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Philosophiae Doctor (PhD) Thesis 2011:28

Norwegian University of Life Sciences • Universitetet for miljø- og biovitenskap
Department of Ecology and Natural Resource Management
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ANALYSES OF THE USE OF THE NORWEGIAN FOREST SECTOR IN CLIMATE CHANGE MITIGATION

ANALYSER AV KLIMAGASSTILTAK I DEN NORSKE SKOGSEKTOREN

Hanne Kathrine Sjølie

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PREFACE

This thesis is a partial fulfillment of the requirements for the PhD degree at the Department of Ecology and Natural Resource Management (INA), Norwegian University of Life Sciences (UMB). The project was funded by the University. Generous funding from the "The Forestry Development Foundation" (Utviklingsfondet for skogbruket) for the stay at Oregon State University (OSU) in the period August 2008 - June 2009 is greatly appreciated.

The advisor group was headed by Birger Solberg, and consisted in addition of Erik Trømborg and Maarit Kallio. Birger was the mastermind of the project ideas. With his open-door policy and enthusiasm, he has always had time for inspiring discussions, but at the same time given me valued freedom. Erik and Maarit have both shared ideas and have been important discussion partners. Erik co-authored on Paper I and has given much constructive inputs along the whole way, while I have benefited much from discussions on modeling with Maarit during the last months prior to defense. I would also like to thank Darius Adams at OSU (co-author on Paper II) for receiving me and providing guidance on important modeling issues, and particularly Greg Latta at OSU (co-author on Paper II and IV), without whom this thesis would not have reached the same qualities. Torjus Bolkesjø introduced me to forest sector modeling and co-authored on Paper I, and has also later shared valuable modeling insight. Terje Gobakken taught me about Gaya and co-authored on Paper IV, and of Kåre Hobbelstad, I learned about forest dynamics at the national level. Even Bergseng has been very helpful in solving all Gaya issues promptly and sharing expertise, while Ann Kristin Raymer freely shared data and knowledge about carbon dynamics. Thank you all. Thank you, Arezoo and Åsa, for spreading much laughter and fun in the department, and to Arezoo for inviting me for dinners in long working evenings. I would also like to thank the administrative and technical staff at INA for good assistance.

I am lucky to have a family who has a great interest in discussing topics as economics, forestry and climate change. My father is better informed about these issues than many people who can devote their full time to study them, and my mother has an especially clear eye for science. Last, but most important, I am indebted to my dear Luiz. Your interest and knowledge about science makes you the best discussion partner any PhD student could wish for, but more invaluable, you have given a moral and practical support across oceans and during numerous too long working days that has been marvelous. Mil obrigados.

Ås, April 2011

Hanne K. Sjølie

SUMMARY

The forest sector plays important roles in the global carbon cycle. Firstly, the global carbon storage in forest biomass and soil is of a considerable size, and the total carbon sequestration in the global forests more than offsets the emissions from deforestation and land degradation. Secondly, the forest sector seems to have potentials to further mitigate accumulation of greenhouse gases in the atmosphere and reduce overall mitigation costs. In Norway, the forests sequester more than half of the human-induced greenhouse gas emissions, due to an increment that exceeds the harvests by a large margin. The sequestration rate is projected to decline as investments in forestry have decreased substantially, although the forests will be an important factor in the Norwegian greenhouse gas account also in the future.

The long investment horizon and the long-term carbon impacts of forest management decisions make projection models important in the forest sector. Despite the relatively large number of analyses related to climate change mitigation and economics in this sector, few studies integrate in an economically consistent manner the biological growth and investments in forestry with timber and wood product markets. The trade-offs between extended use of wood products and increased carbon sequestration in forests renders such integrated analyses suitable for obtaining realistic estimates of carbon policy costs, potentials and impacts. This thesis has two main objectives: 1) to develop a bio-economic model of the Norwegian forest sector that links the timber and wood product markets to the biological basis and investments in forestry, and tracks the carbon flow throughout the entire sector, and 2) to study how the Norwegian forest sector can contribute to climate change mitigation. These objectives are addressed in the four papers of the thesis.

A previously developed model of the Norwegian forest sector was used for the study in Paper I, in which the costs and benefits of heating market policies were compared. The two analyzed policies were carbon tax on domestic heating oil and paraffin and investment grants to district heating installations based on forest-based energy. The results indicate that the carbon tax has a large influence on bioenergy production in the analyzed technologies. Bioenergy production based on chips increased considerably when the carbon price rose from 20 to 60 €/tonne CO_2eq. At carbon prices above 80 €/tonne CO_2eq, pellet production expanded. At the highest analyzed tax level, 160 €/tonne CO_2eq, 7.5 TWh heat was produced annually based on these bioenergy carriers. The corresponding greenhouse gas emission reductions equaled 2.3 million tonnes CO_2eq, or 70% of total emissions from heating in Norway. The investment grant was also shown to increase bioenergy production, but had less effects if combined with high carbon taxes.

Paper II is an application of the forest sector model developed as part of this thesis, NorFor. The study addresses the importance of the foresight assumption in forest sector modeling. In most forest sector models, agents are assumed to be either myopic, i.e. to

have no market information beyond the current period, or to have perfect foresight, i.e. to have perfect information regarding all relevant factors for the entire analyzed horizon. In this paper, the impacts of a hypothetical import ban on coniferous timber beginning in 2020 was analyzed, with three degrees of foresight: perfect (the agents had full information), limited (the agents had information a limited time beforehand) and no information beforehand. We found that when anticipating the ban, the forest owners reduced the harvest in the periods prior to the ban in order to save timber for later when the prices increased. The less information available, the more the prices increased. Bioenergy production was significantly reduced to preserve the production of pulp and paper. We found evidence of adaptive behavior in periods before the ban was implemented, though not of a large magnitude, which may be due to short anticipation time and fixed costs in the industry.

In Paper III, the greenhouse gas emission impacts of using wood pellets in coal power plants were analyzed. A sensitivity analysis was carried out to assess the most important factors determining the net effects of substitution, and the carbon neutrality assumption was discussed. The analyzed case study was a recently opened pellet plant in Norway whose production is mainly destined for export to coal power plants in Europe, based on raw materials from Canada. The single most important factor for the greenhouse gas emission impacts was found to be the carbon neutrality assumption. Including all emissions from pellet combustion led to net substitution effects close to zero. Replacing the most emitting fuels was also revealed to be an important factor for reducing greenhouse gas emissions, while many factors in the production chain had only a marginal impact. Due to large market price differences between pellets and coal, the costs of greenhouse gas reduction was found to be approximately 60 €/tonne CO_2eq.

Paper IV is an analysis of the potentials and costs of mitigating climate change in the Norwegian forest sector, in which the NorFor model was applied. Carbon sequestration and avoided greenhouse gas emissions above baseline were analyzed for carbon prices ranging from 100 to 800 NOK/tonne CO_2eq, targeting all major positive and negative fluxes in forestry, transport, processing, consumption and substitution. Two types of market models were analyzed: one endogenous market model, in which mitigation measures could be undertaken throughout the entire sector, and one exogenous market model, in which industrial production, imports and exports were fixed to base scenario levels with no carbon price. Harvests were allowed to vary within the limits of these constraints. We found large differences in potentials and costs between the two market models, with substantially higher potentials and lower costs in the endogenous market model. Furthermore, mitigation measures in the endogenous market model were undertaken for the entire sector. Harvests, particularly thinning, were reduced and planting was intensified, while pulpwood was allocated from pulp and paper production and low-efficiency stoves to high-efficiency waterborne heating systems. Leakage occurred as imports and exports changed 15-25%. According to the results, the potential for reduced greenhouse gas emissions and increased carbon sequestration in the endogenous market model from today to 2055 in the presence of a carbon price of 800

NOK/CO_2eq was more than 7 million tonnes CO_2eq/year calculated as annuity with discount rate 4% p.a.

The results of these papers indicate that the Norwegian forest sector has considerable potentials to reduce the atmospheric concentration of CO_2. A long-range bio-economic model like NorFor which integrates the entire forest sector, seems suitable to assess costs, potentials and impacts of carbon policies on the sector.

SAMMENDRAG

Skogsektoren spiller en viktig rolle i den globale karbonsyklusen. For det første er karbonlagrene i biomasse og jord i skog meget store og samlet karbonopptak i de globale skoger er større enn utslippene fra avskoging og degradering av land. For det andre ser skogsektoren ut til å ha betydelig potensial for å ytterligere begrense akkumulering av klimagasser i atmosfæren. Fordi skogtilveksten i Norge er mye større enn avvirkningen, tar skogene opp mer enn halvparten av de nasjonale menneskeskapte klimagassutslippene. Selv om det fremtidige karbonopptaket antagelig vil reduseres på grunn av mindre investeringer i primærskogbruket de siste tiårene, vil skog være en viktig faktor i Norges klimagassregnskap også fremover.

Den lange investeringshorisonten og de langvarige virkningene på karbonregnskapet av skogskjøtselstiltak gjør at planleggingsmodeller er viktige i skogsektoren. Det finnes relativt mange analyser av virkninger på klimagassutslipp og økonomi av tiltak i skogsektoren, men det er få studier som på en økonomisk konsistent måte integrerer den biologiske veksten og investeringer i skogbruket med markedene for tømmer og treprodukter. Avveiningen mellom å utvide bruken av treprodukter og å øke karbonopptaket i skog gjør slike integrerte analyser egnet for å frembringe realistiske anslag på potensialer, kostnader og effekter av klimapolitiske tiltak. Denne avhandlingen har to hovedmål: 1) Å utvikle en bioøkonomisk modell av den norske skogsektoren som integrerer biologisk vekst og investeringer i skogbruket med markedene for tømmer og treprodukter, og beregner karbonstrømmene gjennom hele sektoren, og 2) å studere hvordan den norske skogsektoren kan medvirke til å redusere konsentrasjonen av klimagasser i atmosfæren og dermed motvirke globale klimaendringer. Dette er belyst i de fire artiklene i avhandlingen.

En tidligere utviklet modell av den norske skogsektoren ble brukt for studien i artikkel 1, hvor kostnader og nytte av politiske tiltak for varmemarkedet ble sammenlignet. De to analyserte tiltakene var CO_2-avgift på fyringsolje og parafin og investeringsstøtte til fjernvarmeanlegg basert på skogbasert energi. Resultatene indikerer at økt CO_2-avgift på konkurrerende energibærere har stor innvirkning på produksjonen i de analyserte bioenergiteknologiene. Bioenergiproduksjon basert på flis økte drastisk når CO_2-avgiften økte fra 20 til 60 €/tonn CO_2eq, mens pelletsproduksjonen ekspanderte ved en CO_2-pris over 80 €/tonn CO_2eq. Ved det høyeste avgiftsnivået, 160 €/tonn CO_2eq, ble 7.5 TWh varme produsert årlig basert på disse bioenergibærerne. De tilsvarende klimagassreduksjonene var 2.3 millioner tonn CO_2, eller 70% av de årlige utslippene fra varmeproduksjon i Norge. Investeringsstøtte ble også funnet å øke bioenergiproduksjonen, men hadde mindre effekt når den ble kombinert med høye CO_2-avgifter.

Artikkel II er en anvendelse av skogsektormodellen NorFor som ble utviklet som en del av denne avhandlingen. Studien analyserer hvor stor betydning ulike forutsetninger om forhåndskunnskap har i skogsektormodellering. I de fleste skogsektormodeller er

aktørene enten antatt å være "myopiske" (nærsynte), dvs. ikke å ha noe informasjon om framtidige forhold etter den inneværende perioden, eller å ha perfekt forhåndskunnskap. dvs. at alle relevante faktorer er kjent for alle perioder som analysen omfatter. I denne artikkelen analyseres virkninger av et hypotetisk importforbud på all bartretømmer antatt innført i 2020. Tre grader av forhåndskunnskap ble studert: Perfekt (aktørene hadde full informasjon), begrenset (aktørene hadde informasjon en begrenset tid i forveien) og ingen forhåndsinformasjon. Vi fant at når aktørene forutså forbudet, ville skogeierne redusere avvirkningen i tiden før 2020 for å spare tømmer til senere perioder med høyere priser. Jo mindre informasjon som var tilgjengelig, jo mer økte prisene som følge av importforbudet. Bioenergiproduksjonen ble drastisk redusert for å bevare produksjonen av masse og papir. Vi fant støtte for hypotesen om at aktørene tilpasser seg forbudet før implementeringen, men tilpasningen var mindre enn forventet. To mulige årsaker til dette er begrenset tilgjengelig tid for tilpasning og betydelige faste kostnader i industrien.

I artikkel III ble virkninger på klimagassutslippene av å bruke trepellets i kullkraftverk analysert. En sensitivitetsanalyse ble utført for å avdekke hvilke faktorer som påvirker substitusjonseffekten mest, og forutsetningen om karbonnøytralitet ble diskutert. Det analyserte case-studiet var en nylig åpnet pelletsfabrikk i Norge, der pelletsen er tenkt eksportert til kullkraftverk i Europa. Råmaterialene kommer fra Canada. Forutsetningen om karbonnøytralitet ble funnet å være den viktigste enkeltfaktoren for det totale klimagassregnskapet. Hvis alle utslippene fra forbrenning av pellets ble inkludert, men ikke karbonbindingen i skog, endte substitusjonseffekten på omtrent null. Å erstatte de mest forurensende brenslene først var også viktig for å redusere klimagassutslippene, mens mange faktorer i produksjonskjeden bare hadde marginale virkninger. På grunn av store forskjeller i markedsprisene mellom pellets og kull ble kostnaden for å redusere klimagassutslippene estimert til omtrent 60 €/tonn CO_2eq.

Artikkel IV er en analyse med NorFor av potensialer og kostnader ved klimagasstiltak i den norske skogsektoren. Karbonopptak og unngåtte klimagassutslipp utover beregnete strømmer i et basisscenario ble analysert for CO_2-priser fra 100 til 800 NOK/tonn CO_2eq. Alle store positive og negative karbonstrømmer i skog, transport, prosessering, konsum og substitusjon var inkludert i dette avgifts-/subsidieregimet. To typer markedsmodeller ble analysert: En endogen markedsmodell hvor klimagasstiltak kunne foretas i hele sektoren, og en eksogen markedsmodell hvor produksjon i industrien, import og eksport var fastsatt til nivåene i basisscenarioet. Avvirkningen kunne variere fritt innenfor disse rammene. Vi fant store forskjeller i potensialer og kostnader mellom de to markedsmodellene, med betydelige høyere potensialer og lavere kostnader i den endogene markedsmodellen. Videre fant vi at klimagasstiltak ble foretatt i hele sektoren i den endogene modellen. Tømmeravvirkningen, spesielt tynning, ble redusert og plantingen intensivert. Massevirke ble allokert fra papir- og masseproduksjon og vedovner med lav virkningsgrad til vannbåren varmesystemer med høy virkningsgrad. Handelslekkasje oppsto ved at import og eksport endret seg 15-25%. Potensialet for reduserte klimagassutslipp/økt karbonopptak i den endogene markedsmodellen var ifølge resultatene mer enn 7 millioner tonn CO_2eq/år regnet som annuitet med rente 4% p.a. i perioden fra i dag til 2055 ved en karbonpris på 800 NOK/tonn CO_2eq.

Resultatene av disse artiklene indikerer at den norske skogsektoren har et betydelig potensial til å redusere konsentrasjonen av atmosfærisk CO_2. En langsiktig bioøkonomisk modell som integrerer hele sektoren slik NorFor gjør, synes godt egnet til å estimere kostnader, potensialer og virkninger av politiske klimagasstiltak rettet mot sektoren.

PAPER I-IV

Paper I: Sjølie, H.K., Trømborg, E., Solberg, B., Bolkesjø, T.F., 2010. Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. Forest Policy and Economics 12: 57–66

Paper II: Sjølie, H.K., Latta, G.S., Adams, D. M., Solberg, B., 2011. Impacts of agent information assumptions in forest sector modeling. Journal of Forest Economics 17(2): 169-184

Paper III: Sjølie, H.K., Solberg, B., 2011. Greenhouse gas emission impacts of use of wood pellets - a sensitivity analysis. (In review)

Paper IV: Sjølie, H. K., Latta, G.S., Gobakken, T., Solberg, B., 2011. Potentials and costs of climate change mitigation in the Norwegian forest sector. (Manuscript)

CONTENTS

Appendices: Paper I-IV

1 INTRODUCTION

Climate change caused by the accumulation of greenhouse gases in the atmosphere is a highly important topic in society. Forests play important roles, both in the carbon cycle and for the possibilities for mitigation. 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 the forests (Winjum et al., 1993).

Recent estimates of greenhouse gas 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. The contribution of emissions from land use-based activities to total global greenhouse gas emissions varies from 5-12% (Harris et al., 2010) to 18% in these estimates (Denman et al., 2007). However, in total, the world's forests are carbon sinks with a positive net accumulation of carbon, with almost one-third of global greenhouse gas emissions ending up in terrestrial systems (Nabuurs et al., 2007a). 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).

In Norway, intensive planting and afforestation between 1950 and 1990, in combination with relatively stable harvest levels over the last few decades, have resulted in net carbon sequestration in forests equaling more than half of the current national greenhouse gas emissions. Even with a continuation of recent harvest levels, the accumulation rate is projected to decline due to reduced investments in forestry. Nevertheless, the forests will be a major factor in the Norwegian greenhouse gas account also in the future (The Norwegian Climate and Pollution Agency, 2010).

A range of studies on different scales with a variety of different approaches have been carried out to assess the costs and potentials of climate change mitigation in the forest sector. The general consensus is that the sector has a large potential to contribute to mitigation, in addition to reducing the overall cost of mitigation. Prolonged rotations, afforestation, intensified planting and other changes in forest management can increase carbon sequestration (Nabuurs et al., 2007a). Bioenergy can reduce overall greenhouse gas emissions by replacing fossil fuels (Sims et al., 2007) and wood materials by substituting for non-renewable materials such as concrete and steel (Gustavsson et al., 2006).

Mitigation analyses of the forest sector can for simplification be grouped as follows:

- Bioenergy studies: these often come with detailed costs and technologies, but with limited inclusion of the markets, and wood is typically seen as carbon neutral (e.g. Gustavsson and Madlener, 2003; Raymer, 2006);

- Forest management studies: these present detailed representations of forest growth and management, but with exogenous prices and utilization of wood (e.g. Backéus et al., 2005; Hoen and Solberg, 1994; Raymer et al., 2009);

- Studies using large-scale forest sector and CGE models[1]: these may cover an entire continent or the globe with endogenous forest management and wood markets, and are often rather aggregated due to the scale (e.g. Jakeman and Fischer, 2006; Sathaye et al., 2006; Sedjo et al., 2001)

All of the aforementioned types of studies have strengths and disadvantages. However, one general weakness in climate change mitigation assessments of the forest sector is the lack of links between the different approaches. Since there is a trade-off between increasing the carbon sequestration in the forest and the utilization of wood products, these aspects would be better analyzed simultaneously. Furthermore, for all climate change mitigation policies, whether targeted to stimulate carbon sequestration or the use of wood products, an understanding of how the relevant markets function is important in order to realistically estimate costs and potentials.

The particularly long time lag between investment and return for the forest owners and the lengthy carbon impacts of forest management decisions make long-range projections important in the forest sector. Linking the economics in the sector tightly to the biological basis will also provide a framework for detailed studies of adaptations to policy and market shifts, and corresponding costs. This thesis is an attempt in that direction, with the following main objectives:

- Develop a bio-economic model of the Norwegian forest sector with endogenous forest growth and management, harvests, industrial processing, demand for manufactured products, trade and a detailed carbon account of all these various parts. Such a model should be suitable for studying impacts of changes in external economic and policy factors, inter alia carbon policies.

- Study how the forest sector in Norway can contribute towards the mitigation of climate change, both by applying the model mentioned above and by other approaches.

The thesis is structured in the following way: the next chapter provides a description of the forests' role in the carbon cycle and a short presentation of the Norwegian forest sector. A brief introduction of the theoretical basis behind forest sector modeling is then given, followed by an overview of forest sector models developed both internationally and within Norway. Next, relevant studies on costs and potentials of climate change mitigation in the forest sector are reviewed. In Chapter 3, the methods used in the four thesis papers are described. In the description of the two forest sector models, an emphasis is put on NorFor, the model developed as part of this thesis. In Chapter 4, the

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[1] CGE model = computerized general equilibrium model.

main results of each of the four papers are presented, and Chapter 5 provides an overall synthesis and discussion of the results. Lastly, the four thesis papers are presented in Appendices I-IV.

2 BACKGROUND AND THEORETICAL BASIS

2.1 Forest and the carbon cycle

The world's forests are an essential part of the global carbon cycle. About 80% of the world's biomass is in forests, and the carbon storage in the soil is probably higher than in the biomass (Kindermann et al., 2008; Lorenz and Lal, 2010). The preindustrial carbon level in the terrestrial biosphere has been estimated to about 2300 Pg C, almost four times greater than the preindustrial atmospheric carbon level. Since then, an estimated 140 Pg has been lost from terrestrial carbon pools due to land-use changes (Lorenz and Lal, 2010). In the period from 1850 to 1998, an estimated 33% of all global greenhouse gas emissions stemmed from the land use, land-use change and forestry (LULUCF) sector (Watson et al., 2000). Between 5 and 18% of the global greenhouse gas emissions are estimated to be from this 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).

The natural carbon flux between the biosphere and the atmosphere (net primary production) amounts to roughly 60 Pg C 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). CO_2 emissions from fossil fuel combustion, cement production and land-use degradation 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 global net terrestrial uptake of carbon, calculated as emissions from fossil fuel combustion and cement production minus accumulation in the atmosphere and oceans, was estimated to be about 0.7 Pg C/year in the 1990s, but with the 90% confidence interval equaling 1.0 (Watson et al., 2000). However, adding an estimated 1.6 Pg C/year from deforestation and land degradation leads to a so-called residual terrestrial uptake of 2.3 Pg C/year (Figure 1). This is residual in the sense that it is the amount of CO_2 removed from the atmosphere which has not been absorbed by the oceans, but the actual exchanges behind this sequestration are unclear (Common and Stagl, 2005). Thus, despite the large uncertainty in these figures and annual fluctuations due to changing climatic conditions, the world's ecosystems are assumed to more than offset the LULUCF emissions.

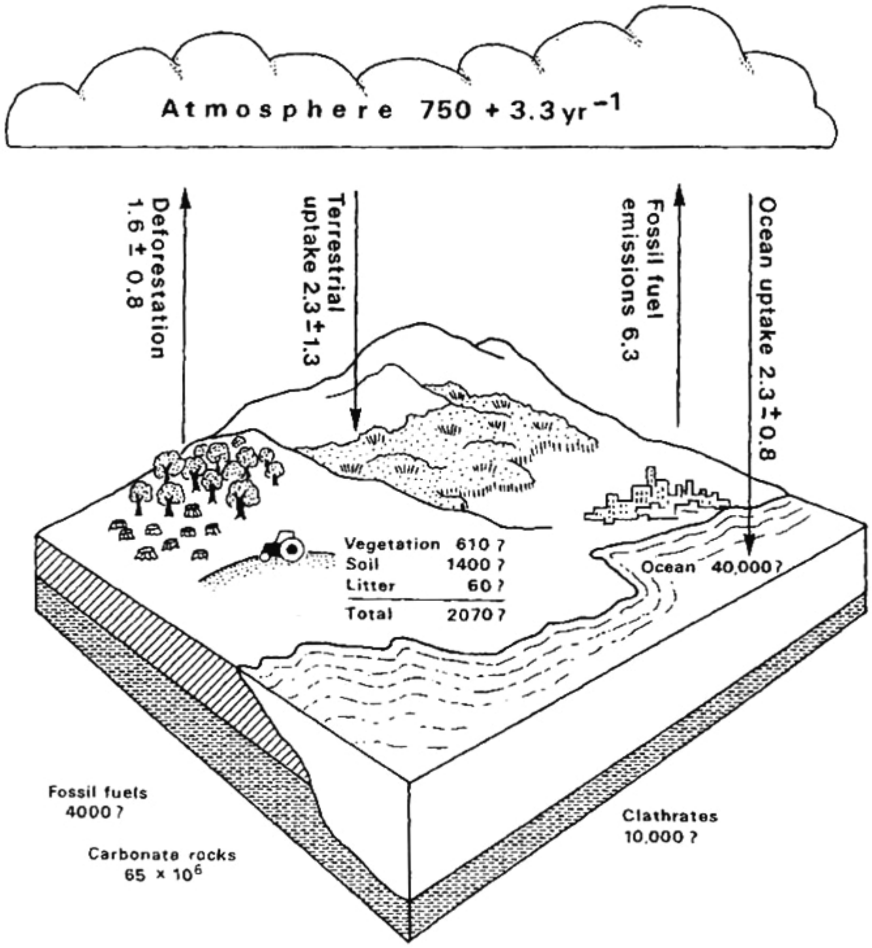

Figure 1: Carbon stocks (Pg) and fluxes (Pg/yr). Fluxes are indicated with arrows. Source: Grace (2004).

The emissions from land-use changes may be overestimated (Harris et al., 2009). Watson et al. (2000) assumed that the global carbon sequestration rate increased by approximately 20% from the 1980s to 1990s, but more recent estimates are considerably higher. Denman et al. (2007) and Sarmiento et al. (2010) found the global land-use sink to have increased by 0.9-1 Pg C/year between the 1980s and 1990s. Using the estimates of Sarmiento et al. (2010), 1 Pg C corresponds to roughly 12% of annual emissions from fossil fuels, cement production and land use.

The boreal forests are the biome with the largest carbon stock, containing more than 20% of the world's terrestrial carbon in less than 10% of the world's land area. 15% of the carbon is contained in vegetation, with the remainder in soil (Watson et al., 2000). The Northern Hemisphere is also assessed to be a major carbon sink, with carbon uptake equaling 0.5 Pg/year in temperate and boreal zones in each of the Eurasian and North American continents (Sarmiento et al., 2010). In the early 1990s, net accumulation in the European forest sector was evaluated at 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). The European forest area is expanding, but the average expansion rate declined from 877 000 hectares/year in the 1990s to 676 000 hectares/year in the years 2000-2010 (FAO, 2010).

Several studies have found evidence of increased plant growth in the boreal and temperate zones in Europe. Spiecker (1999) shows that numerous studies have found increased productivity in many European forest sites, particularly in central Europe. In some sites, volume growth productivity has increased by more than 50% over the last decades. He suggests that this increase in forest growth is caused by forest management and altered species composition, in addition to a higher atmospheric concentration of CO_2 and nitrogen. Myneni et al. (1997) found by using satellite data that an earlier occurrence of spring from 1981 to 1991 has lengthened the growing season in the Northern Hemisphere, which the authors relate to global warming. A phenological study of tree growth in Europe indicates that the average annual growing season has been extended by almost 11 days from the early 1960s to the late 1990s, which can also be attributed to a warmer climate (Menzel and Fabian, 1999).

2.2 Forests in the Kyoto Protocol

The Marrakesh meeting in 2001 decided that emissions from deforestation and land degradation should be implemented in the Kyoto Protocol. Moreover, Annex I countries[2] 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 tonnes CO_2/year, although only about 10% of the potential is actually used (Chopra et al., 2005). As the CO_2 emissions are counted as the trees are harvested, bioenergy in the Kyoto Protocol is considered carbon neutral, independent of its origin (Searchinger et al., 2009).

2.3 The Norwegian forest sector

The forest sector in Norway has limited economic importance on the national level, but constitutes nevertheless a significant part of the economy in rural areas. The sector's share of GDP has decreased by 75% over the last 30 years to about 0.6%, while real timber prices have declined by approximately 50% in the same period (Statistics Norway, 2010a). Recent annual harvest levels fluctuate between 6.5 and 8.5 million m^3, not including 1-2 million m^3 of firewood outside the official statistics. Harvests are concentrated to the eastern part of the country, which is also where most of the

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

industries are located. About 40% of the pulpwood used in industry is imported, mostly from Sweden. The production of newsprint, uncoated paper and linerboard is large, with an essential part of the production being exported.

The Norwegian forests are owned by close to 120 000 private forest owners, and the average forest property size is around 50 hectares. A minor share of the forests is owned by the State and through common ownership. Private owners and municipalities contribute to 92% of the roundwood harvests for sale (Statistics Norway, 2010b).

Approximately 37% of Norway's land area is covered with forests. A total of 7.6 million hectares, or 63% of the forest area, is considered as productive forest land. The forest area is growing in size, particularly towards the North and to the higher altitudes, with temperature increases and reduced grazing by domestic animals assumed to be the main reasons. Over the last few years, Norwegian forests have sequestered between 25 and 30 million tonnes CO_2 annually (The Norwegian Climate and Pollution Agency, 2010), or more than half of the national anthropogenic greenhouse gas emissions, which in 2009 totaled 51.3 million tonnes CO_2eq (Statistics Norway, 2011). The Norwegian forests have seen a massive expansion in terms of volume over the past 100 years. Starting with 300 million m^3 of growing stock and 10 million m^3 of annual increment in 1933, the forests have grown to more than 800 million m^3 today, with an annual increment of 25 million m^3 (Statbank Norway, 2011). During the last 60 years, annual harvests have fluctuated between 6.5 and 10.5 million m^3 according to official statistics (Figure 2). Less than half of the increment has been harvested over the last two decades, leading to a rapid volume accumulation (Statbank Norway, 2011).

The annual increment has probably reached its maximum, and even if annual harvest levels remain at about 10 million m^3, the net increment and consequently the carbon sequestration are likely to decline. With 10 million m^3 in annual harvest, the carbon uptake is expected to be approximately 22 million tonnes CO_2 in 2020, 20 million tonnes CO_2 in 2050 and 15 million tonnes CO_2 in 2080 (The Norwegian Climate and Pollution Agency, 2010). This is likely to be caused by shifts in forestry investments. In the period between 1950 and 1990, planting was at its most intense, with annually planted areas up to three times larger than in recent years (Statistics Norway, 2010b). Additionally, the average planting density has decreased by 30% for the period 1971-2009 (Statbank Norway, 2011), and the number of planted seedlings has declined from 110 million at its height in mid-1960s to about 23 millions in 2009. Furthermore, sales of seeds were around 20 times higher in 1961 than in 2005 (The Norwegian Forest Seed Center, 2009). Afforestation in coastal areas during this period is also an important factor in today's large carbon uptake.

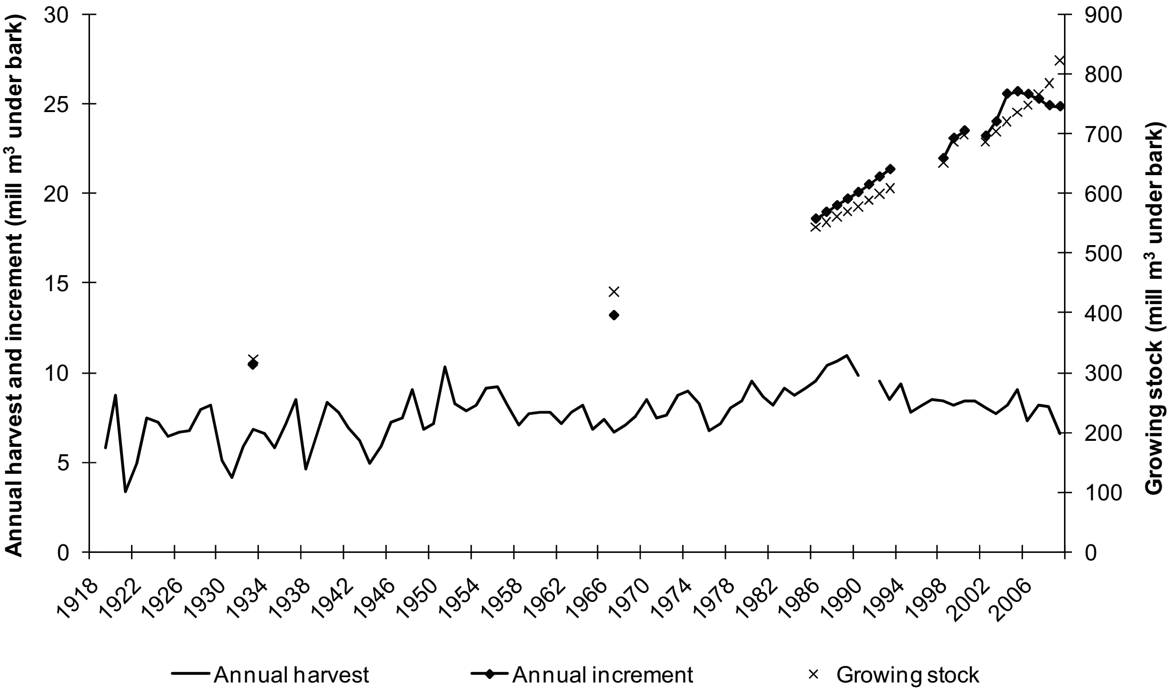

Figure 2: Annual industrial harvest and increment and growing stock in Norway 1919-2009. Source: Statbank Norway 2011.

2.4 Forest sector models and long-range forest management planning

Theoretical basis

Forest sector models are tools used to both project future development and analyze impacts of changes in economic and political factors. Using the definition by Solberg (1986, p. 420), a forest sector model is “a model (numerical or strictly analytical) which takes into account both forestry and forest industries and the interaction between these two activities." In the following, I will for the most part restrict myself to discussing equilibrium forest sector models, which is a subgroup of forest sector models that require market equilibrium, i.e. that the supply equals the demand for each region and product. For Norway and to some extent Europe, other types of models will also be presented.

Depending on the forest sector model’s formulation and assumptions, there are two distinct “groups” of theories forming the theoretical basis, one which is concerned with the intertemporal optimizing of the harvest and the other with market equilibria in spatial, competitive markets.

Forest sector models simulating intertemporal optimizing behavior of agents seem to be indirectly based on the rational expectations hypothesis (REH) proposed by Muth

(1961). The formula for the present value of future harvests was first forwarded by Faustmann (1849) and later solved for the optimal harvest time by Pressler (1860), according to Amacher et al. (2009). The theorem states that a stand shall be harvested when the rate of change in its value is equal to the interest of the stand plus the land rent. Hartman (1976) extended the theorem to include environmental values provided by a forest stand, and showed that such values extend the economic rotation age. He suggested that non-timber values could cause a considerable delay in the optimal harvesting time, if it would ever be optimal to harvest with such values present. During the last decades, there has been a change from regarding non-industrial forest owners as pure profit maximizers to maximizers of the utility derived from the forest resources, of which profit is a part (see e.g. Amacher et al., 2003 for a review).

Spatial equilibrium models project trade between regions that are geographically distant from each other, and between which there are transportation costs involved. Additionally, market equilibrium has to be obtained for each product in each region. Enke (1951) seems to have been the first to generalize the problem of spatial markets and formulate the solution that the trade of a good between two regions will only take place if the price difference exceeds the transport costs, although Cournot (1838) studied the price relationship between two spatially separated markets more than 100 years before. Samuelson (1952) brought Enke’s results further by stating that an optimization problem could provide a solution to a spatial price equilibrium problem. The optimization problem maximizes the “net social payoff," i.e. consumers’ surplus plus producers’ surplus minus transportation costs. Noting himself that the optimization problem is artificial in the sense that no agents in the market will be concerned with it, the main point is that, given competitive markets, the solution to this optimization problem simulates the markets and ensures market equilibrium. He also related Enke's specification to the Hitchcock-Koopmans transportation problem, although the spatial price equilibrium problem was more general. The spatial price equilibrium coincided with the Kuhn-Tucker conditions of the optimization problem (Floudas and Pardalos, 2001). Takayama and Judge (1964a; 1964b) took the spatial price equilibrium theory another step forward and showed how a quadratic programming problem could be solved for spatial prices, production and demand in the cases of linear supply and demand functions. This last step was also important in relation to computational improvements (Floudas and Pardalos, 2001).

The power of these techniques lays in the explicit formulation of the connection between the demand for final products, the costs of processing and transport and the supply of raw materials, and that from the unique model solution, competitive prices and allocations of products are obtained (Takayama and Judge, 1964a). A key feature is that these models reflect the price-taker role of each firm and consumer, and the endogenous prices in the market as a whole at the same time, and find the prices in equilibrium. They are thus assumed to reflect actual profit-maximizing industrial behavior and actual utility-maximizing consumer behavior, even if only the aggregates of supply and demand are modeled (McCarl and Spreen, 1980). Therefore, such model specifications are very useful for modeling competitive markets.

The applications of linear programming (LP) based on these theories have increased dramatically over the last decades due to improved techniques (Todd, 2002) and computational capacity. Applications are widespread, both in research and business. Actually, the research on LP was first triggered by the needs of the U.S. Air Force to optimize schedules for its crew and for maintenance (Dantzig, 1998).

In partial equilibrium forest sector models, the activity in the sector is assumed not to impact the levels of more general economic factors such as interest rates, exchange rates, costs of labor and transport, etc. This approach, in which the unit costs of these inputs are exogenously specified, is the one most commonly used in forest sector analyses (Buongiorno et al., 2003) and seems to be a realistic approach since the forest sector's contribution to GDP is 1% for the world as a whole (Finnish Statistical Yearbook of Forestry, 2010).

Forest sector models

Many forest sector models have their theoretical and technical roots in Samuelson (1952) and Takayama and Judge (1964a; 1964b), in addition to early developments of agricultural sector models (Ince and Buongiorno, 2007). LP models have been important tools in forestry since the 1960s (Hoen, 1990), both for decisions about harvest operations in the short run, as well as strategic long-term planning (see Dykstra, 1984 for early applications). One important, early use was the Timber RAM for the U.S. Forest Service (Navon, 1971). As environmental issues became more important with time, the scope of the forestry planning models was extended to include other factors than production, profits and costs (Weintraub and Romero, 2006). Bethel and Harrell (1957) represent one of the earliest applications of LP in the forest industry.

The first Timber Assessment (Outlook Study) of the U.S. forest sector was published in 1958, and projected inventories and markets (Haynes and Adams, 2007). With the Timber Assessment Market Model (TAMM) in 1980, projection models for the U.S. Forest Service took the step from gap analysis, in which demand and supply were projected independently, to spatial equilibrium models (Adams and Haynes, 1986). TAMM was developed for the Forest Service's 1980 Timber Assessment. The model projects annual sawtimber harvests, production and demand for solid wood products and trade, assuming myopic agents (Adams, 2007). In an early study of carbon policy market impacts, Adams et al. (1993) linked TAMM to the Agricultural Sector Model (ASM) to study impacts of extensive tree planting programs on agricultural lands on the forest sector markets in the U.S. Later, the Forest and Agricultural Sector Optimization Model (FASOM) was developed, with the forest sector part being based to some degree on TAMM (Adams et al., 1996). Important differences include foresight assumptions (in

FASOM, perfect foresight is assumed) and the number of market levels, which is one in FASOM compared to two in TAMM. Pulpwood and fuelwood are also included in FASOM. In addition, forest management is endogenous, incorporating forest growth by even-aged harvest schedule structure in the form of a "Model II" (Johnson and Scheurman, 1977) for private forest lands. Carbon fluxes are included such that the model can be used to study impacts of carbon policies, and the model has been extensively applied to climate change mitigation studies (Adams et al., 1999; Alig et al., 1997; 2010; Lee et al., 2005).

While TAMM focused on the sawlogs and solid wood markets, the PAPYRUS model was developed to make long-range market projections of production, consumption, prices and trade in the North American pulp and paper industry (Gilless and Buongiorno, 1987). Later, PAPYRUS was succeeded by the NAPAP model, which incorporated more detailed industrial consumption and technological changes within the sector. NAPAP maximizes net social payoff in the pulp and paper industries in the U.S. and Canada, assumes myopic agents and is solved with recursive programming (Ince and Buongiorno, 2007).

A major outcome of the Forest Sector Project at IIASA in Laxenbourg, Austria in the 1980s was the development of the forest sector model Global Trade Model (GTM) (Kallio et al., 1987). This model shares several structural similarities to the North American pulp and paper models. Myopically, it maximizes the net social payoff for the given time period, and applies recursive programming for updating the values for the next period. The timber harvest depends on econometrically based relations with price, exogenously given forest growth and changes in growing stock. The model has two market levels, timber and manufactured wood products. Econometrically specified demand functions are included, and the model simulates the optimal interregional trade of logs and products. GTM has been particularly important as a basis for the development of other models such as the global EFI-GTM (Kallio et al., 2004), the SF-GTM of the Finnish forest sector (Ronnila, 1995; Kallio, 2010), the global CGTM (Perez-Garcia et al., 1997; 2002) and the NTM and NTM II of the Norwegian forest sector (Trømborg and Solberg, 1995; Bolkesjø, 2004). NTM II has been applied for a range of studies of impacts on the Norwegian forest sector by changes in economic and policy frames, including increased forest conservation (Bolkesjø et al., 2005), bioenergy policies (Bolkesjø et al., 2006; Trømborg et al., 2007) and changes in industrial capacity (Bolkesjø, 2005).

The Global Forest Products Model (GFPM) is another model similar in structure to the GTM, projecting global changes in production, consumption, prices and trades in the forest sector, also by assuming myopic agents (Buongiorno et al., 2003).

Another group of models are the Timber Supply Model (TSM) (Sedjo and Lyon, 1990) and related models (Sohngen et al., 1999; Sohngen and Sedjo, 2000). These global models maximize the net social payoff for the entire horizon by applying optimal control theory. A global demand curve for logs is included, while the regional supply depends on management intensity and access costs. The models have been used to study costs and potentials of climate change mitigation in global forests (Sedjo et al., 2001; Sohngen and Sedjo, 2000; 2006).

Regional models sharing similarities in the structure of forest inventories and harvests schedules with FASOM have been developed for Oregon (Adams and Latta, 2005; 2007), projecting supply and demand for sawlogs. Each sawmill is a demand center, with a capacity that is allowed to adjust over time. Private timber inventory is modeled with a combination of a "Model I" and "Model II" (Johnson and Scheurman, 1977) approach, with stands divided into condition classes based on stand characteristics and previous harvest treatment and with several possible management intensities. A detailed carbon flow account, including aboveground and belowground biomass, understory carbon, oxidation of wood residues after logging and the storage and flows of carbon in wood products, is incorporated. As for FASOM, the models assume a perfect foresight, explicitly including the spatial aspects and maximize net present social payoff. The models have been applied for projecting future harvest levels (Adams and Latta, 2007), as well as the market and carbon impacts of policy shifts on public land in the region such as restoration thinning programs (Adams and Latta, 2005) and changes in harvest levels (Im et al., 2010).

The simulation model EFISCEN of the European forest resources (Karjalainen et al., 2003) projects future states of forests given specified future harvest levels. Including no forest industries, EFISCEN is not a forest sector model. It has been developed with the aim of projecting long-term changes for large-scale areas, and has been applied for studies covering countries (Karjalainen et al., 2002) as well as the entire continent (Nabuurs et al., 2007b). Projections include assessments of increment, growing stock, carbon sequestration, age class distribution and harvests of different species in each region of the countries.

The first comprehensive Norwegian analysis of long-range inventories and harvest possibilities was provided by Langsæter (1944). By using data from the second national forest inventory (NFI) in the years 1937-41, he projected timber harvest and inventories for Akershus, Østfold and Hedmark counties. His methods were further developed by Seip (1953), Nersten and Delbeck (1965) and by Gotaas (1967), who introduced the first computerized forestry model in Norway. The AVVIRKI and AVVIRKII models (Hobbelstad, 1979; 1981) were the first to integrate forest yield functions in Norway. These models could calculate the maximum sustainable yield (i.e. the maximum harvest yield which does not require a later decline), with costs included later (Hobbelstad, 1988). Investments and final harvest age are defined exogenously, in addition to harvest strategy. Possible strategies include maximization of sustainable yield and strategies more closely related to the Faustmann formula. The models have been extensively applied to projections based on the NFI and the latest version, AVVIRK-2000 (Eid and Hobbelstad, 1999), was applied to investigate carbon sequestration in various harvest scenarios in the forest sector part of the analysis "Climate Cure 2020", a broad ranging analysis that addresses how greenhouse gas emissions in Norway can be reduced by 2020 (The Norwegian Climate and Pollution Agency, 2010).

Hoen (1990) introduced optimization models for forest management in Norway by adapting the Gaya-LP (Hoen and Eid, 1990), originally developed in Sweden (Eriksson, 1987), to Norwegian conditions. Several solvers have been used for the optimization problem. Originally, the MINOS solver was used, which was then replaced by the JLP solver (Lappi, 1992), and later by the J solver (Lappi, 2003). Gaya-JLP was one of the first forest management optimization models in the world to study how forest management can mitigate climate change (Hoen and Solberg, 1994). The carbon account was later extended with substitution effects and the Yasso soil carbon model (Liski et al., 2005) into Gaya-J/C (Raymer, 2005; Raymer et al., 2009). The various Gaya LP models have been applied to study a range of economic and environmental issues in Norwegian forestry, inter alia the relationship between the required rate of return, harvest and growing stock (Hoen et al., 2001), the costs of environmental measures (Bergseng et al., 2008; Eid et al., 2002) and the costs of climate change mitigation (Hoen and Solberg, 1994; 1999; Raymer et al., 2009).

The first forest sector model applied in Norway was the SOS model, a simulation model based on the DYNAMO system approach. It was applied for analyses of how the forest sector in the Nordic countries could evolve as the industrial production was growing much faster than the forest resources (Randers, 1977; Randers et al., 1978). The World Bank IBRD model, an intertemporal optimization model minimizing the costs of producing pre-specified quantities of forest industry products, was parameterized to Norwegian conditions by Gundersen and Solberg (1984). The model simulates the optimal allocation of timber to industry. The next forest sector models used in Norway were the NTM and NorFor models, both of which are described in more detail in Chapter 3.

2.5 Climate change mitigation in the forest sector

Theoretical basis

Hartman (1976) laid the groundwork for analyzes of optimal rotation age when the growing stock has value in addition to the timber value. He found that adding the values of recreation or other environmental services provided by the forest could substantially prolong the optimal rotation age. Van Kooten et al. (1995) built on Hartman's approach to analytically and empirically assess the optimal rotation age when the forest carbon has value. Unlike Hartman's case, in which the non-timber value is a function of volume, the carbon value is a function of growth, or more generally, changes in biomass. In the analysis by van Kooten et al. (1995), storage in wood products is also partially included. As long as the value is a positive function of growth or volume, the optimal rotation age increases. Hoen (1994) analyzed the optimal rotation age with positive carbon values, also including the effects of decay rates of wood products depending on the harvest age.

