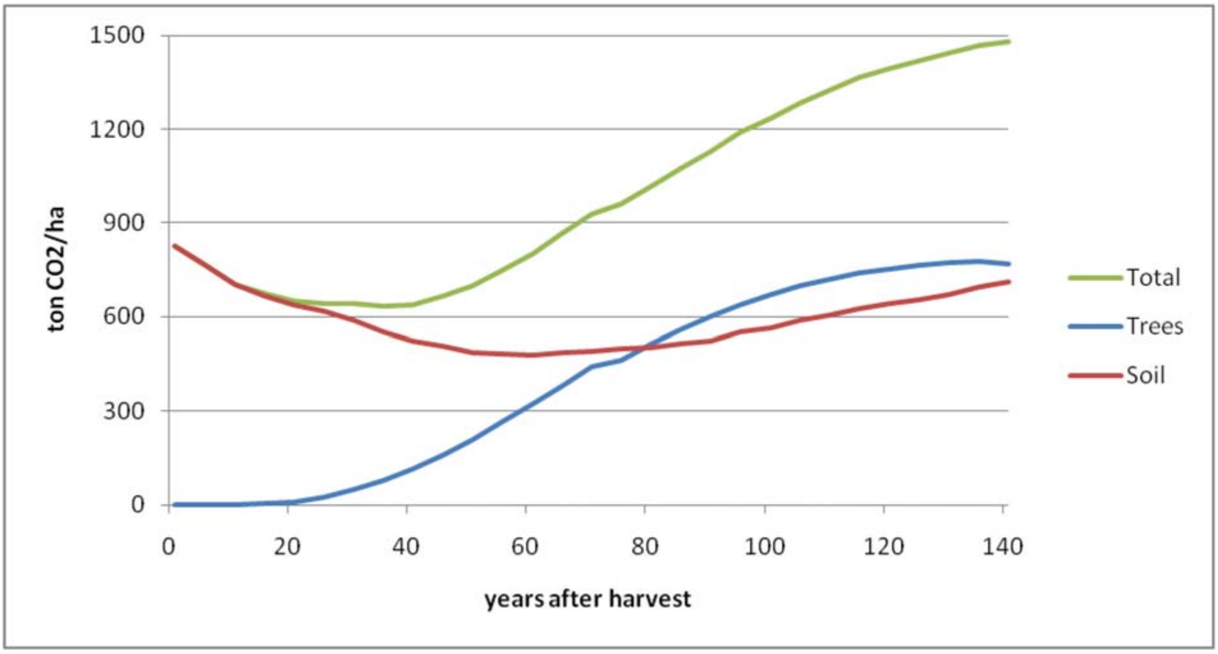

Figure 6. Development of biomass in a typical Norwegian Norway spruce stand (site index 14) after harvest of previous stand at age 90. Source: Climate and Pollution Agency (2011a) and Astrup (pers. comm.).

In the model above, harvest residues (i.e. tops, branches, stumps, roots and stem parts not suitable for industrial purposes) are assumed transferred to the soil pool at the time of harvest. This biomass starts to decay and thus release carbon to the atmosphere. Harvest also affects soil processes by changing radiation, water balance, temperature, etc. This speeds up the decay of organic matter in the soil. For a period of about 70 years, decay is larger than litter accumulation. The level of carbon in soil reaches pre-harvest levels during the rotation (90 years) if we use the carbon storage just before harvest – i.e. without harvest residues – as a reference.

The development over time for biomass in trees shows a sigmoid shape. As there is considerable uncertainty about the development in old forests, we have restricted the analysis to 140 years. The model used indicates a maximum at an age of about 135 years. The sigmoid shape means that the annual growth is low in the beginning, increases up to the point of inflexion (here about 75 years) and thereafter reduces.

The total post harvest biomass will decrease for a period of time. This is due to the rather large decay of harvest residues and carbon in the soil and the low rate of tree growth. After a period of time tree growth will be larger than soil decay and there will be a net accumulation of carbon in the forest. In the example above this happens after about 30 years. At the age of 90, total biomass is back at the pre-harvest level (the starting point of the green curve in the figure plus biomass removed by harvest).

Tree growth and processes in the soil are affected by a large number of external factors including climate, topography, hydrological conditions, nutrient status in the soil, and so on. Development over time and the level of biomass in different pools will therefore vary between stands and even within stands. Differences in tree growth is captured in the site index system (forest stratification system), where stands are classified according to productivity by means of the age and average height of the 10 tallest trees per ha, e.g. G14 for the spruce stand used as an example here. There are also of course differences between species regarding growth rates and production potentials. There is probably a positive correlation between tree growth and the speed of the processes in the soil. It is outside the scope of this report to give a detailed description of these issues, but we will give some general comments with respect to site index. As the site index increases, potential tree biomass storage increases and the potential will be reach at a lower stand age. For soil storage, the minimum will be reached in a shorter time, and the reduction (in absolute terms) will possibly be larger, but this will depend on tree growth as explained above.