Studies of costs and potentials

It has become increasingly clear over the last years that realistic scenarios of global greenhouse gas emissions and mitigation options have to include the land-use sector[3] due to its large emissions and possibilities for mitigation. In some of the studies reported by Fisher et al. (2007), forestry, agriculture and bioenergy use are assessed to contribute between 15 and 60% of the total cumulative greenhouse gas emission reductions up to 2030, of which at least three-fourths is taken in forestry and by reducing non-CO_2 emissions from agriculture. The highest percentage occurs in studies reporting a low abatement of climate change, in which forestry and agriculture are cost-efficient mitigation options.

The forest sector may contribute to climate change mitigation in several ways (Nabuurs et al., 2007a): by maintaining or increasing the 1) the forest area, 2) carbon stocks in existing forests through management, 3) carbon stocks on the landscape level through increased forest conservation and extension of forest rotations, and 4) carbon stocks in wood products and increased substitution of products with high inputs of fossil fuels and replacing fossil fuels.

The literature on how the use of forest and wood products can contribute in the mitigation of climate change is extensive[4]. One very early contribution was made by Dyson (1977), who suggested that society could buy itself time to reduce its dependency on fossil fuels by establishing large-scale forest plantations for carbon sequestration. The wood from those plantations could then be used for replacing fossil fuels, e.g. in coal-fired power plants.

There is clear evidence that including the forest sector in climate change mitigation can substantially decrease overall abatement costs. By reviewing bottom-up studies of the forest sector, Nabuurs et al. (2007a) found that on a global scale forests may mitigate between 1270 and 4230 million tonnes CO_2/year in 2030, bioenergy excluded, to a cost up to \$100/tonne CO_2eq. Approximately half of this potential may be achieved to a cost up to \$20/tonne CO_2eq. These estimates correspond to 8-13.5% of the global mitigation potentials to a cost up to \$100/tonne CO_2eq and 15% for a cost up to \$20/tonne CO_2eq, respectively (Barker et al., 2007). The major part of the sequestration potential in the forest sector, particularly at lower costs, is estimated to take place in the tropics, mostly by reducing deforestation (Nabuurs et al., 2007a). In their review, top-down analyses

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[3] The land-use sector includes the agriculture and forest sectors; in addition, bioenergy is often referred to as a subsector of the land-use sector.

[4] In this review, I do not include stand level analyses.

provided sequestration potentials four to five times higher than the bottom-up studies. They remarked that bottom-up studies often have more accurate implementations of costs and market barriers than the top-down approach. However, the differences in the results also reveal the uncertainty of those figures.

The largest and cheapest mitigation potentials in the forest sector seem to be outside Europe and do not include forest management. By applying a global forest sector model, Sohngen and Sedjo (2006) estimated that up to 80% of all mitigation stems from reduced deforestation and afforestation, whereas the remaining 20% comes from forest management. Nonetheless, this does not imply that temporal or boreal forests are not viable for climate change mitigation. In reviewing studies of mitigation costs in the U.S. forest sector, Stavins and Richards (2005) found that 300 million tonnes of carbon annually, or approximately 20% of the national carbon emissions, could be offset in the forest sector at a cost of \$7.5-\$22.5/tonne CO_2eq. In an application of FASOM, Adams et al. (1999) found that up to 73 million tonnes CO_2/year additional to baseline could be sequestered in the U.S. agriculture and forest sectors at a cost of under \$21/tonne CO_2eq. Carbon projections of the European forests differ much, but the economic potential at a carbon price of \$20/tonne CO_2 in 2040 is estimated to 90-180 million tonnes CO_2eq/year excluding bioenergy (Nabuurs et al., 2007a). The chosen mitigation strategies in European forestry in these estimates included afforestation of abundant agriculture lands, use of bioenergy and forest management in old, saturated stands and in under-stocked stands.

Few sectoral studies of costs and climate change mitigation potentials in the forest sector seem to have been carried out in Europe. Karjalainen et al. (2003) projected the European forest sector's carbon budget until 2050 by applying EFISCEN, and compared a scenario in which harvests increased by 0.5-1% per year until 2020, with a "business as usual" scenario. They concluded that the higher harvest level would decrease the carbon stock in soil and in trees, increase carbon storage in products and decrease the total carbon stock in the sector.

In “Climate Cure 2020” (The Norwegian Climate and Pollution Agency, 2010), carbon sequestration in three national harvest scenarios in Norway, 10 (≈ today's harvest level) ("low"), 13 and 15 million m^3 ("high") were estimated by the use of AVVIRK-2000 (Eid and Hobbelstad, 1999). A harvest level increase of 50% was found to substantially decrease carbon sequestration. For instance, in 2040, around 10 million tonnes CO_2eq less would be sequestered in the high harvest scenario than in the low. By the year 2100, this difference would decrease to about 5 million tonnes CO_2eq due to a faster reduction in the growth rate in the low harvest scenario, where the average forest age increases more. (As mentioned in Section 2.3, carbon sequestration is projected to decrease even if the current harvest level is sustained.) The costs and potentials of other carbon sequestration measures such as increased planting density, afforestation, fertilization and the improvement of plant material were considered. Afforestation, fertilization and plant improvement were measures estimated to have negative or zero costs, though fertilization was the only measure out of all of them to have any significant impact in 2020 (0.45 million tonnes CO_2eq). Increased planting density and plant improvements could both have large impacts in 100 years (1.4-2 million tonnes CO_2eq), while afforestation is the most important measure in terms of carbon sequestration potential. “Climate Cure 2020” also reports substitution effects for the use of bioenergy and wood for materials, but these are not analyzed together with changes in harvest levels.

In Norway, an early "bottom-up" study of costs and potentials of carbon sequestration strategies in Norwegian forests (Lunnan et al., 1991) reported that relative to a base level, an additional 4, 6, 8 and 10 million tonnes of CO_2 could annually be sequestered with low conflicts and costs in 10, 20, 30 and 40 years after the strategies were implemented, respectively. If land-use conflicts were not considered, these estimates rose to 9, 17, 20 and 28 million tonnes of CO_2 per year.

In both Sweden (Backéus et al., 2005) and Norway (Hoen and Solberg, 1994; Raymer et al., 2009), regional studies of costs and potentials of increasing carbon sequestration through forestry have been conducted. These three studies applied detailed stand level management and yields, as well as carbon accounting, to assess how shifts in forest management triggered by higher carbon prices enhances carbon sequestration. However, exogenous prices and utilization of timber are obvious shortcomings in these models. Such models therefore operate better for small forest areas and for policies which are not expected to exert a large influence on the wood markets. Large-scale carbon policies as investigated in these studies may have a rather high impact on the wood markets through a reduced supply and reallocation of wood already in the markets. Hence, the potentials and costs are likely not to be fully revealed in those studies. Nevertheless, their detailed modeling of forest growth and management make such studies important for demonstrating possible forest management options for climate change mitigation.

The increased use of forest-based energy is considered to be an important climate change mitigation measure, even if the economic potentials and costs are highly uncertain (Sims et al., 2007). Bioenergy expansion is also a political target, both in the EU (European Commission, 2010) and Norway (Norwegian Ministry of Petroleum and Energy, 2008). In many European countries, coal-based power plants constitute a major electricity source, but also a great potential for co-firing with bioenergy. Technically, wood pellets are well suited for co-firing, and it is feasible to co-fire several types of coal with pellets. Up to 15% of the fuel can be replaced without much technical changes (Sims et al., 2007). Coal-based electricity is very carbon-intensive (Dones et al., 2003), and large emission reductions can therefore be obtained by such substitutions. Today, bioenergy contributes roughly 2.6% to the OECD electricity mix, and this share may possibly increase to 5% in the next decades, given an increased use of co-firing and the construction of bioenergy plants (Sims et al., 2007). Between 50 and 90 TWh of electricity can possibly be generated by bioenergy through co-firing with coal within the EU (Hansson et al., 2009).

Studies of economic potentials of increased use of bioenergy for heating in Norway include Bolkesjø et al. (2006), Langerud et al. (2007) and Trømborg et al. (2007). The first two mentioned applied the spatial, partial equilibrium model of the Norwegian forest sector NTM II to study the impacts of higher energy prices and subsidies to bioenergy, respectively. They found the economic potential of bioenergy in district heating and central heating installations to be relatively large, with only small increases in energy prices or subsidies.

Many studies have investigated the greenhouse gas impacts of increased use of forest-based energy. Raymer (2006) compared avoided greenhouse gas emissions when replacing fossil fuels with bioenergy in Norway. Bright and Strømman (2009) assessed the greenhouse gas emission reductions by replacing gasoline with forest-based ethanol. Forsberg (2000), Magelli et al. (2009) and Sikkema et al. (2010) all carried out life cycle assessments (LCA) of bioenergy transported long distances, and Hektor (1998) studied the cost efficiency of measures to replace fossil fuels with bioenergy.

The most common approach in LCA of forest-based energy seems to be considering bioenergy as carbon neutral (e.g. Bright and Strømman, 2009; Korpilahti, 1998; Raymer, 2006; Wahlund et al., 2004), which is in line with the approach taken by the Kyoto Protocol. The carbon neutrality is based on the summation over flows 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. A corresponding method would be to use a 0% discount rate in the carbon flows. However, there are concerns that such methods would create “perverse incentives” and actually lead to increased greenhouse gas emissions through deforestation (Searchinger et al., 2009). Schlamadinger and Marland (1996) found that the overall greenhouse gas impacts by harvest are highly dependent on the time frame.

3 METHODS

3.1 Description of the forest sector models NTMII and NorFor

For the work of this thesis, two forest sector models have been applied. In Paper I, the NTM II model was used. For Papers II and IV, a new forest sector model, NorFor, was developed. The models share several similarities: both models are deterministic, partial, spatial equilibrium models of the Norwegian forest sector, projecting impacts of changes in exogenous factors. In addition, the industry structure and data used in NorFor in Paper II were to a large degree taken from the NTM II, with updated data and some structural changes made for the model used in Paper IV.

Both models simulate optimal behavior of the sector's agents with regard to timber harvest, industrial production and consumption of paper, sawn wood, bioenergy and trade of goods between Norwegian regions and to and from abroad. The objective function serving for finding the market equlibria is maximization of the total welfare of the forest sector economy in Norway and with its trade partners. The models, however, are based on different assumptions regarding the forest owners' behavior and the agents' foresight. A key difference between the two models is how forest growth and the timber supply are modeled. In NTM II, the timber supply is aggregated to regions, and regional forest growth is exogenous. Forest growth and management are endogenous in NorFor, and the timber supply is modeled on stand level by the use of National Forest Inventory (NFI) plots.

The consolidated pulp, paper and board industries are represented in both models at the mill level, while sawmill capacities are given at regional level. Both models have bioenergy production specified in various types of heating technologies for each region, although production and demand are modeled differently in NorFor and NTM II.

In the next section, NTM II, and particularly NorFor, will be presented in more detail.

NTM II

The NTM II projects annual, regional harvesting, industrial production, consumption and trade for the next 10 to 20 years in Norway. Forest industry and forest owners are assumed to maximize their profits and the consumers of final products their utility. Several of the products considered final in the model are not actually purchased by consumers, but by other industries within the sector that also maximize their profit. These demand functions are hence derived demand functions for products going into other productions. Trade occurs between regions if the price difference between the regions exceeds the transportation costs. Together, this ensures maximization of the net social payoff (producer surplus plus consumer surplus minus the costs of transportation and investments), as put forward by Samuelson (1952). Agents are assumed myopic, only possessing information about past and current periods. No storage of products between periods is allowed.

Supply of sawlogs and pulpwood of spruce, pine and birch are modeled in the NTM II. For the base year, the levels of harvest, growing stock, increment and log prices are given for each region. Prices are given as FOB to the regional center, i.e. the log price plus the costs of transportation to the regional center. Forest growth is exogenous, and the growing stock for each species and quality in each region is updated for each period based on last year's growing stock, gross increment and harvest. Based on econometric studies, timber supply is a function of the growing stock (assumed elasticity = 0.5) and price, with the functions assuming a constant elasticity of supply. The supply of harvest residues for bioenergy was estimated as a stepwise supply function to reflect increasing transportation costs. Sawlogs are only used for producing sawn wood, while pulpwood is used both in the pulp, paper and board industries, and for bioenergy. Sawlog substitutes for pulpwood if the pulpwood price reaches the sawlog price.

Capacities and production functions for the pulp, paper and board industries are given at the mill level, while two production functions for sawmills, small and large, are included. Production costs are divided into input factors with endogenous and with exogenous prices. Wood and wood derived inputs are price sensitive, while capital, labor, energy and "other costs" have fixed prices. Several bioenergy technologies with various costs and inputs are included such as woodstoves, pellets stoves, central heating systems and district heating systems. Capacity constraints are given for existing and new facilities, as well as joint constraints for cases in which technologies are assumed to compete in the same market segment. Production of the bioenergy carrier is not modeled explicitly, but as a part of the bioenergy technology. The industries are only charged with capital costs up to the current production level. The costs of capacity expansion are amortized, though the full costs are only included in the year of expansion, as the costs are considered as sunk costs in later periods.

Demand is a linear function of price and GDP. The elasticity of demand with regard to price and GDP are assumed constant across Norwegian and foreign regions, but vary by product. For final forest industry products,[5] price elasticity in the base year point varies between -0.3 and -0.9. Since bioenergy constitutes a minor share of the heating market which is dominated by electricity and oil, bioenergy production is assumed not to impact the price, and the elasticity of demand is therefore perfectly elastic. The elasticity with regard to GDP for paper and solid wood products is between 0.5 and 1.

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[5] Final forest industry products are here defined as sawn wood, paper and board products.

In the NTM II, there are 19 domestic and two foreign regions. The domestic regions are similar to the counties[6], and the two foreign regions are Sweden (the part which is close to the Norwegian border and has extensive trade crossing the border) and the "Rest of World" (ROW), which is constituted by the main forest industry trading partners. These two regions are basically treated as the domestic regions regarding harvest, industrial production and consumption, though less detailed. The elasticity of timber supply with regard to price in foreign regions is 1.5, compared to 0.3-0.6 for the Norwegian regions.

NorFor

Two different versions of NorFor have been applied in the thesis. First, the version used for Paper II is described, and then the changes done for Paper IV.

The structure and data for the industry and consumption in NorFor are almost identical to the NTM II, except for the capacity constraints and the demand function. The fundamental differences lay in the modeling of forest management and the timber supply as well as the assumption of foresight.

The forest growth and management parts are from Gaya, a stand simulator parameterized to Norwegian conditions (Hoen, 1990). The structure for integrating the yield tables into the optimization problem is built upon the regional models of Oregon (Adams and Latta, 2005; 2007).

The model projects annual forest management measures undertaken, harvest, production, consumption and trade in five-year periods for a horizon up to 50-100 years. It maximizes the net present value of the integrated demand function for final products plus amenity values plus the integrated demand function for logs and manufactured products in the foreign regions, minus the integrated supply functions for logs and manufactured products in the foreign regions and for (domestic) harvest residues minus the costs of harvest, silviculture, transport, capacity and other production factors for all periods simultaneously. All supply and demand functions, with the exception of the harvest residue supply which is a linear function, are constant elasticity functions. Due to the size of the model, the supply and demand functions are piecewise linearized by the use of separable programming (Hadley, 1964).

In NorFor, the inclusion of forest growth and management is done in two steps: first, forest growth simulations are carried out for existing stands and regenerated stands in the stand simulator Gaya (Hoen and Eid, 1990). Thereafter, the yield tables are imported to NorFor and included in the optimization problem. The choice of management regime for existing and regenerated stands, in addition to the timing of final harvest are done in

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[6] Domestic regions equal counties, with the following exceptions due to large variations in forest resources and industry: Oslo and Akershus are one region, Hedmark and Oppland are both divided in two regions and Finnmark is excluded.

NorFor. The simulated plots are the National Forest Inventory (NFI) plots of close to all of the productive Norwegian forests (close to 9000 units), which are kept disaggregated throughout the entire optimization.

As described by Hoen (1990), a set of criteria are selected for each management activity in Gaya. For instance for thinning, a certain share of the trees are taken out, which will happen if all the stand criteria such as species, height, volume and age are met. A set of mid-rotation activities that together can take place within one rotation for a stand (between regeneration and final harvest) is called a management regime.

Timber growth is simulated for various management regimes for existing stands, i.e. stands not yet undergone final harvest . For this paper, the growth was simulated for up to seven management regimes, depending on the stand conditions[7]. In addition, simulations of various regeneration schemes and management regimes for harvested stands were carried out in Gaya. These two sets of yield tables, existing stands and regenerated stands, were imported into NorFor, where a management regime is chosen for each hectare and the final harvest decision is made. Once harvested, a management schedule for the regenerated stands is selected among the alternative regeneration schedules and management regimes. This is repeated each time an area is clearcut. Hence, the yield tables for each rotation are kept separate throughout the entire optimization. The regeneration scheme include method (natural, under seed/shelter, planting), species composition and density, whereas the management regimes are identical to the existing stands. Except for the seed and shelter wood cuts, where the regeneration depends upon the conditions in the previous stand, conditions in the regenerated stands are independent of the old stand conditions. Consequently, with these exceptions, the forest management model is “Model II,” as defined by Johnson and Scheurman (1977), but instead of having a common pool for all stands harvested in a certain period, there is a pool for each plot to which clearcut areas go after harvest. To leave a stand without regeneration is not an option, but no mid-rotation activities (after regeneration) is a possible management regime for all stands. In the optimization, "never clearcut" is an option for all stands.

The species composition may be altered by regeneration and precommercial thinning, while in thinning and final harvest, species composition in the withdrawal is the same as in the stand. The yields are simulated for sawlogs and pulpwood of spruce, pine and birch. The pulp share is a function of species, diameter and height, as well as the assumed price differences between sawlogs and pulpwood (Blingsmo and Veidahl 1992). In addition, sawlogs may be graded down to pulpwood.

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[7] Forest management regimes were precommercial thinning favoring conifer; precommercial thinning favoring broadleaves; thinning; precommercial thinning favoring conifer and thinning; precommercial thinning favoring broadleaves and thinning; shelter wood cut/seed tree cut and no management.

Production functions for the forest industry in the model used in Paper II are mostly the same as in the NTM II, although the capacity was modeled differently. A low depreciation rate, 8% over five years, is added for all capacity. The industry chooses whether to reduce capacity down to the depreciation rate, maintain all or parts of the capacity to avoid depreciation or to build new capacity, which is more expensive. The capacity expansion constraints were much more relaxed compared to the NTM II.

In the model applied for Paper II, the two foreign regions from the NTM II are merged into one and domestic regions are modified to be identical to the counties, while Finnmark is still not included.

Compared to the version used in Paper II, much of the data are new, whereas the overall structure is kept the same for the version used in Paper IV. The structure and data documented in two reports (Sjølie et al., 2011; Trømborg and Sjølie, 2011, respectively) refer to the version of the model used in Paper IV.

The basis for the harvest decision is extended compared to the previous version. The forest owners are assumed to maximize their utility from the forest, not merely the profit, and the optimal rotation age is therefore prolonged compared to only profit-maximizing behavior (Hartman, 1976). The utility rising from the nonmonetary part here consists of amenity values from having old forest. This inclusion was done because as in several empirical studies (Amacher et al., 2003), it was observed in the model that forest owners do not have the same required rate of return as the industry, i.e. running the model with a high discount rate resulted in too high harvest levels. However, since having different discount rates in different parts of the sector led to technical problems and adding amenity values impacts the optimal harvest and timber stock levels in a similar way as decreasing the discount rate (Gan et al., 2001), the same discount rate was used for the entire sector, and an amenity value was added.

In the forest growth and management part, various planting densities are included as possible management options. Planting costs are a function of planting density, but only one-third of the silviculture costs are included since investments in forestry are subject to a large tax deduction (Norwegian Agricultural Authority, s.a.). The costs of silviculture and harvest are included as described by Hoen and Gobakken (2004) and Trømborg and Sjølie (2011). All costs are fixed, but logging costs vary by region and type of harvest.

County-level linear supply functions of harvest residues, developed by Rørstad et al. (2010) and described in Trømborg and Sjølie (2011), are included.

The forest industry data are partially updated; capacities are fully updated and a depreciation rate of 68% over five years is used in this paper, while production functions are modified where new data are available. The structure of the paper, pulp and board mills are kept the same, but only one production technology for each species is included for sawmills, compared to “large” and “small” sawmills in the previous version. The set of manufactured forest industry products are kept similar to the NTM II. Figure 3 displays the aggregated product flows.

The largest changes are in the bioenergy part, in which structural changes and new data are incorporated for production, capacities, technical potentials and demand. In total, six bioenergy products are included in the model: space heating, waterborne heating, waterborne heating and steam to industry, energy in forest industry, bio-electricity and biofuels. For the current run, the three latter products are excluded. One or several technologies exist for each product: wood stove and pellets stove can both be used to produce space heating, while local heating centrals (fueled with chips or pellets) and district heating centrals (chips) produce waterborne heating. District heating installations are divided into existing installations, which can be expanded, and new ones that can be built with higher capital costs. The technical potentials up to the year 2020 for existing district heating and local heating installations are included.

The bioenergy price is linked to the electricity price, which due to its large market share, is assumed to be the main driver for bioenergy demand. The electricity grid capacity constraints and transmission costs cause differences in the electricity price between regions, and the demand for bioenergy is highest in the winter season when electricity prices are at their highest. Moreover, the electricity price varies between different consumer groups, since households for instance are charged with an electricity tax. All of those aspects are included in the market heating price, which varies by region and consumer group. The elasticity of demand with regard to the price is set to -0.7 for bioenergy, thereby reflecting that increased use may have costs for the consumer, even though the price impact of higher production may be small.

Demand is a function of GDP and price. The IPCC’s A1 scenario for GDP growth, coupled with a region-specific population growth scenario (Statistics Norway “middle” scenario), are used as a proxy for GDP growth in domestic regions.

Compared to the first version of the model, another foreign region and Finnmark county are included, meaning that the total number of regions is now 21. Domestic regions now equal the counties, and the foreign regions are Sweden and ROW. The counties of Oslo and Finnmark have only consumption and no forest or industrial production. The main difference to the NTM II lays in the representation of the foreign regions. Here, the foreign regions are pure trade regions, with no harvest or production modeled, and only the trade flows to and from Norway included in the supply and demand functions.

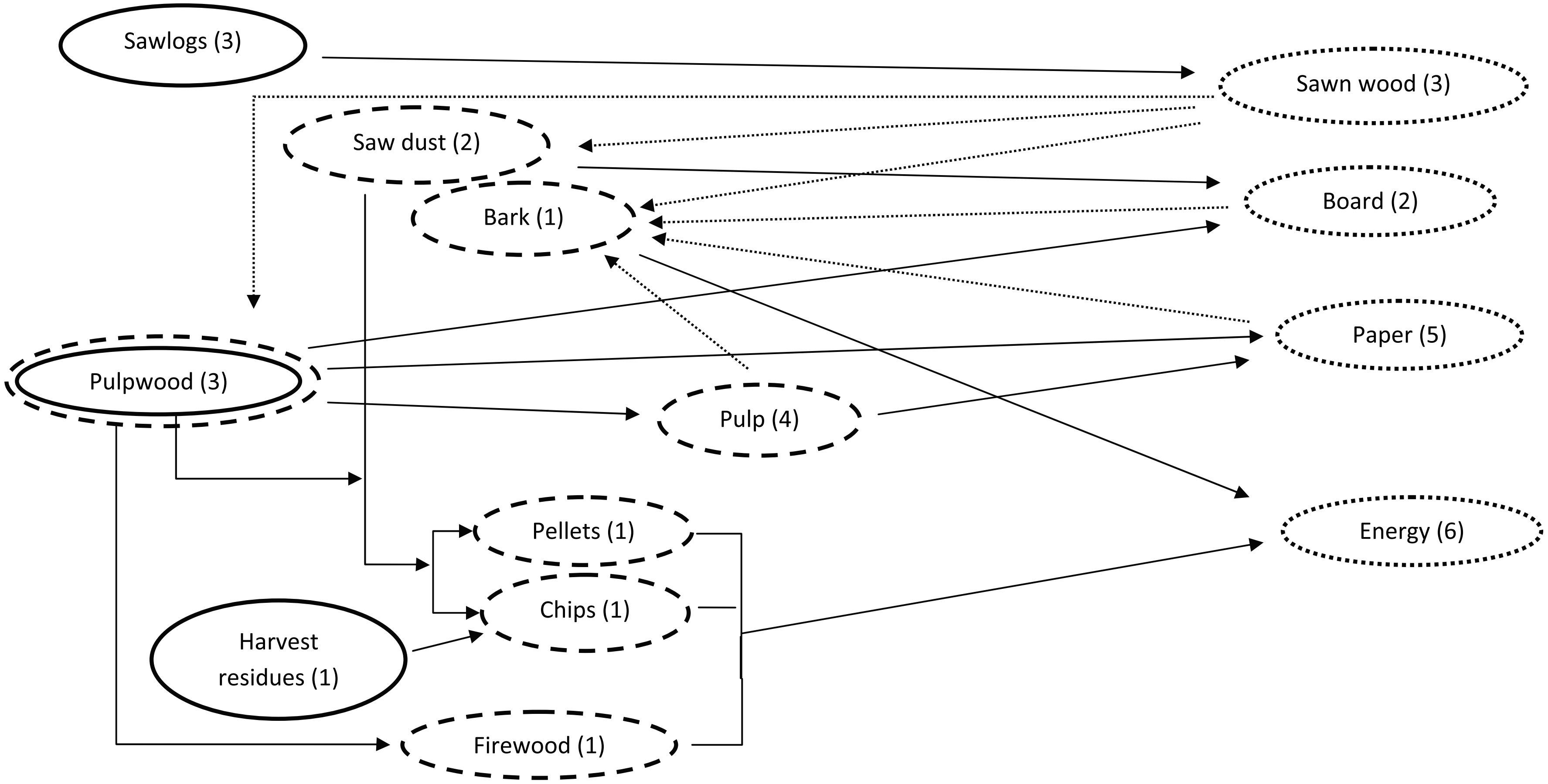

Figure 3: Product flow in the forest industry in NorFor. The solid circles refer to raw materials, the dashed to intermediate products and the dotted to end products. The lines refer to processes and the dotted lines to the production of byproducts. The numbers in parenthesis indicate the number of products in each group.

3.2 Biomass carbon accounting

In the calculation of costs and effects of policies to increase bioenergy production and reduce greenhouse gas emissions from heating in Paper I, upstream greenhouse gas emissions were included for bioenergy as they were for fossil fuels, based on previous LCA, in addition to the direct emissions in fossil fuel combustion. Bioenergy was seen as carbon neutral in this paper. The rationale behind this assumption is that the bioenergy stems from an area where the forest increment is larger than the harvests, which is the case for Norway.

An assessment of the impacts of increased use of wood pellets as a replacement for lignite in power plants on the European continent was carried out in Paper III. The analyzed case study is a pellets plant situated in the western part of Norway, where production was initiated in 2010. All major emissions from harvest, production, transport and consumption were included. A sensitivity analysis was performed, where assumptions regarding the production chain and replaced fuel were altered, and the carbon neutrality criteria were discussed.

In Paper IV, the following greenhouse gas fluxes in the sector were included in the model:

- In forestry, carbon fluxes of aboveground and belowground tree biomass based on biomass functions (Marklund, 1988) and decay functions for harvest residues left in forest based on Yasso (Liski et al., 2005; Raymer et al., 2009)
- Greenhouse gas emissions from the use of machines in silviculture, harvest and transport
- Emissions from processing in industry based on LCA data
- Carbon storage and substitution effects

It is unclear what materials sawn wood actually replaces, but it was assumed to replace half concrete and half steel, using the value of 0.796 tonnes CO_2eq/m^3 sawn wood (Petersen and Solberg, 2005). Bioenergy in space heating was assumed to replace half hydropower and half coal-based power, totally 0.379 tonnes CO_2eq/MWh, since the electricity in Norway is based on a mix of these sources. Bioenergy in waterborne heating was supposed to substitute for domestic heating oil, 0.301 tonnes CO_2eq/MWh. The expected lifespan of products was included based on Raymer (2005). Due to a general landfill ban of organic material in Norway, wood products going out of use were assumed to be combusted in waste facilities, and the heat supposed to replace an electricity mix of half hydropower and half coal-based power.

In the carbon policy study in Paper IV, the carbon flows values, given as differences between periodical carbon stocks multiplied by the carbon price, were included in the objective function.

4 RESULTS

Summary of Paper I: *Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway*

In Paper I, two policies targeting the heating sector were considered: a higher carbon tax on domestic heating oil and paraffin, and investments grants to district heating installations based on forest-based energy. Net greenhouse gas (GHG) emission impacts from replacing one energy unit of fossil fuel in heating with bioenergy were calculated. We compared the achievements, reduced greenhouse gas emissions and increased bioenergy production in district heating and central heating systems in 2020, with the costs of the policies. By applying the NTM II, factors regarding the spatial aspect, competition for the raw materials and profitability of bioenergy production were all included. The carbon tax ranged from 0 to 160 €/tonne CO_2eq in the scenarios, compared to the fixed energy price at 50 €/MWh. Two investments grant levels of 20% and 50% of total investment costs for new district heating installations were investigated.

According to our results, a carbon tax on fossil fuel had a considerable impact on the bioenergy production in district heating and central heating installations. While barely any production took place in the absence of a carbon tax, district heating production based on chips increased rapidly with rising taxes. However, at a carbon tax of 60 €/tonne CO_2eq, the technical potential was fully utilized. Pellets, which were more expensive, required a higher tax in order to become profitable. At the highest tax level, bioenergy production based on chips and pellets totaled 7.5 TWh, almost 20 times the actual production level at that time. The highest carbon tax level could reduce greenhouse gas emissions from fossil fuels in heating by 2.3 million tonnes CO_2eq/year, corresponding to 70% of the actual direct emissions in Norway from heating. About half of that reduction stemmed from district heating installations and half from pellets used in pellets stoves and central heating systems. Investment grants needed to reach 50% in order to have more than a marginal effect on the bioenergy production level. For scenarios in which subsidies were combined with a carbon tax, we found that the policy effects declined rapidly, and the costs increased correspondingly. This was due to that in the presence of the tax, bioenergy was already profitable and the additional effect of the subsidies was small.

To conclude, we found that the policy design is important in order to reach the desired targets (increased bioenergy production or decreased greenhouse gas emissions) and to reduce the costs. Subsidies to bioenergy will not necessarily decrease emissions from fossil fuels, as subsidies tend to lower the price to consumers and thus increase the consumption.

Summary of Paper II: *Impacts of agent information assumptions in forest sector modeling*

The degree of foresight, i.e. how much information about future market and policy conditions agents in the markets possess, is a crucial assumption in economic modeling. The range of foresight in forest sector models varies from no foresight at all beyond the current period (myopic models) to perfect foresight over the entire horizon. Forest sector models are often used to predict the impacts on the sector of changes in economic and policy frames, now or in the future. An exogenous future market shift will presumably have a different impact if the agents have knowledge about it beforehand compared to if they have not. According to economic theory, *a priori* knowledge of the shift will cause the agents to adapt from the period they have acquired this knowledge, since agents attempt to intertemporally maximize their utility or profit.

In this paper, we analyzed differences in behavior caused by a policy shift, depending on how long time beforehand the agents had knowledge about it. The hypothetical policy was a general import ban on all coniferous timber into Norway, beginning in 2020. Such a ban is possible if the Pinewood nematode (PWN) spreads to Northern Europe. This North American species is rather harmless to pines native to that continent, but mortal to Scots Pine, the most important European pine species. Conifer imports into Europe are strictly regulated as a result of PWN findings in imported chips loads from North America in the 1980s. However, the PWN has proved established in Portugal and has been found in Spain, and there is a fear that it will spread even further. Today, import of coniferous timber into Norway from Portugal and outside Europe is in general banned, unless particular measures as heat treatment or bark removal are taken. About 40% of pulpwood in the Norwegian market is imported from other Northern European countries, mostly from Sweden. This large import share presumably makes the pulp and paper industry sensitive to changes in trade conditions.

Using NorFor, we analyzed the impacts of the import ban starting in 2020 with three different assumptions regarding *a priori* knowledge: perfect knowledge (PK), i.e. the ban is known from the beginning of the run in 2010; Limited knowledge (LK), i.e. the ban is known from 2015; and No knowledge (NK), i.e. the ban is not anticipated. These runs were compared to the base case with perfect foresight and no ban.

We found that forest owners reduced their harvest levels by up to 5-6% before 2020 when the ban was perfectly anticipated. However, due to price increases over the entire horizon (also in the base case), forest owners also retained their timber after the ban to increase harvests in the last periods after 2045. Timber prices increased substantially in all scenarios, but much less so under PK than in the others. In the LK scenario, pulpwood prices increased by 9% for the period before the ban took place, implying a future scarcity. The production of sawn wood, pulp and paper was spared to the detriment of bioenergy, which had a lower profitability, lower capacity costs and a constant function for derived demand. The consumption of sawn wood was not affected much before later periods, and paper consumption was barely reduced. Under PK, the consumption of bioenergy, which equaled production, was reduced by up to almost 70% in the last periods, and by 6% in periods prior to the ban.

To conclude, we found adaptations to the ban in periods before its implementation when it was anticipated, but not of a very large magnitude. Fixed costs in the industry may have reduced the adaptation, and ten years anticipation time may be too short to see any large impacts. Price increases in the presence of the ban were large, but lower with more information, as more information smoothes out impacts of shocks. Nevertheless, more studies on this subject and the consistency between the various assumptions and the economy would be of great interest.

Summary of Paper III: *Greenhouse gas emission impacts of use of wood pellets - a sensitivity analysis*

Ambitious goals in renewable energy policies in Europe have triggered a rapidly growing demand for bioenergy. Pellets are demanded since their low volume to energy ratio makes them transportable even over long distances, and their homogeneity and dryness make them suitable for co-firing with coal without big technical changes. Pellets are also likely to be important in the future, as an increasing share of the bioenergy used in Europe is assumed to be supplied from abroad. This paper had two main objectives: the first was to analyze the greenhouse gas emission impacts from using pellets in power plants in Germany, which were produced in Norway based on imported forest chips from Canada. The second goal was to carry out a sensitivity analysis to study the importance of key assumptions with regard to the production chain, substituted fuel and carbon neutrality.

The carbon neutrality assumption was found to be the most decisive factor for the greenhouse gas emission impacts. Including all CO_2 emissions from pellets combustion and no carbon sequestration in forest resulted in substitution effects close to zero, as the carbon content per energy unit is about the same in forest-based energy as in coal. Furthermore, even if carbon neutrality was assumed, it was important to replace the most emitting fuels first. The substitution effect of replacing lignite in low efficiency power installations was found to be almost three times higher than substituting hard coal in combined heat and power installations. Total energy input in transportation equalled 11.6% of the energy content in the pellets. Many factors in the chain such as silviculture, construction of factory, electricity input in production, chipping, loading, unloading and ash handling had all an marginal impact on the overall emissions.

Regarding the carbon neutrality assumption, system boundaries and time frames were discussed. To claim carbon neutrality for bioenergy based on tree stems from final harvests, the time frame should be at least as long as the rotation age with a 0% discount rate of carbon flows, such that the point of time when emissions and sequestration takes place, is of no importance. The other extreme is to include all emissions but no carbon sequestration in forests after harvest, thereby implying that the time frame is very short or the discount rate very high. Often, the spatial condition, i.e. that the annual increment in the forest area has to at least equal the harvests, is used for claiming carbon neutrality. In forestry, many products are produced simultaneously, and raw materials for pellets are often by-products from sawlogs or sawn wood production. Thus, in these cases, the carbon account of pellets cannot be seen independently of the other forest products. To include a full account which varies along with the time frame, the growth and yield of the area supplying the wood, the use and fate of the other products and possibly the future growth if no harvests had been undertaken, should be included.

Simple calculations of cost-efficiency by comparing market prices of the replaced fossil fuels and pellets revealed that pellets may reduce greenhouse gas emissions to a cost of about 60 €/tonne CO_2eq. Yet, if paraffin is replaced instead of lignite or hard coal, the mitigation costs turn negative due to relatively expensive oil compared to pellets.

Paper IV: *Potentials and costs of climate change mitigation in the Norwegian forest sector*

In this paper, we used NorFor to assess the costs and potentials for climate change mitigation in the Norwegian forest sector. We ran two types of models, one with endogenous markets and one with exogenous markets. For both market models, eight scenarios were run, with a carbon price ranging from 100 to 800 NOK/tonne CO_2eq[8]. All positive and negative fluxes described in Chapter 3.2 were subject to this tax/subsidy. We also ran a base scenario with no taxes/subsides. 15 periods runs were done, of which ten (50 years) were analyzed. In the endogenous market model, no constraints other than those present in the base scenario were included. In the exogenous market model, the levels of imports and exports of timber and products and regional industrial production were fixed to base scenario levels. The results of these two model types were compared because many analyses of climate change mitigation costs and potentials in forestry assume fixed harvest and timber price levels, and therefore constrain the mitigation options in forestry. In addition, these studies do not consider the possible reallocation of wood in the industry caused by market changes, which may be an important mitigation strategy. Thirdly, as timber becomes scarcer, prices increase with two effects: the opportunity costs of keeping wood in forests rise which should cause the mitigation costs to increase, while at the same time, higher timber prices are an incentive to forest owners to invest more in forestry. We wanted to examine these aspects in more detail.

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[8] 100-800 NOK ≈ 12.5-100 €

One main result was that the mitigation costs were considerably lower and potentials much higher in the endogenous market model than in the exogenous market model. Potentials also increased over time, and according to our results, potentials would reach 10 million tonnes CO_2eq in 2055 with the highest carbon price level. The results also gave clear indications that mitigation measures were undertaken in several parts of the forest sector. In forestry, thinnings were dramatically reduced and harvests declined up to 20%. Rotation was prolonged, especially for the low site indexes. Natural regeneration for spruce was replaced by planting in order to reduce the waiting time.

Of the industrial branches, pulp and paper were the hardest hit, and production diminished by up to 15%. Sawn wood production was also negatively affected, but less so than for the pulp and paper industry. The production of sawn wood also increased again after the hit in the first period. Space heating based on firewood is the most important bioenergy commodity in Norway. However, the overall low efficiency of stoves reduced the use of firewood in the carbon price scenarios. Instead, waterborne bio heating with an efficiency of 80 to 90% gained large market shares. International trade was also impacted by the carbon policy. In the first period, pulp and paper exports declined by up to 25% in the highest carbon price scenario, whereas the imports of solid wood and timber increased by 15 and 20%, respectively.

We conclude that applying a model which simulates optimal forest management, harvests, industrial production, consumption and trade simultaneously is suitable for revealing the potentials and costs of climate change mitigation in the forest sector.

5 OVERALL SYNTHESIS AND DISCUSSION

5.1 What information can forest sector models provide us?

By analyzing three different types of policies in various modeling frameworks, one conclusion that can be drawn is that with behavioral assumptions such as those in the models, policies have important impacts on the forest sector.

Norwegian forests grow slowly, with the economic rotation age reaching 60-120 years. Hence, policies affecting the forest management are likely to have small market impacts over the next 10-20 years, as the timber available for supply in this timeframe is a function of past management. For that reason, if compared with the NTM II, NorFor will possibly not yield much more insight into the timber supply and forest sector markets in the short to medium term. Still, forest management and investment in forestry are definitely endogenous variables for the long run timber supply, and in this timeframe, NorFor projections can provide further information. NorFor can also be useful for studying carbon policies in the short run, as such impacts may appear quickly in both markets and carbon flows. For short run market analyses in which the periodical fluctuations are of interest, NTM II can provide more detailed results due to its shorter period length. The basic contrast in the foresight assumptions between the models and the timber supply representation can, however, also reveal differences in short model runs.

The magnitude of the discount rate exerts a large influence on harvest and investment levels, but various parts of the sector may have a different required rate of return. In NorFor, a 4% discount rate is used for all future costs and incomes. A 7% rate is used in the NTM II, but only applied to industrial investments. There are reasons to believe that forest owners and the forest industry have different requests regarding return on the capital, due to different risk considerations, management objectives and non-timber values. The required rate of return for forest owners in East and Mid-Norway, the two most important regions in terms of harvest quantities, has been reported to be around 2.6% p.a. (Nyrud, 2004). Nonetheless, a high discount rate plus amenity values have about the same impacts on the optimal timber stock and harvest as a low discount rate (Gan et al., 2001). For a public good such as carbon sequestration, a social discount rate should ideally be applied.

Foresight in forest sector models

We use economic models to obtain knowledge about the economic system and the agents' behavior. Thus, assumptions in the model should correspond well to the real economy. Myopic and perfect foresight models are both much used in forest sector modeling in particular, and in economic modeling in general. Perfect foresight has a stronger base in economic theory, but is nevertheless an extreme assumption and far from observed behavior. However, to assume that the future for the agents is only a "black box," and that expectations about the future do not impact on today's behavior, is a strong simplification and drastic reduction in the complex intertemporal utility maximization. Forest owners do have information about the size of the growing stock for the next year and that timber will have a value next year, even if the exact values are unknown. Depending on the nature of a policy or market change, the agents' true knowledge may be closer or further from perfect foresight. Compared to myopic models which have limited possibilities of adaptations to external changes, perfect foresight models adjust to changes from the first period, and hence reduce the price impacts of future changes. Perfect foresight models may therefore have higher demand and supply elasticities than myopic models (Adams and Haynes, 2007). As shown in Paper II, agents will reduce the intertemporal price differences by allocating more wood to periods with scarcity if they are assumed to have knowledge about it beforehand. Intertemporal optimization based on perfect foresight removes several existing market barriers which may indicate that the results are closer to potentials than forecasts. Perfect foresight models are to a smaller degree than myopic models based on econometric relations. Based on market observations, econometric relations contain much information and may provide useful insights into market behavior, though they may have limitations if applied outside historical ranges.

If the Pinewood nematode is found in Sweden for instance, the risk of serious problems for Norwegian forests would probably be so high that an immediate ban would be put into effect, and the agents would not be given five or ten years to adapt. The analyzed ban with the various degrees of foresight is definitely hypothetical, but some of the results may still be valid for other policies. In the economy, agents frequently face shifts in market and policy factors with various degrees of knowledge beforehand. Such sudden or frequent changes have a cost for the agents in the economy since behavior may be suboptimal with the shift. Consequently, the results of this study can also be seen as indications of the costs of unforeseen policies or market shocks more in general. Such costs may be substantial, but seem not to have been studied much within the forest sector.

It should be noted that despite the fact that we studied the importance of the foresight time length, we have not addressed the issue of uncertainty. Deterministic models do not take into account the uncertain nature of the economy and policy, as well as of biological development. Particularly for long-rang projections, uncertainty may have a very large impact. In the analyzed PWN case, the Norwegian forest sector behaves as if in the presence of the import ban, there is no risk that PWN could spread to Norway and infect Norwegian forests. Facing that uncertainty, different groups of forest owners could have different subjective probability distributions regarding the risk of PWN outbreak in Norway. One frequently applied method for studying the importance of uncertain factors is to perform a sensitivity analysis, Monte Carlo simulations or combinations of these. Monte Carlo simulations have not been used much in forest sector models, although Kallio (2010) is one exception.

Whether the perfect foresight assumption is a strength or weakness is a widely discussed issue. I will close this section with the following quotation reflecting some considerations: "Capitalist economies are complicated. A model is supposed to capture its central features, not reproduce it accurately. Decisions of individuals and firms today are based on future expectations, and are affected by past decisions. Individuals do not have perfect foresight or rational expectations concerning the future. The events which they confront often appear to be unique, and there is no way that they can form a statistical model predicting the probability distribution of outcomes. And there is little evidence that they even attempt to do so. At the same time, individuals are not myopic. They do not simply assume that the future is like the present. Markets are not perfect. But markets do exist" (Greenwald and Stiglitz, 1987 p. 131).

Forest management and timber supply

Where the NTM II has an econometrically specified timber supply curve based on historical data, the "real" timber supply curve is attempted specified in NorFor. The harvest in each period is a function of the specified biological and economic parameters for all periods due to the intertemporal optimization. Key economic parameters and variables are logging and silviculture costs, demand for non-timber services and the demand for timber derived from the demand for final products, as well as timber supply provided by the remainder of the market. Growth of existing and regenerated stands are decisive biological factors. The elasticity of supply with regard to price in the NTM II is based on studies where, in addition to the current price, the expected future price was included as a variable (Bolkesjø and Solberg, 2002). As a result, the supply elasticity with regard to price should give an unbiased relationship with the current price in the myopic model. However, since the elasticities are based on stumpage prices, but in the model are used for prices delivered at the regional center, they may be slightly too inelastic (Cardellichio and Adams, 1990). Logging costs are likely to increase with higher harvests, as timber in the most easily accessible areas are taken first. In the current NorFor model, logging costs are constant per m^3 for a given region and type of harvest (thinning, shelter/seed tree cut and final harvest). This simplification may make the timber supply too elastic and influence the harvest increase, as seen in the second period in Paper IV.

In NorFor, forest owners are assumed to maximize their utility from two factors, harvest income and old-growth forests. There has been a growing amount of literature (Amacher et al., 2003) over the last decades which shows that nonindustrial private forest owners have other objectives than pure profit maximization. Adding a value to old forests in the model may incorporate some of the values that forest owners assign to assets such as capital reserves, smoothed out harvest levels, landscapes values or hunting. Still, this utility function is an extremely simplistic way to represent all 120 000 forest owners in Norway who may have a range of objectives, from pure profit maximization to preservation. In future analyses, including several objective functions, representing various “types” of forest owners would be an interesting extension.

For each clear-cut hectare in NorFor, the forest owner selects a management regime for the harvested stand until it is clear-cut again. The selected management regime cannot be changed between harvests, but as in FASOM this should not constitute a large drawback, as long as the forest owners are assumed to optimize the management over the entire horizon (Adams et al., 1996). Representing all the NFI plots has several advantages. First, we avoid the aggregation problem. Also, as discussed by Adams and Haynes (2007), distributional effects of policies can readily be studied with such a feature as well as climate change impacts, which may differ between sites.