As shown, harvest is followed by emissions of GHGs over a period of time. The net effect of harvest on GHG emissions depends on the use of timber – i.e. substitution effects and carbon storage in final products. Substitution effects are discussed later in this report. In very few cases the use of forest products will lead to lower initial emissions. On the other hand, the carbon balance is restored over a rotation as shown above, and thus, in the long run there will be a positive climate effect due to substitution effects.

Utilization of excess and remaining biomass, i.e. harvest residues, for energy purposes, has a much shorter carbon debt payback time than the main assortments from harvest (Rørstad, 2010; Repo et al., 2011).

3.2 Timber harvesting and forest carbon dynamics - the total forest perspective

The total forest perspective is in principle not different from the single stand perspective since the totality is described by summing up the individual stands. Still, it is the totality that matters and some issues are best understood when using this perspective. One such issue, over which there has been a debate also in Norway (e.g. Holtsmark, 2011), is the effects of a permanent increase in the annual harvest level.

As mentioned, the annual harvest has been remarkably stable over the last century – about 10 million m^3. This is well below both current growth and estimated maximum sustainable harvest. Thus, there is room for increasing harvest without reducing the stock of wood or biomass. Increased harvest will have both short and long terms effects on carbon stocks, emissions and sequestration of carbon, and especially on their rate of change.

Increased harvest will lead to increased direct emissions even though some will be offset by substitution. This effect depends on how the timber is utilized and what it substitutes. Permanently increased harvest will lead to a lower carbon stock in the forest compared to the current situation. This is mainly due to that a larger area has to be harvested. However, increased harvests combined with increased silvicultural investments may still imply higher carbon stocks in the long run than the under present forest management. How large the effects are, depend primarily on the current age structure of the forest, the harvest level and silvicultural investments.

A further complication is that the lack of knowledge regarding stand development (growth rates, tree mortality, stability etc.) for ages above 100-180 years. Presently, the harvest age is increasing, , i.e. the average age of trees is increasing. Due to the lack of knowledge it is hard to predict the development of the Norwegian forests over the next centuries. Still, it is likely that increased harvest will reduce the net rate of biomass accumulation in Norwegian forests in the foreseeable future.

3.3 Carbon flows from other forestry activities

Replanting

Forest owners are required by law to establish a minimum number of trees per hectare after harvest; regeneration may be in the form of planting or by natural regeneration. If rapid sequestration of carbon is a primary objective, it may be beneficial to regenerate clearfellings of conifers with pioneer broadleaved species like birch or aspen since they accumulate more biomass in the short run. This regeneration may take place naturally without any silvicultural investments, but may be speeded up through scarification of the humus layer. The latter may increase GHG emissions from the soil, however. In much of Norwegian forests a natural succession of spruce will follow the initial regeneration of broadleaved species. This will maintain the accumulation of biomass and continue sequestration of CO_2. According to the Climate and Pollution Agency (2010), 40% of the forest area under regeneration in Norway has under-optimal plant density. The number of seedlings planted in Norway has dropped from 62 millions in 1991 to 20 millions in 2010 (Statistics Norway, 2011). Planting more seedlings per hectare and using fast-growing provenances may enhance the carbon sequestration. The Climate and Pollution Agency (2010) found that increasing the planting density may lead to accumulated carbon uptake of 70 million tonnes over the next 100 years, or 2 million tonnes/yr after about 100 years. Furthermore, rising the share of the planted seedlings having improved genetic material from today's 60% to 100% may increase the national carbon uptake with further 1.4 million tonnes CO_2/yr after 100 years. We are, however, not sure that natural regeneration of broadleaved trees and other vegetation in between planted spruce have been accounted for in these calculations.

Fertilizing

Nitrogen is a naturally limiting growth factor in much of the boreal forests, and fertilization may increase the growth considerably in many Norwegian forest stands. Fertilization is mainly of interest in old stands due to the growth response as well as practical and economic considerations. A review of fertilization experiments in Norway (Nilsen, 1999) and Sweden (Nohrstedt, 2001) reveals an increased growth of 1-2 m^3/ha/yr in 6-10 years after fertilization of 150 kg N/ha in old forest.

Except for harvest reduction, fertilization is the forestry measure with the highest carbon sequestration effect the next ten years. By fertilizing 1% of the best suited area every year (about 0.02% of the national forest area), carbon sequestration at the national level may be increased by 0.45 million tonnes CO_2/year (Climate and Pollution Agency, 2010).

Fertilization may result in higher timber dimensions and thus impact the utilization of the wood through the sawlog share. This effect is not included in the above-mentioned studies, but will probably not have a large effect on the results. Several studies suggest (Hoen and Solberg, 1994; Climate and Pollution Agency, 2010; Skogbrukets kursinstitutt, 2005) that even without the carbon sequestration values, fertilization of old forest may have a high internal rate of return, due to increased growth in diameter and height and reduced logging costs (Skogbrukets kursinstitutt, 2005). Hoen and Solberg (1994) found that when the CO_2 values were disregarded and the monetary net present value was maximized, the prescribed area for fertilization in Buskerud County was about 2,000 times larger than the actual area undergoing fertilization in the 1980s. Nitrogen fertilization of forest may possibly impact the local flora, but neither in the Norwegian (Nilsen, 1999) nor in the Swedish (Nordstedt, 2001) literature reviews were changes in species number or composition found under normal fertilization regimes (up to four repeated dosages in the Swedish case). The Swedish study reveals however long-lasting reduction in lichens due to nitrogen fertilization. According to the Swedish review, regular nitrogen fertilization dosages have no significant impacts on water or soil acidification. Leaching of nitrogen from fertilized soil to water was reported in Sweden, but not in the Norwegian review under normal dosages. However, the literature basis is small as few long-term studies of leaching exist.

The forest area fertilized in Norway is currently very low, 2006 figures showed an annual number of around 500 hectares (Statistics Norway, 2011).

Thinning

About 13% of the harvested volume in 2007 was from thinning (StatBank Norway, 2011).Thinning is carried out in dense stands which have reached 50-80% of the maximum height, but still grow vigorously. The objective of thinning vary from increasing the stand value in the final harvest (leaving trees with potential high values in the future), to providing income before final harvest. However, thinning reduces carbon sequestration in the years after thinning because of reduced growth. In addition, timber extracted at such an early age has low sawlog share. Consequently, timber from thinning has a low potential for carbon storage and thus low substitution effects. On the other hand, reduced thinning may also lead to increased mortality in stands and lower timber quality in the final harvest. Several modeling studies have found thinning to be less profitable when carbon sequestration has a value. In a study of Hedmark county, Raymer et al. (2009) found that the area to undergo thinning was reduced by about two-thirds when the net present carbon value was maximized, as compared to maximization of net present monetary value. In a study of carbon sequestration at the national level in Norway, Sjølie et al. (2011) found that in the presence of a carbon price of 800 NOK/ton CO_2eq, thinning was reduced by 15-85% compared to zero carbon price. Climate and Pollution Agency (2010) analyzed potentials and costs for increasing thinning to supply bioenergy raw materials. However, reduced carbon sequestration from increased thinning was not considered, only utilization of biomass from thinning which is not used today.

Other forest operations

About 30,000 hectares undergo pre-commercial thinning in Norway annually (Statistics Norway, 2011). In this operation, which takes place in young stands, a share of the trees are cut and usually left on the ground to decay in order to improve the growth of the remaining trees. Hoen & Solberg (1994) found that the pre-commercial thinning area declined with increasing CO_2 value, due to the reduced carbon sequestration in the period after operation. Using the same forest growth model, but other carbon data and assumptions, Raymer et al. (2009) concluded that the area of pre-commercial thinning declined by 85% when changing from maximizing net present monetary values to maximizing net present carbon values. However, reduced pre-commercial thinning may also lead to lower sawlog share in harvests due to smaller trees and overall lower quality and thus impact the utilization and substitution effect of the timber. Activities like ditching and soil scarification have been reduced significantly in Norway the last 20 years. Ditching is reduced to almost zero and soil scarification is reduced from 8,494 hectares in 1999 to 4,322 hectares in 2010 (Statistics Norway, 2011).

Afforestation

Afforestation, planting of areas which currently are not covered with productive forest, is a much studied measure for climate change mitigation. The most interesting afforestation areas in Norway are situated at fjord sides on the west coast, where the natural forest consist of deciduous and pine trees having much lower growth rates than Norway spruce and Sitka spruce. Whereas Norway spruce is native to Norway, however not in most coastal areas, Sitka spruce is native to the northwest coast of North America.

Switching from native deciduous forest to spruce results in large productivity improvement and thus increased carbon sequestration. While deciduous forest may produce up to 2-10 m^3/ha/yr, the productivity in Norway spruce and Sitka spruce stands may reach 10-20 m^3/ha/yr on the west coast (Øyen et al., 2008).

Several analyses have quantified the carbon benefits of afforesting large areas on the west coast with Norway spruce and Sitka spruce (Climate and Pollution Agency, 2010; Skjelvik and Vennemo, 2011). The Climate and Pollution Agency (2010) concluded that planting totally 0.1 million hectares with Norway spruce in a 20-year period will materialize in about 100 million tonnes CO_2 sequestrated totally over 50 years. According to Skjelvik & Vennemo (2011), planting of Sitka spruce on an area of 0.1 million hectare could provide carbon sequestration of 90-120 million tonnes CO_2 over 60 years. Both studies conclude this measure to be profitable also when disregarding the carbon benefits.