In forestry, plant breeding at nurseries gives enhanced plant seedling growth. If this development continues, leading to future planted seedlings growing faster than today’s seedlings, the model may underestimate future growth and hence carbon sequestration. Introducing genetically modified seedlings has the potential to boost plant growth even further. Fertilization of forests is not incorporated in the model at the current stage, but as shown by Hoen and Solberg (1994; 1999), fertilization has a strong effect on carbon sequestration and could be included in future studies.

Modeling industry and demand

One general difficulty in making long-range predictions is that the data we are using as the basis for predictions are necessarily based on the past. Depending on the time frame and the speed of changes in the sector, this may be a smaller or larger problem. When we try to forecast the forest product markets for the next thirty to fifty years, we undoubtedly encounter problems related to the development of technology and demand patterns.

Technological change is continuously taking place in industry, but is difficult to model due to its uncertain and nonlinear nature. New technologies may drastically reduce the costs of processing or change the input mix. As pointed out by Bright (1978), according to Skog (2007), technological changes may be implemented as extrapolated trends, appearing innovations and expected reactions to changes in economic frames. As of today, the input mix in the two models is fixed for each paper and board mill but varies between mills according to the data, implying that the relative production levels in the mills will change if some input mixes become more profitable than others in the future. Wood species are substitutes as inputs to the bioenergy carriers in NorFor, although increasing the substitution possibilities could improve the model.

Compared to the NTM II, production functions for sawmilling in NorFor have been aggregated from two ("large" and "small," i.e. capacity above and below 25 000 m^3) to one. Limited access to data did not provide a basis to differentiate on size, but regarding the results in Nyrud and Bergseng (2002), only one technology may not represent existing large-scale advantages well. With better data in the future, the number of technologies may be increased.

Technological changes in the utilization of wood products, and the processing and utilization of competing and complementary products as well as changes in consumer preferences impact all on demand beyond GDP growth. Those aspects may be included in the elasticities of demand with regard to price and GDP. Again, those parameters are fixed over time, which clearly is a simplification seen for instance in the newsprint markets over the last few years. However, forecasting demand trends is possibly even more difficult than predicting technological changes in the industry, and should probably be limited to scenarios in forest sector models. Except for the bioenergy markets, in which several technologies are perfect substitutes for each other, demand for the various final products operates completely independent of each other in the models described here. Improving the possibilities of substitution between those products could make the demand functions more realistic (Cardellichio and Adams, 1990).

Paper is a global commodity, with market conditions in Europe and other continents affecting the Norwegian market. Together with huge investment costs for new paper mills, this makes the investment decisions in the pulp and paper sector rather complex. A regional forest sector model of the type of NorFor or NTM II may therefore not be well suited for forecasting large capacity changes within this industry. Thus, as with demand, paper production capacity may preferably be based on scenarios.

It should be added that due to the linearity of NorFor, new investments cannot be forced to be of a certain size, such as the representation of a new paper machine. The practical implication is that when demand increases, capacity is adjusted upwards in "steps." However, when taking into consideration upgrading, smaller investments and an increased number of work shifts, it is not sure that this will cause maladjustments in the model runs.

International market and trade

Norway is part of an international market for timber and wood products, with a considerable amount of import and export. For example, between 30 and 40% of the pulpwood in the Norwegian market is imported, and Norway exports a large part of its paper production. How international trade is treated in the models exerts an influence inter alia on policy impacts. At least to a certain degree, Norway can be considered as a price taker, with domestic prices equaling international prices adjusted for transportation costs. Particularly for pulp and paper products, markets are highly international, with trade crossing continents (Nyrud et al., 2004). Due to the European CE standard for sawn wood (Steiner and Nyrud, s.a.), there are few formal barriers today for international trade within the European Economic Community, though sawn wood trade between continents is limited by different quality system requirements (pers. comm., Øvrum, 2011). With the exception of pellets, bioenergy carriers are quite bulky and therefore more locally traded. International trade is more constrained for timber than paper for reasons of forest hygiene (see for instance Paper II), and high water content makes timber transportation more expensive. Foreign supply and demand for timber may therefore be assumed less elastic than manufactured products. To implement more of the price-taker role in the model, scenarios with varying foreign demand and supply prices can be run to study their impacts on the Norwegian market. A "middle way" between a price-taker representation and a model where foreign and domestic regions in the model have the same impact on the prices, is a specification of more elastic supply and demand functions in the international region to dampen the price impacts of domestic market changes. This was to some extent done in both NTM II and NorFor. Nevertheless, it would be of great interest to have more data on the elasticities of supply and demand both from and to foreign markets.

By default, all associated costs are included in the transportation costs. Although due to the consolidation in the pulp and paper industry and the high transportation costs of timber, there may be local monopsonies carrying out market power by discriminating against wood suppliers located close to the mill and paying them less in order to subsidize purchases further away (closer to other competitors). If so, there are reasons to believe that only about half of the transportation costs are actually reflected in the price to the forest owner (Trømborg, 1999).

Bioenergy demand

The heating market in Norway is dominated by domestic heating oil and particularly electricity, with bioenergy constituting less than 20% (Paper I). It was assumed in the NTM II that bioenergy production does not influence the heating price because of this relatively minor share in the market. Further, bioenergy and other energy carriers used for heating were considered to be perfect substitutes. Hence, the heating price was defined with a perfectly elastic demand curve. It was realized that this assumption caused unrealistic leaps in bioenergy production when the heating prices for which the different bioenergy technologies become profitable were reached. The perfect substitutes assumption was also questioned, as consumer preferences and differences in time consumption (i.e. heating with firewood requires more work from the consumer than an electric wall heater) may indicate that different energy carriers give different utility. In incorporating new data and bioenergy structure in NorFor, the bioenergy demand function was therefore revised. Bioenergy in space heating, such as in wood and pellets stoves, is probably the market segment that competes most directly with electricity since there are few other alternative heating sources. Waterborne heating in Norway is fed with a range of energy inputs such as various fossil fuels, bioenergy and waste, and its main market is the service industry (Statistics Norway, 2010c). This price typically follows electricity price patterns, while being a little lower (Trømborg and Sjølie, 2011). Manufacturing industries have substantially lower electricity prices than other consumers (Statistics Norway 2010d), and only constitute a small market potential for bioenergy. The bioenergy prices in the model used in Paper IV are a function of the electricity price in each region, adjusted for market segment, consumption and price patterns throughout the year. However, it would possibly reflect the heating market even better if prices and potentials for each season were included.

5.2 To sink or to burn the Norwegian forests?

A reduction of the atmospheric concentration of CO_2 is a global good, and where the reductions take place is indifferent. Therefore, if not considering other factors, mitigation measures should take place where in the world costs are the lowest, whether they are in the forest sector or in other sectors. In Paper IV, we found strong evidence that the Norwegian forest sector can contribute to climate change mitigation, and that the associated costs can make mitigation strategies in this sector interesting. Nonetheless, the costs of bioenergy policies found in Paper I and Paper III imply that mitigation in the stationary heating sector may be rather expensive, but depends to a large degree on the assumed prices of replaced fuels. Approaches and mitigation options in all these papers are very different, but when attempting to compare the results of Paper I and Paper IV, some key differences in the approaches may explain some of the large variation in results. Firstly, the study in Paper IV employs the entire forest sector for mitigation, and emission reduction and carbon sequestration takes place where it is cheapest, compared to the Paper I study, which only addresses a rather narrow range of mitigation options in waterborne heating systems and paraffin/pellets stoves. Secondly, the representation of the bioenergy market was completely changed from Paper I to Paper IV, and we believe it is better represented in the latter paper, with more detailed costs and potentials and a closer connection to the electricity market for various regions and market segments to help avoid large leaps with small changes in the carbon price. In Paper III, we analyzed a real production chain with possible variations, and compared emissions from this chain to the market prices of fossil fuels and pellets. Thus, the chains investigated in Paper III are likely to contain a more exact representation than the various production chains represented by LCA in Paper I. However, the findings of these two papers are to some degree contradictory concerning the costs of increased pellet use in Norway to replace heating oil. Despite lower prices on domestic heating oil and paraffin in Paper III than in Paper I (36 €/MWh compared to 50 €/MWh), the replacement of domestic heating oil with pellets cost from 80 €/tonne CO_2eq and up in Paper I, while the costs were negative in Paper III. One important reason for this difference is the assumed price of pellets. The current European market price was used in Paper III (27 €/MWh), and added costs for producing pellets in Norway in Paper I (65-80 €/MWh), which also included capacity costs. Paper I also includes the competition for fiber, whereas no competition aspects are included in Paper III. The different results underline the importance of the model's assumptions and specifications.

Even if the carbon neutrality assumption is convenient for life cycle assessments of bioenergy and may yield useful estimates, this simplification may lead to a large underestimation of the actual emissions in some cases. On the other hand, including all CO_2 emissions from bioenergy combustion leads to a large overestimation. The time dimension in forestry and the important site-specific parameters (Schlamadinger and Marland, 1996) make proper carbon accounting of forest-based energy difficult. Simultaneous productions of several products and market dynamics that can shift timber already in the market to bioenergy, further increase the complexity of this issue. A framework or methodology for including those aspects in a bioenergy emission account based on a global consensus does not exist. Forest sector models as NorFor may be useful tools here.

Other studies have found that the greenhouse gas emission impacts of various mitigation options in the forest sector depend to a large degree on the specific parameters, and that more generalized conclusions are difficult to draw. Schlamadinger and Marland (1996) found that the obtained carbon benefits of storing carbon in forests versus increasing the harvest to displace fossil fuels is highly dependent on the growth rates, the efficiency of wood processing and use and the displacement rates, as well as the time dimension. Valsta (2007) found the discount rate to be of crucial importance for whether carbon sequestration or the displacement of fossil fuels is the most beneficial, in addition to avoided emissions and the costs of emissions.

Harvests were in Paper IV reduced up to a maximum of 20% in the highest carbon price scenario. 800 NOK/tonne CO_2eq corresponds to about 600 NOK/m^3 (more if including the carbon content in other biomass parts), which is well above current sawlog prices, thereby implying that such a carbon policy has large impacts on the economy in forestry. Mitigation measures were taken in all parts in the forest sector. Reducing thinning is one way to quickly increase carbon sequestration above baseline. Together with altering regeneration schemes, forest management can substantially enhance carbon sequestration.

Reallocating wood already in the markets is another obvious mitigation option. As pulp and paper have no substitution effects in the model and relatively high greenhouse gas emissions from processing, this industry becomes vulnerable to carbon policies. Bioenergy should be combusted in installations with high efficiency when CO_2 emissions from bioenergy have a cost. The utilization of bioenergy and wood in construction as climate change mitigation measures depend on a crucial factor: that the increased use of wood actually displaces fossil fuels and other materials, and does not come in addition. In the model simulations, substitution is assumed to be one-to-one, which may be too optimistic. There seems to be a lack of data on substitution rates, but this is definitely a parameter which deserves further investigation. One first step may be to conduct sensitivity analyses in NorFor to assess the importance of this assumption.

To conclude, the answer to whether the Norwegian forests should be "burned or sunk," is of course not an "either-or." First, this is highly dependent on the carbon price. A low carbon price has a small impact on industrial production, as the product value is still relatively higher. Second, it is contingent upon the mitigation possibilities. Technical potentials in waterborne heating limit this mitigation option in Norway. Third, it depends on the time frame and when the mitigation ought to take place. Should we try to reduce the atmospheric carbon content as much as possible over the next few decades, or is the challenge how we can change the direction into a renewable energy path? Varying the carbon price over time could reflect some of these considerations.

5.3 Uncertain and omitted factors

Even if we found evidence that changes in forest management may lead to increased carbon sequestration, it is important to emphasize that the timber and carbon values studied here are only parts of the benefits to society that forests provide. Internalizing only the carbon value, and not values such as biodiversity, recreation and landscape, could possibly decrease the values of some of these other factors (Caparrós et al., 2007). On the economic side, the analysis disregards factors such as the local economy and jobs, as well as the distributional impacts of policies.

It was found in Paper IV that a high carbon price would have a large impact on the growing stock. The carbon storage in the growing stock expanded by almost 40% in 50 years in the highest carbon price scenario, with the growth being close to linear. The mortality functions (Eid and Tuhus, 2001) are based on NFI data with various sites, forest structures and treatments. Since the data contain few plots of forests older than 120-130 years, they may underestimate the mortality rate in old stands (Eid and Øyen, 2003). High density in the presence of high carbon prices may further add to the risk. In addition to the mortality rate, a possible quality reduction in very old stands may reduce the sawlog share and hence both the economic and carbon values. The risk of catastrophes in the forest naturally leads to a shorter optimal rotation age in a stand producing timber and carbon benefits, and the reduction is greater with a higher carbon price. Thus, including risks in the forest could dampen the effects of carbon prices (Stainback and Alavalapati, 2004).

Several factors which may influence the carbon sequestration rates and costs in the forest sector are not included in the analyses. Betts (2000) showed that the reduced albedo effect[9] may be so large that it offsets half of the avoided warming due to sequestration in forestation projects in boreal forest areas. This may imply that keeping old forests is less efficient for reducing global warming than the results in Paper IV indicate. Bonan (2008) argued that effects from both albedo and fire should be considered in forest and climate change analyses. To the best of my knowledge, no studies have combined both these factors with forest sector mitigation analyses to look into the total impacts, albeit Thompson et al. (2009) included albedo effects in a carbon tax/subsidy scheme in a stand level analysis.

Climate changes may have large impacts on the boreal forests, but in the present models a continuation of the current climate is assumed. Pussinen et al. (1997) applied a forest simulation gap model which includes climatic variables, and found that a temperature increase (with a corresponding precipitation change) of 0.1°C would expand the carbon pools in both forests and products in Finland. If the temperature rises 0.4°C or more, the carbon storage in the forest sector would be reduced.

5.4 Future research

The development of NorFor makes possible improved analyses of the Norwegian forest sector. It also clears the ground for possible future extensions, both within the model to make it more flexible and to increase the range of policy and market changes which can be analyzed, as well as linking it to other models. In the model, replacing the stand simulator with a single tree simulator would lead to a more realistic modeling of growth, mortality and harvests. Also, such a model would simulate the management of multi-aged stands better than a stand simulator with only a single age class in each stand.

Today, the plots are allocated on regions, but combining the stand features with a GIS analysis would provide an exact location of each plot to help single out stands impacted by the various scenarios. Information about slope gradient, terrain difficulties and terrain transport length are available from the NFI, and the model could therefore be extended with site-specific logging costs.

For the study of greenhouse gas impacts by increased taxation of fossil fuels in heating (Paper I), we used LCA data of bioenergy (Raymer, 2006) to include the upstream emissions. Those data were obtained for Norway, and it can therefore be assumed that they represent well the actual emissions. Still, to improve the accuracy of this study, most of the upstream emissions could have been calculated directly by using the actual

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[9] Albedo is the fraction of light which is reflected from a surface. A surface which absorbs all the light therefore has an albedo of 0, while a surface from which all light is reflected has an albedo of 1 (Encyclopædia Britannica, 2011). A reduced albedo due to, e.g. changes in vegetation, may increase global warming.

activity levels related to bioenergy use, such as harvest, transport and processing, in combination with emission rates. In the same way, other emissions and resource uses related to the forest sector could have been investigated by applying NTM II or NorFor. NOx emissions have already been studied (Trømborg et al., 2009). Water consumption in industry and emissions to watersheds are other issues that could be analyzed.

Carbon accumulation in dead wood and soil is included, although not changes caused by forest management. Emissions from soil disturbance during harvests could possibly affect the optimal rotation age. Including this factor would require data more reliable than what we currently have available on soil processes with different types of management, species composition, etc. Correspondingly, if data become available, it would be of interest to include carbon in understory vegetation.

As of today, functions of non-timber inputs (labor, energy, capital and "other") in the processing are all perfectly elastic. However, as discussed and analyzed for land and capital by Adams et al. (1998), this assumption may be incorrect and give misleading results such as too rapid adaptation to external changes. Instead of a perfect capital market, agents may face restrictions concerning budget limitations, lumpiness, etc. The forest sector's little importance in the Norwegian economy is an argument to have inputs as capital and labor exogenously defined, though this may be a simplification. Small communities where forest industry is a large employer and higher labor costs when increasing the number of shifts are arguments for price-sensitive labor costs, at least in the short run. However, the importance of this factor is probably modest in Norway.

Gaya has already been applied to study the economic impacts of stricter biodiversity measures on the local level (Bergseng et al., 2008; Solberg et al., 2008). Such studies would have been of great interest on a regional or national level as well, but require data sets with the location of areas of high biological interest, and how those areas may be managed. Yet, including measures to improve biodiversity and recreational values can also be done in a less detailed way, using data available from the NFI as proxies for such values.

Optimal allocation of land is simulated in the model, but as of today this is limited to productive forest land. Marginal agricultural land does not constitute large areas in Norway, but could nevertheless be included as possible areas for afforestation. The afforestation of lands currently not in economic use seems to have particularly high potentials and low costs with regard to carbon sequestration (Norwegian Climate and Pollution Agency, 2010).

NorFor could also be linked with other models, e.g. to forest sector models in other countries or models of adjacent sectors. Good candidates are the energy sector, transport sector or other land-use sector models. National models are rather sensitive to the magnitude of export and import elasticities, and by applying a global model such as EFI-GTM, more realistic estimates of these elasticities can be obtained.

REFERENCES

Adams, D.M., 2007. Solid wood - Timber Assessment Market Model (TAMM). Chapter 3 in: Adams, D. M., Haynes, R. W. (eds.). Resource and Market Projections for Forest Policy Development. Twenty-five Years of Experience with the US RPA Timber Assessment. 589 pp. *Managing Forest Ecosystems* 14. Springer

Adams, D.M., Haynes, R.W., 2007. The utility of forest sector models in addressing forest policy questions. Chapter 17 in: Adams, D. M., Haynes, R. W. (eds.). Resource and Market Projections for Forest Policy Development. Twenty-five Years of Experience with the US RPA Timber Assessment. 589 pp. *Managing Forest Ecosystems* 14. Springer

Adams, D.M., Latta, G.S., 2007. Timber Trends on Private Lands in Western Oregon and Washington: A New Look. *Western Journal of Applied Forestry* 22(1): 8-14

Adams, D.M., Latta, G.S., 2005. Costs and Regional Impacts of Restoration Thinning Programs on the National Forests in Eastern Oregon. *Canadian Journal of Forest Research* 35(6):1319-1330

Adams, D.M., Alig, R.J., McCarl, B.A., Callaway, J.M., Winnett, S.M., 1999. Minimum Cost Strategies for Sequestering Carbon in Forests. *Land Economics* 75: 360-374

Adams, D.M., Alig, R.J., McCarl, B.A., Winnett, S.M., Callaway, J.M., 1998. The effects of factor supply assumptions on intertemporal timber supply behavior: the cases of investable funds and land. *Canadian Journal of Forest Research* 28: 239-247

Adams, D.M., Alig, R.J., Callaway, J.M., McCarl, B.A., Winnett, S.M., 1996. The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications. *Research Paper* PNW-RP-495 September 1996 USDA Forest Service, Pacific Northwest Research Station. 30 pp. + appendix

Adams, R.M., Adams, D.M., Callaway, J.M., Chang, C.C., McCarl, B., 1993. Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets. *Contemporary Policy Issues* Vol. XI: 76-87

Adams, D.M., Haynes, R.W., 1986. A spatial equilibrium model of U.S. forest products markets for long-range projection and policy analysis. Page 73-87 in: Kallio M, Andersson ÅE, Seppälä R, Morgen A (eds.). System analysis in forestry and forest industries. *Studies in Management Sciences* 21. TIMS Elsevier (North Holland)

Alig, R., Latta, G., Adams, D., McCarl, B., 2010. Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices. *Forest Policy and Economics* 12: 67-75

Alig, R., Adams, D., McCarl, B., Callaway J.M., Winnett, S., 1997. Assessing Effects of Mitigation Strategies for Global Climate Change with an Intertemporal Model of the U.S. Forest and Agricultural Sectors. *Environmental and Resource Economics* 9: 259-274

Amacher, G.S., Ollikainen, M., Koskela, E., 2009. Economics of Forest Resources. The MIT Press. Cambridge, Massachusetts and London, England

Amacher G.S., Conway, M.C., Sullivan, J., 2003. Econometric analyses of nonindustrial forest land owners: Is there anything left to study? *Journal of Forest Economics* 9: 137-164

Backéus, S., Wikström, P., Lämås, T., 2005. A model for regional analysis of carbon sequestration and timber production. *Forest Ecology and Management* 215: 28-40

Barker, T., Bashmakov, I., Alharthi, A., Amann, M., Cifuentes, L., Drexhage, J., Duan, M., Edenhofer, O., Flannery, B., Grubb, M., Hoogwijk, M., Ibitoye, F. I., Jepma, C. J., Pizer, W.A., Yamaji, K., 2007: Mitigation from a cross-sectoral perspective. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Bergseng, E., Ask, J. A., Framstad, E., Gobakken, T., Solberg, B., Hoen, H.F., 2008. Biodiversity protection and economics in long term boreal forest management - a detailed case for the valuation of protection measures. In: Bergseng, E. Analyses of Norwegian forest policy: cost sharing, biodiversity and conflicts. PhD thesis 2008: 24, Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management

Bethel, J.S., Harrell, C., 1957. The Application of Linear Programming to Plywood Production and Distribution. *Forest Products Journal* 7: 221-227

Betts, R.A., 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo *Nature* 408: 187-190

Blingsmo, K.R., Veidahl, A., 1992. Funksjoner for bruttopris av gran- og furutrær på rot. *Rapport fra Skogforsk* 8/92 [Norwegian Forest Research Institute] [in Norwegian]

Bolkesjø, T.F., 2005. Projecting pulpwood prices under different assumptions on future capacities in the pulp and paper industry. *Silva Fennica* 39(1): 103-116

Bolkesjø, T.F., 2004. Modelling supply, demand and trade in the Norwegian forest sector. Dr. Scient. thesis 2004: 10, Agricultural University of Norway (Norwegian University of Life Sciences), Department of Ecology and Natural Resource Management

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2006. Bioenergy from the forest sector: Economic potential and interactions with timber and forest products markets in Norway. *Scandinavian Journal of Forest Research* 21(2): 175-185

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2005. Increasing forest conservation in Norway: Consequences for timber and forest products markets. *Environmental and Resource Economics* 31: 95-115

Bolkesjø, T.F., Solberg, B., 2002. A Panel Data Analysis of Nonindustrial Private Roundwood Supply with Emphasis on the Price Elasticity. *Forest Science* 49(4): 530-538

Bonan, G.B., 2008. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Nature* 320: 1444-1449

Bright, J. R., 1978. Practical technological forecasting. Industrial Management Center, Inc, Austin, Texas, U.S.

Bright, R. M., Strømman, A. H., 2009. Life Cycle Assessment of Second Generation Bioethanols Produced From Scandinavian Boreal Forest Resources. A Regional Analysis for Middle Norway. *Journal of Industrial Ecology* 13(4): 514-531

Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D., 2003. The Global Forest Products Model. Structure, Estimation, and Applications. Academic Press, Elsevier Science, USA

Caparrós, A., Cerdá, E., Ovando, P., Campos, P., 2007. Carbon Sequestration with Reforestations and Biodiversity-Scenic Values. Fondazione Eni Enrico Mattei (FEEM), Fondazione Eni Enrico Mattei (FEEM). 24 pp. + appendix

Cardellichio, P. A., Adams, D. M., 1990. An Appraisal of the IIASA Model of the Global Forest Sector: Advances, Shortcomings, and Implications for Future Research. *Forest Science* 36(2): 343-357

Chopra, K., Leemans, R., Kumar, P., 2005. Ecosystems and Human Well-Being: Policy Responses: Findings of the Responses Working Group Vol. 3. Millennium Ecosystem Assessment.

Common, M., Stagl, S., 2005. Ecological Economics. An Introduction. Cambridge

Cournot, A.A., 1838. Mathematical Principles of the Theory of Wealth. Chap. X.

Dantzig, G.B., 1998. Linear Programming and Extensions. Princeton University Press, New Jersey/West Sussex. 11th ed.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy S.C., Zhang, X., 2007: Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor M., Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dones, R., Heck, T., Hirschberg, S., 2003. Greenhouse gas emissions from energy systems: comparison and overview. In: PSI Annual Report 2003 Annex IV, 27-40. Paul Scherrer Institut, Villigen, Switzerland.

Dykstra, D.P., 1984. Mathematical Programming for Natural Resource Management. McGraw-Hill

Dyson, F.J., 1977. Can we control the carbon dioxide in the atmosphere? *Energy*, 2: 287-291

Eid, T., Øyen, B.H., 2003. Models for prediction of mortality in even-aged forest. *Scandinavian Journal of Forest Research* 18(1): 64-77

Eid T., Hoen, H.F., Økseter, P., 2002. Timber production possibilities of the Norwegian forest area and measures for a sustainable forestry. *Forest Policy and Economics* 4(3): 187-200

Eid, T., Tuhus, E., 2001. Models for individual tree mortality in Norway. *Forest Ecology and Management* 154: 69-84

Eid, T., Hobbelstad, K., 1999. AVVIRK-2000 - et EDB-program for langsiktige investerings-, inntekts- og avvirkningsanalyser i skog. NLH/NIJOS [AVVIRK-2000 - a computerized program for long-range analyzes of investments, income and harvests in forest] 63 pp. [in Norwegian]

Encyclopædia Britannica, 2011. "Albedo". *Encyclopædia Britannica Online*. Web. 02 Mar. 2011. http://www.britannica.com/EBchecked/topic/12612/albedo

Enke, S., 1951. Equilibrium among Spatially Separated Markets: Solution by Electric Analogue. *Econometrica* 19(1): 40-47

Eriksson, L.O., 1987. Ranking stands with treatment indices. *Scandinavian Journal of Forest Research* 2: 239-251.

European Commission, 2010. The EU climate and energy package. http://ec.europa.eu/clima/policies/brief/eu/package_en.htm Updated 18.10.2010, visited 28.03.2011

FAO, 2010. Global Forest Resources Assessment 2010. Main report. *FAO Forestry Paper* 163. FAO, Rome. 194 pp. + appendix

Faustmann, M., 1849. Calculation of the Value which Forest Land and Immature Stands Possess. Reprinted in *Journal of Forest Economics* 1: 89-114

Finnish Statistical Yearbook of Forestry 2010. Metla. 166 pp.

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., de la Chesnaye, F., Hourcade, J.-Ch., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D., Warren, R., 2007: Issues related to mitigation in the long term context, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Floudas, C.A., Pardalos, P.M. (eds), 2001. Encyclopedia of optimization. Kluwer Academic Publishers. Dordrecht, The Netherlands

Forsberg, G., 2000. Biomass energy transport - Analysis of bioenergy transport chains using life cycle inventory method. *Biomass and Bioenergy* 19: 17-30

Gan, J., Kolison, S. H. Jr., Colletti, J. P., 2001. Optimal forest stock and harvest with valuing nontimber benefits: a case of US coniferous forests. *Forest Policy and Economics* 2(2): 167-178

Gilless, J.K., Buongiorno, J., 1987. PAPYRUS: A Model of the North American Pulp and Paper Industry. *Forest Science Monograph* 28

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S., Houghton, R. A., Jenkins, J. C., Kohlmaier, G. H., Kurz, W., Liu, S., Nabuurs, G.J., Nilsson, S., Shvidenko, A. Z., 2002. Forest carbon sinks in the northern hemisphere. *Ecological Applications* 12(3): 891-899

Gotaas, P., 1967. Beskrivelse av regneprogrammet for "Langsiktige beregninger med EDB-maskinen Univac 1107 over internt resultat, masseproduksjon og verdien av hogstuttakene, til bruk ved driftsplanarbeidet i skogbruket". [Description of the computational program for "long-term calculculations with the computer Univac 1107 for internal results, timber production and harvest values, for use in operational plans in forestry] Oslo. 18 pp. [in Norwegian]

Grace, J., 2004. Understanding and managing the carbon cycle. *Journal of Ecology* 92: 189-202.

Greenwald. B., Stiglitz, J.E., 1987. Keynesian, New Keynesian and New Classical Economics. *Oxford Economic Papers, New Series* 39(1): 119-133

Gundersen, G., Solberg, B., 1984. A mathematical description of the IBRD model. *Report* 1/1984, Department of Forest Economics, Agricultural University of Norway. 14 pp.

Gustavsson, L., Madlener, R., Hoen, H.F., Jungmeier, G., Karjalainen, T., Klöhn, S., Mahapatra, K., Pohjola, J., Solberg, B., Spelter, H., 2006. The role of wood material for greenhouse gas mitigation. *Mitigation and Adaptation Strategies for Global Change* 11: 1097-1127

Gustavsson, L., Madlener, R., 2003. CO_2 mitigation costs of large-scale bioenergy technologies in competitive electricity markets. *Energy* 28(14): 1405-1425

Hadley, G., 1964. Nonlinear and dynamic programming. Addison-Wesley

Hansson., J., Berndes, G., Johnsson, F., Kjärstad, J., 2009. Co-firing biomass with coal for electricity generation—An assessment of the potential in EU27. *Energy Policy* 37: 1444-1455.

Harris, N.L., Saatchi, S.S., Hagen, S., Brown, S., Salas, W., Hansen, M.C., Lotsch, A., 2010. New Estimate of Carbon Emissions from Land-Use Change. Poster, Forest Day, 16th Conference of the Parties (COP), Cancun, Mexico, 05.12.2010.

Hartman R, 1976. The Harvesting Decision when a Standing Forest has Value. *Econonomic Inquiry* 16: 52-58

Haynes, R.W., Adams, D.M., 2007. The challenge of developing models to support forest sector policy analysis. Ch. 1 in: Adams DM, Haynes RW (eds.). Resource and Market Projections for Forest Policy Development. Springer, Dordrecht, the Netherlands

Hektor, B., 1998. Cost effectiveness of measures for the reduction of net accumulation of carbon dioxide in the atmosphere. *Biomass and Bioenergy* 15: 299-309.

Hobbelstad, K., 1988. Planleggingsprogrammet AVVIRK3 [The planning program AVVIRK3]. *Melding* 42:1-38. Department of Forest Inventories, Agricultural University of Norway [In Norwegian]

Hobbelstad, K., 1981. EDB- program for avvirkningsberegninger. [Computational program for harvest assessments] Department of Forest Inventories, Agricultural University of Norway *Melding* 29:1-27 [in Norwegian]

Hobbelstad, K., 1979. Computational program for non-declining yields assessments [EDB-program for beregning av balansekvantum] In: Bruaset, A. (ed.). *Landbrukets årbok* 1979: 190-198. Tanum, Oslo [in Norwegian}

Hoen, H.F., 1994. SSFE Proceedings. The Faustmann rotation in the presence of a positive CO_2-price. pp. 278-287 in: Helles, F., Linddal, M. (eds.). Proceedings from the biennial meeting of the Scandinavian Society of Forest Economics, Denmark, November 1993. *Scandinavian Forest Economics* 35

Hoen, H.F., 1990. Theoretical and empirical studies of long range forest management planning. Doctor scientiarum thesis 1990: 23, Agricultural University of Norway [Norwegian University of Life Sciences], Department of Forest Sciences [Department of Ecology and Natural Resource Management]

Hoen, H.F., Gobakken, T., 2004. Brukermanual for bestandssimulatoren Gaya v1.30. [Use manual for the stand simulator Gaya v1.30] Norwegian University of Life Sciences. 63 pp. [in Norwegian]

Hoen, H.F., Eid, T., Økseter, P., 2001. Timber Production Possibilities and Capital Yields from the Norwegian Forest Area. *Silva Fennica* 35(3): 249-264

Hoen, H.F., Solberg, B., 1999. Policy options in carbon sequestration via sustainable forest management: an example from the North. In: Palo, M. (ed): Forest transition and carbon fluxes – global scenarios and policies. *World Development Studies* 15:117-132. UNU/WIDER. Helsinki.

Hoen, H.F., Solberg, B., 1994. Potential and Economic Efficiency of Carbon Sequestration in Forest Biomass Through Silviculture Management. *Forest Science* 40(3): 429-451

Hoen, H.F., Eid, T., 1990. A model for analysis of treatment strategies for a forest applying standvice simulations and linear programming. [En modell for analyse av behandlingsalternativer for en skog ved bestandssimulering og lineær programmering] *Report of Norwegian Forest Research Institute* 9/90, 35 pp. [In Norwegian with English summary]

Houghton, R.A., 2008. Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005. In *TRENDS: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Im, E.H., Adams, D.M., Latta, G.S., 2010. The impacts of changes in federal timber harvest on forest carbon sequestration in western Oregon. *Canadian Journal of Forest Research*. 40: 1710–1723

Ince, P.J., Buongiorno, J., 2007. North American Pulp & Paper Model (NAPAP). Ch. 4 in: Adams, D.M., Haynes, R.W. (eds.). Resource and Market Projections for Forest Policy Development. Springer, Dordrecht, the Netherlands

Jakeman, G., Fischer, B. S., 2006. Benefits of Multi-Gas Mitigation: An Application of the Global Trade and Environment Model (GTEM) *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy, Special Issue #3 28(1): 323-342

Johnson, K.N., Scheurman, H.L., 1977. Techniques for prescribing optimal timber harvests and investment under different objectives. *Forest Science Monograph* 18. 31 pp.

Kallio, A.M.I., 2010. Accounting for uncertainty in a forest sector model using Monte Carlo simulation. *Forest Policy and Economics.* 12(1): 9-16.

Kallio, M.I., Moiseyev, A., Solberg, B., 2004. The Global Forest Sector Model EFI-GTM—The Model Structure. *Internal Report* No. 15. European Forest Institute

Kallio, M., Dykstra, D.P., Binkley, C.S., 1987. The Global Forest Sector: An Analytical Perspective. John Wiley & Sons, New York

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Eggers, T., Lapveteläinen, T., Kaipainen, T., 2003. Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. *Forest Policy and Economics* 5: 141-155

Karjalainen, T., Pussinen, A., Liski, J., 2002. An approach towards an estimate of the impact of forest management and climate change on the European forest sector carbon budget: Germany as a case study. *Forest Ecology and Management* 162(1): 87-103

Kindermann, G.E., McCallum, I., Fritz, S., Obersteiner, M., 2008. A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica* 42(3): 387-396.

van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effects of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. *American Journal of Agricultural Economics* 77: 365-374

Korpilahti, A., 1998. Finnish forest energy systems and CO_2 consequences. *Biomass and Bioenergy* 15 (4/5): 293-297

Langerud, B., Størdal, S., Wiig, H., Ørbeck, M., 2007. Bioenergi i Norge - potensialer, markeder og virkemidler [Bioenergy in Norway - potentials, markets and measures] 194 pp. [in Norwegian]

Langsæter, A., 1944. Skogen i Østfold, Akershus og Hedmark [The forest in Østfold, Akershus and Hedmark] Det norske skogselskap, Oslo. 67 pp. [in Norwegian]

Lappi, J., 2003. J-user's guide. The Finnish Forest Research Institute. Suonenjoki, Finland.

Lappi, J., 1992. JLP: a linear programming package for management planning. The Finnish Forest Research Institute. *Research Papers* 414: 1-134. Suonenjoki, Finland.

Lee, H.-C., McCarl, B., Gillig, D., 2005. The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration. *Canadian Journal of Agricultural Economics* 53: 343-357

Liski, J, Palosuo, T., Peltoniemi, M., Sievänen, R., 2005. Carbon and decomposition model Yasso for forest soils. *Ecological Modelling* 189: 168-182.

Lorenz, K., Lal, R., 2010. Carbon Sequestration in Forest Ecosystems. Springer

Lunnan, A., Navrud, S., Rørstad, P.K., Simensen, K., Solberg, B., 1991. Skog og skogproduksjon i Norge som virkemiddel mot CO_2-opphopning i atmosfæren. *Aktuelt fra Skogforsk* 6/91 [Norwegian Forest Research Institute] [in Norwegian]

Magelli, F., Boucher, K., Bi, H. T., Melin, S., Bonoli, A., 2009. An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy* 33: 434-441

Marklund, L.G., 1988. Biomass Functions for Pine, Spruce and Birch in Sweden (Biomassafunktioner för tall, gran och björk i Sverige). Sveriges Lantbruksuniversitet, *Report* 45, Umeå, Sweden, 73 pp.

McCarl., B.A., Spreen, T. H., 1980. Endogenous Mathematical Programming as a Tool for Sector Analysis. *American Journal of Agricultural Economics* 62(1): 87-102

Menzel, A., Fabian, P., 1999. Growing season extended in Europe. *Nature* 397: 659

Muth, J., 1961. Rational Expectations and the Theory of Price Movements. *Econometrica*, 29(3): 315-335

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698-702

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., Zhang, X., 2007a: Forestry. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Nabuurs, G.J., Pussinen, A., van Brusselen, J., Schelhaas, M.J., 2007b. Future harvesting pressure on European forests. *European Journal Forest Research* 126: 391-400

Navon, D.I., 1971. Timber RAM: A long-range planning method for commercials timber lands under multiple-use management. *Research paper* PSW70, USDA Forest Service, Berkeley, CA

Nersten, S., Delbeck, K., 1965. Avkastningsprognoser i skogbruket. I: *Melding* nr. 3 fra Institutt for Skogtaksasjon, NLH. Ås-NLH. [Yield prognoses in forestry. In: Report from Department for Forest Inventory, Norwegian University of Life Sciences] 92 pp. [in Norwegian]

Norwegian Agricultural Authority (s.a.). Skogfond for bærekraftig skogbruk [Forest fund for sustainable forestry] Booklet 4 pp. http://www.slf.dep.no/iKnowBase/Content/6264/SKOGFOND_BOKM.PDF Visited 26.03.2011. [in Norwegian]

Norwegian Climate and Pollution Agency, 2010. Klimakur 2020. Tiltak og virkemidler for økt opptak av klimagasser fra skogbruk. Sektorrapport skogbruk [Climate cure 2020. Measures and instruments for achieving Norwegian climate goals by 2020. Sectoral report forestry] [in Norwegian with English summary]

Norwegian Forest Seed Center, 2009. Plantesalg norske planteskoler [Plant sales Norwegian nursieries] Frøsalg [Seed sales] http://asp.gitek.no/skogfroverket/pmws.dll/DocFolder Last updated 06.01.2009. Visited 21.03.2011. [in Norwegian]

Norwegian Ministry of Petroleum and Energy, 2008. Strategi for økt utbygging av bioenergi [Strategy for bioenergy expansion] 57 pp. [in Norwegian]

Nyrud, A.Q., 2004. Analysing Norwegian Forest Management Using an Optimal Harvesting Rule. *Scandinavian Journal of Forest Research* 19(Suppl. 5): 74 - 81

Nyrud, A.Q., Michie, B., Sande, J.B., 2004. Investigating Globalization: The Case of Forest Products' Markets. *Scandinavian Forest Economics 40* Proceedings Biennial

Meeting of the Scandinavian Society of Forest Economics. Vantaa, Finland, 12.-15.05.2004

Nyrud, A.Q., Bergseng, E., 2002. Production Efficiency and Size in Norwegian Sawmilling. *Scandinavian Journal of Forest Research* 17(6): 566-575

Perez-Garcia, J.M., Joyce, L.A., McGuire, A.D., Xiao, X., 2002. Impacts of climate change on the global forest sector. *Climatic Change* 54: 439-461

Perez-Garcia, J.M., Joyce, L.A., Binkley, C.S., McGuire, A.D., 1997. Economic impacts of climate change on the global forest sector. *Critical Reviews in Environmental Technology* 27: S123-S138

Petersen, A.K., Solberg, B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics* 7: 249-259

Pressler, M.R., 1860. For the Comprehension of Net Revenue Silviculture and the Management Objectives Derived Thereof. Reprinted in *Journal of Forest Economics* 1: 45-87

Pussinen, A., Karjalainen, T., Kellomäki, S., Mäkipää, R., 1997. Potential contribution of the forest sector to the carbon sequestration in Finland. *Biomass and Bioenergy* 13(6): 377-387

Randers, J., 1977. A system dynamic study of the transition from ample to scarce wood resources. *Report* GRS-34, Resource Policy Group, Oslo

Randers, J., Stenberg, L., Kalgraff, K., 1978. Skognæringen i overgangsalderen [The forest sector in a critical time]. J.W. Cappelen, Oslo. [in Norwegian]

Raymer, A.K.P., 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy* 30: 605–617

Raymer, A. K. P., 2005. Modelling and analysing climate gas impacts of forest management. PhD Thesis 2005: 11, Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management

Raymer, A.K.P., Gobakken, T., Solberg, B., Hoen, H.F., Bergseng, E., 2009. A forest optimisation model including carbon flows: Application to a forest in Norway. *Forest Ecology and Management* 258: 579-589

Ronnila, M., 1995. Medium-term scenarios for the Finnish pulp and paper industry. *IIASA Working Paper* WP-95-38. April 1995. 104 pp. Available at http://www.iiasa.ac.at/Admin/PUB/Documents/WP-95-038.pdf

Rørstad, P.K., Trømborg, E., Bergseng, E., Solberg, B., 2010. Combining GIS and forest modelling in estimating regional supply of harvest residues in Norway. *Silva Fennica* 44(3): 435-451

Samuelson, P.A., 1952. Spatial Price Equilibrium and Linear Programming. *The American Economic Review* 42(3): 283-303

Sarmiento, J.L., Gloor, M., Gruber, N., Jacobson, A.R., Fletcher, S.E.M., Pacala, S., Rodgers, K., 2010. Trends and regional distributions on land and ocean carbon sinks. *Biogeosciences* 7: 2351-2367

Sathaye, J., Makundi, W., Dale, L., Chan, P., Andrasko, K., 2006. GHG Mitigation Potential, Costs and Benefits in Global Forests: A Dynamic Partial Equilibrium Approach. *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy, Special Issue #3 28(1): 127-162

Schlamadinger, B., Marland, G., 1996. Full fuel cycle carbon balances of bioenergy and forestry options. *Energy Conversion and Management* 37(6-8): 813-818

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., Robertson, G. P., Schlesinger, W. H., Tilman, G. D., 2009. Fixing a Critical Climate Accounting Error. *Science* 326: 527-528.

Sedjo, R., Sohngen, B., Mendelsohn, R., 2001. Estimating Carbon Supply Curves for Global Forests and Other Land Uses. *RFF Discussion Paper* 01-19

Sedjo, R., Lyon, K., 1990. The long-term adequacy of world timber supply. Resources for the Future, Washington DC

Seip, H.K., 1953. Prognoser over framtidige hogstkvantum i noen av våre viktigste skogfylker. [Prognoses of future harvest quantum in some of our most important forest counties] Skogindustriens økon.inst., info.B.nr.6, Oslo 60 pp. [in Norwegian]

Sikkema, R., Junginger, M., Pichler, W., Hayes, S., Faaij, A.P.C., 2010. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts & Biorefining* 4: 132-153

Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., 2007. Energy. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Sjølie, H.K., Latta, G.S., Gobakken, T., Solberg, B., 2011. NorFor - a forest sector model of Norway. Model overview and structure. *INA Report* 17. Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences

Skog, K. E., 2007. Projecting technological change. Chapter 15 in: Adams, D.M., Haynes, R.W. (eds.). Resource and Market Projections for Forest Policy Development. Twenty-five Years of Experience with the US RPA Timber Assessment. 589 pp. Managing Forest Ecosystems no. 14. Springer

Sohngen, B., Sedjo, R., 2006. Carbon Sequestration in Global Forests Under Different Carbon Price Regimes. *The Energy Journal* 3: 109-126

Sohngen, B., Sedjo, R., 2000. Potential carbon flux from timber harvests and management in the context of a global timber market. *Climatic Change* 44: 151-172

Sohngen, B., Mendelsohn, R., Sedjo, R., 1999. Forest management, conservation, and global timber markets. *American Journal of Agricultural Economics* 81(1): 1-12

Solberg, B., 1986. Forest Sector Simulation Models as Methodological Tools in Forest Policy Analysis. *Silva Fennica* 20(4): 419-427

Solberg, B., Bergseng, E., Lindstad, B.H., 2008. Potential impacts of international regimes for biodiversity protection and carbon sequestration in forestry – a quantitative approach. In: Lindstad, B. Determining effects of international policy processes on national forest policies and management. PhD Thesis 2008: 43, Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management

Spiecker, H., 1999. Overview of recent growth trends in European forests. *Water, Air and Soil Pollution* 116: 33-46

Stainback, G.A., Alavalapati, J. R., 2004. Modeling catastrophic risk in economic analysis of forest carbon sequestration. *Natural Resource Modeling* 17(3): 299-317

Statbank Norway, 2011. Area 10.04.20 Forestry. Tables 03834: Commercial roundwood removals (1 000 m^3); 04454: Commercial roundwood removals (1 000 m^3); 06289: Stående kubikkmasse under bark, og årlig tilvekst under bark, etter treslag (1 000 m^3) [growing stock under bark, and annual increment under bark, by species]; 03522: Forest planting [Skogplanting] http://statbank.ssb.no//statistikkbanken/default_fr.asp?PLanguage=1

Statistics Norway, 2011. Emissions of greenhouse gases. 1990-2009. http://www.ssb.no/english/subjects/01/04/10/klimagassn_en/ Modified 15.02.2011, visited 20.03.2011

Statistics Norway, 2010a. Forests. http://www.ssb.no/english/subjects/10/04/20/skog_en/ Last modified 2010, visited 21.03.2011

Statistics Norway, 2010b. Landbruket i Norge 2009, kapittel 2 Skogbruk [Agriculture in Norway 2009 Chapter 3 Forestry] Statistical Analyses 116, Dec. 2010. 182 pp. [in Norwegian]

Statistics Norway, 2010c. Increased consumption of district heating. http://www.ssb.no/english/subjects/10/08/10/fjernvarme_en/ Last updated 28.10.2010. Visited 18.03.2010.

Statistics Norway, 2010d. Prices on electricity and grid rent excluding taxes, by consumer group. 2008. Øre/kWh. http://www.ssb.no/english/subjects/10/08/10/elektrisitetaar_en/tab-2010-05-26-13-en.html Last updated 2010. Visited 19.01.2011

Stavins, R.N., Richards, K.R., 2005. The cost of U.S. forest-based carbon sequestration. The Pew Center on Global Climate Change. 38 pp.