Afforestation with Norway spruce on the west coast started in the 1950s, but is today reduced considerably. The number of planted seedlings has declined by 85% from 1971 to 2010 in the six counties stretching from Rogaland to Nord-Trøndelag (StatBank Norway, 2011). The total number of planted seedlings in Norway is reduced from 62 millionion in 1991 to 20 million in 2010 (Statistics Norway, 2011).

4. GHG EMISSION IMPACTS OF THE USE OF FOREST BIOMASS

Several output streams such as sawlogs, pulpwood, energy wood and harvest residues are produced simultaneously during harvest. To assess the GHG impacts of the use of wood, all streams have to be considered. Carbon stored in the wood is emitted during combustion or decay, the carbon storage in wood products depends thus on the wood content and the time the wood products can be expected to be in use, the so-called anthropogenic lifetime. Due to the short anthropogenic lifetime of paper products and bioenergy carriers, only the carbon storage in solid wood products (sawn wood and board) is of practical interest.

The following section reports on utilization of biomass in Norway today, and empirical findings regarding carbon storage, GHG emissions and substitution possibilities by the use of wood products.

4.1 Forest biomass utilization in Norway

Annual national harvest of roundwood (sawlogs and pulpwood) for sale varied between 6.6 and 8.2 million m^3 in the years 2006-2010 (Statbank Norway, 2011). 46-53% were sawlogs and the remainder pulpwood, mostly purchased by pulp, paper and board industries. In addition to the 8.2 million m^3 roundwood harvested in 2010, net import amounted to about 400,000 m^3, mostly consisting of coniferous pulpwood (Figure 7). Sweden is the main supplier of roundwood to Norway. In addition to the above-mentioned harvest levels, 2-3 million m^3 of wood which do not appear in the statistics is harvested for firewood (Trømborg and Sjølie, 2011; StatBank Norway, 2011). There is an increasing production of wood chips not stemming from regular harvest operations for energy production which are not included in the figures above. According to the Norwegian Agricultural Authority (2011) – who administer a support scheme for such wood chips – about 0.2 million m^3 (solid) chips were produced in 2010. This is almost a doubling from 2009. However, only a small share (10- 15%) is from traditional forest operations (i.e., harvest residues). The major share of the chips is from maintenance of the cultural landscape.

An average lumber yield of about 52% in the largest sawmills (Trømborg & Sjølie 2011) implies that out of one cubic meter of harvested logs, about 0.25 m^3 ends up as sawn wood. The remaining parts of the sawlog (off-cuts, chips, shavings and dust) as well as the bark is used for sawn wood drying or sold to other industries. Pulp and paper industries are large purchasers of chips, while the board industries buy mostly dust and shavings. Bioenergy producers buy all these byproducts.

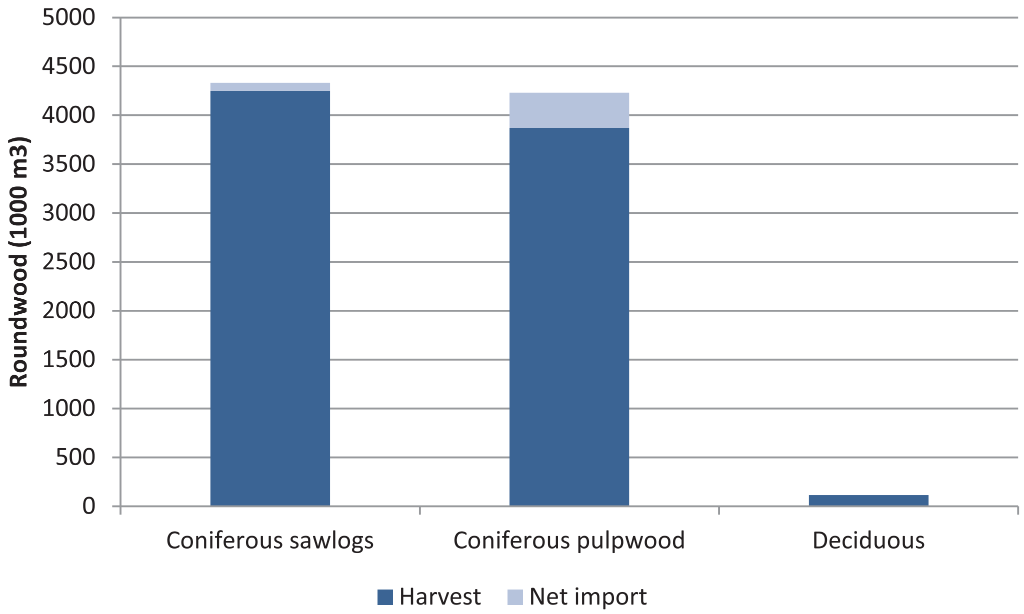

Figure 7: Available roundwood in the Norwegian market in 2010. 1000 m³. Source: Statbank Norway, 2011.

According to Rødland (2009), 2.4 million m^3 sawn wood was produced in 2006 with net imports totaling 0.6 million m^3 and domestic consumption thus amounting to almost 3 million m^3. The anthropogenic lifetime depends on the utilization (Table 1). Plywood and composites have shorter anthropogenic lifetimes than most sawn wood products; consumption of plywood and composites added up to about 575,000 m^3 in 2006. Due to the general landfill ban of organic waste in Norway (Lovdata, 2011), decay rates of wood products are not included.

Table 1: Consumption of sawn wood to different purposes and of plywood and composites in 2006 (m^3) and antroprogen lifetime (years). Consumption numbers from Rødland (2009). Antropogen lifetime and GHG emissions with one asterisk from Hoen & Solberg (1994), two asterisks from Wærp et al. (2009), three asterisks from Rivela et al. (2006) and four asterisks from Rivela et al. (2007).

Purpose	Domestic consumption 2006 (m^3)	Anthropogenic lifetime (years)	Lifecycle GHG emissions (kg CO_2eq/m^3)
Sawn wood for roof truss	145,000	60*	29**
Sawn wood to laminated wood	45,000	60**-100**	79**
Sawn wood for new constructions of residential and non-residential buildings	750,000	50**-80*	6**-29**
Sawn wood for renewal, rebuilding and extensions	1, 000,000	50**-80*	6**-29**
Sawn wood for woodwork and furniture	600,000	20*	
Sawn wood for constructions, packing, transport etc.	420,000		
Sum consumption sawn wood	**2, 960,000**		
Consumption plywood and composites	**575,000**	17*	59***-216****

4.2 Substitution effects of wood biomass use

The common method in assessments of the environmental impacts of using woody biomass is life cycle assessment (LCA). LCA aspires to include all inputs of the products' lifecycle, from cradle to grave. In this approach, not only factual data inputs determine the outcome of a comparison, but several methodological assumptions play an important role for the reported results. Different studies differ in their underlying assumptions and system completeness, and results can vary considerably between studies of the same product chain.

Most studies addressing replacement effects assume that for each additional unit of wood product consumed, one unit of another material or fuel fulfilling the same need is replaced. However, it is highly uncertain if there is actually such a one-to-one replacement. Lack of empirical data is a major obstacle for accurate assessments. In general, it can be argued that subsidies may result in higher total consumption as they lower the product prices to the consumers, thereby violating the one-to-one assumption (Sjølie et al., 2010). Sathre & O'Connor (2010) estimated the GHG displacement factors of wood product substitution in a meta-analysis. They found that when the wood is used for different material applications, such as buildings, poles, flooring etc., the emission is on average reduced by 3.9 ton CO_2eq/ton of dry wood

Wood for energy

Increased use of forest-based bioenergy is internationally considered an important climate change mitigation measure, but the economic potentials and associated costs are uncertain (Sims et al., 2007).. Bolkesjø et al. (2006) and Trømborg et al. (2007) found the economic potential of bioenergy in district heating and central heating installations in Norway to be relatively large, with only small increases in energy prices or subsidies.

Heat and power

Producing heat from woody biomass is an energy-efficient way to use the biomass. But while little energy is lost in conversion, heat has few applications. Pure electricity production from biomass (bioelectricity) has poorer energy efficiency in the production process, but more applications. CHP (combined heat and power) technology has high energy efficiency (up to 90% dependent of scale and feedstock). In the long run, biomass CHP with carbon capture and storage is an interesting solution that imply negative net GHG emissions.

A number of studies have investigated the GHG impacts of increased use of forest-based bioenergy. Energy for heating is often divided between space heating systems (electric wall heater, wood stove and pellet stove) and hydronic heating systems (central heating and district heating) which may be fed with a range of energy carriers. For instance pellets in central heating installations may be assumed to replace domestic heating oil used in the same installations as few technical changes are necessary. In space heating, firewood may be assumed to replace electricity. The origin of electricity replaced if bioenergy use increases depends on the supply-demand balance in the power market. Wærp et al. (2009) used the electricity mix consumed in Norway (96% domestic) as input to wood processing, while Sjølie et al. (2010) argued that due to higher marginal costs of coal power than hydropower, coal power may be assumed replaced by bioenergy. Capacity limits on the electricity grids may however limit the possibilities of substituting coal power.