Steiner, Y., Nyrud, A.Q. (s.a.). Acceptance for deformation of dried sawnwood: Survey among practitioners in Norwegian sawmilling. Norwegian Institute of Wood Technology. 8 pp. Available at www.treteknisk.no/PaperBledFinalfinal_L4bNf.pdf.file

Takayama, T., Judge, G.G., 1964a. An Interregional Activity Analysis Model for the Agricultural Sector. *Journal of Farm Economics* 46(2): 349-365

Takayama, T., Judge, G.G., 1964b. Equilibrium among Spatially Separated Markets: A Reformulation. *Econometrica* 32(4): 510-524

Thompson, M.P., Adams, D., Sessions, J., 2009. Radiative forcing and the optimal rotation age. *Ecological Economics* 68: 2713-2720

Todd, M.J., 2002. The many facets of linear programming. *Mathematical Programming, Ser. B* 91: 417-436

Trømborg, E., 1999. En analyse av det norske massevirkemarkedet: Konsekvenser av endringer i markedsstrukturen. [An analysis of the Norwegian pulpwood market: Consequences of changes in the market structure] *Oppdragsrapport* 7/99 Norwegian Forest Research Institute [in Norwegian]

Trømborg, E., Sjølie H.K., 2011. Data applied in forest sector analyses in the forest sector models NorFor and NTMIII. *INA Report* 16. Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management

Trømborg, E., Sjølie H., Solberg, B., Hovi, I.B., Madslien, A., Veisten, K., 2009. Economic and environmental impacts of transport cost changes on timber and forest product markets in Norway. *Scandinavian Journal of Forest Research*, 24(4): 354-366

Trømborg, E., Bolkesjø, T.F., Solberg, B., 2007. Impacts of policy means for increased use of forest-based bioenergy in Norway - A spatial partial equilibrium analysis. *Energy Policy* 35(12): 5980-5990

Trømborg, E., Solberg, B., 1995. Beskrivelse av en partiell likevektsmodell anvendt i prosjektet "Modellanalyse av norsk skogsektor" [Description of a Partial Equilibrium Model Applied in the Project "Model analysis of Norwegian Forest Sector"] *Skogforsk Research paper* 14/95. Agricultural University of Norway [Norwegian University of Life Sciences] [in Norwegian].

UNFCCC, 2002. Conference of the parties. Report of the conference of the parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001 Addendum. Part two: action taken by the conference of the parties. FCCC/CP/2001/13/Add.1

UNFCCC (s.a.). List of Annex I Parties to the Convention http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php Visited 21.03.2011

Valsta, L., 2007. Sequester or Harvest – the Optimal Use of Managed Forests to Mitigate Climate Change. University of Helsinki, *Department of Forest Economics Report* 46. 23 pp.

Wahlund, B., Yan, J., Westermark, M., 2004. Increasing biomass utilisation in energy systems: A comparative study of CO_2 reduction and cost for different bioenergy processing options. *Biomass and Bioenergy* 26: 531-544

Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J., and Dokken, D. J., 2000. Land Use, Land-Use Change, and Forestry. Special report. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge

Weintraub, A., Romero, C., 2006. Operations Research Models and the Management of Agriculture and Forestry Resources: a Review and Comparison. *Interfaces* 36(5): 446-457

Winjum, J.K., Dixon, R.K., Schroeder, P.E., 1993. Forest management and carbon storage: an analysis of 12 key forest nations. *Water, Air, and Soil Pollution* 70: 239-257

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Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway

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ABSTRACT

In many European countries, the use of policy measures to decrease greenhouse gas (GHG) emissions from energy consumption, including heating, is high on the political agenda. Also, increasing the absolute consumption of bioenergy seems to partly be an objective in itself. But neither the costs of replacing fossil fuels with bioenergy in heating, nor the effects on the GHG emission account are clear.

This study analyses first the avoided GHG emissions from substituting one energy unit of fossil fuel with forest based bioenergy (wood fuel) in several heating technologies. Secondly, the effects on bioenergy production of two policy measures in Norway - higher tax on domestic heating oil and paraffin and investment grants to district heating installations based on wood fuels - are investigated. Thereafter, the results are combined to display how the emissions from heating are affected. Finally, the achievements are compared to the costs. The analysis is done by using a partial, spatial equilibrium model of the Norwegian forest sector, wood fuels included.

Based on model runs we conclude that a tax of 60 €/CO_2eq on competing fossil fuels could increase the bioenergy use in district heating installations with almost 4000 GWh/year. The same amount of bioenergy could be used in pellet stoves and central heating systems, but a higher tax is then necessary. 50% investment grant to district heating installations may also have a large effect on the bioenergy use, but the effect of the subsidies decreases rapidly if applied together with a tax. Around 70% of the emissions from heating in Norway may potentially be avoided, but such achievements depend on very high taxes on fossil fuels. Both taxes and subsidies may greatly influence the energy market, but should be used with caution in order to obtain the preferred goals. Few similar studies are carried out in this field, and the results might be of interest for the bioenergy industry and the energy policy authorities.

1. Introduction

Norway has ratified the Kyoto protocol and made the commitment to limit the average GHG emissions in the period 2008–2012 to 1% above the 1990 level. However, they were 11% higher in 2007 than in 1990 (Statistics Norway, 2008b). A white paper published in 2006 (The Norwegian Ministry of the Environment, 2006) concludes that all GHG emissions from heating in Norway may be avoided in 2050 by energy savings and change of heating sources from fossil fuels to heat pumps and bioenergy. Currently, 6% of the national emissions stem from heating.

As in many European countries, the attention on bioenergy has increased significantly in Norway the last years. Arguments for this public spending are reduction of GHG emissions, increased industry development in rural areas, improved security of supply and reduced areas of overgrown cultural land (The Norwegian Ministry of Petroleum and Energy, 2008). The authorities have set an objective of more than double the use of bioenergy by 2020, and are therefore providing financial support to the bioenergy sector, as investment grants to individuals and enterprises that shift to bioenergy from electricity or petroleum. There exist also taxes of fossil fuel use, but because of low public acceptance and fear of negative distributional effects, the authorities are cautious to increase them further. Actually, the carbon tax on heating oil is 0.07 €/l or circa 25 €/ton CO_2 (SFT, 2008).

From a purely economic point of view, subsidies to renewable energy carriers are less efficient than taxes on fossil fuels if the goal is to reduce GHG emissions, because subsidies tend to increase the total amount of energy consumed due to lower prices to consumers, and fail to put the burden of the negative externalities (GHG emissions) on the polluter. Despite this problem, subsidies to renewable energy carriers is a popular public policy throughout Europe, and is implemented as investment grants for heat production from biomass in eleven countries; in addition, tax break is introduced in four (Ragwitz et al., 2005; acc. to Bürger et al., 2008). If the goal of public intervention is to reduce

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GHG emissions, tax on the fossil fuels is to prefer, since this will, *ceteris paribus*, higher the price to consumers and therefore reduce the consumption. If, as stated by both the Norwegian and the EU authorities, the goal is also to increase the quantity of bioenergy used, this can be done by giving subsidies to bioenergy production or consumption, but this will not ensure reduced GHG emissions (Golombek and Hoel, 2005). Increasing the use of bioenergy might, however, steepen the learning curve, and thereby lead to reduced use of fossil fuels in the longer run because of lowered bioenergy production costs. Earlier studies suggest that tax credits were successful in increasing the market share of solar equipment in the U.S. (Durham et al., 1988; Fry, 1986; acc. to Tietenberg and Lewis, 2009).

Bioenergy stems mainly from forestry and forest industry in Norway today, and wood is assumed to continue to be the major raw material. Currently, less than half of the actual forest increment is harvested, causing a rapid accumulation of the growing stock and an increasing potential for bioenergy supply. The maximum volume that can be harvested sustainably in Norwegian forests, i.e. the volume that can be harvested without the need of reducing it later, is today about 21 million (M) solid m^3, of which harvest residues, trees on cultural land and road sides make up 5.6 Mm^3. The actual annual exploitation accounts for about 11.5 M solid m^3, the yearly non-declining additional biological potential is thus 9.5 Mm^3, corresponding to an energy gross output of about 19 TWh/year (Gjølsjø, 2006). Thus, harvests may be increased substantially while keeping the forests as a net CO_2 sink. The gap in harvested volume between the official statistics (Fig. 1) and the study referred to is due to non-commercial removals, i.e. harvested wood which is used directly by forest owners or for other reasons does not appear in official statistics.

The only purpose of wood fuels in Norway today is heating, because bioelectricity is hardly installed due to low profitability. Half of the energy consumed for room and water heating and process heating in Norway stems from electricity (which may be renewable or not, depending on the source), 25% from oil and 18% from bioenergy (Enova, 2007). Bioenergy consumption adds up to 12 TWh per year (Table 1); 60% of the bioenergy is consumed as fire wood. More than a third is used in manufacturing industry, mainly in forest industry, with residues from production as the main resource. Pellet stoves and district heating are still in the beginning of market development. Fire wood has negative impacts on local air quality when combusted imperfectly, and is bulky and cumbersome for consumers to handle. For environmental and economic reasons, pellets and chips are more suitable and are given more public support. Despite the fact that some investments in district heating are profitable at the present market prices (Trømborg et al., 2007), district heating contributes to only 4% of the heat market in Norway, totalling 2.8 TWh (2007). The use of district heating does not necessarily mean the use of renewable energy, since parts of district heating are based on fossil fuels (Statistics Norway, 2008a).

Table 1
Net bioenergy consumption in Norway 2006 (GWh) by type of fuel and categories of consumers.
(Sources: Statistics Norway, 2008a, *s.a.*; NOBIO, *s.a.*).

Consumer category	District heating (chips and pellets)	Pellets in pellet stove	Fire wood	Wood, black liquor	SUM
Manufacturing industry	47			4420	4467
Service industry	273				273
Households	69	27	7398		7495
SUM	389	27	7398	4420	12 234

Potential analyses of climate policies, energy and forest resources carried out in Europe are numerous, as well as studies of effectiveness and costs of measures to increase renewable energy production. Povellato et al. (2007) give a review of cost-efficiency of policy measures in agriculture and forest sector in Europe; in most of these studies where the costs are estimated, it is done via calculating the relative change in income or welfare, or costs per another unit. In Sweden and Finland, several studies have analysed the energy and emissions policy, as well as effectiveness and cost-efficiency of policy measures (e.g. Gustavsson et al., 1995; Hektor, 1998; Ericsson et al., 2004), but also there, we have not come across studies which, in a realistic economic framework, simultaneously analyse the effects of energy policies affecting bioenergy and GHG emissions, together with the costs of these policies. Such studies seem particularly few in the cases when wood is the raw material. Practically all wood used for bioenergy in Norway is potential raw material for the traditional forest industries. As policy incentives for increased use of bioenergy will increase the competition for fibre, and

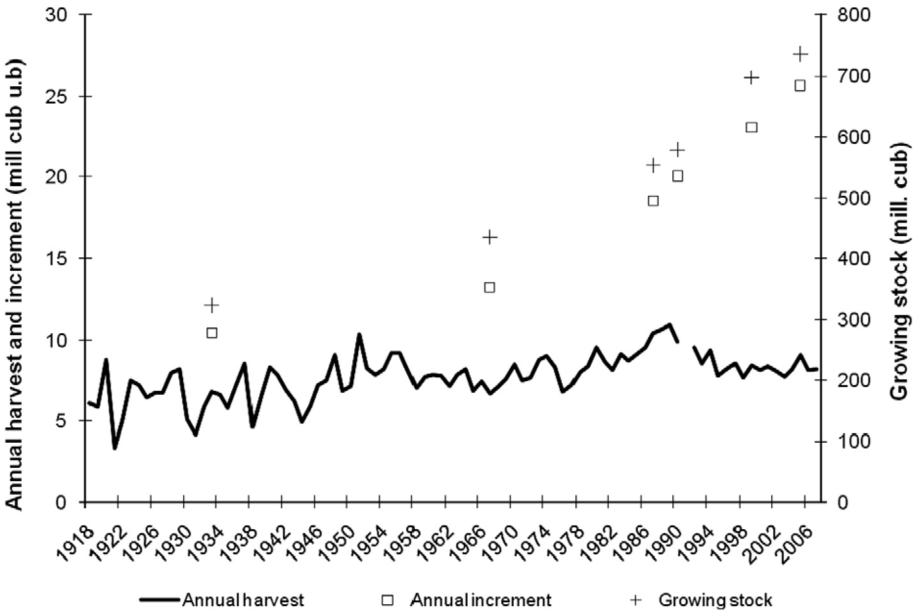

Fig. 1. Growing stock, annual harvest and increment in Norwegian forests. M m^3 under bark (u.b.).
(Source: Statistics Norway, 2008c).

thus the costs for both the traditional forest industries and the bioenergy industries, it is important to include also this aspect in the analysis.

In order to be able to impose well-working energy and GHG emissions policies in Norway, more knowledge is needed about wood fuels' capacity to reduce GHG emissions as well as effects and costs of such policies. The objective of this study is therefore to analyse (1) the impacts on GHG emissions by replacing one energy unit of fossil fuel with wood fuel in various types of heating facilities, (2) the effects on bioenergy consumption of investment grants to district heating systems based on wood fuels, (3) the effects of increased taxes on domestic heating oil and paraffin ("carbon tax") on GHG emissions from heating in various heating technologies, and (4) the cost associated with these two policy measures.

2. Methods and materials

2.1. Main outline and assumptions

To address the first problem, life cycle inventories (LCI) earlier carried out of all fossil and wood fuels considered in the analysis are compared. To model the changes in bioenergy production under changing policy and economic frames (objectives 2 and 3), an economic model, the Norwegian Trade Model II (NTM II), is applied. In the model, the development in the Norwegian forest industry, including wood fuels, is projected. The third problem is approached by combining the results from objective 1 (avoided GHG emissions from substituting one energy unit of fossil fuel with wood fuel) with NTM II simulations of changes in bioenergy production caused by higher carbon taxes. The associated costs (objective 4) are the costs for the society to achieve the obtained changes in bioenergy production or GHG emissions. Only the direct costs are included in this study, and both effects and costs are calculated for year 2015.

Five different groups of heating technologies based on wood fuels are considered in the NTM II. Each group includes one or several heating technologies, and some of the technologies may be, as described in the Appendix, fueled with different wood fuels. However, in the analyses of GHG emissions, each technology group is assumed to have only one wood fuel option: wood stoves (fire wood); pellet stoves (pellets); central heating bio boiler (pellets); and district heating bio boiler (chips). The fifth group, bioenergy in forest industry (based on residues and bark) is not included in the analysis since this use is only a function of activity in forest industry, and does not change (directly) with changes in economic frames for bioenergy. The assumed fossil fuels to be replaced in these four technologies are displayed in Table 2. The actual use of fossil fuels in district heating installations in Norway today is negligible, wood fuel in district heating installations is therefore assumed to substitute for oil in central heating systems and not in district heating installations. Electricity used for heating replaced by fire wood is only considered in objective 1, and not in the policy analyses, because of unclear electricity source and country of origin.

Table 2
Fossil energy technologies and fuels substituted by bioenergy technologies and wood fuels in the analysis.

		Bioenergy technology and wood fuel			
		Fire wood stove	Pellet stove	Central heating bio boiler (pellets)	District heating bio boiler (chips)
Fossil fuel technology and fuel substituted	Electric wall heater (coal-based electricity)	X			
	Paraffin stove		X		
	Domestic heating oil in central heating			X	X

The fossil fuel technologies eligible for carbon tax are in italic.

Two technologies/fossil fuels are eligible for carbon tax (objective 3), domestic heating oil in central heating installations and paraffin in paraffin stoves. Only district heating installations fueled with wood may receive financial support in the analysis (objective 2), but projection for all heating technologies is included also in this part to improve the accuracy of the results, since there may be interactions between the technologies. Three different types of district heating technologies are considered, all which are to be fueled with wood chips, and with the corresponding investment assumptions (investments include both plant and infrastructure):

A: Existing district heating systems based on bioenergy. No investments are required.
B: Existing water borne heating systems (central heating) in urban areas for industry buildings and tenement houses based on fossil fuels (fossil fuel to be replaced). The water borne system is assumed to be used also for wood fuels, but investments for heating plant and feeding system are needed when changing fuel and equal to a total of 500 000 €.
C: Heating systems in new buildings (same type as for B) to be constructed. Investments for heating plant, feeding system and water borne distribution system equal 1.1 million €.

Three levels of investment grants to district heating installations based on wood chips are analysed:

Basis	No investment support to district heating installations.
Alternative 1	District heating installations based on wood chips (B and C) are subsidised with 20% of the investment costs.
Alternative 2	District heating installations based on wood chips (B and C) are subsidised with 50% of the investment costs.

Bioenergy production takes place in A independently of policies, since there are no investments in this technology. B and C receive 20% or 50% subsidy of their respective investment costs — 500 000 or 1 100 000 €. Eight carbon tax levels are investigated, from 20 to 160 €/ton CO_2eq. All scenarios are run with an interest rate of 7% p.a. An exchange rate of 8 NOK/€ is applied throughout the paper.

2.2. Model description

2.2.1. General description

A partial and spatial equilibrium model, Norwegian Trade Model II (NTM II), was applied. The model projects production, consumption, trade and transport in the Norwegian forest sector, wood fuels included, given assumptions of competitive markets. Prices and quantities of wood raw materials and forest industry products are endogenously determined in the model, whereas all other production input prices are exogenously determined. Thus, activity in the forest sector is assumed not to influence the economy outside the sector. The results are given in a medium-long perspective (10–15 years from the base year). The NTM II is an improved version of the NTM, developed in Norway in the 90s (Trømborg and Solberg, 1995), based on the first model of this type, the Global Trade Model (GTM) (Kallio et al., 1987) and the EFI-GTM (Kallio et al., 2004). Earlier, this model has been applied in Norway for market and policy studies (Bolkesjø et al., 2005a,b, 2006; and Trømborg et al., 2007). For more data and assumptions and for mathematical specification of the model, see Bolkesjø (2004).

The objective function of the model is to maximize the producers' surplus plus the consumers' surplus minus the transport costs for all products in the model. As shown by Samuelson (1952), this assures that the model simulates the behaviour of profit maximizing producers and welfare maximizing consumers under the assumption of perfect competition. Each good's equilibrium price and quantity is determined from the optimal solution.

The model consists of four sub-modules: (1) timber supply, (2) forest industry including wood fuels, (3) products demand and (4) transport and trade. 2003 is set as the base year, but due to uncertainty of the exact time of investment, the impacts are analysed for 2015.

2.2.2. Timber supply

Observed prices and volumes determine the base year's supply. Timber supply is positively price elastic, while supply shifts annually according to changes in the growing stock — given as annual growth minus harvest.

In total, there are six timber products in the NTM II, saw logs and pulp logs of Scots pine, Norway spruce and non-coniferous (mainly birch). Harvest waste is also a possible raw material for bioenergy, but the traded volumes of this product are marginal. The harvest waste supply is in the model defined as a step-wise increasing supply function to reflect increasing transport costs, based on Aalde and Gotaas (1999). The actual biological–technical potential of harvest waste is estimated to be around 2 $\mathrm{M\,m^3}$/year, or 4 TWh/year (NVE, 2003).

2.2.3. Forest industry and wood fuel production

Five mechanical forest industry products are specified in the NTM II, together with two pulp grades and nine paper grades. Since the Norwegian pulp, paper and board industries are very concentrated, these industries are described at enterprise level. The saw mill industry is described at regional level. As a result of the assumption that all actors are profit maximizing, all factories produce up to the level where marginal costs equal marginal revenues, or to their capacity constraints. Investments will take place as long as the profit (revenues–variable costs) covers the annual interest and depreciation costs of the new investments.

In the saw mill industry, the surpluses of chips, dust and bark are sold as by-products, wood fuel included. Prices of the by-products are endogenously determined in the model.

The bioenergy market is divided into eight technologies, as specified in Table A1, and it is assumed that they cover the complete heat market based on biomass. The wood fuels considered are fire wood, chips and pellets. The bioenergy production costs and capacities at the start of the analysis period are specified for each region.

Product categories and transformations included in the model are shown in Fig. A1 in the Appendix.

2.2.4. Product demand

Like the supply functions, the demand functions are based on data from the base year in addition to exogenous price elasticities for each product. The demand curves are positively elastic to the exogenous income growth proxied by GDP growth. The derived demand curve for bioenergy is assumed nearly horizontal (highly elastic), reflecting the assumption that consumers may choose between perfect substitutes, and that bioenergy use hardly affects the energy price. The price of energy is assumed to be 50 €/MWh in the base year and remains almost perfectly the same independently of bioenergy production. This energy price, or the "heat price", is determined by the prices in the energy market of power and oil, as well as network charges and taxes, VAT excluded. Carbon taxes on heating oil and paraffin result in a horizontal upward shift of the demand curve, thus giving the same effect as changes in the heat price. Since the demand curve is determined by the price of *alternative* energy carriers, a price/tax increase for these fuels leads to an upward demand curve shift, thus more profitable bioenergy. Table A1 in the Appendix describes all bioenergy technologies included in the model, and their assumed efficiency and potential production increase. Each of them has technical and regional specific potentials exogenously determined, based on data from Statistics Norway on total energy consumption, structure of population and buildings, as well as existing heating systems and plans for future construction activity. In addition, the rate of growth of bioenergy consumption is restricted, to avoid unlikely increases from one year to another. For other assumptions and data of how bioenergy is included in the NTM II, see Trømborg et al. (2007).

2.2.5. Trade and transport

Forestry is a transport intensive industry, making the spatial aspect important. In the model, Norway is divided into 19 regions, which mainly follow the county borders. In addition, two international regions are included in the model — Sweden (the part of Sweden close to the Norwegian border) and the "rest of the world" (consumption mainly in Western Europe, and production made in order to balance the model). For each product, the model solution secures that trade between any two regions takes place if it is profitable for any producer, i.e. if the difference in the product prices exceeds the transport costs.

2.3. Avoided GHG emissions from substituting fossil fuels with wood fuels

2.3.1. Unit GHG emissions from the heating technologies considered

For all fuels considered, life cycle inventories (LCI) were obtained which give emissions over the life cycle per unit of wood fuel, electric power or fossil fuel. The emission estimates are based on Spath et al. (1999), Statoil according to Petersen (2003), SFT (*s.a.*) and Raymer (2006), and include the emissions from exploitation, processing and transport of the products, but not construction, maintenance and demolition of buildings and machines. It should be emphasized that parts of the emissions from the life cycle occur outside Norway, and also, parts of the emission reductions due to substitutions will take place in other countries. Where the emission reduction takes place depends on where the fossil energy production is situated. Substitution of coal-based electricity will reduce the emissions in countries which sell such electricity to Norway, while replacement of oil and paraffin in stoves reduces emissions in Norway. The analysed carbon tax applies to consumption of fossil fuel for heating in Norway (paraffin and oil in central heating systems) and may reduce emissions mostly in Norway, where the production actually takes place.

Wood fuels emit some CO_2 and other GHG during the production process and transport; all these emissions are included in the account. But no emissions of CO_2 stemming from combustion are taken into consideration, since wood fuels are assumed carbon neutral (assuming 0% discount rate in the CO_2 accounting, so 1 ton of CO_2 has the same value at all points of time). During the combustion process, other GHG are emitted, namely methane (CH_4) and nitrous oxide (NH_4). All emissions of these two gases are converted to CO_2 equivalents (CO_2eq) by the use of their respective global warming potential (GWP) and included in the analysis. Hence, wood fuels are seen as carbon neutral, but not entirely GHG neutral. A 100-years horizon is used for the GWP, in this time perspective, CH_4 and NH_4 have respectively a potential 24 and 360 times higher than CO_2 has (Sygna et al., 1999).

The energy content in wood fuels is calculated after Gjølsjø (1990). The physical properties of the wood fuels are displayed in Table 3.

To obtain the GHG emissions per GWh utilised, the following formula from Raymer (2006) was applied (the energy content in wood (higher heating value) is denoted by "high" and the energy output after conversion (lower heating value) by "low"):

$$Tons\,CO_2eq\,/\,GWh = kg\,CO_2eq\,/\,solid\,m^3\,/\,(MWh_{\mathrm{high}}\,/\,solid\,m^3{*}efficiency).$$

3. Results

3.1. Unit GHG emissions

Table 4 displays the unit GHG emissions from LCI of fossil fuels. The coal efficiency is for a pure power plant, with no use of the produced heat.

Table 3
Physical properties of wood fuels.
(Sources: Hohle, 2005; Heje and Nygaard, 1997).

Wood fuels	Energy content kWh/ton pellets	Base density roundwood kg/solid m^3	Moisture content (wet basis)	Energy content roundwood, kWh/solid m^3	Solid m^3 roundwood/ ton pellets
Fire wood coniferous		440	35%	2182	
Fire wood non-coniferous		489	35%	2425	
Pellets coniferous	4800	394	8%	2067	2.322
Pellets non-coniferous		489	8%	2565	2.322
Chips coniferous		394	35%	1954	
Chips non-coniferous		489	35%	2425	

Table 5
GHG emissions from harvest, production, transport and combustion of wood fuels consisting of 70% coniferous and 30% non-coniferous.
(Source: Raymer, 2006).

Wood fuel and technology	Tons CO_2eq/ GWh_{high} from harvest, production and transport	Tons CO_2eq/ GWh_{high} from combustion	Efficiency(%)	Total tons CO_2eq/GWh_{low}
Fire wood in wood stove	10	19	60	48
Pellets in pellet stove	7	4	90	13
Pellets in central heating system	7	4	80	15
Chips in district heating system	7	5	80	15

Tons CO_2eq/GWh.
Emissions from harvest, production and transport include CO_2, as well as the other GHG considered in the study. CO_2 is excluded in calculation of emissions from combustion, as the wood is considered carbon neutral.

The unit quantities of GHG emissions of wood fuels, all weighted with shares of 70% coniferous and 30% non-coniferous wood, reflecting the actual harvest in Norway, are shown in Table 5. Pellets and chips of coniferous and non-coniferous are assumed to have identical emissions per cubic metre, but as a result of higher density in non-coniferous, the latter has lower emissions per energy unit.

The net effect of substitution per energy unit is displayed in Table 6.

3.2. Effects of policy measures

As described in the Introduction, investment grants to bioenergy installations cannot ensure lowered GHG emissions, so this policy is only reflected in increased bioenergy consumption. On the other hand, increased taxes on competing fuels may increase bioenergy consumption, even if this measure is not directly designed to do so (but to decrease fossil fuel consumption).

Fig. 2 shows that increased carbon tax on competing petroleum products has a great effect on bioenergy production, according to model runs. Increase of the tax up to 60 €/ton CO_2eq results in a yearly production of 4000 GWh in district heating systems, compared to almost zero without implementation. Pellets are more expensive, and need fossil fuel tax of 100–120 €/CO_2eq.

Fig. 3 presents the bioenergy production in district heating systems distributed into NTM II technologies and shows how it changes with the subsidy level, without any taxes. Without subsidies, no investments are done and there is only some very minor production in existing district heating systems (technology A). Production in this technology is independent of the subsidies, since there are no investments taking place (but it depends on the price of competing fuels). While 20% investment grant only has a minor effect on the production in existing buildings with already water borne heating (technology B), 50% grant increases the production level many times.

The interaction between tax and subsidies (Fig. 4) shows that if no or only low taxes are imposed, subsidies may significantly increase the bioenergy production. If taxes of 40 €/ton CO_2eq are introduced, subsidies to district heating installations give less effect in terms of bioenergy production. Above that tax level, there is hardly any effect at all — the small effect of 50% subsidies at the highest carbon tax levels is crossed out by reduced bioenergy use in central heating installations. Thus, if the goal is to increase bioenergy production, the policy measures should be chosen carefully in order to avoid negative interactions.

Taxes on fossil fuels reduce GHG emissions because consumption of the products decreases when their prices increase. Chips in district heating installations are the first to replace fossil fuels with higher taxes (20–60 €/ton CO_2eq), while pellets hardly enter the market below a tax of 100–120 €/CO_2eq (Fig. 5). The potential in existing wood-based district heating installations (A) is limited, and the major reduction takes place in installations with existing infrastructure where the fossil fuels is replaced by wood fuels (B). Without subsidies, there is no production in new buildings (C), even at the highest tax levels.

3.3. Costs of public intervention

The costs part of analyses of public intervention is as central as the study of the GHG and bioenergy production effects, in order to make different measures comparable. The direct marginal costs associated with the carbon tax are simply the tax itself. The costs are less straightforward to estimate for the subsidies to bioenergy production. In this study, the cost per GWh of bioenergy production per year is calculated as the direct support given by the authorities divided by the additional yearly bioenergy production, i.e. the difference in

Table 4
GHG emissions from exploitation, production, transport and combustion of fossil fuels.
(Sources: Spath et al. 1999; Statoil according to Petersen, 2003; SFT, *s.a.*).

Fossil fuel	Tons CO_2eq/GWh_{high} from exploitation, production and transport	Tons CO_2eq/ GWh_{high} from combustion	Efficiency(%)	Total tons CO_2eq/GWh_{low}
Electric wall heater (coal)	12	310	40	805
Paraffin stove	12	253	80	331
Domestic heating oil in central heating	12	273	90	317

Tons CO_2eq/GWh.

Table 6
Net effect of substitution per energy unit.

Substituting wood fuel and technology	Fossil fuel and technology substituted	Net effect of substitution tons CO_2eq/GWh_{low}
Fire wood in wood stove	Electric wall heater (coal)	758
Pellets in pellet stove	Paraffin stove	318
Pellets in central heating system	Domestic heating oil in central heating	302
Chips in district heating system	Domestic heating oil in central heating	301

Tons CO_2eq/GWh_{low}.

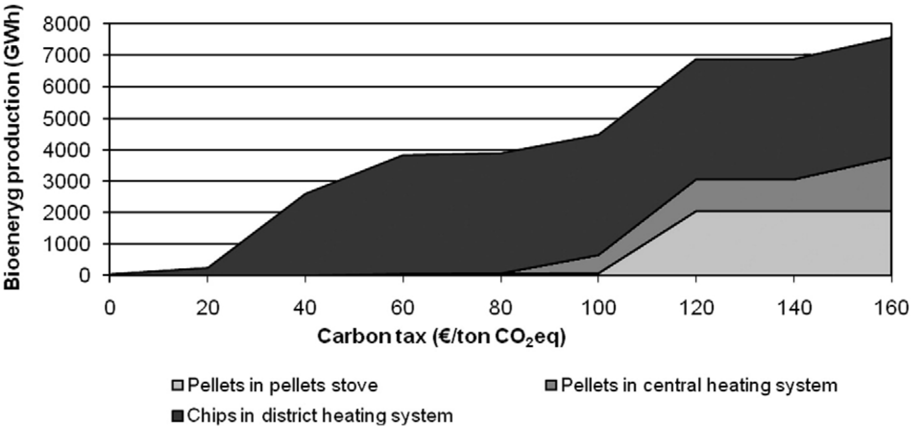

Fig. 2. Projected bioenergy production in pellet stoves, central heating systems and district heating systems in year 2015 (GWh) with varying tax level on fossil fuels.

production per year between the subsidies-scenario and the basis. Fig. 6 displays the interaction between the costs of subsidies to wood-based district heating installations (€/GWh produced heat from bioenergy) and the carbon tax level (€/ton CO_2eq on fossil fuels). As the graphs show, the subsidies tend to provide less bio-heat per Euro as the tax on competing fuels increases. The reason is as the tax increases, bioenergy becomes more competitive also without subsidies, and the effect of subsidies will thus be reduced. The cost graphs are not displayed for the whole tax range, because the production level remains unchanged between some tax levels. 20% investment grants to district heating installations, if there are no carbon taxes, cost with our calculations 50 000 €/GWh produced heat.

4. Discussion and conclusion

4.1. Unit emissions

The emissions from processing and combustion of fossil and wood fuels used in this study are of the same magnitude as in comparable works (Hektor, 1998; Wihersaari, 2005; and Korpilahti, 1998).

As described, we have assumed that wood fuels are not entirely GHG neutral, only carbon neutral. The carbon neutrality of bioenergy is often taken for granted, but for this to be true, the forest increment has to be at least as great as the harvest. As explained earlier, the harvest in Norway is much smaller than the increment; the condition of carbon neutrality is thus met. The highest increase in wood fuel consumption in the scenarios, 7500 GWh, corresponds to a wood input of around 5 Mm^3. It is outside the scope of this study to analyse where this wood would stem from, from decreased input to particleboard, pulp and paper or from increased harvest. But even if all the wood would be additional to the base scenario harvest, the Norwegian forests would still be a net CO_2 sink. Bolkesjø et al. (2006) applied the NTM II to analyse the consequences of higher energy price and increased bioenergy consumption on the forest industries, and found that most forest industries, except particleboard industry, seem rather robust to increase in the energy prices, even if it causes higher pulpwood prices. Increase in energy price triggers, according to their study, both more domestic harvest and more imports.

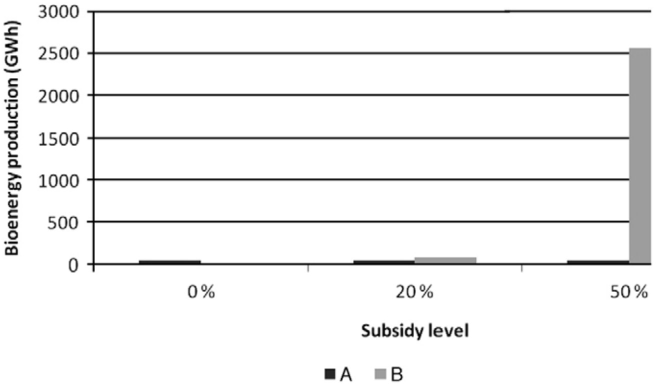

Fig. 3. Projected bioenergy production in district heating installations based on wood fuels (GWh) in year 2015 with varying subsidy level, no taxes on fossil fuels. A = existing district heating (no investments) and B = existing buildings with water borne heating. (No production in new buildings (C)).

Ideally, we would include net emissions of CH_4 and N_2O, i.e. the emissions from combustion subtracted the emissions if the wood had undergone decomposition in the forest. Because of lack of literature on emissions of wood undergoing decomposition, these emissions are not considered. Thus, all combustion emissions of CH_4 and N_2O are included. Because of these emissions, combustion of bioenergy is also eligible for carbon tax (or "GHG tax", which would be a more precise name for taxes on fossil fuels as well). But this tax would be negligible, circa $2.5*10^{-4}$ €/kWh for pellets and chips with a tax level of 20 €/ton CO_2eq.

Even though LCI may provide useful information about the impacts from a product's entire value chain, there are also often problems in comparing LCIs because different LCIs may have considerably different underlying assumptions — cf. e.g. Petersen and Solberg (2005). It is not always clear how far-reaching the analyses are, i.e. which impacts are included. In addition, some analyses include several GHGs, while others concentrate only on CO_2. Finally, there is always a question whether the analysed value chain is representative for the actual chains used. Despite such uncertainties, the LCI used in this study provides in our opinion good indications about the products' environmental impacts.

Fire wood is only included in the first part of the analysis, in estimating emissions and emission reductions per energy unit. Fire wood is assumed to substitute coal-based electricity, even if almost the entire Norwegian electricity production is based on hydro power. Norway trades electricity with the other Scandinavian countries, where the marginal production is coal-based electricity, because its marginal costs are higher than for hydro and nuclear powers, substitutes in these countries. But there are also capacity limits on the grids between Norway and those countries, and the limits were binding in 40% of the time in 2006 (Nordpool, *s.a.*). This makes it unclear what the substituted energy source at different points of time would be. If fire wood substitutes hydro power instead of coal power, the net effect of substitution turns to be negative because fire wood emits more GHG over the life cycle than hydro power does (Vattenfall, 2005). Additionally, coal power supply is rather inelastic because of high shut-down and start-up costs, which may further reduce the substitution effect. Since fossil fuel taxes typically are each nation's affairs, it would be less relevant to address taxes on foreign coal power in this paper.

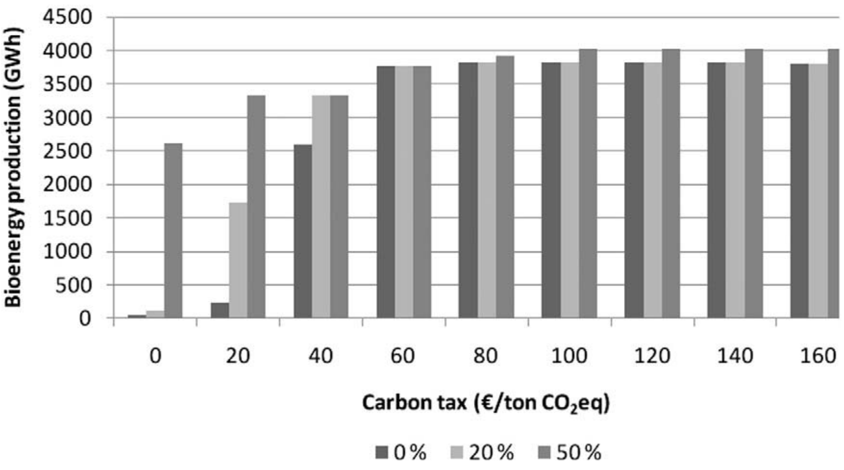

Fig. 4. Projected bioenergy production in district heating installations based on wood fuels (GWh) in year 2015 with varying subsidy and tax level.

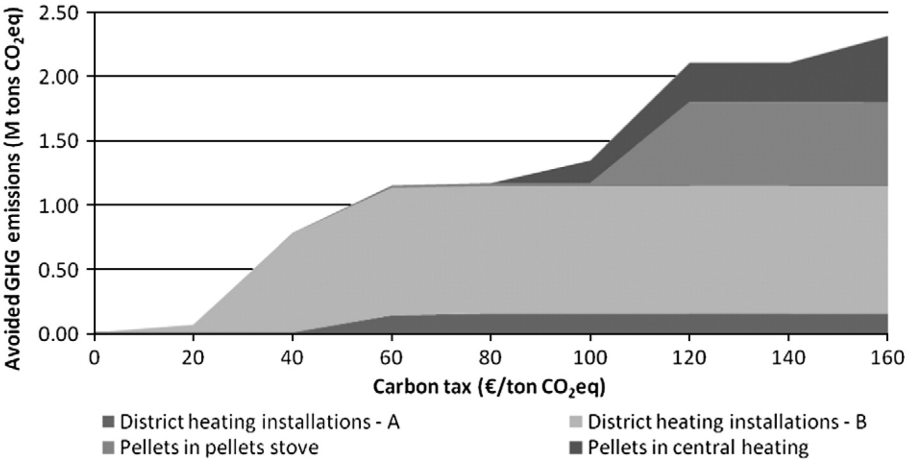

Fig. 5. Avoided GHG emissions (M ton CO_2eq) in year 2015 from replacement of fossil fuels in different installations with varying carbon tax (€/ton CO_2eq). No subsidies assumed. A = existing district heating (no investments) and B = existing buildings with water borne heating. (No production in new buildings (C)).

4.2. Effects and costs of public intervention

Investment grants to district heating installations may have large impacts on the bioenergy production. However, in order to have any significant effect, according to our analyses, the grant has to be greater than 20% of the investment costs if the measure is not combined with higher tax on fossil fuels. On the other hand, if the tax on competing fuels reaches 40 €/ton CO_2eq, the subsidy cost per GWh additional bioenergy production increases substantially.

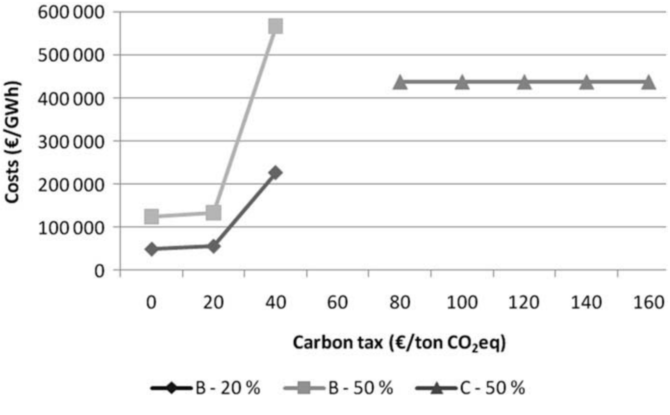

Fig. 6. Relationship between carbon tax on fossil fuels (€/ton CO_2eq) and costs of 20% and 50% investment grants to bioenergy production in district heating installations (€/GWh) in year 2015 for technologies B (existing buildings with water borne heating) and C (new buildings). (No production in technology C takes place with 20% support.)

The taxes seem effective in the area around 40 €/ton CO_2eq, where fossil fuels in district heating installations are widely replaced. More substitutions occur in pellet stoves and central heating systems, but only at tax levels which probably are unrealistic, at least today. Such replacements in district heating systems may reduce the total GHG emissions by 1.15 M tons CO_2eq at a tax at 60 €/ton CO_2eq or more, while the reductions from replacing fossil fuels with pellet indoors add up to the same at the highest tax level analysed (160 €/ton CO_2eq). For comparison, the total GHG emissions from heating in Norway are around 3.2 M tons CO_2eq (The Norwegian Ministry of the Environment, 2006). According to the results, emissions from heating may thus be reduced by 70% with the use of taxes, but these taxes have to be very high to make the second half of these reductions happen.

As the results display, both subsidies to bioenergy and taxes on fossil fuels increase bioenergy production. Even if both measures make wood fuel relatively more competitive compared to fossil fuel, the total energy consumption depends on the chosen measure. Investment grants tend to increase total energy consumption, while taxes will reduce it. If the objective is to increase the total quantity consumed of bioenergy, investment grant is the most efficient measure. Taxes on fossil fuels will also increase bioenergy consumption, but cannot ensure efficiency in this case. If reduction of GHG emissions is the goal, a tax on fuels emitting such gases is the most efficient measure — and the tax should be the same per CO_2eq for all emission sources (Golombek and Hoel, 2005).

In the analysis, we have evaluated how much higher carbon tax reduces emissions by replacing petroleum consumption with wood fuel, which occurs because bioenergy becomes relatively more competitive. But this estimate is likely to be conservative, because the emissions may also be further decreased with higher tax due to reduced overall energy consumption. For the district heating installation subsidy policy, it is possible to estimate the amount of wood heating increase, but not the amount of fossil fuel decrease, nor the amount of GHG reduction. Because subsidies tend to lower the costs to consumers, we cannot ensure that the increased use of wood fuels will displace the same energy amount of fossil fuels, hence the GHG emissions will probably decrease less than an estimated amount of fossil fuel emissions that the wood energy systems could ideally displace. These aspects are not analysed in the study, and should preferably be approached by the use of a broader energy model or a computable general equilibrium (CGE) model.

In December 2008, the expected price of CO_2 emission allowances for 2008–2012 in the European Union (EUAs) is 15–20 €/ton (Nordpool, 2008). The Norwegian carbon tax of petrol is 43 €/ton CO_2, while the oil and natural gas exploitation industry pays 32–43 €/ton CO_2 (The Norwegian Ministry of Finance, *s.a.*). The Norwegian government's project of capturing CO_2 from a gas heat and power plant at Mongstad in Norway will probably have abatement costs of more than 63 €/ton CO_2 (The Norwegian Ministry of Petroleum and Energy, 2007). Reducing GHG emissions by higher taxes on fossil fuels used in heating is thus less costly than many of these other measures taken.

The calculated costs in our study only include direct effects, and should be interpreted as a lower bound. Effects and costs are calculated for year 2015 and include investment costs in that year, with assumed 20 years lifetime of installations. Any indirect effects, as technological improvements from learning, rural employment, alternative costs of subsidies, use of tax revenues, etc. are excluded.

4.3. Overall discussion

Inclusion of production of all commercial wood products in Norway makes the NTM II adequate to model development in the bioenergy sector. Only a minor part of the wood fuels in Norway stems from logging residues, and the main share of the wood fuel is also suitable for other purposes, as pulp and particle board. An integrated modelling of the entire forest industry sector as provided by the NTM II is therefore a necessity to consistently project developments of bioenergy production. On the other hand, this analysis only looks at the effects on the forest sector, and excludes the rest of the economy, except for the assumptions made regarding economic growth. There might be smaller effects on other parts of the economy which are not included. Use of CGE models might have addressed these effects, as well as these effects' feedbacks on the forest sector. On the other side contributes the forest sector to less than 1% of the GDP in Norway, so the effects on the economy outside the forest sector are probably small.

According to the results, the maximum potential in some bioenergy technologies is reached quite fast with increasing carbon tax, once the production is initiated. This trend is especially clear for district heating installations and pellet stoves. It is, however, possible that the potentials are reached faster in the model than the actual development, because the model does not cover all variations in the actual cost structure in some bioenergy technologies.

The base energy price of 50 €/MWh assumed in the model analyses, taxes included (but VAT excluded), is lower than the recent historic prices in Norway. During the last fifteen years, the domestic heating oil price has increased from around 40 €/MWh to 100 €/MWh, which also includes the current carbon tax of 0.07 €/l. In the model's base year, 2003, the price was circa 70 €/MWh (Statistics Norway, 2009). However, even if the energy price is too low, we consider the results to still be of relevance. To improve further analyses, prices of both energy and input factors (which partly have increased since the base year) should be updated. Increasing the energy price in the simulations would have the same effect on bioenergy production as higher tax on fossil fuels. For example, an energy price of 70 €/MWh (the actual price in the base year) corresponds to a carbon tax of 60 €/ton CO_2eq with an energy price of 50 €/MWh.

The energy prices in district heating are today lower than the average electricity price for end-consumers, implying that district heating should to a higher degree attract investments than what the present investment rate indicates. A reason for this lack of accordance may be that modification and installation of district heating plants and infrastructure take such a long time that the results are not visible yet, since the energy price has reached this level only recently. Uncertainties of future energy prices and policies may also cause inertia in the investments, as well as market imperfections may do. When developing infrastructure for district heating, constructions have to be build in a large scale and for many consumers to be profitable. Lack of pipes for water borne heating is probably also delaying the development of district heating in Norway.

5. Conclusion

In this study, we found that a tax on domestic heating oil and paraffin could increase bioenergy consumption in district heating installations with almost 4000 GWh per year, if the tax level is at least 60 €/ton CO_2eq. More bioenergy use could take place as pellets in stoves and central heaters if the carbon tax is augmented to more than 100 €/ton CO_2eq. 50% investment grants to wood fuel-based district heating installations could also increase the bioenergy use significantly. However, if these two measures are combined, the costs associated with promoting use per unit of bioenergy output are likely to increase. Investment grants to bioenergy installations cannot ensure reduced GHG emissions because the price the consumers face tends to be lower with subsidies. Subsidies should be used if the goal is to increase the use of bioenergy. Taxes on fossil fuels are more likely than subsidies to reduce GHG emissions since higher energy price leads to lowered consumption. We found the potential for reduced emissions from district heating to be about 1.15 M tons CO_2eq/yr with a carbon tax of 60 €/ton CO_2eq and a similar reduction potential from indoor installations switching to pellets with a carbon tax of 160 €/ton CO_2eq. With a carbon tax of 160 €/ton CO_2eq, emissions from heating in Norway may be reduced by 70% with resulting changes to wood energy systems. But due to several inertias in the energy market and development of district heating systems, these numbers are not likely to be achieved directly. However, both taxes and subsidies seem to be effective policy measures to reach the respective goals.

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Appendix A

Table A1
Description of the bioenergy technologies analysed.
(based on Trømborg et al., 2007).

Technology	Description	Fuel	Efficiency	Potential for increased production
Wood stove	Traditional wood stoves in private households.	Fire wood	60%	In households with wood stoves, limited to 7000 kWh for single houses and 3000 kWh for other. Min/max increase per county set to 25%/100%
Pellet stove	Stoves in private households using wood pellets.	Pellets	90%	Replacement of ovens for kerosene in private household with potential production set to 10 000 kWh. Replacement of 90% of the kerosene consumption in service sectors. Implies investment in pellet stoves.
Wood based central heating — single houses	Bio boilers in private households with water borne heat distribution.	Wood, pellets or briquettes	80%	Replacement of oil boilers. Potential production set to 90% of the net energy production based on light fuel oil in private households and agriculture.
Wood based central heating	Bio boilers in single buildings in service sectors and multi-dwelling buildings with water borne heat distribution.	Wood, pellets or briquettes	80%	Replacement of oil boilers. Potential production set to 90% of the net energy production based on light fuel oil in service sectors and multi-dwelling buildings
Wood based district heating	Water borne distribution to several buildings from a central bio boiler.	Wood chips, or forest fuel (waste)	80%	Substitution of up to 90% of the consumption of light fuel oil in service sectors and multi-dwelling buildings in urban areas. Implies investments in bio boiler and infra structure to buildings.
Bioenergy in industries	Bio boilers in industrial buildings	Wood, pellets or briquettes	80%	Replacement of oil boilers. Potential production set to 75% of the net energy production based on light fuel oil in industrial sectors.
Bioenergy in forest industries	Existing energy production for heating and drying in forest industries.	Bark and residues	80%	Closely linked to the production in the forest industries.

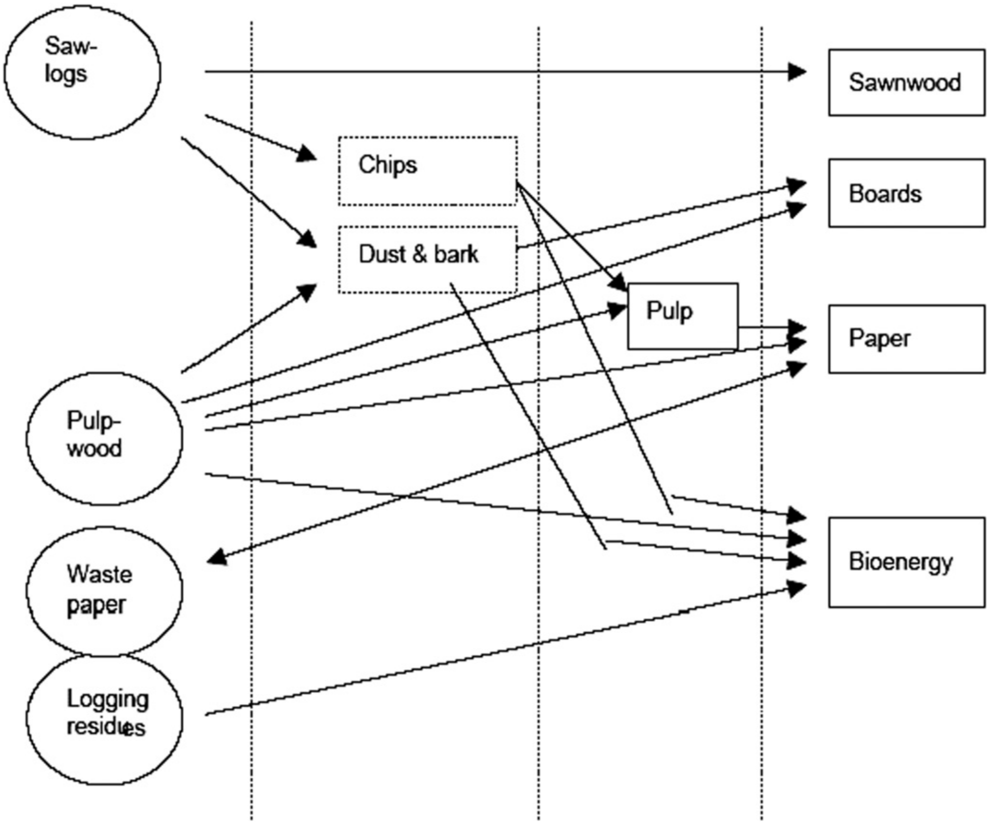

Fig. A1. Product categories and transformations in NTM II (each product category may include several products). Bioenergy contains wood, pellets and chips, as well as bioenergy products in forest industry.
(from Bolkesjø, 2004).

References

Aalde, H., Gotaas, P., 1999. Clarification of Harvest Possibilities in Norwegian Forestry. Report No. 10/99 NIJOS (Norsk Institutt for Skog og Landskap) [Norwegian Forest and Landscape Institute. [in Norwegian].

Bolkesjø, T.F., 2004. Modelling supply, demand and trade in the Norwegian forest sector. Agricultural University of Norway (Norwegian University of Life Sciences) Dr. Scient. thesis 2004:10.

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2005a. Economic consequences of increased forest conservation in Norway. Environmental & Resource Economics 31, 95–115.

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2005b. Projecting pulpwood prices under different assumptions on future capacities in the pulp and paper industry. Silva Fennica 39, 103–116.

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2006. Bioenergy from the forest sector: economic potential and interactions with timber and forest products markets in Norway. Scandinavian Journal of Forest Research 21, 175–185.

Bürger, V., Klinski, S., Lehre, U., Leprich, U., Nast, M., Ragwitz, M., 2008. Policies to support renewable energies in the heat market. Energy Policy 36, 3150–3159.

Durham, C.A., Colby, B.G., Longstreth, M., 1988. The impact of state tax credits and energy prices on adoption of solar energy systems. Land Economics 64 (4), 347–355.

Enova, 2007. Development of Market for Renewable Heating in Norway. Enova Heating Conference, Speech by the Managing Director of Enova. 23.01.2007 [in Norwegian].

Ericsson, K., Huttunen, S., Nilssson, L.J., Svenningsson, P., 2004. Bioenergy policy and market development in Finland and Sweden. Energy Policy 32, 1707–1721.

Fry, G.R.H., 1986. The economics of home solar water heating and the role of solar tax credits. Land Economics 62 (2), 134–144.

Gjølsjø, S., 1990. Wood Fuels in the Energy Supply, Resource Survey. Terminology and Energy Content for Biomass]. NISK (Norsk Institutt for Skog og Landskap) [Norwegian Forest and Landscape Institute]. [in Norwegian].

Gjølsjø, S., 2006. The Roles of Agriculture and Forest in Norwegian Energy Supply. RENERGI conference 28.11.2006. [in Norwegian].

Golombek, R., Hoel, M., 2005. Pliktige elsertifikater [Obligatory Electricity Certificates]. Ragnar Frisch Centre for Economic Research Report 1/2005. [in Norwegian].

Gustavsson, L., Börjesson, P., Johansson, B., Svenningsson, P., 1995. Reducing CO_2 emissions by substituting biomass for fossil fuels. Energy 20, 1097–1113.

Heje, K.K., Nygaard, J., 1997. Skoghåndboka [Forestry handbook]. [in Norwegian].

Hektor, B., 1998. Cost effectiveness of measures for the reduction of net accumulation of carbon dioxide in the atmosphere. Biomass and Bioenergy 15, 299–309.

Hohle, E.E. (Ed.), 2005. Bioenergi - Miljø, teknikk og marked [Bioenergy - Environment, Technique and Market]. Energigården, Norway. [in Norwegian].

Kallio, M., Dykstra, D.P., Binkley, C.S., 1987. The Global Forest Sector: An Analytical Perspective. John Wiley & Sons, New York.

Kallio, M.I., Moiseyev, A., Solberg, B., 2004. The Global Forest Sector Model EFI-GTM — The Model Structure. Internal Report No. 15. European Forest Institute.

Korpilahti, A., 1998. Finnish forest energy systems and CO_2 consequences. Biomass and Bioenergy 15, 293–297.

NOBIO *s.a.* (Norsk Bioenergiforening) [Norwegian Bioenergy Association] Bioenergi i Norge – Markedsrapport for 2006 [Bioenergy in Norway – market report for 2006]. [in Norwegian].

Nordpool, 2008. (26.11.2008) CO_2 Allowances. www.nordpool.com [27.03.2008].

Nordpool, *s.a.* Area price http://www.nordpoolspot.com/.

NVE, 2003. (Norwegian Water Resources and Energy Directorate). Bioenergiressurser i Norge [Bioenergy resources in Norway] Assignment report 7/2003 [in Norwegian].

Petersen, A.K., 2003. Sparte klimagassutslipp ved bruk av bioenergi: ved, flis, pellets og briketter [Avoided climate gas emissions by use of bioenergy: fire wood, chips, pellets and briquettes]. Department of Forest Sciences (Department of Ecology and Natural Resource Management), Agricultural University of Norway (Norwegian University of Life Sciences) [in Norwegian].

Petersen, A.K., Solberg, B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics 7 (3), 249–259.

Povellato, A., Bosello, F., Guipponi, C., 2007. Cost-effectiveness of greenhouse gas mitigation measures in European agro-forestry sector: a literature survey. Environmental Science and Policy 10, 474–490.

Ragwitz, M., Schleich, J., Huber, C., Resch, G., Faber, T., Voogt, M., Cleijne, H., Bodo, P., 2005. Analysis of the Renewable Energy's Evolution up to 2020, FORRES 2020. Fraunhofer IRB Verlag.

Raymer, A.K.P., 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass and Bioenergy 30, 605–617.

Samuelson, P.A., 1952. Spatial price equilibrium and linear programming. American Economic Review 42, 283–303.

SFT, 2008. CO_2-avgift [carbon tax] [in Norwegian] http://www.miljostatus.no/tema/Klima/Klima/Nasjonale-virkemidler/CO2-avgift/ [Updated 10.07.2008, visited 02.03.2009].

SFT *s.a.* (Norwegian Pollution Control Authority) Nøkkeltall [Key figures]. http://www.sft.no/artikkel____38940.aspx [13.03.2007] [in Norwegian].

Spath, P.L., Mann, M.K., Kerr, D.R., 1999. Life Cycle Assessment of Coal-fired Power Production. National Renewable Energy Laboratory, United States.

Statistics Norway, 2008a. Electricity, Gas, Stem and Hot Water Supply. http://www.ssb.no/english/subjects/10/08/10/ [Visited 26.11.2008].

Statistics Norway, 2008b. Air. http://www.ssb.no/english/subjects/01/04/10/ [Visited 25.09.2008].

Statistics Norway, 2008c. Forestry. http://www.ssb.no/english/subjects/10/04/20/ [Visited 26.11.2008].

Statistics Norway, 2009. Energy. . http://www.ssb.no/english/subjects/01/03/10/ [Visited 03.03.2009].

Statistics Norway, *s.a.* http://www.ssb.no/english/subjects/ [Visited 25.09.2008].

Sygna, L., Fuglestvedt, J.S., Aaheim, A., 1999. Metodar for å samanlikne utslepp av klimagassar – GWP-konseptet og alternative metodar [Methods for comparison of GHG emissions – the concept of GWP and alternative methods]. CICERO Working Paper 1999:11. Center for International Climate and Environmental Research — Oslo.

The Norwegian Ministry of the Environment, 2006. (Norwegian Official Reports) 2006:18. Et klima-vennlig Norge [A Climate — Friendly Norway]. [in Norwegian].

The Norwegian Ministry of Finance s.a. Dagens grønne skatter (Miljørelaterte avgifter i Norge i 2007) [Green taxes today (Environmental taxes in Norway in 2007)]. http://www.regjeringen.no/nb/dep/fin/tema/andre/Saravgifter/Dagens-gronne-skatter.html?id=439338 [20.04.2007] [in Norwegian].

The Norwegian Ministry of Petroleum and Energy, 2007. (07.02.2007) Energiverket på Mongstad og avtale mellom staten og Statoil om CO_2 — håndtering [The Energy Plant at Mongstad and the Agreement Between the Government and Statoil About Capture and Storage of CO_2]. http://www.regjeringen.no/nb/dep/oed/tema/CO2/Energiverket-pa-Mongstad-og-avtale-mello.html?id=439428 [in Norwegian].

The Norwegian Ministry of Petroleum and Energy, 2008. Strategi for økt utbygging av bioenergi [Strategy for Increased Development of Bioenergy]. [in Norwegian].

Tietenberg, T., Lewis, L., 2009. Environmental and Resource Economics 8th edition. Pearson.

Trømborg, E., Solberg, B., 1995. Beskrivelse av en partiell likevektsmodell anvendt i prosjektet “Modellanalyse av norsk skogsektor” [Description of a Partial Equilibrium Model Applied in the Project “Model analysis of Norwegian Forest Sector”] Skogforsk Research paper 14/95. Department of Forest Sciences (Department of Ecology and Natural Resource Management), Agricultural University of Norway (Norwegian University of Life Sciences) [in Norwegian].

Trømborg, E., Bolkesjø, T.F., Solberg, B., 2007. Impacts of policy means for increased use of forest-based bioenergy in Norway—a spatial partial equilibrium analysis. Energy Policy 35, 5980–5990.

Vattenfall, 2005. Vattenfall AB Nordic Generation's Certified Environmental Product Declaration EPD of Electricity from Vattenfall's Nordic Hydropower. S-P-00088.

Wihersaari, M., 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28, 435–443.

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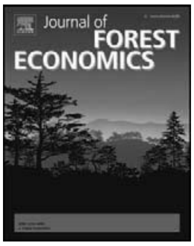

Impacts of agent information assumptions in forest sector modeling

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ABSTRACT

The forest sector faces changing political paradigms and volatile policy measures. Policy makers rely on economic and biological models to inform them of the impacts and risks associated with both anticipated and unforeseen policies or shocks to the system. Assumptions about agents' knowledge of future events are fundamental in all forms of models suggesting that the degree of information of future events may have large behavioral impacts. Despite the importance of this assumption, few studies have looked into what this difference in information may imply, and few studies have analyzed the importance of varying the degree of *a priori* information on the impacts of policy measures. This paper attempts to elucidate some of these impacts by comparing how an exogenous shock affects the Norwegian forest sector if the agents are assumed to have: (i) perfect information, (ii) information about the market shift only a limited time before its implementation or (iii) no *a priori* information. The shock analyzed is an import ban on all coniferous wood into Norway, which is possible if the Pinewood nematode (PWN) becomes more widespread in Europe. To examine this question, we adapt the Norwegian forest sector model NorFor to reflect perfect, limited and no prior information. The results indicate that if the agents anticipate the shock, they will begin to adjust harvest and production levels before it occurs. Due to high opportunity costs, harvest is reduced in the first periods to allow increases later. Bioenergy, with much lower profit than pulp and paper on the margin, is the hardest hit by the ban, while paper production is little affected. This may also be due to high capital costs in the paper

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industry and a perfectly elastic wood demand curve for bioenergy use. Substantial price increases for both raw materials and final products are suggested under either limited or perfect foresight. The analysis may provide useful insight about how agents react to sudden changes depending on their *a priori* information.

Introduction

Forest sector models are widely used to analyze the impacts of changes in economic or policy frames, which may be gradual or occur as shocks. Depending on the assumptions about agent foresight in the models, such changes may imply different policy impacts. In a perfect foresight model, the agents are assumed to have perfect market information for the whole projection horizon. Thus, market shocks are actually not shocks in such models, as they are anticipated from the first period and the behavior is adapted accordingly. Examples of forest sector models assuming perfect information include the FASOM model (Adams et al., 1996), the various regional models of Oregon developed by Adams and Latta (2005, 2007), the Timber Supply Model (TSM) (Sedjo and Lyon, 1990) and models related to the TSM by Sohngen and Mendelsohn (1998) and Sohngen et al. (1999).

Yet, most models assuming that information available to the agents is imperfect are myopic models. These models assume that agents only possess information about the current period and the past, and know nothing about future conditions. The GTM (Global Trade Model) family, such as the GTM (Kallio et al., 1987), CGTM (Cardellichio et al., 1989), EFI-GTM (Kallio et al., 2004) and NTM (Trømborg and Solberg, 1995; Bolkesjø, 2004) as well as the Global Forest Products Model (GFPM) (Buongiorno et al., 2003) all operate under this assumption.

Questions have arisen over the degree to which perfect foresight models are fit to predict behavior since the underlying assumption of perfect information over the whole time horizon is extreme and rather far from observed behavior. On the other hand, it is also a simplification to assume that agents have no information beyond the current period. The questions should rather be how much information agents are assumed to have, and how different degrees of information impact behavior?

The purpose of the present study is to analyze behavioral impacts resulting from agents' foresight conditions, i.e., no foresight, or foresight limited to some time, or full foresight, in a forest sector model. The study utilizes the Norwegian forest sector model NorFor, a dynamic equilibrium model with the default assumption of perfect foresight. The model is adapted to be able to reflect limited or no *a priori* knowledge of a future market shift.

We analyze the impacts of a general import ban on all coniferous timber to Norway beginning in 2020. Based on economic theory, several different forms of response are possible:

i. Having full information, agents will begin adapting from the first period of the simulation.
ii. If forest owners anticipate the ban, they will reduce timber harvest in the years before the ban in order to save timber for later periods when prices are higher.
iii. Due to (ii), harvests will increase more after the ban is introduced if the agents have perfect foresight than if they have not.
iv. If industry agents do not possess information about the ban, industrial production will be reduced considerably after the ban is imposed.

To test these hypotheses, four scenarios are run:

1. Base scenario with no ban (BASE).
2. Import ban in 2020 with perfect knowledge, i.e., the ban is known from 2010 (PK).
3. Import ban in 2020 with limited knowledge, i.e., the ban is known from 2015 (LK).
4. Import ban 2020 with no knowledge, i.e., the ban is known from 2020 (NK).

In scenarios 3 and 4, the model is solved iteratively over time periods with periods prior to knowledge of the import ban constrained to base scenario levels, reflecting the assumption that agents have no information of the ban and hence no basis on which to change behavior. From the period the import ban is known, the model is allowed to adjust. The differences in behavior among scenarios 2–4 reflect how the agents may adjust depending on whether they have information about the shock beforehand or not.

The introduction continues with a brief literature review of the underlying theory and its application, an overview of the Norwegian forest sector and the Pinewood nematode to provide further context for the study. The section "Methods" describes the NorFor model and how it incorporates forest investment decisions interrelated with industrial capacity, processing, and forest products trade. The results of the scenario analysis are presented in the third section and discussed in the section "Discussion and conclusions", where also the main conclusions are drawn.

Foresight assumptions in economic modeling

The rational expectations hypothesis (REH), put forward by Muth (1961), asserts that the subjective expectations of the agents equal the expectations conditional on the information available. Or, by Muth's (1961) own words (p. 316): "...that expectations of firms (or, more generally, the subjective probability distribution of outcomes) tend to be distributed, for the same information set, about the prediction of the theory (or the "objective" probability distributions of outcomes)". The expectations may differ from the actual values due to unpredictable uncertainty. As Muth (1961) stated, "... nor does it [the hypothesis] state that predictions of entrepreneurs are perfect or that their expectations are all the same" (p. 317). He did not see the REH as the way agents make their expectations, but he considered more the hypothesis' predictive power (Pesaran, 1987). The REH was based on two phenomena that averages of expectations in industry are more precise than models, and that "reported expectations generally underestimate the extent of changes that actually take place" (Muth, 1961, p. 316). However, the hypothesis has been subject to much debate, and there are even disagreements about what the hypothesis actually states (Gomes, 1982). Pesaran (1987) argues that this hypothesis is extreme and only holds within the frames of long-run steady state.

Contrary to the REH, the perfect foresight theory does not allow for uncertainty in the system. Perfect foresight corresponds to the REH without any uncertainty, and in this case, the expectations would equate the actual values (Sheffrin, 1996). Thus, the perfect foresight assumption is much stronger than the REH. Nevertheless, it is widely used in economic modeling.

Also in forest sector models, behavioral assumptions have been the subject of some debate. It has been claimed that the (global) market equilibrium in one period is "essentially independent of future market equilibria" (Dykstra and Kallio, 1987, p. 460). However, use of a perfect foresight model (where the opportunity costs of decisions in all other periods are considered in the harvest decisions in each period) may still give us useful information about how agents would act if they had perfect information. The basic theory of harvest behavior also indicates that future price expectations belong in the model, as owners determine harvest over time to maximize intertemporal utility. Depending upon the objective of the study and the type of impact to be studied, limited or perfect foresight could be assumed.

Despite the importance of future information on behavior and adaptations, few studies have dealt with this question in the forest sector. One exception is Sohngen and Sedjo (1996, 1998), who compared the price and inventory impacts resulting from several types of exogenous changes in a myopic and a perfect foresight model. This analysis has some limitations, however, since the model was extremely simple, involving only a timber demand curve, a simple age class-based forest inventory representation, and (in the myopic model) a timber supply curve. The sole source of dynamic adjustment in this analysis is the timber inventory. More complex models involving multiple market levels (beyond timber) may display different behaviors because of other dynamic elements, such as product inventories, capacity and capacity investment behavior. Fixed demand functions for timber that do not allow substitution adjustments over time may also have limited the analysis (Adams and Haynes., 2007). Finally, Sohngen and Sedjo did not consider changes in behavior that might occur in periods before exogenous conditions shift. All changes occur in the "first" period of the analysis and there is no opportunity for anticipatory adjustment in the perfect foresight model.

Heide et al. (2004) applied the general equilibrium model MSG6 of the Norwegian economy to study behavior patterns of exogenous shifts depending on whether the shifts are of permanent of transitory nature, and whether the shifts are anticipated or not. There are twelve exogenous shifts in their study, ranging from changes in export and import prices (Norway is considered a price-taker in the world market) to productivity changes, taking place in the first year or year ten. Their results indicate that the degree to which a world market shift is anticipated or not influences the investment, consumption and leisure time behavior prior to the shift, and that anticipation of a shift reduces the disturbances in the market. Furthermore, the impact of the *a priori* knowledge assumption is the largest just after the market shift occurs and is dampened with time. Babiker et al. (2009) compared climate change mitigation costs in a myopic and perfect foresight version of the MIT Emissions Prediction and Policy Analysis (EPPA) model, a global CGE model. Without any abatement of greenhouse gas emissions, perfect foresight gives lower energy prices and hence higher consumption and emissions. An equal relative reduction in greenhouse gas emissions is more costly when the agents lack perfect information about the future, because future-looking agents can adjust production and consumption beforehand.

The Norwegian forest sector

The Norwegian forest sector constitutes a minor share of the GDP, 0.6% (SSB, 2010a), but is important for rural economies and employment. Recent annual harvest for sale fluctuates between 6 and 8 million m^3 (in addition to approximately 1–2 million m^3 outside official markets), which is well below half of the annual increment of approximately 25 million m^3 (Statistikkbanken, s.a.). The bulk of the productive Norwegian forest is owned by as many as 120,000 private landowners with the average property size being scarcely 60 ha (SSB, 2010b). Thus, almost all forest owners have their main income from outside the forest sector. The pulp and paper industry has consolidated over the last few decades, and consists of about 20 mills today. Newsprint, uncoated paper, and linerboard are the primary products with a large proportion of the output destined for export.

Approximately 40% of the pulpwood in the Norwegian forest economy is imported, of which 85% originates in Sweden and the remainder from other North European countries. In addition, between 700,000 and 1.1 million m^3 of chips are imported annually (Statistikkbanken, s.a.). Most of the mills consuming pulpwood and chips are situated in the eastern part of the country close to the Swedish border, and transport distance may be shorter for Swedish than for domestic wood. The sawlog import is limited to about 5% of the harvest. At the same time, pulpwood exports are about half of imports, while the sawlog exports are similar in magnitude to imports.

The Pinewood nematode in Europe

The North American Pinewood nematode (PWN), *Bursaphelenchus xylophilus*, is harmless to trees native to that continent, but kills Scots Pine *Pinus sylvestris*, the abundant pine species in Europe. Spruce is not killed by the PWN, but may be a host. PWN has caused great harm to pine in Asia, to where it was introduced (FCEC, 2008). North Europe has import restrictions on conifer timber and chips since the 1980s, when the PWN was discovered in pine chips loads imported from Canada and the U.S. Later, those restrictions were adopted by the EU and applied to most of Europe (Dwinell, 1997). Nevertheless, in 1999, the first proof of European PWN establishment was found in Portugal (Økland et al., 2010). Findings of PWN in wood pallets exported from Portugal to other European countries triggered measures, and the European Commission banned imports of all coniferous wood originating in Portugal which was not proved of going through specific heating treatment (European Union, 2008). The PWN is an important risk factor to European forests, and large amounts of money have been spent in an effort to control its spread. In Spain, where one single tree has proved infested, 3 million Euros were spent in 2010 for combat (EPPO, 2009). Import restrictions vary between European countries (EPPO, 2009). In Norway, an overall import ban of coniferous timber with bark from outside Europe and from Portugal has been in place since 2001. Measures such as bark removal and heat treatment are required depending on origin (LMD, 2000). Based on the fear in Europe of PWN spread and the large pulpwood import into Norway, our hypothesis is that if the PWN is found in Sweden, it may have large impacts on the Norwegian wood market, due to the import ban which is likely to be imposed in such a situation.

Methods

NorFor is a spatial, partial equilibrium model of the Norwegian forest sector based on the assumption of perfect competition and perfect foresight. As such it is important to note that the model solution is intended to represent market potential and simulated policy changes shift projected market potential. Based on the objective function of the discounted value of the annual net social payoff, the model determines the optimal behavior of the agents in primary forest production and industry as well as consumers. A condensed mathematical description of the model is given in Appendix A.

The structure and data input of the forest industry portion of the model derives in large part from the NTMII (Bolkesjø, 2004), with updated capacity data. Forest growth depending on management is simulated with the stand simulator Gaya (Hoen and Eid, 1990). The incorporation of the forest management yields into the dynamic linear programming harvest schedule problem comes to a large extent from the regional models of Oregon (Adams and Latta, 2005, 2007).

NorFor includes 18 Norwegian counties (all counties except Finnmark) along with one foreign region for import and export and operates in five-year periods. The foreign region is a pure trade region with no industrial production and includes only the net trade with Norway.

The NorFor model can be divided into four parts: forest management and harvesting; industrial capacity and processing; wood products consumption and prices; and trade of timber and wood products.

Forest management and harvesting

The forest data are comprised of approximately 9000 national forest inventory plots covering all productive Norwegian forest land. The growth and yield for each plot is simulated with Gaya for up to seven management options in addition to final harvest: no management; thinning; precommercial thinning favoring hardwoods; precommercial thinning favoring hardwoods and thinning; precommercial thinning favoring softwoods; precommercial thinning favoring softwoods and thinning; and shelter wood harvest. The criteria for stand ages at which thinning occurs are set exogenously whereas timing of final harvest is endogenous. Yields are also generated for regenerated stands following final harvest and depend on site class, species, and regeneration methods. With the exception of shelter wood harvests, the conditions in a stand after final harvest are independent of the conditions of the prior.

In the dynamic optimization problem, the model selects the appropriate management options through time for each hectare of forest land. This management selection includes current stand harvest timings as well as regenerated stand silvicultural investment and harvest timings. Planting, site preparation as well as precommercial thinning options comprise the silviculture investments choices. The timber supply consists of sawlogs and pulpwood from thinning and final harvest of pine, spruce and birch species. Supply from abroad of wood and intermediate products is defined by a constant elasticity import supply function.

Industrial capacity and processing

The industry structure and data are to a large extent taken from the NTMII (Bolkesjø, 2004) but with updated capacity data for the pulp and paper industry. The solid wood industry is defined at the county level, while the pulp, paper and board industry is defined at mill level. Sawmills process the logs into lumber, and sell the slabs and off-cuts to the pulp, paper and board industries or for bioenergy. If no action is taken, capacity is depreciated at a fixed percent per year. Industry agents may also choose to maintain the capacity level or to add new capacity. Inputs other than wood and intermediate wood products, such as capital, labor, energy and recycled paper are priced exogenously.

The share of sawlogs and pulpwood in a stand is defined by Gaya, but sawlogs may be downgraded to pulpwood. Pulpwood can be used for producing pulp, paper and board, or downgraded as well for bioenergy purposes.

Wood products consumption and prices

The demand for final products is the engine for processing and harvesting. In all regions, demand functions for final products, such as sawnwood, paper grades and bioenergy, are represented by basic prices and quantities from NTMII runs and elasticities based on econometric studies. All products, raw material, intermediate and final products, can be exported, facing export demand functions similar to those for final products in Norway.

Bioenergy is a rather insignificant commodity in the large heating market, dominated in Norway by electricity. Thus, the energy demand is perfectly elastic at a fixed price, implying that bioenergy production does not impact the energy price.

Trade of timber and wood products

The forest sector is transport intensive, with long distances between the forest, forest industry and consumers. Wood and wood products can be transported between all regions in Norway and to/from abroad, and shipments will take place if the price difference is greater than the transport costs, to ensure the maximization of the net social payoff (Samuelson, 1952).

Results

The scenarios were run for 15 five-year periods, using a discount rate of 3%. To reduce the potential for the terminal valuation impacting the policy analysis, only two thirds of the modeling time horizon, i.e., from year 2010 to 2055, is presented.

Base scenario: no ban

In the base scenario, domestic harvest level is at 19.6 million m^3 the first period, decreasing until 2055, when 8.3 million m^3 is harvested. Almost half of the harvest (9 million m^3) in the first period is birch, but the relative contribution of birch declines rapidly, to about 10% of total harvest in 2055 (840,000 m^3). Harvested volume of coniferous sawlogs starts at 2.4 million m^3 increases to its maximum in 2020 (4.0 million m^3) and thereafter declines.

Timber imports increase steadily from about 3.6 million m^3 in first period to 4.3 million m^3 in end of the modeling horizon. 75% of the imports are coniferous pulpwood and 17% are birch pulpwood. Spruce is the only sawlog imported. Exports of timber amount to approximately 800,000 m^3, of which about half is pine pulpwood, and the remaining divided almost equally between spruce sawlogs and spruce pulpwood.

Prices for most final products increase over the time horizon. For spruce sawnwood, the most important solid wood product in terms of volume, the price growth is about 50% over the 10 period horizon, starting at ~150€ (1,200 NOK).[1] The relative price increase of newsprint is similar in magnitude, starting at 523€, while uncoated paper sees a smaller increase of 13% from its first period price of 777€.

Demand for sawnwood increases from first to second period, and thereafter remains quite stable with spruce near 1.9 million m^3 and pine roughly 900,000 m^3. More than 75% of the pine sawnwood demand is met with imported wood; while the number for spruce sawnwood is 15–21%. Spruce sawnwood production follows the same basic pattern as demand. Newsprint demand experiences a small decrease to the second period, but is thereafter stable at 750,000 tonnes. Uncoated paper demand is 740,000 tonnes initially then increases stepwise to 800,000 tonnes. Bioenergy demand is volatile,

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[1] An exchange rate of 0.125 between Norwegian crones (NOK) and Euros has been applied throughout the paper.

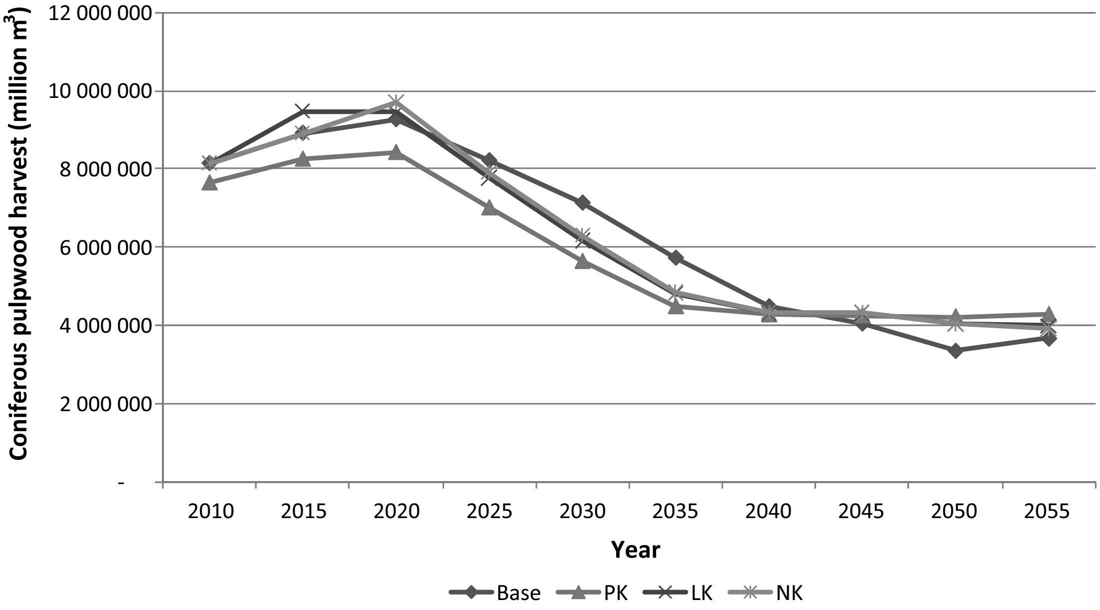

Fig. 1. Harvest of coniferous pulpwood (million m^3) in all scenarios.

Table 1
Harvest levels of coniferous and birch pulpwood relative to BASE.

Period	Coniferous pulpwood and sawlogs			Birch pulpwood		
	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)
2010	−5	–	–	−5	–	–
2015	−6	4	–	−3	−10	–
2020	−5	2	4	−4	−12	−22
2025	−9	−2	−1	17	13	7
2030	−12	−7	−6	43	47	38
2035	−12	−8	−8	32	42	40
2040	−2	−1	−1	−18	4	4
2045	3	2	2	−38	−13	−13
2050	13	6	6	−66	−42	−39
2055	9	−1	−2	−25	−37	−29

and the patterns follow the harvest levels. The first period demand is 20 TWh delivered heat in wood stoves, which is reduced to less than 5 TWh in the last period.

Forest management and harvest

Harvest levels of coniferous pulpwood for the four scenarios are given in Fig. 1. Some trends become apparent in analyzing the output. The PK scenario reduces its harvest levels immediately below the base and remains below until after 2040. The LK and NK both increase coniferous pulpwood harvest levels in the period agents gain knowledge of the import ban, however their harvest behavior is nearly identical following the 2020 period as harvests fall below the base case, yet remain above the PK scenarios until 2040.

Table 1 presents the percentage change from the base levels in total coniferous and birch pulpwood harvest for the scenarios. The coniferous total harvest numbers have the same basic traits as the coniferous pulpwood harvests discussed above. In the PK scenario, harvest is reduced prior to the ban, but the reduction continues, and increases in magnitude until 2040. The harvest patterns are similar, but of smaller magnitude, in the LK and NK scenarios. The birch pulpwood harvest behaves differently. Having knowledge from the first period, the agents reduce the harvest, but increase it substantially in periods after the ban is introduced, for reducing it even more later. Without any anticipation of the ban, birch pulpwood harvest is reduced by 22% in 2020. Birch sawlogs harvest is

Table 2
Industrial production in ban scenarios relative to BASE.

Period	Pulp and paper			Coniferous sawnwood			Bioenergy		
	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)
2010	0	–	–	−1	–	–	−6	–	–
2015	−1	0	–	−2	−2	–	−6	0	–
2020	−3	−2	−2	−4	−3	−3	−31	−26	−26
2025	−2	−3	−3	−4	−3	−3	−35	−28	−29
2030	−2	−2	−2	−4	−3	−3	−39	−33	−33
2035	−2	−3	−3	−5	−4	−4	−46	−37	−37
2040	−3	−4	−4	−6	−6	−5	−55	−45	−45
2045	−3	−5	−5	−7	−10	−10	−63	−53	−53
2050	−4	−7	−7	−7	−14	−15	−68	−58	−57
2055	−4	−8	−9	−7	−18	−18	−60	−63	−61

Table 3
Spruce pulpwood prices relative to BASE.

Period	PK (%)	LK (%)	NK (%)
2010	1	–	–
2015	2	9	–
2020	8	10	14
2025	7	9	17
2030	8	13	28
2035	15	25	49
2040	21	45	82
2045	29	75	98
2050	38	90	116
2055	33	106	137

very stable between the scenarios, starting at 43,000 m^3 in first period and increases to 82,000 m^3 in 2055.

Coniferous harvest is reduced to some degree in all ban scenarios in the first decades, but it levels off by 2040. When the ban is introduced in 2020 and not perfectly anticipated, the intertemporal allocation is smaller. Coniferous and birch pulpwood are substitutes in bioenergy (but not for pulp and paper), and harvest of birch stands increase considerably with the decrease in coniferous harvest which counterweights the coniferous decline. When coniferous harvest increases after 2040, harvest of birch goes down.

In the PK scenario, coniferous pulpwood is retained with between 0.5 and 1.5 million m^3, compared to BASE until 2035, and in 2050, pulpwood harvest is 0.85 million m^3 higher in the PK scenario than in BASE.

Industrial capacity and processing

In the model, pulpwood is used for pulp, paper, boards and bioenergy. The results indicate a shift in production with the ban. While pulp and paper production is relatively stable throughout the horizon, bioenergy declines rapidly (Table 2). Even if the ban is anticipated, production decrease accelerates only after the ban is imposed. Sawnwood production decreases to maximum 7–8% in the perfect knowledge scenarios, and up to 18% if anticipation is somewhat or completely limited.

Wood products consumption and prices

Wood prices would potentially be impacted by the ban. Results indicate that reducing the time agents know about the ban prior to its implementation may lead to greater price impacts (Table 3). Consequently, an import ban in 2020 has the largest impact when it is not anticipated.An import ban imposed in 2020 which is not anticipated beforehand or only five years beforehand may have large

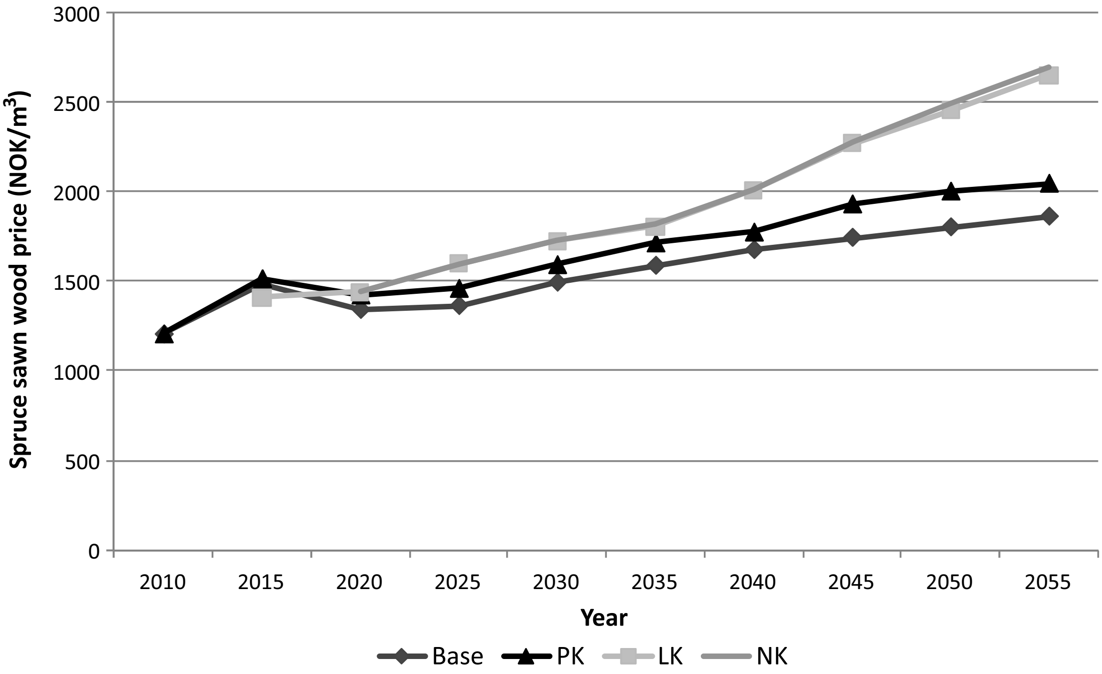

Fig. 2. Domestic price of spruce sawnwood (NOK/m^3) in the scenarios. (Prices in NK scenario are almost identical to LK.)

impacts on product prices. Such a ban may cause the spruce sawnwood price to more than double over the horizon. The results suggest that a ban anticipated in ten years disturbs sawnwood prices less than the same ban with no prior information (Fig. 2). Similar patterns are found for newsprint (Fig. 3). The differences in prices between the scenario where the ban is known five years prior to the enforcement (LK) or not known beforehand at all (NK), are small. The degree of anticipation seems to have more impact on prices of pulpwood than on wood products.

Both sawnwood and paper consumptions are relatively stable in the years after introduction of the ban (Table 4), but sawnwood consumption is more disturbed than paper, and reduced *a priori* knowledge triggers larger impacts, also in later periods. Since bioenergy in the model is not tradable (only wood for energy), consumption equals production.

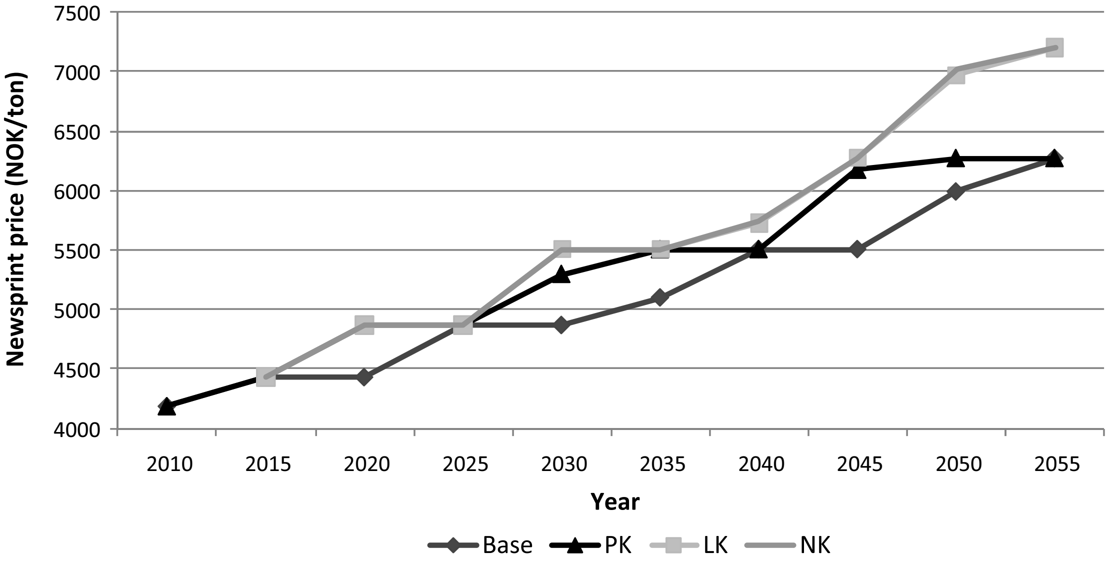

Fig. 3. Domestic newsprint price (NOK/tonne) in the scenario. (Prices in NK scenario are almost identical to LK.)

Table 4
Consumption of coniferous sawnwood and paper relative to BASE.

Period	Coniferous sawnwood			Paper		
	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)
2010	−0	–	–	1	–	–
2015	−1	−1	–	0	0	–
2020	−2	−2	−2	−0	−1	−0
2025	−2	−2	−2	1	0	−0
2030	−2	−2	−2	−0	−3	−3
2035	−2	−2	−2	−2	−4	−4
2040	−3	−3	−3	−1	−1	−1
2045	−4	−6	−6	−0	−3	−3
2050	−4	−7	−8	0	−4	−4
2055	−3	−8	−9	0	−4	−4

Table 5
Import of wood products relative to BASE.

Period	Pulp and paper			Coniferous sawnwood		
	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)
2010	3	–	–	1	–	–
2015	0	0	–	3	1	–
2020	2	3	3	2	1	1
2025	2	1	1	2	1	1
2030	2	1	1	3	1	1
2035	2	2	2	2	2	1
2040	1	1	1	3	2	1
2045	0	0	0	3	4	4
2050	0	1	0	3	6	6
2055	−1	7	18	3	8	8

Trade of timber and wood products

Import of manufactured wood products (pulp, paper, boards and sawnwood) is not much changed with the ban. Only in the last periods of the time horizon do imports increase in the non-perfect knowledge scenarios (Table 5). Import of birch is not affected by the ban.

Export of coniferous timber is reduced by up to 10% in the PK scenario, and up to 21% in the LK and NK scenarios (Table 6). However, it is only in the latest periods that this reduction takes place. A 10% reduction corresponds to about 90,000 m^3. Sawnwood export is only slightly impacted by the ban, while pulp and paper export is reduced to some extent.

Table 6
Export of coniferous timber, coniferous sawnwood and pulp and paper relative to BASE.