Assessment of the market clearing prices since the deregulation of the Nordic electricity market in 1996 shows that Nordic and Norwegian power prices has cleared close to the short term marginal cost of coal power generation for a large portion of the time, indicating that coal power will often be replaced if more renewable energy is introduced. In very wet periods and periods with low consumption, however, other technologies such as nuclear power or even run-of-the-river hydropower are on the margin (Thema, 2011). Holttinen & Tuhkanen (2004) simulated the production mix in the Nordic power market in 2010 for different wind power generation scenarios. In a scenario assuming 12.5 TWhnew wind power generation, coal power generation is reduced by 8.5 TWh/a (68% of the wind power increase), gas power generation is reduced by 1.8 TWh/a (14%), oil power generation by 1,4 TWh/a (11%) and finally peat power generation is reduced by 0,2 TWh/a (2%). Overall, there is rather strong evidence that when bioenergy replaces electricity, a large share of reduced electricity generation would be from technologies based on fossil fuels, in particular coal. It should be added though, that the Nordic power generation capacity mix is expected to change in the coming years towards a larger share of renewables like hydro power, wind power and bioenergy CHP plants, and a lower share of coal power plants. This development would affect the substitution effect of using bioenergy.

Table 2: Net effect of substituting various fossil fuels for heat production with woody bioheat. Net effect of substitution = Lifecycle GHG emissions replaced product - Lifecycle GHG emissions replacing product. Numbers for bioenergy are from Sjølie et al. (2009). * Numbers are from Solli et al. (2009).

Wood energy and technology	Replaced product and technology	Net effect of substitution (g $CO_2eq/kWh_{low)}$ (given CO_2 neutrality of biomass combustion	Relative GHG emissions reduction
Fire wood in wood stove	Electric wall heater (coal)	758	94%
Fire wood in wood stoves	Electric heat (Nordic Electricity mix)	100-130*	43-56%
Pellets in stove	Paraffin in stove	318	96%
Pellets in central heating systems	Domestic heating oil in central heating systems	302	95%
Chips in district heating systems	Domestic heating oil in central heating systems	301	95%

Biofuels

According to OECD and the International Transport forum (2007), advanced biofuels such as bioethanol and BTLs can possibly meet 10-20% of current biofuel demand. These fuels can be made from woody biomass, but there are still technical, social, economic and environmental barriers for successful implementation of these (Gnansounou, 2010).

Biofuels from woody biomass is also called second-generation biofuels and is still technologically challenging to produce. At present, low conversion rates (40-45%) of both ethanol and diesel prevent full commercialization of these fuels. The GHG emission estimates for these fuels are therefore only preliminary. A study by Baitz et al. (2004) indicates that GHG impacts can be reduced by 61-91% if driving on woody diesel instead of fossil diesel (timing of CO_2 emissions not considered). Bright and Strømman (2009) assessed the GHG emission reductions by replacing gasoline with forest-based ethanol in Norway, reporting emission reductions of 46-68%.

Sawn wood products

Wood can replace carbon intensive materials such as metals, concrete and plastic materials. As the carbon storage is retained in such products, the net substitution effect is in most cases clearly positive. Petersen & Solberg (2005) found by reviewing Norwegian and Swedish life cycle assessments (LCA) and substitution effects between wood and alternative materials that when wood replaces steel, 36-530 kg CO_2eq emissions are saved for each m^3 timber input, while the corresponding number for concrete replacement is 93-1,062 kg CO_2eq emissions/m^3 timber. Some average numbers are referred to in Table 3, displaying that replacing steel with wood may reduce the GHG emissions by up to 88%. The relatively large range in GHG emission impacts is due to different system boundaries and assumptions regarding, inter alia, forest carbon sequestration and waste treatment. The large variation in net substitution effects also suggests the importance of assumptions and the difficulty of comparing different LCA results directly.

Table 3: Substitution effects by replacing various materials with sawn wood products. Numbers from Petersen & Solberg (2005) and Kristensen (1999), the latter marked with *.

	Wood product and technology	**Replaced product and technology**	**Net effect of substitution (given CO_2 neutrality of biomass combustion)**	**Substitution unit**	**Relative GHG emission reduction**
Roof beams	Glulam	Steel	250	tonnes CO_2eq/m^3 timber input	88%
Warehouse frames	Glulam	Concrete	299*	tonnes CO_2eq/m^3 timber input	64%

Paper and chemical products

Energy-intensive manufacturing and short lifetime give a mixed picture regarding GHG impacts of pulp- and paper products. The pulp and paper industry produces a range of products where some have no evident substitute, such as toilet paper, newspaper and cardboard. Some of the wood based products are substitutes for oil-based chemicals and plastics with positive substitution effects. (Basak, 2010).