Period	Coniferous timber			Coniferous sawnwood			Pulp and paper		
	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)	PK (%)	LK (%)	NK (%)
2010	–	–	–	−1	–	–	−1	–	–
2015	–	–	–	0	0	–	−2	0	–
2020	−2	−2	−2	0	0	0	−3	−2	−3
2025	0	–	–	–	–	–	−4	−4	−4
2030	−3	−3	−3	0	6	6	−3	−2	−2
2035	–	–	–	−6	0	0	−1	−2	−2
2040	−8	−5	−5	0	0	0	−3	−4	−4
2045	−10	−10	−10	–	−1	−1	−4	−5	−5
2050	−10	−15	−15	−1	−1	−1	−6	−8	−8
2055	−10	−21	−21	−1	−7	−7	−6	−9	−9

Discussion and conclusions

This study provides insight into how agents in the Norwegian forest sector could react to a sudden exogenous change depending upon their *a priori* information. Given that the model chosen for the analysis, NorFor, utilizes perfect information in its dynamic optimization of intertemporal welfare its resulting allocation of resources should be viewed as a sort of maximum market potential rather than a forecast. Scenario analysis using such a model provides decision makers with relevant information in the form of the change in market potential with the introduction of a policy. In general, perfect foresight smoothes out the impacts of shocks, since optimal decisions are made simultaneously for all periods. The constraint of limited foresight before the ban reduces the possibilities for intertemporal adjustment. In the model runs, the adaptations in the perfect knowledge scenario begin in the first period, by saving timber for later periods when its value increases. Similar results in the scenarios with LK and NK suggest that anticipating the ban five years beforehand does not give many chances for adaptations. The small differences between the results in the LK and NK scenarios compared to the PK case may also be caused by the fact that the investments in the first period in the LK case are done with incorrect assumptions about future market conditions, and the investments limit the possibilities of changes in the short run.

Comparing the model runs, the output levels of pulp and paper and sawnwood products change at most by −9% and −18%, respectively, from the base case. In these instances there is little difference in the extent of response between the LK and NK cases, being 2–3 times the changes in the PK case. Similarly, consumption changes in the product markets are at most −9% for sawnwood and −4% for paper, and the pattern of larger but nearly equal changes in the LK and NK cases compared to the PK case is preserved.

In log markets, not much change is seen in the domestic harvest of sawlogs, which increases slightly with the ban due to less downgrading of sawlogs to pulpwood. Changes in pulpwood markets are larger than those observed in the product markets and more complex. Unlike the product market, the largest changes are seen for the PK case with smaller and roughly equal changes for the LK and NK cases. Stability in product markets is obtained at the expense of greater variation in the factor markets (a phenomenon commonly observed due to elasticity differences). The PK case with the smallest changes in product output and consumption (and trade) requires the largest shifts in the log market.

A large share of the pulpwood is used for bioenergy before the ban. Since bioenergy profit is considerably lower than for paper grades, bioenergy is the first to be the phased out. The high capacity costs in the pulp and paper sector and the fixed price assumption for wood for bioenergy may also be factors in this result. Stability in pulp and paper production is attained at the expense of bioenergy. This is to some extent also true for sawn wood as well. Under PK, bioenergy production is reduced more and pulp, paper and sawn wood production is sustained correspondingly more than under LK and NK.

Patterns of change are roughly similar in log and product trade. Relative changes from the base case are smallest for products. Sawnwood imports show a larger relative increase than pulp and paper, and the sawnwood LK and NK import cases are nearly the same at about twice the PK case levels in the last periods. In exports, reductions in coniferous timber exports are only slightly larger for LK and NK than the PK case, while there is very little difference between the sawnwood and pulp and paper export cases.

The relative price impacts are not completely uniform but display pattern similar to those for production and consumption. Percentage changes in log prices are larger than those in the product markets. When the ban is implemented the spruce pulpwood price increases in the LK case are larger than in the NK case, which again are larger than those observed in the PK case. For products, the price impacts are very similar under LK and NK, substantially higher than under PK.

In the earlier Sohngen and Sedjo (1998) study, their scenario of sudden young timber dieback comes closest in wood supply effects to our import ban scenario – though they deal only with a timber market and their dieback occurs before the start of the simulations as a change in initial conditions. They find larger price impacts in the myopic model in the first years after the shift than in the perfect foresight model and that the prices in the two models converge with time. We also find larger initial changes in log prices under the LK and NK cases, but the log price projections diverge over time.

In the application of MSG6 (Heide et al., 2004) for exogenous market changes anticipated and unanticipated ten years in the future, the import price increase case is maybe the most comparable to our study. They found that consumers begin to adapt from the first period by reducing consumption and leisure. After the market shift has occurred, they reduce less if it is anticipated, and over the entire horizon, the anticipation leaves consumers better off, compared to the non-anticipation scenario. This is a general equilibrium model which has a totally different and more complex representation of consumption than NorFor, but we believe the results are of interest to compare.

To summarize the answers to the hypotheses posed in the introduction:

i. Having full information, agents will begin adapting from the first period of the simulation.

   We found clear evidence of adaptive behavior before the ban takes place, however the extent depended on the length of time ahead of the ban that the agents had knowledge. Knowledge five years ahead of time led to behavior similar to that of agents who received no *a priori* information of the ban.

ii. If forest owners anticipate the ban, they will reduce timber harvest in the years before the ban in order to save timber for later periods when prices are higher.

   This behavior is illustrated in Figs. 1 and 2. Forest owners continue to retain timber after the ban is imposed, as they foresee even greater price increases later.

iii. Due to (ii), harvests will increase more after the ban is introduced if the agents have perfect foresight than if they have not.

   Given Norwegian forests growth rates and the relatively short modeling time frame of this analysis, it may be difficult to determine if the harvest behavior noted in our results is consistent with this hypothesis. When the ban is perfectly foreseen, the agents do appear to retain more coniferous timber after the ban is imposed which would be consistent with a lengthening of rotations moving closer to the biological rotation thus leading to higher long term harvest levels. For birch, the trend is unclear.

iv. If industry agents do not possess information about the ban, industrial production will be reduced considerably after the ban is imposed.

   Post-ban production of pulp and paper and sawnwood does decline more in the LK and NK cases, as displayed in Table 2. For bioenergy, the production reductions are greater for the PK cases than for the LK and NK cases.

In considering our results, limited possibilities of substitution in the model may affect the simulation outcomes. A tree-level forest growth simulation model could to a greater extent optimize the species composition in harvest. In the present model, a stand or a part of a stand is harvested with all the species it contains. Pulp and paper industries may to some degree change the composition of input factors, particularly over time. However, due to technological development, this may be difficult to model for a longer period. Also, different species of sawnwood are probably substitutes in demand, even if not necessarily perfect substitutes.

The year of the introduced ban, 2020, is hypothetical and not based on projections of market changes. Choosing another year for the introduction of the ban might have impacted on the results, for instance might a more distant ban have caused larger differences between the scenarios.

The harvest levels reported here are substantially higher than recently observed levels, as the large growth increment gives flexibility to harvest increases and we have assumed a relatively high real term interest rate of 3% p.a. Forest owners may, however, have other, or additional, objectives than maximization of net present worth. Typically, forest owners prefer to pay for a more stable harvest level, or to even have non-declining yield. The additional harvest given here compared to the statistics, is to a large extent birch wood. Almost all birch, independently of quality, is used for bioenergy and is outside the demand for the traditional forest industry. This indicates that birch could be used to a much larger extent. However, it is important to keep in mind that the harvest levels given by the model are potentials of what might happen if all agents follow the behavior indicated by the objective function and constraints, and is therefore not necessarily comparable with historical data.

Interesting future research could be to compare NorFor with NTM, or to develop a myopic version of the NorFor model. It could also be possible to replace the forest management model with a simple growth model in NorFor to make the perfect foresight and myopic models more comparable. It would also be of interest to analyze the impacts of having a ban further into the future, to investigate further the importance of the time available for adaptation.

Conclusions

The impacts of the hypothetical import ban seem, according to the results, to depend upon the degree of information available about the shock before it occurs. Possessing this information before the shock may lead the agents to save more timber to later periods, when its value increases. Actually, the price increase over the whole horizon leads forest owners to save wood also after the ban is introduced. The PK results indicate that production in the industry may also be altered before the shock takes place. Because bioenergy production has relatively low profitability and a perfectly elastic demand for wood, pulp and paper production is conserved to the detriment of bioenergy. The prices of both raw materials and final products increase substantially, but more if there is no advanced information about the ban. In general, more information will smooth out shocks. More studies about the impacts and the consistency with the "real world" of the assumptions of foresight would be of great interest.

Appendix A. Model specifications

Objective function:
Maximize

$$\sum_{t=1}^{T}\left[\sum_{r}\sum_{fp}D_{r,fp}(Q_{r,fp,t})+\sum_{p}D_{p}^{F}(Q_{p,t}^{FD})-\sum_{p}S_{p}^{F}(Q_{p,t}^{FS})-\sum_{r}\sum_{l}\sum_{cf}FC_{r,cf}\times H_{r,l,cf,t}\right.$$

$$-\sum_{r}\sum_{ip}\sum_{m}\sum_{f}EC_{r,t,f}\times R_{ip,r,m,f}\times PR_{ip,r,m,t}-\sum_{r}\sum_{ip}\sum_{m}IC_{r,ip}\times(Ck\times C_{r,ip,m,t}$$

$$\left.+Cm\times CM_{r,ip,m,t}+Cb\times CB_{r,ip,m,t})-\sum_{ar}\sum_{ar2}\sum_{p}TC_{ar,ar2,p}\times TR_{ar,ar2,p,t}\right](1+i)^{-t}$$

subject to:

$$\sum_{XM}\sum_{t}EX_{pl,t,XM}=HA_{pl}\quad\forall pl \tag{1}$$

$$\sum_{XM}EX_{pl,t,XM}=\sum_{t2}\sum_{XM}\sum_{NM}NEW\_XN_{pl,t,t2,XM,NM}\quad\forall t,pl \tag{2}$$

$$\sum_{t2}\sum_{XM}\sum_{NM}NEW\_XN_{pl,t,t2,XM,NM}+\sum_{t2}\sum_{NM}\sum_{NM2}NEW\_NN_{pl,t,t2,NM,NM2}$$
$$=\sum_{t2}\sum_{NM}\sum_{NM2}NEW\_NN_{pl,t,t2,NM,NM2}\quad\forall t,pl \tag{3}$$

$$H_{r,l,cf,t}+Q_{p,t}^{FS}+\sum_{ar2}TR_{ar2,ar,p,t}+\sum_{m}PR_{p,r,m,t}-WD_{p,r,t}-\sum_{ar2}TR_{ar,ar2,p,t}$$
$$-\sum_{m}\sum_{p}R_{ip,r,m,p}\times PR_{ip,r,m,t}-Q_{p,t}^{FD}=Q_{r,p,t}\quad\forall t,p,r \tag{4}$$

$$C_{ip,r,m,t-1}(1-dr)+CM_{ip,r,m,t}+CB_{ip,r,m,t}=C_{ip,r,m,t} \quad \forall\, t, ip, r, m \tag{5}$$

$$CM_{r,ip,m,t} \le C_{ip,r,m,t-1}(1-dr) \quad \forall\, t, ip, r, m \tag{6}$$

$$PR_{ip,r,m,t} \le C_{ip,r,m,t} \quad \forall\, t, ip, r, m \tag{7}$$

$$CB_{r,ip,m,t} \le CMax_{r,ip,m} \quad \forall\, t, ip, r, m \tag{8}$$

Explanation of constraints

(1): Allocation of existing forest
(2): Harvested existing stands go into a new management regime.
(3): Regenerated and re-regenerated stands go into a new management regime.
(4): Balance of wood inputs and outputs in industry.
(5)–(8): Capacity constraint.

Definition of symbols

Sets

ar, *ar*2: all regions, within and outside Norway.
cf: forestry cost factor, i.e., costs of logging (final harvest and thinning) and silviculture.
f: costs in industry of input with exogenously determined prices.
fp: end products, i.e., with a demand function in Norwegian regions.
ip: industrial product, i.e., intermediate and end products from industrial production.
l: log products, i.e., sawlogs and pulpwood of spruce, pine and birch.
NM, *NM*2: management regimes for forest land regenerated once (XN) or more (NN).
p: products, including log products, industrial products and end products.
r: regions within Norway.
t: periods.
T: last period.
XM: management regimes for existing forest lands, i.e., which have not been clearcut yet.

Scalars

Cb: costs to build new capacity as a share of IC.
Ck: costs of keeping capacity as a share of IC.
Cm: costs to maintain capacity as a share of IC.
dr: depreciation rate in industry.
i: interest rate.

Parameters

$CMax_{i,ip,m}$: maximum capacity for all periods.
$FC_{r,cf}$: forestry costs in region *r* and of cost factor *cf*.
$EC_{r,t,f}$: exogenous costs in industry, in region *r*, period *t* and of factor *f*.
HA_{pl}: area in each forest plot.
$IC_{r,ip}$: investment costs in region *r* and for industrial product *ip*.
$R_{ip,m,f}$: input ratio of factor *f* to production of industrial product *ip* and in technology *m*.
$TC_{ar,ar,p}$: costs of transport a product from region *ar* to region *ar*2.

Variables

$C_{r,ip,m,t}$: capacity level in region *r*, of industrial product *ip* and of machines *m*.
$CB_{r,ip,m,t}$: new capacity in region *r*, of industrial product *ip* and of machines *m*.

$CM_{r,ip,m,t}$: maintained capacity in region *r*, of industrial product *ip* and of machines *m*.

$D_{r,fp}(Q_{r,fp,t})$: area under the demand curve for end product *fp* in region *r* as a function of volume *Q*.

$D_p^F(Q_{p,t}^{FD})$: area under the demand curve for product *p* in the foreign region as a function of volume Q^{FD}.

$EX_{pl,t,XM}$: area in plot *pl* allocated to management regime *XM* and harvested in period *t*.

$H_{r,l,cf,t}$: harvest in region *r*, of log product *l* with forestry cost factor *cf* in period *t*.

$Inv_{l,r,p}$: growing stock of log product *l*, in region *r* in period *p*.

$NN_{pl,t,t2,NM}$: area in plot *pl* allocated to management regime *NM*, re-regenerated in period *t* and harvested in period *t*2 (after been through XN) $NN_{pl,t,t2,XM}$.

$PR_{ip,r,m,t}$: production of industrial product *ip*, in region *r*, in machines *m* in period *t*.

$S_p^F(Q_{p,t}^{FS})$: supply function for product *p* in the foreign region as a function of volume Q^{FS}.

$S_p^{FT}(Q_{p,t}^{FS})$: supply function for product *p* in the foreign region as a function of volume Q^{FS} in the last period.

$TR_{ar,ar2,p,t}$: transport of product *p* from region *ar* to region *ar*2 in period *t*.

$WD_{p,r,t}$: wood debris of product *p*, in region *r* and in period *t*.

$NEW\_XN_{pl,t,t2,XM,NM}$: area in plot *pl* allocated to management regime *NM*, allocated to management regime XM before harvest, harvested and regenerated in period *t* and harvested in period.

$NEW\_NN_{pl,t,t2,NM,NM2}$: area in plot *pl* allocated to management regime *NM*2, allocated to management regime NM before harvest, harvested and regenerated in period *t* and harvested in period.

References

Adams, D.M., Haynes, R.W., 2007. Methodological considerations in developing the timber assessment projection system. In: Adams, D.M., Haynes, R.W. (Eds.), Resource and Market Projections for Forest Policy Development: Twenty-five Years of Experience with the U.S. RPA Timber Assessment. Springer Science + Business Media, Dordrecht, 589 pp. (Chapter 2).

Adams, D.M., Latta, G.S., 2005. Costs and regional impacts of restoration thinning programs on the national forests in Eastern Oregon. Canadian Journal of Forest Research 35 (6), 1319–1330.

Adams, D.M., Latta, G.S., 2007. Timber trends on private lands in Western Oregon and Washington: a new look. Western Journal of Applied Forestry 22 (1), 8–14.

Adams, D.M., Alig, R.J., Callaway, J.M., McCarl, B.A., Winnett, S.M., 1996. The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications. Research Paper PNW-RP-495. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Babiker, M., Gurgel, A., Paltsev, S., Reilly, J., 2009. Forward-looking versus recursive-dynamic modeling in climate policy analysis: a comparison. Economic Modelling 26 (6), 1341–1354.

Bolkesjø, T.F., 2004. Modelling supply, demand and trade in the Norwegian forest sector. Dr. Scient. thesis, Agricultural University of Norway (Norwegian University of Life Sciences), 2004, p. 10.

Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D., 2003. The Global Forest Products Model (GFPM): Structure, Estimation, and Applications. Academic Press, San Diego, 301 pp.

Cardellichio, P.A., Youn, Y.-C., Adams, D.M., Joo, R.-W., Chmelik, J., 1989. A Preliminary Analysis of Timber and Timber Products Production, Consumption, Trade, and Prices in the Pacific Rim until 200. Work Pap WP-22. CINTRAFOR. University of Washington, College of Forest Resources, Seattle, WA.

Dwinell, L.D., 1997. THE PINEWOOD NEMATODE: regulation and mitigation. Annual Review of Phytopathology 35, 153–166.

Dykstra, D.P., Kallio, M., 1987. Introduction to the IIASA Forest Sector Model. In: Kallio, M., Dykstra, D.P., Blinkey, C.S. (Eds.), The Global Forest Sector: An Analytical Perspective. John Wiley & Sons, p. 703 (Chapter 19).

EPPO (European and Mediterranean Plant Protection Organisation), 2009. PEST RISK ANALYSIS FOR: *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle. Available from: http://www.eppo.org/QUARANTINE/Pest_Risk_Analysis/PRAdocs_nematodes/09-15449%20PRA%20revision%20for%20Bursaphelenchus_xylophilus_2010_03_22.doc.

European Union, 2008. COMMISSION DECISION of 19 August 2008 (2008/684/EC).

FCEC, 2008. Analysis of the socio-economic and environmental impacts of banning or not banning the movement of susceptible wood products from Portugal for stopping the spread of Pine wood nematode (PWN). Framework contract for evaluation, impact assessment and related services Lot 3: Food Chain. European Commission. 63 pp.

Gomes, G.M., 1982. Irrationality of “rational expectations”. Journal of Post Keynesian Economics 5 (1), 51–66.

Heide, K.M., Holmøy, E., Lerskau, L., Solli, I.F., 2004. Macroeconomic Properties of the Norwegian Applied General Equilibrium Model MSG6. Statistics Norway report 2004/18. Available from: http://www.ssb.no/emner/09/90/rapp_200418/rapp_200418.pdf.

Hoen, H.F., Eid, T., 1990. En modell for analyse av behandlingsalternativer for en skog ved bestandssimulering og lineær programmering. Rep. Norw. For. Res. Inst. Ås-NLH. 9, 35 pp. (in Norwegian with English summary).

Kallio, M., Dykstra, D.P., Binkley, C.S., 1987. The Global Forest Sector: An Analytical Perspective. John Wiley & Sons, New York.

Kallio, M.I., Moiseyev, A., Solberg, B., 2004. The Global Forest Sector Model EFI-GTM – The Model Structure. Internal Report No. 15. European Forest Institute.

Lmd (Norwegian Ministry of Agriculture and Food), 2000. Rule: FOR 2000-12-01 nr 1333: Regulation of plants and measures against harmful organisms [Forskrift om planter og tiltak mot planteskadegjørere]. Available from: http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20001201-1333.html (in Norwegian).

Muth, J., 1961. Rational expectations and the theory of price movements. Econometrica 29 (3), 315–335.

Økland, B., Skarpaas, O., Schroeder, M., Magnusson, C., Lindelöw, Å., Thunes, K., 2010. Is Eradication of the Pinewood nematode (*Bursaphelenchus xylophilus*) likely? An evaluation of current contingency plans. Risk Analysis 30 (9), 1424–1439.

Pesaran, M.H., 1987. The Limits to Rational Expectations. Basil Blackwell, Oxford, 325 pp.

Samuelson, P.A., 1952. Spatial price equilibrium and linear programming. The American Economic Review 42, 283–303.

Sedjo, R., Lyon, K., 1990. The Long-term Adequacy of World Timber Supply. Resources for the Future, Washington, DC.

Sheffrin, S.M., 1996. Rational Expectations, 2nd ed. Cambridge University Press, 184 pp.

Sohngen, B., Mendelsohn, R., 1998. Valuing the impact of large-scale ecological change in a market: the effect of climate change on U.S. timber. American Economic Review 88 (4), 686–710.

Sohngen, B., Sedjo, R., 1996. A Comparison of Timber Models for Use in Public Policy Analysis. Discussion Paper 96-12. Resources for the Future, Washington, DC.

Sohngen, B., Sedjo, R., 1998. A comparison of timber market models: static simulation and optimal control approaches. Forest Science 44 (1), 1998.

Sohngen, B., Mendelsohn, R., Sedjo, R., 1999. Forest management, conservation, and global timber markets. American Journal of Agricultural Economics 81 (1), 1–12.

SSB, 2010a. Focus on forests. Available from: http://www.ssb.no/english/subjects/10/04/20/skog_en/Visited (25.11.10.).

SSB, 2010b. Forestry, structural statistics, 2009. Fewer properties cut timber for sale. Available from: http://www.ssb.no/english/subjects/10/04/20/stskog_en/ (updated 22.10.10, visited 25.11.10.).

Statistikkbanken (s.a.), Subject: 09 National accounts and foreign trade Table 03057: Import and export, from product number and country Product number 44-49 Wood, wood products and wood pulp [Emne:09 Nasjonalregnskap og utenrikshandel Tabell 03057: Import og eksport, etter varenummer og land Varenummer 44-49 Tre, trevarer og tremasse.] Subject: 10 Industrial activities Table 06291: Annual increment under bark [Emne: 10 Næringsvirksomhet Tabell 06291: Årlig tilvekst under bark]. Available from: www.statbank.ssb.no/statistikkbanken/ (in Norwegian).

Trømborg, E., Solberg, B., 1995. Beskrivelse av en partiell likevektsmodell anvendt i prosjektet "Modellanalyse av norsk skogsektor" [Description of a Partial Equilibrium Model Applied in the Project "Model analysis of Norwegian Forest Sector"]. Skogforsk Research paper 14/95. Department of Forest Sciences (Department of Ecology and Natural Resource Management), Agricultural University of Norway (Norwegian University of Life Sciences) (in Norwegian).

Paper III

Greenhouse gas emission impacts of use of wood pellets -

a sensitivity analysis

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ABSTRACT

The rapid growth in wood pellet consumption in Europe has promoted an increase in imports from other continents. In this study, we analyse: i) the resource use and greenhouse gas (GHG) emissions over the life cycle of wood pellets produced in Western Europe, ii) the net GHG emission effects of replacing brown coal with these pellets, iii) the most important factors impacting on GHG emissions, and iv) the costs of replacing brown coal with pellets with regard to decreasing the GHG emissions. Over the life cycle of wood pellets, total emissions amount to 236 kg CO_2eq/tonne pellets, but can vary between 109 and 511 kg CO_2eq/tonne pellets. Substituting brown coal in power plants can reduce GHG emissions by about 1070 kg CO_2eq/MWh energy output (1620 kg /CO_2eq/tonne pellets), but only by 200 kg CO_2eq/MWh energy output if the production chain of pellets is unfavourable and paraffin is replaced. The criteria for carbon neutrality are discussed. If all CO_2 emissions from pellet combustion are included, but not sequestration in forest, GHG emissions from the use of pellets are slightly less than from the replaced lignite. The results of our sensitivity analyses indicate the importance of utilizing bioenergy optimally. Including all or no CO_2 emissions from combustion are two extreme cases, and, depending on the time frame, system boundaries and reference path, net CO_2 emissions from pellets lie somewhere between the two. Simple cost estimates suggest that reducing GHG emissions by replacing coal with pellets costs about 60 €/tonne CO_2eq, but that the costs turn negative if the pellets are used to replace paraffin, due to higher market prices for paraffin than for pellets.

Key words: Bioenergy; co-firing; greenhouse gas emissions; carbon neutrality; substitution.

1. INTRODUCTION

Adoption of the European Union's (EU) renewable energy directive, with a target of 20% of overall gross energy consumption in the EU renewable by 2020, is currently one of the main driving forces for bioenergy consumption worldwide. Each member state is given a renewable energy target as a function of gross domestic product and existing energy mix and has to decide on how much renewable energy should be implemented in each of the sectors electricity, heating/cooling and transport (EU, 2009).

Today, bioenergy is the most important, and fastest growing, renewable energy carrier in Europe, contributing almost two-thirds of renewable energy production or 7.8% of gross energy demand (Eurostat, 2009a). Wood and wood waste are the main types of bioenergy in terms of volume. The production of biomass and wastes increased by 40% in the period 1990 to 2006 in EU27, and although wood-based electricity production is growing even faster, it is still limited in volume (Eurostat, 2009a, 2009b).

Wood-based energy is likely to play a major role in the future renewable energy mix in Europe, but import will probably have to increase as demand may exceed the supply potential; Smeets et al. (2007) have estimated that by 2050 the demand for bioenergy in Western Europe is likely to be 2-10 times greater than potential supply. Bioenergy produced in Europe might be enough for about 10.5% of gross energy consumption by 2020 – taking environmental concerns into consideration – and thus contribute to more than half of the renewable energy target. About 17% of this potential is from forest (EEA, 2006, 2008). A leading import to Europe, wood pellet is suited to international trade owing to its product homogeneity and low volume-to-energy ratio compared to many other bioenergy carriers. However, raw material costs affect imports and in recent years European pulpwood prices (hardwood and softwood) have been up to 15-20 $/m^3 higher than South and North American prices (RISI, 2009).

In 2008, pellet production in Europe was 8.2 million tonnes, or more than 4 times 2001 production. Growth in consumption in this period was much the same, with its centre of gravity in the world now in north and northwest Europe (Herold, 2009). Most of the pellets consumed in Europe originate in Europe, but Canadian and American production, aimed at export to Europe, has grown tenfold during the past ten years (RISI, 2010). The trend in trade is clear: From local via regional markets, the pellet markets have grown in recent decades to become highly international, with trade crossing oceans (Junginger et al., 2008).

Co-firing coal and biomass in power production is considered a viable option in the implementation of more renewable energy, also in the short run, since a smaller share (5-10%) of the coal can be replaced by bioenergy at relatively low cost and without major technological changes having to be made (Baxter, 2005). In this way, 50-90 TWh electricity/year can possibly be generated from bioenergy in the EU (Hansson et al., 2009).

Pellet production has recently been initiated at Averøya in western Norway, where it is expected that up to 450 000 tonnes will be produced annually from 1.2 million m^3 wood. European coal power producers are expected to be the main purchasers of the pellets, for co-firing with coal. In the first few years the raw material will originate overseas, but may later consist of local wood. For this analysis, Germany is assumed to be the main pellet purchaser.

In Germany, about 23.5% of electricity generated is based on lignite; about the same share as for black coal (CIAB, 2010; OECD/IEA, 2009). But lignite has the highest emissions per kWh produced electricity and may thus be vulnerable within a cap-and-trade scheme (Böhringer and Rosendahl, 2009) or CO_2 tax (Voorspools and D'haeseleer, 2006). It is therefore reasonable to assume that pellets will replace lignite in power plants – a process that is as technically unproblematic as for hard coal (Baxter, 2005).

There have been few environmental assessments of pellets produced at such large plants in Europe. Although some life cycle analyses (LCAs) of long-distance transportation of pellets have been carried out (Forsberg, 2000; Magelli et al., 2009; Sikkema et al., 2010), none address raw material import to Europe from overseas, along with manufacturing and further export. Very few studies have looked in detail at the effects of uncertainty, and there is little discussion around the issue of carbon neutrality, which nearly all previous studies have taken for granted.

Against this background, the aims of our study have been to analyse: i) the resource use and GHG emissions from production, transport, use and ash handling of wood pellets produced at Averøya in western Norway, ii) the net effect on GHG emissions of substituting brown coal with this pellets, iii) the most important factors influencing the GHG impacts including the carbon neutrality assumption, and iv) the related costs of the GHG emission reductions.

2. METHODS AND MATERIALS

2.1 Overview of the project and system analysed

The case analysed is a pellet plant owned by the energy company Hafslund and opened in summer 2010 at Averøya on the west coast of Norway. Resource use and GHG emissions over the entire life cycle of pellets were assessed, from construction of plant to raw material procurement, transport, manufacturing and end use. The partial product approach was applied, i.e. the raw material was charged with emissions from the entire production chain on a volume basis.

The raw material consists of birch originating in Nova Scotia, Canada, and the pellet consumers are coal power plants on the European continent, where the pellets will be used in co-firing and replace lignite. The net impact on GHG emissions from electricity production by replacing lignite with pellets was assessed.

The life cycle was divided into three steps to facilitate analysis:

1. Procurement and transport of raw material
2. Production

3. Transport and use of pellets and ash disposal

Each step is described in more detail in Section 2.3

2.2 GHG emissions

GHG emissions per MWh theoretical energy (MWh_{theo}) and MWh effective energy output (MWh_{eff}), i.e. with combustion efficiency taken into account, were calculated using the following formulae:

$$\text{Kg CO}_2\text{eq/MWh}_{theo} = \frac{kgCO_2eq/tonne}{MWh/tonne} \qquad (1)$$

$$\text{Kg CO}_2\text{eq/MWh}_{eff} = \frac{kgCO_2eq/tonne}{MWh/tonne \text{ x } efficiency} \qquad (2)$$

Emissions of the GHG carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were taken into account in the analysis. Methane and nitrous oxide were weighted according to their global warming potential compared to CO_2 in a 100-year perspective, i.e. 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2007).

The pellets were considered carbon neutral in the base case, but sensitivity analyses were carried out in which all the CO_2 emitted during combustion was included. The fossil fuels were charged with all the CO_2, methane and nitrous oxide emitted during combustion.

2.3 Boundaries and assumptions

The steps of the life cycle and substitution are described in more detail below, while numerical assumptions are given in Appendix Table A1.

1. Procurement and transport of raw materials

It was assumed that the chips originating in Nova Scotia, Canada, would consist of Paper Birch (*Betula papyrifera*) and be shipped from Halifax on specially constructed chip vessels directly to the quay at Averøya alongside the plant. Empty back-haul was assumed for all transport.

Estimates of emissions from forestry operations and road transport in Canada were taken from a life cycle analysis of forestry operations in the Pacific Northwest (Johnson et al., 2005). The timber was assumed chipped by the roadside using roller chippers before being loaded on to trucks.

2. Production

Emissions from the construction of buildings and infrastructure at the pellet plant were estimated, including those from the production of steel (CPM, 1996), concrete (Sjunnesson, 2005) and asphalt (Stripple, 2000), transport and use of construction machinery. The pellets are dried with the use of chips, and processed using hydropower.

3. Transport and use of pellets

The pellets were assumed transported to costumers in Hamburg, Germany, by vessel and truck. The Swedish emission calculator NTMCalc (2003) was used to calculate CO_2 emissions from transport by truck. Non-CO_2 GHG emissions from all transport by road and sea were added with data from an American LCI of diesel (U.S. LCI Database Project, 2003). Data for loading were from another LCI of biomass (Forsberg, 2000), and the impacts of unloading assumed to be the same as for loading. A hammer mill was assumed used for crushing the pellets before co-firing (Wood pellet mill, s.a.).

Factors of methane and nitrous oxide emissions during combustion were taken from Raymer (2006) and data on emissions from handling of ash from Forsberg (2000).

2.4 Substitution

It was assumed that electricity produced from lignite emits 1230 kg CO_2eq/MWh (Dones et al., 2003). The average efficiency of lignite plants given in the Dones et al. analysis (31.5%) is assumed in our study. The net effect of substitution equals emissions from the replaced fuels minus emission from the use of pellets.

2.5 Sensitivity analysis

The impacts of varying some key factors in the life cycle were analysed. Specifically, these were:

- Origin and species of raw material
  - Liberia – rubber wood (*Hevea brasiliensis*)
  - Norway – Norway spruce (*Picea abies*)
  - Byproduct approach
- Load factor for raw material transport
  - Full back-haul
- Production
  - Electricity based on coal rather than hydropower
- Transport and use of pellets
  - Full back-haul
  - By truck to Oslo, used in residential heating in Oslo and substituting paraffin
  - Pellets replacing hard coal (31.5% efficiency)
  - Pellets replacing hard coal (40% efficiency)
  - Pellets replacing lignite in a CHP plant (75% efficiency)
  - Wood not carbon neutral

Because of a lack of information about energy use and GHG emissions in Liberian plantations, estimates for the Southern U.S. were applied (Johnson et al., 2005). Emission rates for procurement of Norwegian wood were taken from Michelsen et al. (2008) and all wood was assumed to have a transport distance of 120 km.

In the sensitivity analysis, the electricity used for pellet manufacturing was assumed based on coal power rather than hydropower, with the same emission rates as for the substituted coal power (Dones et al., 2003).

GHG emissions over the life cycle from production and use of paraffin for residential heating is assumed to be 331 kg CO_2eq/MWh with 80% efficiency (Sjølie et al., 2010). Pellet stoves, too, were assumed to have 80% efficiency.

2.6 Costs of substitution

Simple cost estimate of substitution were carried out based on observed market prices of pellets and fossil fuels. Hard coal and heating oil were in 2009 observed to cost 70.6 USD/tonne and 70 USD/barrel, respectively (BP, 2010). Because none European prices were found for lignite, North American prices were used (U.S. EIA, 2010). For pellets, an estimated average market price for 2009 of 27 €/MWh (Foex (s.a.)) was used. Except for differences in heating value and efficiency, no other costs in shifting the energy carrier were included.

3. RESULTS

3.1 Resource use and energy input

Vessel transport of raw materials and the production process are the most energy-intensive steps of the life cycle (Table 1). Total energy input over the life cycle is 252 kWh/MWh_{theo}. Energy input in transport total about 11.6% of the energy content in the pellets.

3.2 GHG emission impacts

Total life cycle emissions are 236 kg CO_2eq/tonne pellets, or 49 kg CO_2eq/MWh_{theo} with our assumptions (Table 2). Transport of raw materials and pellets by vessel are the parts emitting most, contributing almost 40% and 20% of the life cycle emissions, respectively. Steps impacting insignificantly on emissions are silviculture, installation of factory, use of hydropower, loading/unloading and ash handling. Together, these components contribute less than 1.5% of the life cycle emissions.

Table 1: Resource use over the life cycle of pellets (per tonne pellets) and energy input (kWh) per MWh_{theo} in pellets.

Step in life cycle	Factor	Per tonne pellets	Unit	kWh input/ MWh_{theo} in pellet
Raw materials	Wood	1.5	tonnes	1000
	Fuel for silviculture and harvest	6.7	litre	14
	Fuel for road transport	8.4	litre	18
Production	Heavy oil for vessel transport	26.2	kg	62
	Steel	0.08	kg	-
	Concrete	0.72	kg	-
	Asphalt	0.04	kg	-
	Fuel for construction and transport of construction parts	0.002	litre	0.005
	Electricity	200	kWh	42
	Moist chips	130	kg	80
Transport and use of pellets	Heavy oil for vessel transport	13.2	kg	31
	Fuel for road transport	1.2	litre	2.6
	Fuel for loading/unloading	0.59	litre	1.2
	Electricity for crushing	4.21	kWh	0.9
	Fuel for handling of pellets and ash	0.12	litre	0.2
Total	**(excluded wood)**			**252**

Table 2: GHG emissions over the life cycle of pellets. Kg CO_2eq/tonne pellets.

Factor	kg CO_2eq/tonne pellets	Share of total emissions (%)
Silviculture	0.4	0.2
Felling, terrain transport	13	5.4
Chipping	7	2.9
Road transport	25	10.5
Cargo boat transport	91	38.6
Subtotal raw material procurement and transport	**136**	**57.6**
Construction of factory	0.2	0.1
Chips	12	5.0
Electricity	1	0.4
Subtotal production	**13**	**5.5**
Loading	1	0.3
Cargo boat transport	46	19.5
Unloading and loading	1	0.3
Truck Hamburg - customers	3	1.4
Unloading	0.02	0.01
Crushing	4	1.7
Loading of crushed pellets	0.02	0.01
Emissions of methane and nitrous oxide during combustion	32	13.7
Handling of ash	0.2	0.1
Subtotal transport and use	**87**	**36.9**
Total	**236**	**100**

Figure 1 shows that co-firing the pellets together with coal with 31.5% efficiency gives emissions of 156 kg CO_2eq/MWh_{eff}, while replacing brown coal in a power plant reduces total GHG emissions by 1074 kg CO_2eq/MWh_{eff}. This replacement corresponds to 1623 kg CO_2eq/tonne pellets and an 87% reduction. With our assumptions, using the planned annual production at Averøya (450 000 tonnes pellets) to replace coal in power plants gives a reduction potential of 0.73 million tonnes CO_2eq.

The substitution effect increases to more than 1100 kg CO_2eq/MWh_{eff} if the production chain of pellets is more favourable, such as with use of local wood or assuming full back-haul. If the electricity input in production is based on lignite power rather than hydropower, the GHG emissions from use of electricity in production increase from 1 to 246 kg CO_2eq/tonne pellets, while emissions over the life cycle more than double.

If pellets are used for residential heating in Oslo as a replacement for paraffin, the emission from transport decreases by 13 kg CO_2eq/tonne pellets. Assuming 80% efficiency for pellets as for paraffin gives a net effect of substitution of 273 kg CO_2eq/MWh_{eff}.

Figure 1 shows that replacing hard coal in a power plant producing electricity at 31.5% efficiency realizes a net effect of substitution of 900 kg CO_2eq/MWh_{eff} or 1361 kg CO_2eq/tonne pellets; 709 kg CO_2eq/MWh_{eff} is avoided if hard coal in a power plant with 40% efficiency is replaced. Correspondingly, substituting hard coal in a CHP plant with 75% efficiency leads to 378 kg CO_2eq lower emissions per MWh_{eff}. According to formula (2), the marginal effect of improved efficiency on GHG emissions declines non-linearly with higher efficiency. However, between 30% and 40% efficiency, the net GHG effect of substitution of hard coal decreases by about 3.2 - 2.5% for each percentage efficiency increase.

Emissions over the pellet life cycle are minimized: if raw material is assumed supplied locally with full back-haul, if a byproduct approach is used, if electricity input is assumed based on hydropower and if the pellets are shipped to Oslo with full back-haul and used for residential heating. In this case, emissions total 28 kg CO_2eq/MWh_{eff} ("Min. emissions pellets" in Figure 1). However, the substitution effect here is low (308 CO_2eq/MWh_{eff}), since paraffin is assumed replaced.

In the “Max. substitution effect” scenario, the assumptions are the same as in "Min. emissions pellets", except for transport of the pellets, increasing the emissions from 109 to 117 kg CO_2eq/tonne. However, co-firing with lignite in a power plant with 31.5% efficiency lead to substantially higher emissions in this last case compared to the former (77 kg versus 28 kg CO_2eq/MWh_{eff}).

Correspondingly, a “Min. substitution effect” scenario has for pellets the least favourable assumptions, with raw materials supplied from Liberia with empty back-haul, coal power in production and pellets replacing paraffin in residences in Oslo. Total emissions from pellets in this scenario amount to 499 kg CO_2eq/tonne pellets (104 kg CO_2eq/MWh_{theo}), of which 246 kg CO_2eq/tonne stem from use of brown coal power in production. Replacing one MWh_{eff} of paraffin gives 201 kg CO_2eq lower emissions, corresponding to 363 kg CO_2eq/tonne pellets. Combining the production chain in this scenario (except for transport of pellets) with the use of pellets in a CHP plant with 75% efficiency reduces GHG emissions by 302 kg CO_2eq/MWh_{eff}. In this case, the total life cycle GHG emissions, which is a "Max. emissions pellets" scenario, amounts to 511 kg CO_2eq/tonne pellets.

Including all the CO_2 emitted from pellets during combustion increases GHG emissions from combustion from 32 to 1614 kg CO_2eq/tonne, i.e. 1577 kg CO_2 is emitted from each tonne of pellets combusted. Combining the non-neutrality assumption with the base scenario gives a total of 1813 kg CO_2eq/tonne pellets, equivalent to 378 kg CO_2eq/MWh_{theo} and 1199 kg CO_2eq/MWh_{eff}. The associated substitution effects decrease to 31 kg CO_2eq/MWh_{eff} if lignite is replaced and -143 kg CO_2eq/MWh_{eff} in the case of hard coal.

Assuming that the pellets are non-carbon neutral and combusted in a pellet stove gives life cycle emissions of 468 kg CO_2eq/MWh_{eff}. The corresponding substitution effect is -137 kg CO_2eq/MWh_{eff} if this heat replaces paraffin, or 762 kg CO_2eq/MWh_{eff} if it replaces electricity based on lignite.

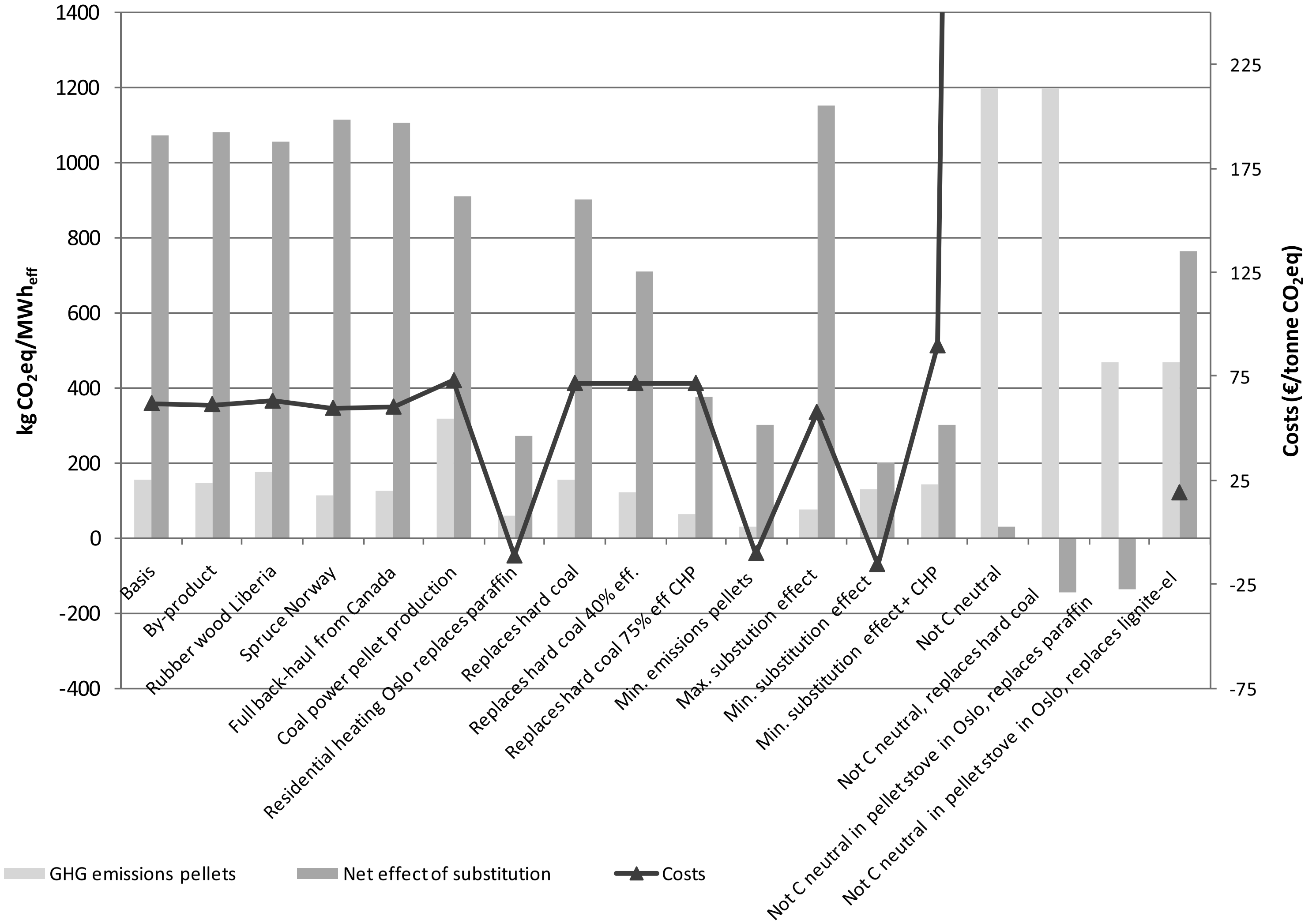

Figure 1: Life cycle GHG emissions from pellets and net effect of substituting fossil fuels (kg CO_2eq/MWh_{eff}) on left axis, costs of substitution (€/tonne CO_2eq) on right axis. The scenario names indicate the assumptions modified from the base scenario. See text for explanation. Combustion efficiency basis: 31.5%. Energy content pellets: 4.8 MWh/tonne.

3.3 Costs

Simple cost calculations reveal that replacing lignite or hard coal with pellets in power plants costs about 60 €/tonne CO_2eq (Figure 1). However, replacing paraffin with pellets has a negative cost, as paraffin is in our data more expensive than pellets. It should be emphasized that these cost estimates are not considered accurate, but were included to provide a suggestion of the order of magnitude, and may of course change considerably with market changes.

4. DISCUSSION

4.1 Methods

In this study, we have attempted to include all the important phases in the GHG emissions of pellets. The additional information which inclusion of the entire life cycle of emissions gives, compared to direct impacts from the consumption stage alone, varies considerably from product to product. For hard coal power, more than 95% of GHG is emitted during combustion (Spath et al., 1999). Lignite, typically, has lower upstream emissions than hard coal owing to lower methane emissions during mining and often shorter transport distances (Weisser, 2007). In the base case, 14% of emissions from the pellet chain occur during combustion.

Saw logs, pulpwood and energy wood are produced simultaneously in forestry. In principle, resource use and emissions may be debited to products in one of two ways – a partial product approach or a byproduct approach. With a partial approach, each product is debited its proportion of the impacts determined by a norm of distribution, such as weight or economic value. If a byproduct approach is applied, only the main product is charged with the impacts – the byproducts are charged nothing. This approach is appropriate if any one product dominates the material share or value, as well as the environmental impacts. For pellets based on forest raw material, as in our study, it could be argued that, economically, saw logs are not just the most important part of the wood, their price is the driver for harvest. However, our results indicate that the analysis is fairly robust with regard to the approach applied. Using a byproduct rather than a partial product approach reduces the emissions from pellets by 13 kg CO_2eq/tonne pellets owing to excluded emissions from silviculture and harvest.