5. TO SINK OR BURN?

5.1 Carbon cycle effects of utilization of the forest resources in Norway

The carbon cycle effects of utilization of forest resources depend on a number of factors described in this report:

- Development of forest biomass if not harvested (growth rate and mortality)
- Development of carbon storage in soils (with no harvest and after harvest)
- Growth rate of new forest stands
- Share of biomass utilized after harvest
- Decomposition rates of not utilized biomass
- Utilization of biomass and substitution effects

Harvest of a forest stand in Norway normally implies reduced capture and storage of carbon in trees and soil for several decades. Chapter 3.1 shows that it may take 90 years before the carbon storage of new forests equals the storage at the time of harvest in a typical Norwegian Norway spruce stand. In forest types with higher growth, this time span will be shorter, and in stands with low site productivity, the payback time may be significantly longer than 90 years. With the current knowledge base, it is difficult to draw general conclusions regarding the long-term effects of forest management on soil carbon pools, as the reported studies have rather diverging conclusions. Both marginal, negative and positive impacts of forest management on the soil carbon were reported by the meta-analyses referred to in chapter 2.3, while widely used soil carbon models predict slightly negative impacts of harvest on soil carbon.

In Norway, about 60% of the biomass in a forest stand is usually left in the forest. A low utilization rate and high residue decomposition rate reduce the GHG effects (including substitution) of harvest compared to maintaining the stand. Utilization of harvest residues implies a shift in the flow of carbon and the time of emissions, as all carbon is emitted immediately instead of over time. Utilization of harvest residues may give a net reduction in GHG emissions after 5 – 15 years depending on assumed substitution effect and biomass decay rate.

The substitution effect of use of biomass depends on the efficiency in biomass conversion and the GHG emissions from the replaced products. The long anthropogenic lifetime of solid wood products and high GHG emission intensity of replaced products like steel and concrete imply positive GHG impacts of solid wood products. The fact that sawn wood products going out of use often are recovered and used for energy add further to the positive GHG effect of sawn wood. The pulp and paper industry produces a wide range of products where some have no evident substitute. Energy-intensive manufacturing and short lifetime of many of the products but positive substitution compared to oil-based chemicals and plastics give a mixed picture regarding GHG impacts of pulpwood. Regarding the use of biomass for energy production, combustion of wood is less energy efficient / more carbon intensive than natural gas and oil, and about as carbon intensive as coal. The combustion efficiency is a decisive factor in the overall carbon account of bioenergy utilization. Old wood stove is an example of technology with low energy efficiency, often less than 50%, whereas combustion in pellets stove has an energy efficiency of about 90%. The replacement of hydropower with bioenergy will lead to increases in the overall GHG emissions, whereas replacement of heating oil and especially coal-based power may lead to emission reduction. Increased transmission of electricity between Norway and the European continent will increase the relevance of coal-based electricity in the GHG accounting in Norway. Increased use of bioenergy in central and district heating will mainly replace oil. However, waterborne bioenergy heating systems may also replace electricity, particularly in new buildings. Foregone sequestration in the existing stand, low share of the biomass being utilized after harvest and slow initial growth of the new stand are factors that indicate a relatively long pay-back time for the carbon debt from increased harvest in Norway. A positive carbon price implies longer rotations for forest stands, the more if foregone sequestration is high, re-growth is slow and substitution effects are low. At a certain point in time a forest stand will however reach a state of slow and eventually negative growth. In this situation, harvest followed by regeneration can improve the GHG balance also in the short run. Increased use of harvest residues have positive GHG effects also in the short run.

Even if rise in the GHG emissions is a likely outcome of increased forest harvest in the short to medium term, use of biomass will reduce GHG emissions in the long run – given that the increased use of biomass actually substitutes products based on fossil fuels or with high GHG emission rates. A central question is hence the relevant time horizon for GHG mitigation efforts. To assess the pros and cons of short term versus long term emissions one need to broaden the scope from pure GHG emission calculations to the entire climate system, including inertias from actual emissions to a long term stabilization of the (global) temperature. There is also a risk that there exist certain threshold levels of climate gases in the atmosphere that trigger accelerating climate change (tipping point). The magnitude of this risk is not known today, but it can be argued that the risk of such effects warrants strong emphasis on reducing GHG emissions in the short term, also from renewable energy sources like woody biomass. However, continuation of a relative low harvest level will in the long run reduce the forests' capacity to sequester carbon and to supply raw materials for renewable solid products and energy. Thus, with the current state of forest and wood product use, there are trade-offs between the use of forests for short-run mitigation and for long-run mitigation and possibilities for renewable energy and material supply. The optimal strategy depends thus upon the climate change scenarios including effects as atmospheric carbon accumulation, tipping points considerations, time preferences and expected technological development. Discounting is a consistent method to weigh GHG fluxes occurring at different points in time which may reflect the aspects described above. Stern et al. (2006), using 1.4 % p.a. as the real discount rate, arguing that climate change is an intergenerational policy issue and a low discount rate should be applied in the analyses. The report has however received critics for the low discount rate, from among others Nordhaus (2007).

5.2 Other impacts of use of forest resources

As shown above, the annual timber harvest in Norway has been relatively stable around 10 million m^3 the last 90 years. Reductions in real timber prices, stable harvest level and high economic growth in many other sectors have resulted in a reduction in the economic importance of forestry and forest industries. The forest sector now constitute about 0.8% of GDP in Norway, a reduction from 2.5% in 1979 (Statistics Norway, 2011). The forest sector is however still of considerable economic importance in certain rural areas.

Net imports account for 20-30% of domestic wood consumption in Norway and changes in the harvest level will most likely affect wood import as there are few barriers to timber and wood product trade in Europe. Thus, possible leakage effects must be considered if implementing policies to change the harvest level in order to mitigate climate change.

Forests are important ecosystems in Norway and changes of management have implications for biodiversity. A range of species are dependent on old forest and decaying trees. Leaving large quantities of forest to decay for biodiversity purposes may however reduce the climate change mitigation effect of the forests.

From a climate change mitigation point of view, the non-GHG effects - of which albedo seems to be the most important - may imply shorter rotations, more mixed or broadleaved forests and less afforestation than what is optimal when only considering carbon.

5.3 Conclusions

The GHG effect contributing to climate change is primarily a result of decades of large scale combustion of fossil fuel, transferring huge amounts of carbon from fossil stocks to CO_2 in the atmosphere (in addition to deforestation). Sustainable use of wood for energy or materials has not caused the climate change, but forests can contribute in climate change mitigation. However, the long rotation period of Norwegian forests causes a so called “carbon debt” when timber is harvested, processed and consumed for various purposes. The trade-off between GHG mitigation efforts in the near future versus the longer term is thus of critical importance in the assessments of the optimal use of forest resources.

Independently of this trade-off, the following conclusions are regarded as rather robust for utilization of the Norwegian forest resources given the existing knowledge of GHG impacts of forest management strategies and the current state of forests and wood product markets in Norway:

- Domestic and imported wood are to a large extent substitutes and changes in the domestic harvest levels can change harvest levels elsewhere. Impacts of global GHG emissions of changes in domestic harvest levels require broader analyses than carried out in this study.

- Higher demand for bioenergy in Norway is likely to be covered by a mix of increased harvest, more harvest residue utilization, shifts from other fiber uses (like pulp, paper and particleboard production) and increased import.

- With the present forest management and wood utilization, increased harvest in Norway as a result of growing demand for biomass in the energy sector, will in the short to medium term cause an increase in the GHG emissions to the atmosphere. If fossil-fuel based commodities are replaced, increased use of wood products will reduce GHG emissions in the long run.

- Utilization of harvest residues can be increased within the current harvest level and have positive GHG effects also in the short run.

- Forest carbon sequestration may be increased by changing forest management practices like more fertilization, higher planting densities and rapid regeneration after harvest, improved plant material, changed species, less thinning and allocation of harvest to stands with current low growth but with potential of higher growth. Except for fertilization and allocation of harvest, these measures have limited carbon sequestration impacts in the short run, but considerable impacts in the medium and long run.

- Harvesting young, fast-growing stands should be avoided from a climate change mitigation perspective.

- Keeping the present harvest level in Norway will result in older forests than today, which in the long run will reduce the forests' carbon sequestration capacity.

- Wood used for sawn wood has normally more positive short term GHG impacts compared to wood used for energy and for paper. To improve the substitution effects of wood products and thus the GHG impacts of harvest, it is important that the wood products actually replace fossil-fuel intensive products and do not come in addition, that the most GHG-intensive fossil fuels and materials are replaced, that the wood product chain has high GHG efficiency including the cascading possibilities of substituting fossil-fuel intensive products several times (e.g. reuse of construction material and paper which then finally is used for energy).

- The understanding of the development of old, dense stands is limited, and thus the carbon effects by keeping such stands far beyond regular forest management practices are very uncertain, in particular for spruce and birch.

- Lastly, but not least, the magnitude of albedo effects is still unknown, but there are studies indicating that it might be of a magnitude that could change the conclusions drawn when considering only GHG.

The GHG impacts of forest management strategies are to a large extent a question of short-run versus long-run considerations. More research regarding the growth and mortality of old forest and substitution effects of wood product use is needed to describe in more detail the GHG effects of different management strategies for the Norwegian forest resources. Efforts to change the national harvest level to mitigate climate change should be coupled with consideration of factors such as economic development, biodiversity and carbon leakage, in addition to short-run versus long-run global warming impacts, including the albedo effects, in order to have the desired outcomes.

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