4.2 Carbon neutrality

The extent to which bioenergy can be considered carbon neutral, i.e. that utilization does not lead to (additional) CO_2 emissions over the life cycle is an important, and much debated assumption. Most studies analysing GHG impacts resulting from replacing fossil fuels with wood-based energy assume the carbon neutrality of bioenergy (e.g. Korpilahti, 1998; Raymer, 2006; Wahlund et al., 2006). However, there is no consensus on this issue, and there are worries whether not including the CO_2 emissions from combustion may actually lead to an increase in GHG emissions through wrong incentives being given (see, e.g., Schlamadinger and Marland, 1999; Searchinger et al., 2009).

The degree to which wood products can be considered carbon neutral depends on the system boundaries and time frame. A reference path for comparison must be included if the *additional* CO_2 emissions are in question (additional must be compared to something). If bioenergy based on stems from final harvest is to be claimed carbon neutral, the system has to include forest growth and a time frame at least as long as the time needed for the forest to grow to the same size it was before harvest. In addition, the time preference has to be zero, implying that the point of time when emission/sequestration takes place is of no importance. These conditions are often assumed implicitly when bioenergy is considered carbon neutral. In addition, using wood that is already on the market (for example, demolition wood and pulpwood which otherwise would have been used for other purposes) may lead to the conclusion that bioenergy is carbon neutral, since the use of wood for bioenergy does not lead to additional CO_2 emissions (i.e. the above-mentioned byproduct approach is assumed). However, one could argue that this carbon neutrality criterion does not persist, but varies with the current market conditions.

The time aspect regarding carbon neutrality is of particular interest in the case of forest products because of the slow growth of trees. In addition to time, however, it is important to consider the spatial aspect when discussing the concept of carbon neutrality of forest products. When wood products are said to be carbon neutral, it is often argued (implicitly or explicitly) that they originate from a forest area where the annual increment is at least as large as the annual harvest, i.e. the area's long-term growing stock is non-declining (the sustainability argument). Hence, the spatial dimension is used instead of the time dimension to define carbon neutrality. For this study, the yearly harvested area in Canada remains stable (Canadian Forest Service, 2007) and the volume harvested is clearly exceeded by annual growth. Similarly, less than half the incremental growth in Norwegian forests is harvested (Statistics Norway, 2010).

By limiting the time frame, the net CO_2 emission from the use of pellets is positive. As long as the system boundaries include the forest, the future uptake of CO_2 on the harvested forest land will be included (assuming that the forest is managed sustainably and regenerated after harvest). Thus, the net accumulated emissions from pellets gradually decrease before carbon neutrality is met when the forest has again reached the size it was when cut. However, to include this factor, future growth of the forest has to be known for the right species as well as site indices over time in the supply area. If a reference path is used to compare the additional carbon flow by this use of pellets, the growth of the forest if it had not been cut has to be known.

Including no emissions from bioenergy combustion or, alternatively, all emissions, as in this study, are extremes implying a zero discount rate or a very short time frame/high discount rate, respectively. There is an inconsistency in the Kyoto protocol, as all biomass leaving forests is assumed to emit the entire quantity of CO_2 directly, but since the LULUCF sector in Annex 1 countries cannot freely be used to meet the emission targets, the harvested wood is only for accounting purposes, and not for the action to be taken to reduce the national GHG emissions beyond the small maximum limit set for each country (1.5 million tonnes CO_2 for Norway). Furthermore, as the biomass is counted as emitted when it leaves the forest, storage, combustion and decay of the products have no direct implications on the accounts (UNFCCC, 2003).

As long as pellets are considered carbon neutral, emissions do not have any "GHG cost" and combustion efficiency is of no importance. However, as shown, including all CO_2 emissions from combustion results in marginal reductions in GHG emissions, even when lignite is replaced. But, combusting pellets in stoves with high (80%) efficiency reduces GHG emissions considerably if coal-based electricity is replaced by this pellets. This illustrates the importance of utilizing bioenergy in the best way.

Carbon neutral biomass is not necessarily GHG neutral, because non-CO_2 GHG such as methane and nitrous oxide are emitted during combustion. Because of a lack of data we did not use emissions of these gases as the basis for comparison (i.e. we have assumed that wood undergoing decay in nature does not cause such emissions), and included all those emissions during combustion, which may be a slight overestimate.

For the carbon neutrality discussion, we emphasize the following:

- In most cases, bioenergy is more a byproduct than a product produced independently of raw materials for other purposes, and for a full carbon account this aspect has to be included and an appropriate distribution of emissions has to be chosen.

- Both full carbon neutrality and full non-carbon neutrality are extremes and, to reveal the right carbon impacts, growth and yield of the actual supply area have to be included and possibly also future growth if the forest has not been harvested.

- The net CO_2 emissions of wood products depend on the time frame/discount rate and how we consider the spatial aspects. In the Kyoto protocol, the spatial unit is the country, and a zero discount rate and 100 years time frame is used.

- We have used the term 'carbon neutrality' in the article, but we doubt its usefulness in contributing to clarity of the wood product carbon account.

4.3 Results

The largest resource use and GHG emissions over the life cycle of pellets is in cargo boat transport of the chips. Total life cycle emissions of pellets would have been 191 kg CO_2eq/tonne if manufactured in East Canada before being shipped to Europe, owing to the lower moisture content of pellets. Magelli et al. (2009) found the GHG emissions from long-distance ocean vessel transport to be almost 70% higher per km than we did, but transport on specially constructed cargo ships may make transport more efficient.

This sensitivity analysis suggests that factors such as the source of power in production are more important than others. Even if the electricity input in production is less than 5% of the energy content in the pellets, the emissions over the life cycle more than double when changing from hydropower to coal power. Nearly all Norwegian electricity production is based on hydropower, which may be assumed to be the source of electricity at the plant. However, Norway is part of a larger Nordic electricity market, where coal is often traded on the margins, but capacity constraints on the grids limit the trade. It is thus uncertain how much of the electricity should be considered based on hydropower and how much on coal power. This question could be further investigated in a (North) European energy model.

Furthermore, the results indicate that the energy and GHG impacts of the variables included in the study differ markedly, as half of them make up less than 1.5% of total emissions. Transport of raw materials by road and sea, cargo transport of pellets and emissions of non-CO_2 GHG during combustion contribute to more than 80% of the total emissions. Thus, emphasis should be placed on estimating the variables with the largest impacts as accurately as possible.

Finally, the net CO_2 emissions should be further investigated. Too little attention has been paid to the complex carbon dynamics of wood products. Claiming full (or none) carbon neutrality is a simplification. Including the forest carbon dynamics requires a much more complex model framework, but will provide better answers.

5. CONCLUSIONS

Our results indicate that GHG emissions over the life cycle of pellets produced in Norway – based on Canadian wood and used in European co-firing power plants – total 236 kg CO_2eq/tonne pellets, but vary between 109 and 511 kg CO_2eq/tonne pellets depending on assumptions. Furthermore, assuming carbon neutrality, GHG emissions from power production in Europe could be reduced by about 1074 kg CO_2eq/MWh_{eff} if brown coal were replaced with wood pellets, corresponding to 87% decreased emission. The net effect of substitution is almost six times greater in the "max. substitution effect scenario" than in the "min. substitution effect scenario", still assuming wood as carbon neutral. Assuming that pellets are not carbon neutral, and including all the CO_2 emitted during combustion (but no carbon uptake in forest), still gives a positive substitution effect when lignite-based electricity is replaced by pellets in stoves. For other replacements, however, the substitution effect is negative.

ROLE OF THE FUNDING SOURCE

The plant-specific data used here are based on two reports produced by us in 2008 and 2009 for Hafslund ASA and Biowood Norway, respectively. While these companies funded the reports, their only involvement was in the provision of data (specified in Table A1). The study design, analysis and interpretation were our responsibility alone. We were not sponsored to publish this paper, but decided to submit it for publication with the approval of these companies.

REFERENCES

Baxter, L., 2005. Biomass-coal co-combustion: opportunity for affordable renewable energy. Fuel 84, 1295-1302.

Böhringer, C., Rosendahl, K. E., 2009. Green Serves the Dirtiest. On the Interaction between Black and Green Quotas. Discussion Papers No. 581, April 2009. Statistics Norway, Research Department.

BP, 2010. BP Statistical Review of World Energy June 2010. Available at bp.com/statisticalreview

Canadian Forest Service, 2007. Natural Resources Canada; 2007. http://cfs.nrcan.gc.ca/news/544 Updated 05.10.2007, visited 28.04.2008.

CIAB (Coal Industry Advisory Board), 2010. International Coal Market & Policy Developments in 2009. February 2010. 62 pages.

CPM (Center For Environmental Assessment Of Product And Material Systems), 1996. SPINE LCI dataset: Ore-based steel production. http://www.cpm.chalmers.se/CPMDatabase/Scripts/sheet.asp?ActId=1997-07-011294 Updated 01.10.1996, visited 27.05.2008.

Demirbas, A., 1997. Calculation of higher heating values of biomass fuels. Fuel 76 (5), 431-434.

Dones, R., Heck, T., Hirschberg, S., 2003. Greenhouse gas emissions from energy systems: comparison and overview. In: PSI Annual Report 2003 Annex IV, 27-40. Paul Scherrer Institut, Villigen, Switzerland.

EEA, 2006. How much bioenergy can Europe produce without harming the environment? EEA report No 7/2006, Copenhagen.

EEA (European Environment Agency), 2008. Maximising the environmental benefits of Europe's bioenergy potential. EEA Technical report No 10/2008, Copenhagen.

EU, 2009. Directive 2009/28/EC Of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

Eurostat, 2009a. Sustainable development in the European Union 2009 - Monitoring report of the EU sustainable development strategy, European Communities, Belgium.

Eurostat, 2009b. Energy Yearly Statistics 2007. 2009 edition, European Communities, Belgium.

Eurostat, 2009c. Panorama of energy - Energy statistics to support EU policies and solutions, European Communities, Luxembourg.

FOEX (s.a.). PIX Indexes Pellet Nordic CIF Index History. Available at http://foex.fi/uploads/bioenergy/PIX_Nordic_Pellet_History.pdf Visited 04.04.2011

Forsberg, G., 2000. Biomass energy transport - Analysis of bioenergy transport chains using life cycle inventory method. Biomass and Bioenergy 19, 17-30.

Hansson., J., Berndes, G., Johnsson, F., Kjärstad, J., 2009. Co-firing biomass with coal for electricity generation—An assessment of the potential in EU27. Energy Policy 37, 1444-1455.

Heje, K. K., Nygaard, J., 1990. Norsk Skoghåndbok [Norwegian Forest Hand Book] Landbruksforlaget, Oslo, Norway. [in Norwegian]

Herold, I., 2009. Biomass & Waste-to-Energy Investment Trends. 17th European Biomass Conference and Exhibition, EUBIA, Hamburg, Germany, 01.07.2009.

Hohle, A. M. E., 2008. Energy consumption of wood fuel harvesting [Energiforbruk ved høsting av skogsbrensel] Semester report Norwegian University of Life Sciences, May 2008. [in Norwegian]

Hohle, E. E. (ed.), 2005. Bioenergi [bioenergy] Energigården, Brandbu, Norway.

IPCC, 2007. Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (eds.)]. Cambridge, United Kingdom and Cambridge University Press, New York, NY, USA.

Kabir, M. F., Daud, W. M., Khalid, K. B., Sidek, H. A. A., 2001. Temperature dependence of the dielectric properties of Rubber wood. Wood and Fiber Science, 33(2), 233-238.

Johnson, L. R., Lippke, B., Marshall, J. D., Comnick, J., 2005 Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. Wood and Fiber Science 37 Corrim Special Issue, 30-46.

Junginger, M., Bolkesjø, T., Bradley, D., Dolzan, P., Faaij, A., Heinimö, J., Hektor, B., Leistad, Ø., Ling, E., Perry, M., Piacente, E., Rosillo-Calle, F., Ryckmans, Y., Schouwenberg, P.-P., Solberg, B., Trømborg, E., Walter, A. da S., Wit, M. de, 2008. Developments in international bioenergy trade. Biomass and Bioenergy 32, 717-729.

KLIF (s.a.) (Norwegian Climate and Pollution Agency) Nøkkeltall [Key figures]. http://www.klif.no/artikkel____40918.aspx [in Norwegian]. Visited 21.09.2010.

Korpilahti, A., 1998. Finnish forest energy systems and CO_2 consequences. Biomass and Bioenergy, 15 (4/5), 293-297.

Magelli, F., Boucher, K., Bi, H. T., Melin, S., Bonoli, A., 2009. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass and Bioenergy 33, 434-441

Michelsen, O., Solli, C., Strømman, A., 2008. Environmental Impact and Added Value in Forestry Operations in Norway. Journal of Industrial Ecology 12**,** 69-81.

NTMCalc. http://www.ntm.a.se/ntmcalc/ Last updated 17.10.2003. Visited 19.09.2008.

OECD/IEA, 2009. Electricity generation by fuel Germany. IEA Energy Statistics. http://www.iea.org/stats/pdf_graphs/DEELEC.pdf

Panshin, A. J., Zeeuw, C. de., 1980. Textbook of Wood Technology, 4th ed. McGraw-Hill, New York.

Pettersen, R. C., 1984. The chemical composition of wood. In: Rowell, R. M., (ed.) The chemistry of solid wood. Advances in chemistry series 207. American Chemical Society, Washington, DC, Chapter 2.

Raymer, A. K. P., 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass and Bioenergy 30, 605-617.

RISI, 2009. World Timber Price Quarterly. December 2009.

RISI, 2010. Multi-Client Study. 2010 Wood Biomass Policy Review.

Schlamadinger, B., Marland, G., 1999. Net effect of forest harvest on CO_2 emissions to the atmosphere: a sensitivity analysis on the influence of time. Tellus 51B, 314-325.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., Robertson, G. P., Schlesinger, W. H., Tilman, G. D., 2009. Fixing a Critical Climate Accounting Error. Science 326, 527-528.

Sikkema, R., Junginger, M., Pichler, W., Hayes, S., Faaij, A. P. C., 2010. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. Biofuels, Bioprod. Bioref. 4, 132-153.

Sjunnesson, J., 2005. Life Cycle Assessment of Concrete. Master thesis, Lund University, Department of Technology and Society.

Sjølie, H. K., Trømborg, E., Solberg, B., Bolkesjø, T. F., 2010. Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. Forest Policy and Economics 12, 57-66

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., Turkenburg, W. C., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 33, 56-106.

Spath, P.L., Mann, M. K., Kerr, D. R., 1999. Life Cycle Assessment of Coal-fired Power Production. National Renewable Energy Laboratory, NREL/TP-570-25119, Colorado.

Statistics Norway, 2010. Forestry; 2010. http://www.ssb.no/english/subjects/10/04/20/skog_en/ Updated 17.02.2010, visited 12.03.2010.

Stripple H., 2000. Life Cycle Inventory of Asphalt Pavements. IN LTD, I. S. E. R. I. (Ed.) Gothenburg, IVL Swedish Environmental Research Institute Ltd; 2000.

UNFCCC, 2003. Estimation, reporting and accounting of harvested wood products. Technical paper. FCCC/TP/2003/7. October 27, 2003. 44 pp.

U.S. EIA (Energy Information Administration), 2010. Annual Energy Review 2009. DOE/EIA-0384(2009). 364 pp.

U.S. LCI Database Project. Fuels and Energy Precombustion, 2003. http://www.nrel.gov/lci/database/default.asp Visited 25.05.2008.

Vattenfall, 2005. Vattenfall AB Nordic Generation´s Certified Environmental Product Declaration EPD of Electricity from Vattenfall´s Nordic Hydropower. S-P-00088.

Voorspools, K. R., D'haeseleer, W. D., 2006. Modelling of electricity generation of large interconnected power systems: How can a CO_2 tax influence the European generation mix. Energy Conversion and Management 47, 1338–1358.

Wahlund, B., Yan, J., Westermark, M., 2004. Increasing biomass utilisation in energy systems: A comparative study of CO_2 reduction and cost for different bioenergy processing options. Biomass and Bioenergy 26, 531-544.

Weisser, D., 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32, 1543–1559.

Wood pellet mill (*s.a.*). Water Drip Figure Pellet Hammermills http://www.biofuelmachine.com/hammermills.html Visited 30.04.2009

APPENDIX

Table A1

Data	Quantity	Unit	Source
Procurement and transport of raw materials			
Fuel consumption silviculture Southeast U.S.	0.515	liters/m^3	Johnson et al. (2005)
Fuel consumption harvest Southeast U.S.	2.93	liters/m^3	Johnson et al. (2005)
Fuel consumption road transport logs Southeast U.S.	4.2	liters/m^3	Johnson et al. (2005)
Fuel consumption silviculture Northwest U.S.	0.088	liters/m^3	Johnson et al. (2005)
Fuel consumption harvest Northwest U.S.	2.85	liters/m^3	Johnson et al. (2005)
Fuel consumption road transport logs Northwest U.S.	5.53	liters/m^3	Johnson et al. (2005)
GHG emissions silviculture Norway	2.677	kg CO_2eq/m^3	Michelsen et al. (2008)
GHG emissions harvest Norway	9.374	kg CO_2eq/m^3	Michelsen et al. (2008)
GHG emissions road transport logs Norway	11.628	kg CO_2eq/m^3	Michelsen et al. (2008)
Diesel consumption chipping roller chipper	1.5	liter/solid m^3	Hohle (2008)
Diesel consumption loading (chips)	0.31	liter/solid m^3	Hohle (2008)
Density Paper Birch (12%)	38	lb/cub feet	Panshin and Zeeuw (1980)
Density Rubber wood (oven-dry)	620	kg/m^3	Kabir et al. (2001)
Moisture content raw materials w.b. (wet basis)	40	%	Biowood Norway
Energy density diesel	10.1	kWh/liter	KLIF (s.a.)
Energy density heavy oil	11.3	kWh/kg	KLIF (s.a.)
Sailing time round trip Buchanan-Averøya	26	days	Biowood Norway
Sailing time round trip Halifax-Averøya	20	days	Biowood Norway
Sailing time round trip Savannah-Averøya	26	days	Biowood Norway
Cargo load	27 500	tonnes	Biowood Norway
Fuel consumption cargo ships	24	tonne/day	Biowood Norway
CO_2 emissions heavy oil fuel	3.17	tonne CO_2/tonne fuel	Biowood Norway
Production			
Use of chips for drying of total raw material supply	8	%	Biowood Norway
Energy density moist chips	1900	kWh/tonne	Hohle (2005)
Consumption steel Averøya	2200	tonnes	Biowood Norway
Consumption concrete Averøya	19 500	tonnes	Biowood Norway
Consumption asphalt Averøya	1050	tonnes	Biowood Norway

Time consumption construction machinery	18000	hours	Biowood Norway
Greenhouse gas emissions big truck	0.033	kg CO_2eq/tonne km	NTMCalc (2003)
Greenhouse gas emissions hydropower	4.22	kg CO_2eq/MWh	Vattenfall (2005)
Greenhouse gas emissions steel production	1276.96	kg CO_2eq/tonne	CPM (1996)
Greenhouse gas emissions concrete production	143.15	kg CO_2eq/tonne	Sjunnesson (2005)
Greenhouse gas emissions asphalt production	80.63	kg CO_2eq/tonne	Stripple (2000)
Year of production Averøya	60	years	Biowood Norway
Annual production of pellets	450 000	tonnes	Biowood Norway
Annual electricity consumption at mill	90 000	MWh	Biowood Norway
Moisture content of pellets	10	%	Biowood Norway
Transport and use of pellets			
Cargo load	5000	tonnes	Biowood Norway
Sailing time round trip	6	days	Biowood Norway
Fuel consumption cargo ships	11	tonnes/day	Biowood Norway
Average transport distance truck transport	50	km	Biowood Norway
GHG emissions truck	0.036	kg CO_2eq/tonne km	NTMCalc (2003); U.S. LCI Database Project (2003)
GHG emissions lignite-based electricity	1230	kg CO_2eq/MWh	Dones (2003)
CO_2 emissions coal plants (100 % efficiency)	325.4	kg/MWh	Spath et al. (1999)
CH_4 emissions coal plants (100 % efficiency)	0.292	kg/MWh	Spath et al. (1999)
Energy content pellets	4.8	MWh/tonne	Biowood Norway
CH_4 emissions during combustion of pellets	0.3	kg/tonne	Raymer (2006)
N_2O emissions during combustion of pellets	0.07	kg/tonne	Raymer (2006)
Base wood density Spruce	380	kg/m^3	Heje and Nygaard (1990)
Share of carbon in wood	50	%	Pettersen (1984)
Heat value Spruce wood	20.1	MJ/kg	Demirbas (1997)
Costs			
Price	27	€/MWh	FOEX (s.a.)
Price hard coal	70.66	USD/tonne	BP (2010)
Heat value hard coal	27	GJ/tonne	BFIN (s.a.)
Price lignite	21.53	USD/short ton	U.S. EIA (2010)
Heat value lignite	10	10 MJ/tonne	Euracoal (s.a.)
Price gas oil	70	USD/barrel	BP (2010)
Heat value gas oil	6.1	GJ/barrel	BFIN (s.a.)

Paper IV

Potentials and costs of climate change mitigation in the Norwegian forest sector

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Abstract

Numerous studies have been carried out investigating the forests' potential to mitigate climate change through increased carbon sequestration. In many of these analyses changes in forest management is carried out with exogenously determined prices and utilization of wood products. However, large-scale forest sector policies would be expected to influence the markets indirectly through changes in silvicultural investment and harvest regimes, and directly through changes in profits for different wood products. Thus, expectations of climate policy effectiveness will possibly be affected by including market impacts. We utilize a spatial, partial equilibrium model of the Norwegian forest sector, which projects forest management, harvest, industrial production, consumption, trade and greenhouse gas fluxes. Impacts of a carbon tax/subsidy regime for greenhouse gas fluxes in the whole forest sector are evaluated for carbon prices ranging from 100 (≈12.5 €) to 800 NOK (≈100 €)/tonne CO_2eq. We compare results of an endogenous market solution to a case with no market changes, i.e., international trade and industrial production are fixed to base levels (base scenario defined with no carbon policy) allowing only forest management and domestic harvest to vary. Results indicate that with endogenous markets, more than 7 million tonnes CO_2eq/year additional to the baseline can be sequestered/avoided in the period up to 2055 for a carbon price of 800 NOK/tonne CO_2eq. Potentials are considerably lower when forest sector production and international trade levels are exogenously determined. Assuming no market impacts, carbon sequestration in forestry is increased by reducing thinning, allocating stands to be harvested and intensifying planting. In the endogenous market model, similar carbon measures are taken in forestry, but in addition, harvests and net exports decrease, production shifts from the pulp and paper and solid wood industry to high-efficiency bioenergy. We conclude that incorporating market impacts in forest climate change mitigation studies is important in order to assess full potentials and costs.

Key words: Bio-economic modeling, partial equilibrium, carbon sequestration, dynamic optimization, spatial model, boreal forestry

1. Introduction

The importance of the forests' role in the global carbon cycle is well documented, e.g. by IPCC (Nabuurs et al., 2007) and Lorenz and Lal (2010). Nabuurs et al. (2007) point out four ways in which the forest sector may contribute in climate change mitigation: by maintaining or increasing the forest area, by maintaining or increasing the carbon stock in existing forests through management, by maintaining or increasing the carbon stock on landscape level through increased conservation of forests and extending forest rotations, and by products substitution.

A range of studies on costs and benefits of carbon sequestration have been carried out on various scales, degrees of detail, representation of forest, representation and modeling of wood market and general modeling approach. Richards and Stokes (2004) detail a number of carbon sequestration cost studies completed by the mid 1990's and the literature has continued to grow. One distinction between the analysis approaches is whether the market for timber (and possibly derived products) is included or not, i.e. whether the price and allocation of wood to different purposes are endogenous. This assumption is important because exogenous wood prices imply that analyzed policies will not affect the wood market. For small-scale policies, this assumption may hold, but for large-scale policies such as national carbon sequestration policies, wood markets may possibly be impacted, by changes in both short-term and long-term timber supply. Short-run timber supply may be reduced if policies target prolongation of the rotation age as a way to sequester more carbon (Liski et al., 2001). Altered forest management as a result of policies may influence the long-run timber supply both in terms of quantity and quality. Changes in prices due to altered timber supply are likely to impact the climate policy costs, as the opportunity costs of keeping old forests increase with higher wood prices, but at the same time, incentives for investing more in forestry increase with higher timber prices.

To the authors' knowledge, few carbon policy analyses integrating forest management on a detailed scale with the wood markets have been carried out. We have neither come across analyses which have compared the effects of including versus excluding market impacts in forest carbon sequestration policies. The primary objectives of this paper are to (i) construct and compare marginal cost curves for climate change mitigation in the Norwegian forest sector, with endogenous and exogenous wood markets, (ii) for the two market models, study in detail which forest management measures are implemented under various carbon prices, and (iii) for the endogenous market model, examine market impacts and measures undertaken in the wood market under various carbon prices.

The paper continues with a brief description of the Norwegian forest sector economy and current forest carbon sequestration rates, followed by a literature review and hypotheses set up for the study. Next , we describe the model used. Chapter 3 displays the results and in Chapter 4, the results are discussed and conclusions drawn.

The Norwegian forest sector

Although the forest sector in Norway contributes only 0.6% of the GDP (Statistics Norway, 2010), it is the single largest sector in the national greenhouse gas (GHG) account. 31 million tonnes CO_2, or 58% of Norway's total emissions outside the LULUCF (land use, land use change and forestry) sector, was sequestered in the forests in 2008 (Norwegian Climate and Pollution Agency, 2010). However, according to the Kyoto Protocol, Norway is only allowed to credit sequestration up to 1.5 million tonnes CO_2 in the forests (UNFCCC, 2002). Extensive planting investments and afforestation from 1950 through 1990 (Statistics Norway, 2010) combined with stable harvest levels has considerably increased the net CO_2 uptake. The current official harvest level fluctuates between 6.5 and 8.5 million m^3/year with an additional to 1 to 2 million m^3 harvested outside official markets, while the annual increment recently has been about 25 million m^3 (Statbank Norway, 2011). Net imports of wood were approximately 1.8 million m^3 in 2008 with most of that being spruce pulp wood (Statbank Norway, 2011). 120 000 private land owners own the majority of the Norwegian forest with an average holding size of just 60 hectares (Statistics Norway, 2010). Paper production in Norway is significant with large quantities of newsprint, uncoated and coated printing paper and linerboard exported to European markets. Sawn wood production is about 2 million m^3, of which most is targeted for domestic use with an additional 500 000 m^3 (Statbank Norway, 2011) of net import in 2008. Roughly 4 TWh of wood-based energy was generated in households in 2008, mostly as firewood (Trømborg and Sjølie, 2011) and about the same amount in forest industry (Sjølie et al., 2010).

Forest mitigation studies

Most studies of forest carbon sequestration costs and potentials seem to employ exogenous wood prices and utilization of wood. In Scandinavia, simulations and optimization of forest management have recently been carried out on regional level in Norway (Raymer 2005; Raymer et al., 2009) and Sweden (Backéus et al., 2005), on a national level in Switzerland (Warner et al., 2010) and earlier on a national level in Finland (Pussinen et al., 1997). Hoen and Solberg (1994; 1998) examined trade-offs between maximizing net present worth of timber income and net CO_2-sequestration in Norway using the same forest model (but a different soil model) as Raymer et al. (2009). Eriksson et al. (2007) analyzed the net greenhouse gas emissions with various management regimes for Spruce stands in Sweden and with different substitution effects. While Backéus et al. (2005) constrained her model to ensure an even harvest flow over time and a minimum terminal inventory, Hoen and Solberg (1994, 1998) and Raymer et al. (2009) constrained their model to historical harvest levels to avoid leakage problems. Backéus et al. (2005) discounted carbon emitted over time from harvested wood products to the point of time of harvest. Raymer et al. (2009) compared cost and benefit impacts of including or excluding wood products pools and product substitution. Including substitution effects increased the overall carbon benefit by 60% over 120 years when timber revenues were maximized.

Two exceptions to the exogenous wood market approach in forest carbon sequestration are the TSM (Timber Supply Model) with related models and FASOM (Forest and Agricultural Sector Optimization Model) models. Sohngen and Sedjo (2000) applied a global timber supply model based on the TSM to calculate GHG emission impacts of changes in demand and Sedjo et al. (2001) used a modified version of the same model to estimate marginal cost curves for carbon sequestration in global forests. Adams et al. (1999) employed FASOM to analyze the costs of carbon sequestration in the U.S. agriculture and forest sectors.

On the wood products side, several studies have analyzed GHG impacts by increasing bioenergy and wood consumption in construction. Petersen and Solberg (2005) did a review of the substitution effects of replacing concrete and steel with wood in Norway and Sweden, and concluded that the substitution effects amount to 93-1062 kg CO_2eq per m^3 of timber input and 36-530 kg CO_2eq per m^3 of timber input for concrete and wood, respectively. Raymer (2006) studied the net effects of substitution when various types of wood fuels replace certain fossil fuels, given carbon neutral wood, while Sjølie et al. (2010) analyzed the impacts of carbon taxation on fossil fuels on GHG emissions due to shifts from fossil fuels to wood fuels, also assuming carbon neutrality of wood.

Scenarios

Inclusion of carbon sequestration values in the forest management decision process will, *ceteris paribus*, increase the rotation age (Hartman, 1976; van Kooten, 1995). However, most forest carbon studies with detailed representations of forest management have exogenously determined prices and use of wood. Still, basic economic theory suggests that large-scale policies targeted to, e.g., increase net carbon sequestration in forests, will influence the wood markets through reduced wood supply. Consequently, the cost of carbon sequestration increases as the opportunity cost of retaining older forests increases. Further, faced with carbon policies, the allocation of the wood resource to wood products manufacturing may change thus changing the mitigation potential of the sector. Higher timber prices due to wood scarcity are also a strong incentive to forest owners to increase investment in forestry. Thus, potentials and costs may be altered by including all these aspects. Lastly, it is of interest to assess the size of leakage in carbon policies, as it is of considerable concern.

We utilize two different markets models: one fully endogenous timber and wood products market, and one exogenous timber and wood product market. We use a base scenario for two purposes: setting the reference carbon flux level, as only additional carbon fluxes are paid for, and for constraining the exogenous market model. In the exogenous market model, quantities of imports, exports and regional industrial production are set at base scenario levels for each period, i.e. the levels which are determined by the model's optimal solution when assuming a carbon price of zero. Carbon benefits of wood products (storage and substitution effects) are included in both market models, but in the exogenous markets model, this mitigation option cannot be further utilized beyond the base scenario. Mitigation options in forestry in the exogenous markets model are limited to investments in forest management (planting, precommercial thinning, thinning and species composition) and selection of harvesting methods and timing. Substitution in industrial production is limited to bioenergy, which indicates the constraint in mitigation through reduced harvest in the exogenous markets model. In the endogenous markets model, adjustments can take place without any other constraints than present in the base scenario.

For both market models, eight carbon price scenarios are run, from 100 (≈12.5 €) to 800 NOK (≈100 €)/tonne CO_2eq. Payments are given for additional carbon sequestration / avoided GHG emissions above baseline (where the carbon flux fluctuates over periods) and taxes are paid for negative carbon fluxes compared to the baseline. In the results, “Endo 100”, “Endo 200”, “Endo 300” etc, indicate the endogenous market model with various carbon price scenarios, and “Exo 100” and so on the exogenous market model with carbon price scenarios.

Compared to scenarios excluding market impacts, we believe that including market impacts result in:

1. Altered mitigation costs: The opportunity costs of keeping old forests increase as more timber is withheld, but the portfolio of mitigation options also increase, and the sign of total effects are unclear
2. Higher long-term sequestration potentials in forests, due to the incentive for more investments in forestry caused by increased timber prices
3. Shifts in the use of timber compared to the base scenario, as use of different products have different greenhouse gas emissions impacts and substitution potentials

2. Methods

For the analysis, we utilize the spatial, perfect foresight equilibrium model NorFor of the Norwegian forest sector. The model structure is described in Sjølie et al. (2011) and the data in Trømborg and Sjølie (2011), but a brief description of the model is provided here.

NorFor simulates investments in forestry, timber harvest, investments and processing of timber into wood products in industry, consumption of wood products, trade and the carbon flows of the sector. The 19 Norwegian counties form the domestic regions, and there are two foreign trade regions, Sweden and Rest of World (ROW). The period length is five years, beginning in 2010. Perfect competition is assumed, and the well-fare in the sector (i.e. producer surplus plus consumer surplus minus transport and investment costs) is maximized over the horizon. A discount rate of 4 % p.a. is applied for all monetary and non-monetary values.

In forestry, possible mid-rotation management strategies include precommercial thinning favoring conifers, precommercial thinning favoring broadleaves, thinning, shelter wood / seed tree cuts and certain combinations of those. Final harvested stands can be regenerated by planting or natural regeneration, with various possibilities regarding density and species composition. Yields for existing stands (i.e. stands which in the first period have timber stock) and regenerated stands (stands which have been harvested) are simulated for ~9000 National Forest Inventory plots in the stands simulator Gaya (Hoen and Eid, 1990), and imported to NorFor on a disaggregated level. Final harvest timing is endogenously determined in NorFor. No management (except regeneration) and no harvest are possible options. An amenity value of 5 NOK/m^3 of standing stock older than 90 years is included to represent other nontimber values associated with mature forests. As Gan et al. (2001) showed analytically and with examples for coniferous forests in the U.S., a high discount and an amenity value corresponds to having a low discount rate without amenity values, with the same harvest and inventory results.

Forest owners supply sawlogs and pulpwood of pine, spruce and birch, as well as harvest residues to the forest and bioenergy industries. The ~20 Norwegian pulp, paper and board industry mills are individually specified in the model with capacities and input coefficients. Capacities for sawmills and bioenergy processing are given on county level. The industry processes wood into sawn wood and boards, pulp and paper products and bioenergy carriers.

Demand for the final products sawn wood, boards, paper and bio heat are specified on county level based on population. Demand is elastic with regard to GDP growth, county-specific population growth and price changes. The elasticity with regard to price varies from -0.3 to -0.9. Three types of bio heat are modeled: space heating for households based on wood stoves and pellet stoves, waterborne heating based on central heating and district heating systems fed with chips or pellets, and heat to industry. These three products face different market prices and technical potentials.

Two foreign trade regions ensure market balance in the country. All raw materials and products may be traded between all domestic regions and with the foreign regions, with respective transport costs. Trade between two regions takes place if the price difference exceeds the transport costs (Samuelson, 1952). Supply elasticity with regard to price for imports is set to 0.8 for logs and 2 for manufactured products. Export elasticity is -0.8 and -2 for logs and products, respectively.

The carbon flow is calculated for the following parts of the sector: In trees, stem, bark, living and dead branches, needles, stump and small and coarse roots are included. Carbon is sequestered during growth, and emitted during decay in old forest and from harvest residues after thinning or final harvest if they are not taken out of the forest for fuel. Net emission rates from dead wood and soil are based on the YASSO model used for Norwegian conditions (Raymer et al., 2009). GHG emissions from use of machines in soil scarification, planting, silviculture, harvest, terrain transport, forest road construction, transport to industry by truck and processing in industry are included. For carbon flow in wood products, the current carbon storage and substitution effects in Norway are attempted reflected. Wood products are assumed to go out of use gradually, but due to a general landfill ban in Norway, all wood products going out of use are assumed to be combusted. Substitution is assumed to be one-to-one, i.e. that one unit of wood product replaces one unit of another product having the same usage. Sawn wood is assumed to replace half steel, half concrete, and bioenergy in waterborne facilities and in industry are assumed to replace domestic heating oil. Firewood and pellets inside homes and wood waste combusted are assumed to substitute half hydropower and half coal power.

For the analysis, fifteen periods were modeled, and the results in the first ten periods analyzed.

3. Results

Base scenario

Important for both model applications is the Base scenario. It forms not only the “business as usual” case for determining additionality, but also the industrial production levels used in the exogenous model solutions. In the Base scenario, harvest moves from 10.9 million m^3 in the first period, to between 12.5 and 13 million m^3 for all later periods. 40 000 hectares were annually regenerated in the Base scenario, of which about 27 000 hectares planted with spruce, 4000 naturally regenerated with spruce and 8500 hectares naturally regenerated with birch. Thinning fluctuates between 15 000 and 20 000 hectares per year.

The industrial production on national level increases in general as the harvest rises over the horizon in the Base scenario. Total sawn wood production is about 2 million m^3 the first period and increases to 2.7 million m^3 in period 10, of which 75%-80% is spruce. The production of particle boards is 200 000 m^3 the first period and 255 000 m^3 the last period. Corresponding numbers for fiberboards are 110 000 tonnes and 320 000 tonnes, respectively. The production of pulp is about 725 000 tonnes/year the first period, and 800 000 tonnes/year from the second period, with increases seen in both mechanical and chemical pulp. Paper production leaps from 2 million tonnes/year in the first period to 2.5 million tonnes/year in the second period, and thereafter rises steadily, ending on 2.9 million tonnes/year in period 10. Increases are seen in uncoated paper, linerboards and other paper and boards. Bioenergy-based space heating, mainly consisting of firewood, starts at 3.1 TWh/year in the first period, but levels off at 3.7 TWh/year from the second period. Waterborne bio-heating fluctuates between 0.7 TWh and 0.8 TWh with the same pattern as energy chips production. Pellets production is, however, very stable.

In the Base scenario, net imports of spruce, pine and birch timber equal 530 000 m^3 the first period, of which most is spruce and particularly pine pulpwood. Net imports of sawn wood total 265 000 m^3 and fiberboards 195 000 tonnes. Net export of pulp is 470 000 tonnes, of newsprint 460 000 tonnes and of linerboards 270 000 tonnes.

The spruce sawlog price for the Østfold is 320 NOK/m^3 in the first period, which increases to 490 NOK/m^3 the last period. However, the spruce sawn wood price do not see the same increase, and fluctuates between 1270 NOK/m^3 and 1660 NOK/m^3. The newsprint price increases from 4130 NOK/tonne to 4880 NOK/tonne over the horizon. The price for firewood is approximately 200 NOK/MWh for the whole horizon, while the energy chips price is considerably lower with prices down to 63 NOK/MWh.

Harvest

In the endogenous market model, where timber harvest can adapt to carbon price levels there is a significant reduction as carbon price increases (Figure 1). The maximum reductions in harvest at a carbon price of 100 NOK/tonne CO_2eq is 800 000 m^3, and the for the carbon price of 800 NOK/tonne CO_2eq, harvests decreases by maximum 2.6 million m^3 compared to the Base.

In the exogenous market model, while the harvest level is fixed, the model optimizes which stands to harvest. In the Base, the average age at harvest in 2020 varies from 126 at site index 8 to 56 at site index 20 (Figure 2). A carbon price of 400 NOK increases the rotation age 5-25 years, and most for less productive sites. Endogenous markets increase this flexibility and harvests are further delayed on less productive land.

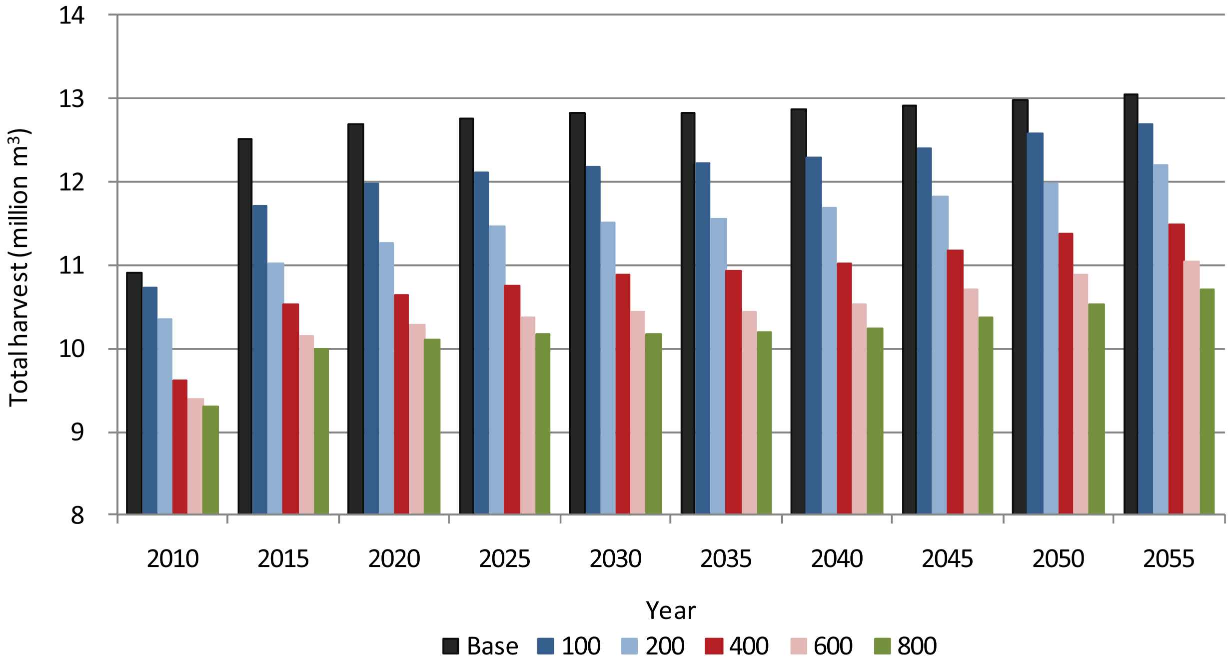

Figure 1: Total harvest levels in the scenarios. Note that the scale on the y axis begins at 8 million m³.

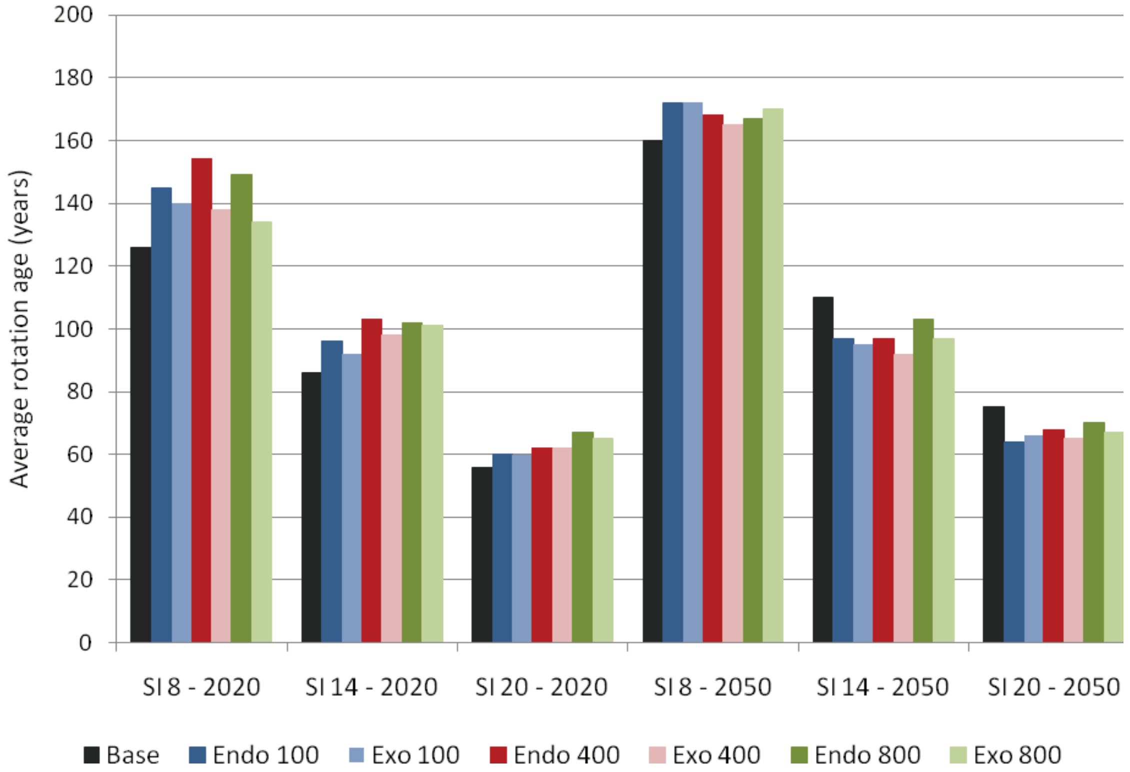

Figure 2: Average harvest age in 2020 and in 2050 for site indices 8, 14 and 20. (The site index refers to the average height of the 100 largest trees per hectare at 40 years age, and 8 is generally considered a low site index, 14 an middle good and 20 good.)

The average density of clearcut stands depends upon the carbon price (Figure 3). In the Base, stands harvested in the first period are denser than stands harvested last period. This changes with increasing carbon price, particularly are the stands harvested in the last period denser with a high carbon price. This may be both due to a reallocation of which stands to harvest, as well as changes in silviculture with higher carbon prices. While the differences between the two market models are small in 2010, the harvested stands in 2055 are on average 26% denser in the endogenous market model compared to the exogenous.

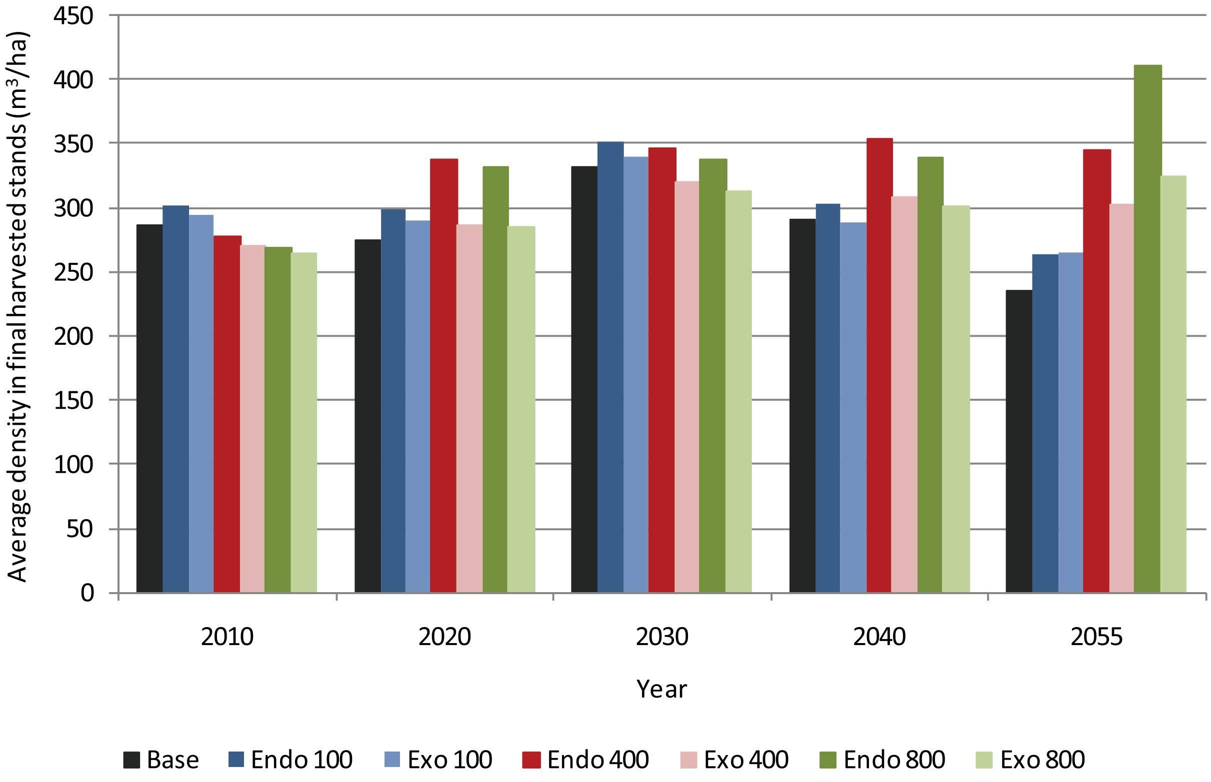

Figure 3: Average density of final harvested stands (m³/hectare) varying with carbon prices in the two market models.

Silviculture

All stands which are clear-cut and regenerated independently of the previous stand's conditions, are regenerated with birch and spruce in the model solutions (Figure 4). However, the combination of methods depends on the carbon price and the assumed market impacts. With an increasing carbon price, total regenerated area declines in the endogenous market model as harvests are reduced. For the exogenous market model, however, total regenerated areas increase with higher carbon price. Regeneration methods change with the carbon prices, but does not vary much between the two market models. When the carbon price reaches 300-400 NOK/tonne CO_2eq, almost no areas are regenerated naturally with spruce. Instead, spruce are planted, and in the exogenous market model, some more areas are devoted to birch, which has high regeneration density and high specific weight.

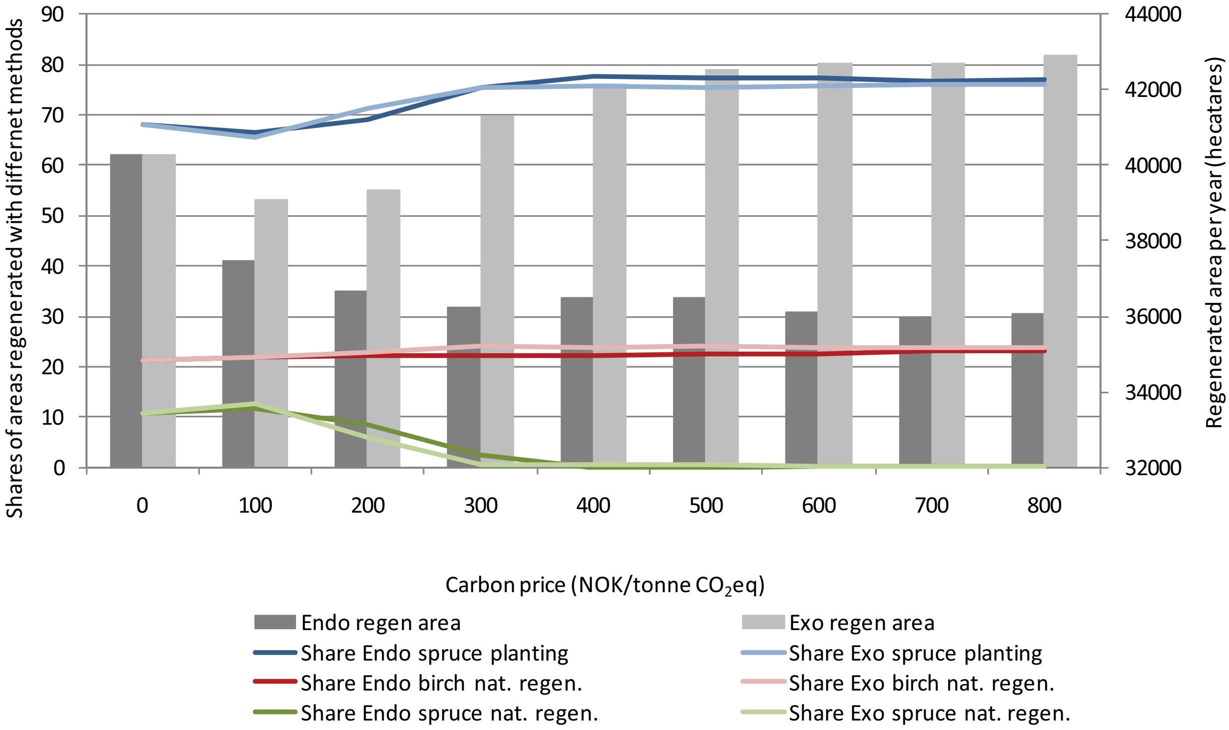

Figure 4: Shares of regenerated areas regenerated with different methods in first period: planting spruce, natural regeneration spruce and natural regeneration birch (left axis) and total regenerated areas in first period (right axis). Areas regenerated under shelter/seed tree cuts are not included. Note that the right axis starts at 32 000.

Thinning is reduced substantially with higher carbon price, particularly in the endogenous market model (Figure 5). At the latest periods with the highest carbon price, barely any thinning is carried out in the endogenous market model. However, if the markets are assumed exogenous, thinning increases slightly during the period 2020-2040. The main reason for this difference is that with endogenous markets, it is possible to use the market mechanisms to avoid thinnings and thus get denser stands with higher growth, as well as keeping the stands until more of the standing volume enters sawlog dimensions.

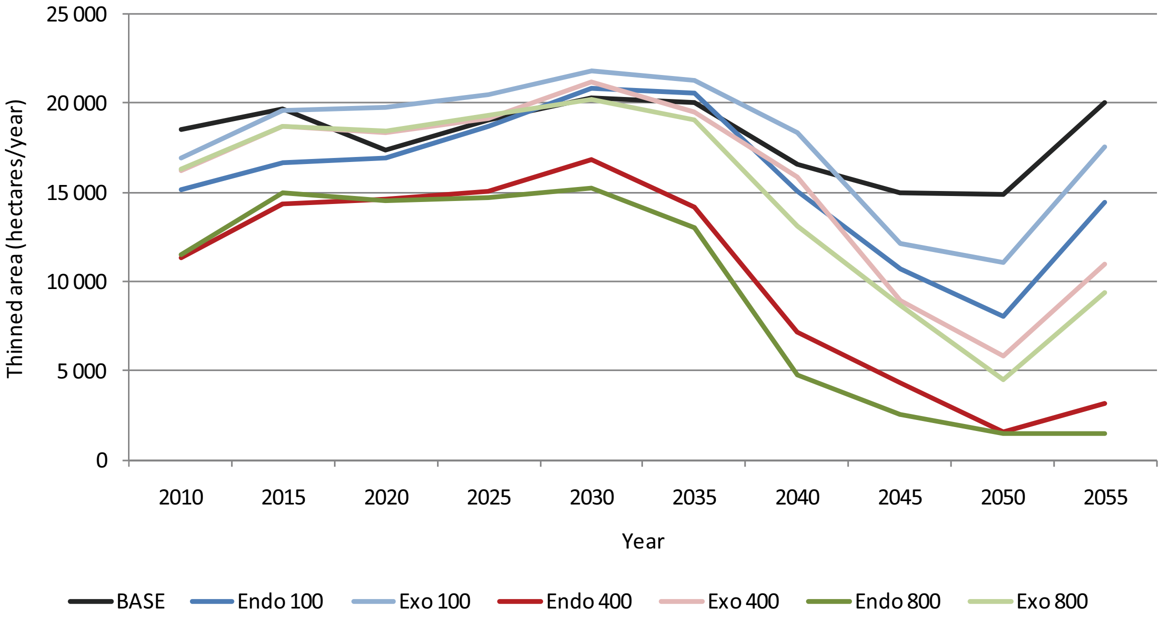

Figure 5: Total areas subject to thinning (hectares/year) in various scenarios.

Industrial production

Introducing high carbon prices has large industrial impacts, both in the traditional forest industries (Figure 6) and the bioenergy production (Figure 7). Production of pulp and paper is reduced by up to 15% in the highest carbon price scenario, and more with time. For the solid wood, the trends are more ambiguous. For the lowest carbon price scenario, the production is barely hit, and less with time. However, for a carbon price of 800 NOK/tonne CO_2eq, production is reduced by 8-12% because of high sawlog prices.

For bioenergy, a carbon price will trigger a shift from space heating to waterborne heating. More than 90% of the space heating in the Base scenario is provided by fire wood stoves, with are assumed to have an average efficiency of 54% in the model. Waterborne heating systems are assumed to have higher efficiency, 80-90%. Particularly in the short run, waterborne heating increases a lot, but still in the long run, production of bio heat in such systems are doubled at the carbon price of 800.

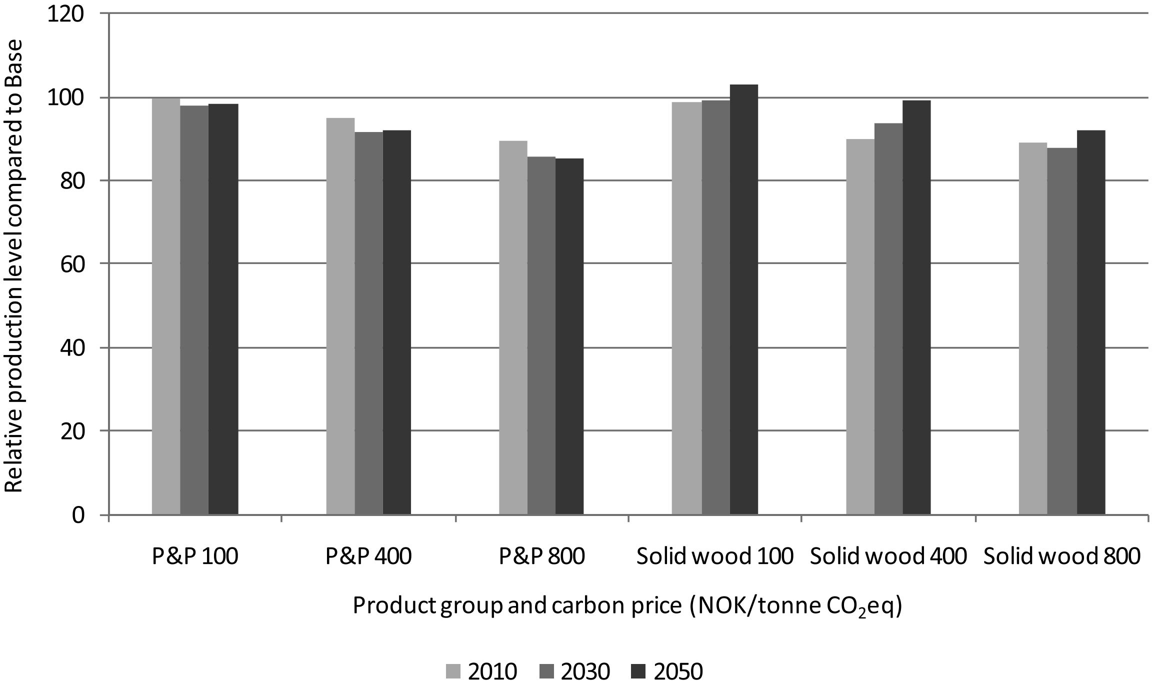

Figure 6: Relative production level compared to Base of pulp and paper (P&P) and of solid wood, including sawn wood and boards. (100 means equal to Base.)

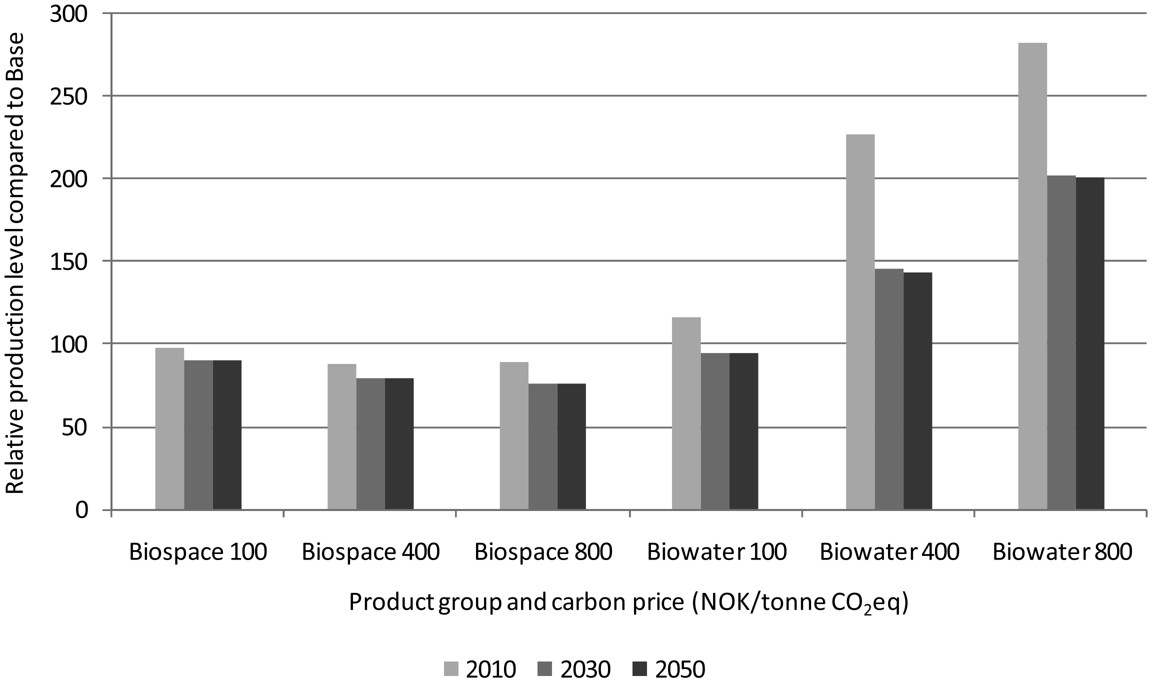

Figure 7: Relative production level compared to Base of bio heat in space heating including wood stoves and pellet stoves (Biospace) and of bio heat in central heating and district heating systems (Biowater). (100 means equal to Base.)

Trade

The trade impacts of a carbon tax in Norway are displayed in Figure 8. The maximum reduction in pulp and paper net export is 25% at carbon price 800 NOK/tonne CO_2eq. The net import of solid wood and timber increases by up to 20% and 14%, respectively. Different from pulp and paper, the import of timber and solid wood increases initially, but is thereafter rather stable with higher carbon price.

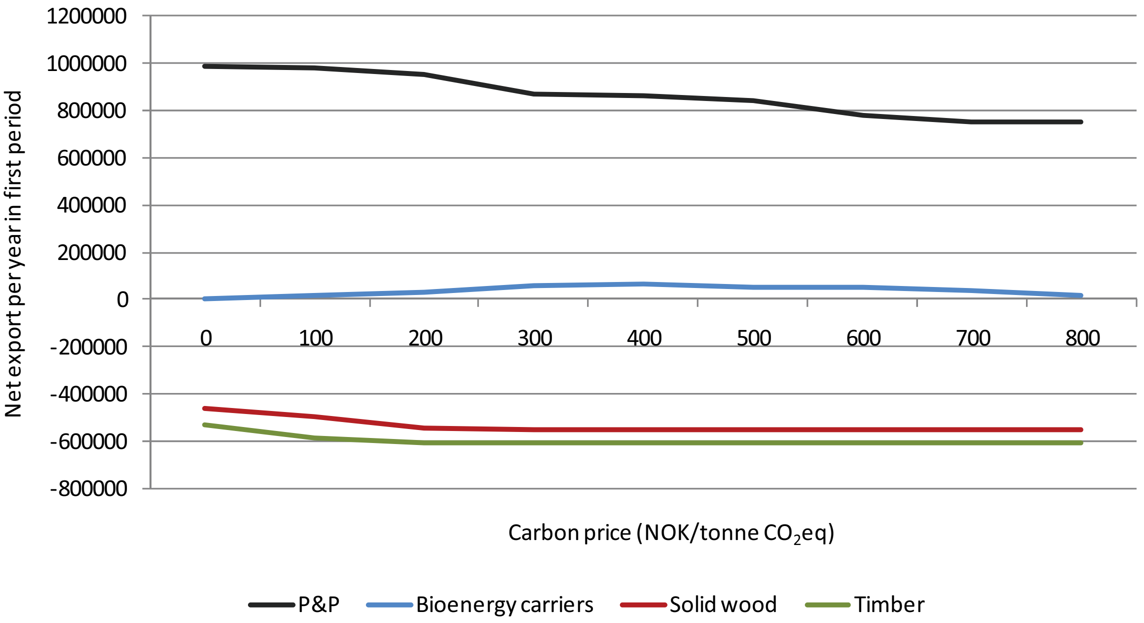

Figure 8: Net export (export-import) of wood and wood products in various carbon price scenarios. Bioenergy carriers are measured in MWh, pulp and paper in tonnes and solid wood and timber in m³.

Prices

The carbon policies showed to have large impacts on the prices. Spruce sawlog prices increase from 319 NOK/m³ without carbon policy to 1394 NOK/m³ with a carbon price of 800 NOK/tonne CO_2eq in first period (Figure 9). The relative increases for birch are even greater, as with the highest carbon price, the birch price reaches the spruce sawlog price.

Increases are also seen for the manufactured wood products, but of smaller magnitude. For spruce sawn wood, the price increase in first period is about 44% with the highest carbon price compared to no carbon policy (Figure 10). For newsprint, the price impact increases with time, from 31% increase for a carbon price of 800 NOK/tonne CO_2eq in first period compared to no carbon policy.

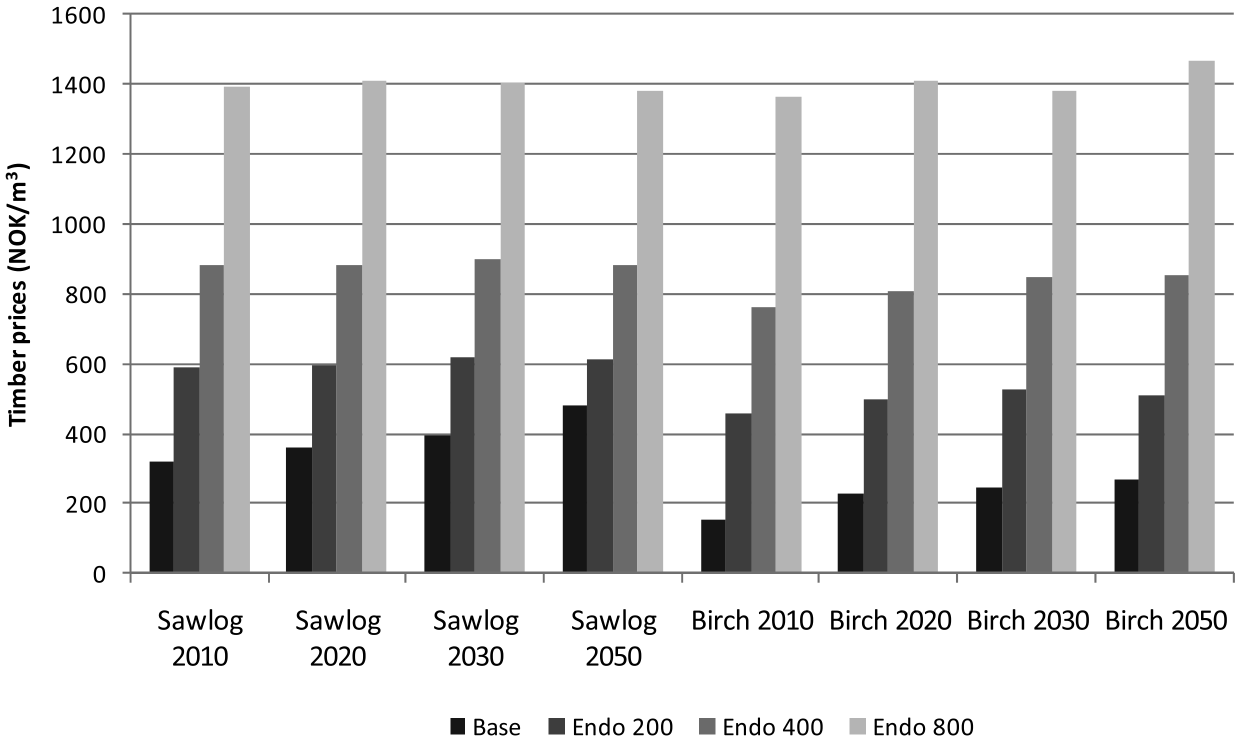

Figure 9: Prices (NOK/m^3) for sawlog (spruce) and birch (pulpwood) in years and with different carbon prices.

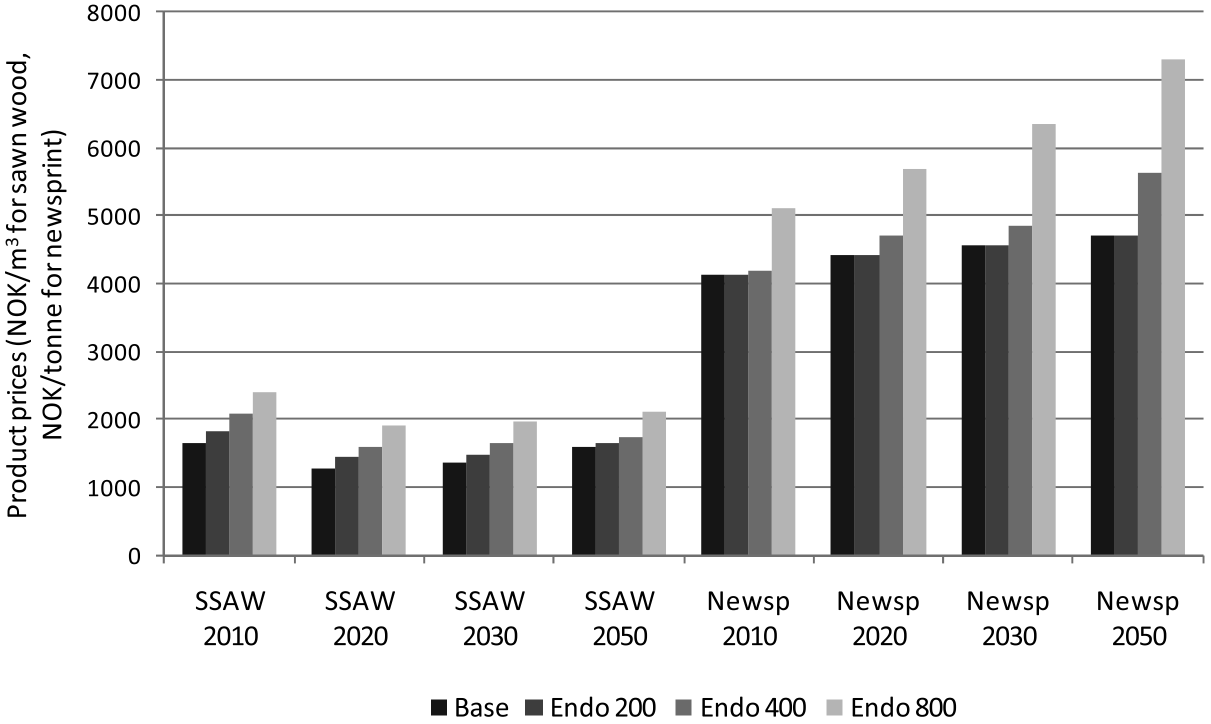

Figure 10: Prices for spruce sawn wood (SSAW) and newsprint (Newspr) in years and with different carbon prices.

Overall costs and potentials

For the calculation of mitigation costs, the differences between the fluxes and the baseline were calculated for each period and discounted to the first period. Thereafter, this discounted sum was converted to annual potentials by using the annuity factor. As seen in Figure 11, the potentials are increasing with the longer time length included in the carbon flows. Moreover, the potentials are considerably higher in the endogenous market model than in the exogenous market model. The same curves, but on a hectare basis, are displayed in Figure 12. The potentials for the same costs are 3-4 times higher in the endogenous market model than in the exogenous market model. These potentials include all additional sequestration and avoided greenhouse gas emissions in the entire sector compared to Base.

Table 1 displays the maximum annual undiscounted potentials of avoided greenhouse gas emissions and carbon sequestration in the sector with years.

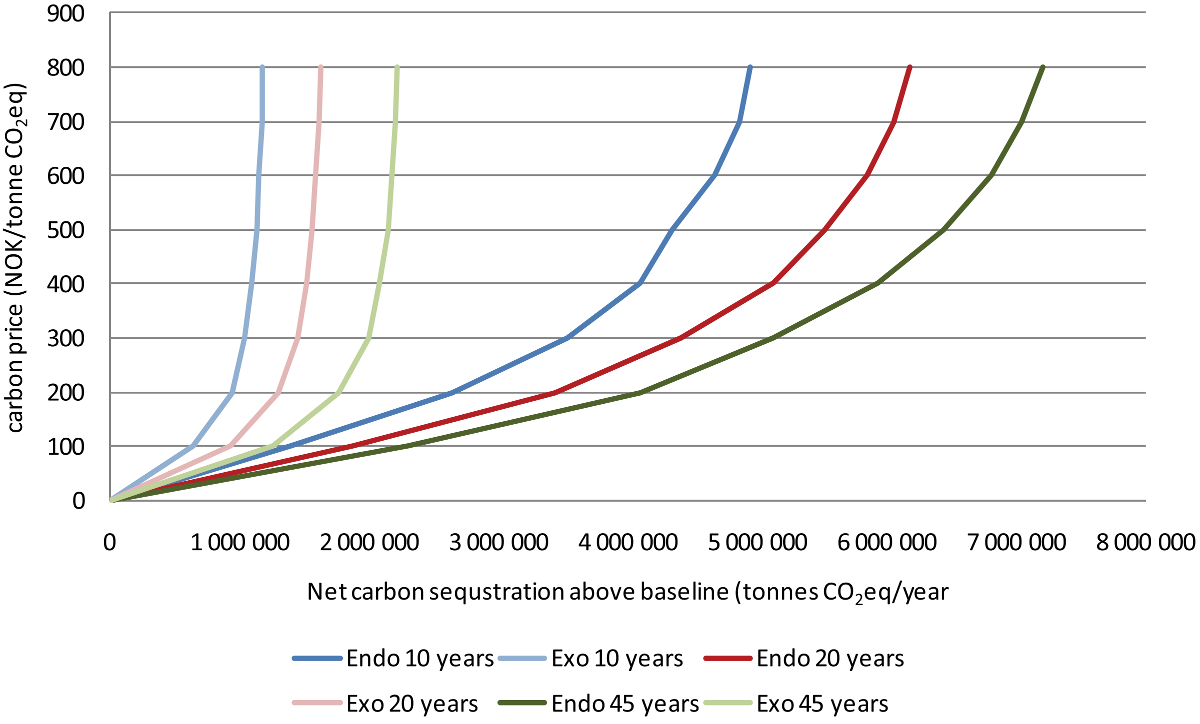

Figure 11: Marginal cost plots for increasing net sequestration of greenhouse gases in the forest sector for various horizons.

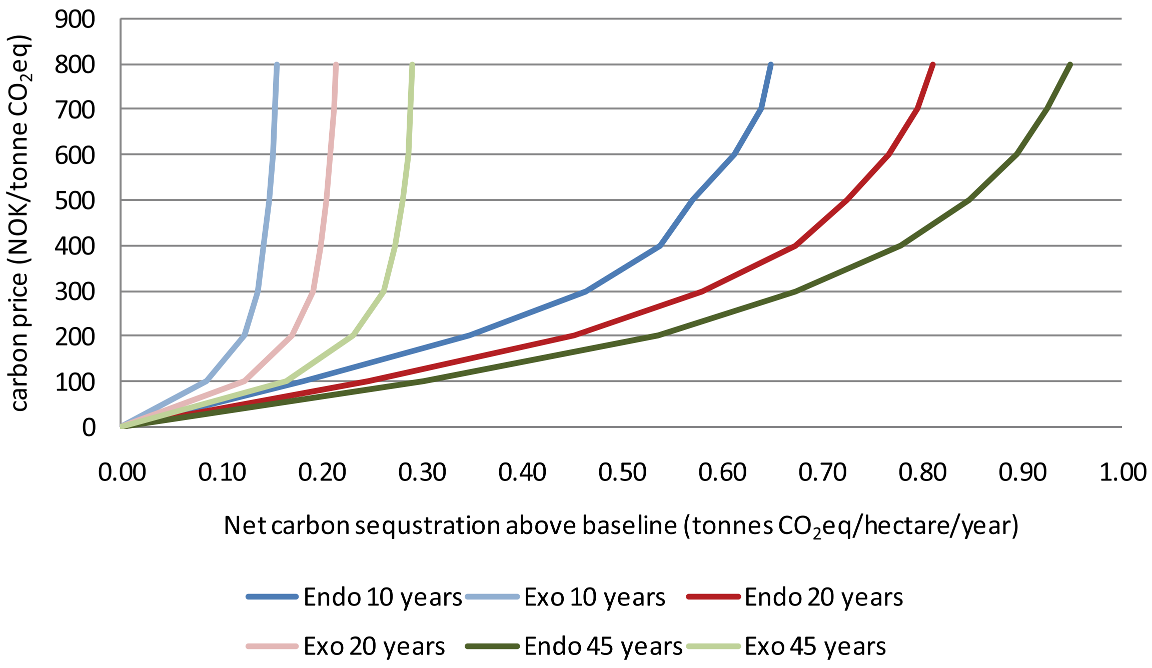

Figure 12: Marginal cost plots for increasing net sequestration of greenhouse gases in the forest sector per hectare productive forest for various horizons.

Table 1: Maximum annual undiscounted net CO_2 sequestration potential above baseline (million tonnes CO_2eq/year) in the sector with a carbon price of 800 NOK/tonne CO_2eq.

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055
Endogenous market	4.11	6.87	8.16	9.30	10.01	9.62	9.82	10.31	10.14
Exogenous market	1.70	2.21	2.82	3.77	3.17	3.56	3.85	3.94	3.90

In the Base scenario, the carbon storage is rather stable over time, close to 1.2 billion tonnes CO_2. (Figure 13). However, the carbon storage in forests is 37% higher in the Endo 800 scenario than in Base in the last period. Total carbon sequestration is considerably higher in the endogenous market models than in the exogenous market models.

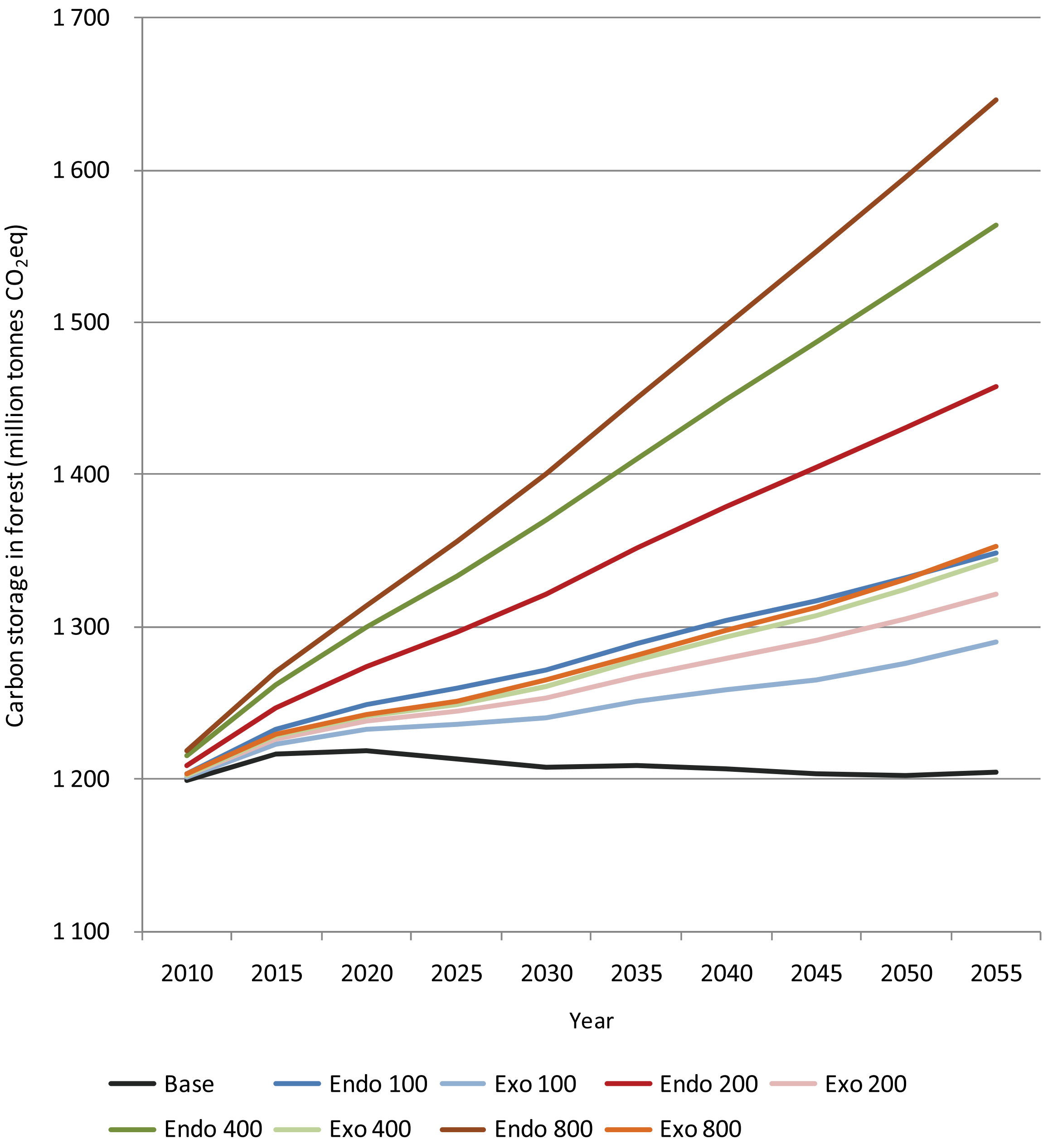

Figure 13: Carbon stored in forests (tonnes CO_2eq) over time in various carbon price scenarios and market models.

4. Discussion

Our results clearly indicate the importance of including wood market interactions in analyzing the forest sector climate change mitigation policy effectiveness. Both short and long term potential is substantially higher with endogenous markets and carbon sequestration costs are much lower. This is true even when considering only forest carbon sequestration. At a carbon price of 100 NOK/tonne CO_2eq with an endogenous market carbon storage in forests increases by approximately the same amount as a carbon price of 800 NOK/tonne CO_2eq with an exogenous market.

A number of possible reasons may explain this large difference. First, the spatial and dynamic optimization modeling makes possible a detailed representation of regional forest and forest industry characteristics (including bioenergy). This allows better utilization of domestic wood raw material both over time and space. Another, closely linked reason is that in the endogenous model the trade quantities are flexible whereas in the exogenous model they are predetermined at Base scenario levels. This allows the endogenous model further flexibility with regard to not only the harvest level, but also in the selection of stands to be harvested. Rotation ages on sites with low productivity which require a long time to build up the carbon stock after harvest, are longer in the endogenous market model. Fewer hectares are also allocated to thinning regimes in the endogenous market model, as thinning is expensive when facing carbon prices due to reduced carbon stock, emissions from harvest residues, and low share of sawlogs. In both market models, the average density in clear-cut stands decline in the first period when facing a high carbon price compared to Base. Total regenerated area increases thus in the exogenous market model. The changes seen in total regenerated areas in both market model may also be caused by alterations in methods between shelter wood/seed tree cuts and clear-cuts. These results, included forestry investments, should be evaluated more in detail in order to better reveal changes in regeneration methods, densities and pre-commercial thinning with different carbon prices and market models.

Pulp and paper production is sensitive to carbon tax/subsidy regimes, as it causes increased competition for the raw materials, as well as increased costs of production as the paper production has considerable greenhouse gas emissions. The solid wood industry faces a loss in value due to the increased timber price caused by the reduction in harvest, while it benefits from the increased competition for byproducts such as slabs and offcuts. A carbon policy as modeled could also possibly shift more bioenergy from fire wood stoves to high-efficiency central and district heating systems. Such installations are today quite limited in Norway with almost all household bioenergy use taking place in fire wood stoves.

Leakage is of great concern in the climate change policy debate. In our study, leakage occurs primarily through reduced export of pulp and paper, but also through the increase in imported timber and solid wood products. However, this leakage is highly dependent upon the assumed elasticities of demand and supply in foreign markets. There is considerable uncertainty in what those elasticities actually are, and Norway as a small agent in a highly international market of wood and wood products could be considered a price taker, particularly for manufactured products. Factors such as timber quality standards and forest hygiene concerns could possible create additional barriers and inertia for timber trade. Nevertheless, it would be of great interest to study those effects more closely.

Due to different scales and calculations of costs and benefits, it is limited how much we can compare our results with other studies. However, in the earlier-mentioned Swedish study (Backéus et al., 2005), depending on the carbon tax magnitude (they analyzed for tax levels up to 630 SEK/tonne CO_2, about 550 NOK/tonne CO_2), it was found that the average carbon sequestration above the baseline is 0.64 tonnes carbon/ha, for the highest carbon tax. Assuming that this flow is stable throughout the horizon, we calculate an annualized carbon flow of 0.661 tonnes CO_2/hectare/year using 4% discount rate. This is not far from our estimate in the endogenous market model over 20 years. However, their analysis calculated carbon benefits over 100 years.

Raymer et al. (2009) calculated trade-off curves between increased timber production in net present value and net present value of carbon benefits, with and without substitution effects. They found the net present value of carbon benefits to increase by almost 50% when substitution effects were included. By assuming a 2.5% discount rate, they found that the carbon benefits may be increased by 0.15-0.22 tonnes CO_2eq/hectare/year above baseline for a price up to 10 €/tonne CO_2eq. This is rather close to the 45 years results for the endogenous market model in our study, but again, they had a horizon of 120 years in their study.

Based on the results on these two other studies together with our study, the endogenous market model seems to provide a larger potential for the same mitigation cost for the same time length. The study of Backéus et al. (2005) was less constrained in the harvest than the study of Raymer et al. (2009), as in the latter, harvest was restricted to present levels, but in the former, only the fluctuations were constrained, in addition to terminal conditions. However, as their studies have a broader range of forest management options, including fertilization in the study of Raymer et al. (2009), the forest management measures may yield larger potentials than in our study.

As with any policy effectiveness analysis, our results are burdened with considerable uncertainty. It is not clear how well our forest growth model behaves with per hectare standing volumes as great as we see in the high carbon price scenarios. These volumes are far above the empirical data on which the forest growth (and mortality) functions are based. As discussed above, there is considerable uncertainty surrounding not only import and export elasticities, but also with regard to future trade policy. Additional analyses empirically estimating these elasticities could prove useful, or global trade models such as EFI-GTM could be utilized to estimate those elasticities.

5. Conclusions

Our study suggests that including the wood markets is necessary in order to assess the forest sector's full climate change mitigation potential. This is because a carbon tax/subsidy policy would undoubtedly alter the industrial allocation of wood which would in turn impact the wood products' mitigation potential. With regard to our hypotheses posed in the introduction, we believe that the results support all three. Regarding altered mitigation costs, the effect of an increased mitigation potential of wood products appears to be more important than the increased opportunity costs in our study. This is due in large part to the overall lower policy costs with endogenous market interactions. Long-term carbon storage in the forest is indeed considerably higher with the endogenous market model. We also found that changes in wood markets will occur, as production are shifted from products with high greenhouse gas emissions and low substitution effects to products which benefit from the analyzed carbon policy. Furthermore, as greenhouse gas emissions from bioenergy combustion have a cost, bioenergy in high-efficiency installations see great increases on the detriment of firewood. Overall, we conclude that applying a modeling tool that integrates the wood markets with the forest management and harvest reveal the costs and carbon sequestration potentials in a better way than a model which only has one of these parts endogenous.

References

Adams, D. M., Alig, R. J., McCarl, B. A., Callaway, J. M., Winnett, S. M., 1999. Minimum Cost Strategies for Sequestering Carbon in Forest. Land Economics 75(3): 360-374.

Backéus, S., Wikström, P. Lämås, T., 2005. A model for regional analysis of carbon sequestration and timber production. Forest Ecology and Management 215: 28-40.

Eriksson, E., Gillespie, A. R., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R., Stendahl, J., 2007. Integrated carbon analysis of forest management practices and wood substitution. Can. J. For. Res. 37:671-681.

Gan, J., Kolison, S. H. Jr., Colletti, J. P., 2001. Optimal forest stock and harvest with valuing nontimber benefits: a case of US coniferous forests. *Forest Policy and Economics* 2(2): 167-178

Hartman, R., 1976. The Harvesting Decision when a Standing Forest has Value. Econ. Inquiry 16: 52-58

Hoen, H.F., Eid, T., 1990. A model for analysis of treatment strategies for a forest applying standvice simulations and linear programming. [En modell for analyse av behandlingsalternativer for en skog ved bestandssimulering og lineær programmering] *Report of Norwegian Forest Research Institute* **9/90**, 35 pp. [In Norwegian with English summary]

Hoen, H. F., Solberg, B., 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. Forest Science 40(3), 429-451.

Hoen, H. F., Solberg, B., 1999. Policy options in carbon sequestration via sustainable forest management: an example from the North. In: Palo, M. (ed): Forest transition and carbon fluxes – global scenarios and policies. World Development Studies, vol. 15:117-132. UNU/WIDER. Helsinki.

van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effects of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. *Amer. J. Agr. Econ.* 77: 365-374

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R., Karjalainen, T., 2001. Which rotation length is favorable to carbon sequestration? Can. J. For. Res. 31: 2004-2013.

Lorenz, K., Lal, R., 2010. Carbon Sequestration in Forest Ecosystems. Springer, 277 pp.

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., Zhang, X., 2007: Forestry. In Climate Change 2007: Mitigation. Contribution of

Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Norwegian Climate and Pollution Agency, 2010. Greenhouse Gas Emissions 1990-2008. National Inventory Report 2010. TA 2639/2010. 320 pp.

Petersen, A.K., Solberg, B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics 7: 249–259.

Pussinen, A., Karjalainen, T., Kellomäki, S., Mäkipää, R., 1997. Potential contribution of the forest sector to carbon sequestration in Finland. Biomass and Bioenergy 13(6): 377-387.

Raymer, A.K.P., 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass and Bioenergy 30: 605–617.

Raymer, A.K.P., 2005. Modelling and analysing climate gas impacts of forest management. Norwegian University of Life Sciences, Department of Ecology and Management of Natural Rsources. Ph.D. Thesis 11/2005. Ås, Norway.

Raymer, A.K.P., Gobakken, T., Solberg, B., Hoen, H.F. and Bergseng, E., 2009. A forest optimisation model including carbon flows: Application to a forest in Norway. Forest Ecology and Management 258: 579-589.

Richards, K.R., Stokes, C., 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63: 1–48.

Samuelson, P.A., 1952. Spatial price equilibrium and linear programming. Am. Econ. Rev., 42: 283-303

Sedjo, R., Sohngen, B., Mendelsohn, R., 2001. Estimating Carbon Supply Curves for Global Forests and Other Land Uses. *RFF Discussion Paper* 01-19

Sjølie, H.K., Latta, G.S., Gobakken, T., Solberg, B., 2011. NorFor - a forest sector model of Norway. Model overview and structure. *INA report* 18. Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences

Sjølie, H.K.S., Trømborg, E., Solberg, B., Bolkesjø, T.F., 2010. Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. Forest Policy and Economics 12: 57-66.

Sohngen, B., Sedjo, R., 2000. Potential carbon flux from timber harvests and management in the context of a global timber market. Climatic Change 44: 151–172.

StatBank Norway, 2011. Subject: 09 National accounts and foreign trade Table 03057: Import and export, from product number and country Product number 44 - 49 Wood, wood products and wood pulp [Emne:09 Nasjonalregnskap og utenrikshandel Tabell 03057: Import og eksport, etter varenummer og land Varenummer 44 – 49 Tre, trevarer og tremasse.] Subject: 10 Industrial activities Table 06289: Stående kubikkmasse under bark, og årlig tilvekst under bark, etter treslag (1 000 m^3) [growing stock under bark, and annual increment under bark, by species]; 03522: Forest planting [Skogplanting] [Emne: 10 Næringsvirksomhet Tabell 06291: Årlig tilvekst under bark] www. *statbank.ssb.no/statistikkbanken/ [In Norwegian]*

Statistics Norway, 2010. Landbruket i Norge 2009 [Agriculture in Norway 2009]. Chapter 3. Skogbruk [Forestry] 45 pp. http://www.ssb.no/emner/10/04/sa_landbruk/sa116/skogbruk.pdf [in Norwegian]

Trømborg, E., Sjølie H.K., 2011. Data applied in forest sector analyses in the forest sector models NorFor and NTMIII. INA *Fagrapport* 17 Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences

UNFCCC, 2002. Conference of the parties. Report of the conference of the parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. Addendum. Part two: Action taken by the conference of the parties. FCCC/cp/2001/13/add.1. 21 January 2002. 69 pp.

Warner, F., Taverna, R., Hofer, P., Thürig, E., Kaufmann, E., 2010. National and global greenhouse gas dynamics of different management and wood use scenarios: a model-based assessment. Envrionmental Science and Policy 13: 72-85.