Norwegian University of Life Sciences
Faculty of Environmental Sciences and Natural
Resource Management

Philosophiae Doctor (PhD)
Thesis 2019:01

Modelling forest sector impacts of increased use of wood-based bioenergy in Europe and US South

Modellering av virkninger på skogsektoren av økt bruk av skogbasert bioenergi i Europa og syd-østlige USA

Rafał Piotr Chudy

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Ås (2019)

Thesis number 2019:01
ISSN 1894-6402
ISBN 978-82-575-1553-9

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PREFACE

It took me many years to deeply understand the meaning and the power of research and development work, and I firmly believe that it was worth the time and the effort! Together with my Master and Ph.D. thesis work, I spent over 5 years to understand the forest sector complexity and relationships. Without any doubts, the modelling methods, exercises and deep analysis of results, helped me to better understand interlinkages between forestry and wood industry worlds. My first day of work seems like it was just yesterday. I did not realize how quickly the days and years were passing. The research work has been absorbing, and many people have contributed in different ways to my advance. Here I want to acknowledge them:

First, I would like to thank my mentor, professor Birger Solberg, for his scientific guidance, his excellent remarks and for the support and trust he showed during this time. My gratitude extends to Dr. Gregory Latta, who generously hosted me at Oregon State University in 2017. It was a memorable experience, and a chance to understand better forestry practices and challenges in the Pacific Northwest region. I would like also to express my gratitude to professor Maarit Kallio and Dr. Hanne Sjølie for their support in scientific papers, inspiring comments, and pushing the scientific boarders to higher levels. Thanks to Professors Robert Abt, Frederick Cubbage, Jeffrey Prestemon and Dr. Ragnar Jonsson for their support with the article based on my Master thesis, which is also included in this dissertation. I must admit that it is a special article to me as I think that my forest economist and forest sector modelling path has begun with it, and prepared me well for Ph.D. challenges. In addition, I wish to thank Dr. Ragnar Jonsson, my previous supervisor and currently my officemate at the European Commission – Joint Research Centre, for reviewing this thesis and helping me to improve its flow.

Thanks to all my wonderful Ph.D. colleagues and other staff from NMBU and MINA in Ås who made the work atmosphere enjoyable, helped me speak Norwegian in the lunchroom and initiated me into the Norwegian way of being. My warmest thanks to all the friends that I made here: Kaja, Patricia, Ana, Marek, Victor, Leenart and many others.

Nevertheless, this thesis could have not been finished without the warmest support from my two beloved girls, my wife Karolina, and my little daughter Zosia, who were supporting me continuously during more than last 3 years of my Ph.D. effort. Finally, I would like to thank my entire family in Poland, who was helping me in difficult moments.

Rafał P. Chudy, Ispra, 10th December 2018

DEDYKACJA

Chciałbym zadedykować moją pracę doktorską mojej ukochanej babci Teresie oraz dziadkom Władysławowi i Stefanowi, którzy nie mogli świętować jej ukończenia razem ze mną.

SUMMARY

The European Union (henceforth, EU) is now well on track to meet the 2020 targets for renewable energy production and consumption, and recently a new 2030 Framework for climate and energy has been proposed. The forest sector is supposed to make a significant contribution towards meeting green economy objectives. Moreover, it is of high interest to analyze the potential impacts of EU's renewable energy directive (RED 1 and the ongoing RED 2) on the forest sector in Europe and overseas.

In order to examine global challenges regarding energy, climate change, ecological impacts, technology developments and sustainable use of land and natural resources in the upcoming circular bioeconomy era (EEA 2018), improved analysis tools are required. The utilization of Forest Sector Models (henceforth, FSMs), linking forestry and forest industry activities, has been found useful for assessing the interplay between forest resources and forest commodity markets, accounting for competition and synergies between different uses of wood.

This thesis investigates the impacts of increased use of wood-based bioenergy on forest resources and markets of forest and wood products, and explores the strengths and weaknesses of FSMs. The thesis consists of five papers:

Paper I analyses impacts of wood-based second-generation biofuel on forest products markets based on a Norwegian case study, including the impacts on trade and the wood industry markets. The paper focuses on harvest, timber net import/export, and forest industry production. The intertemporal, partial equilibrium model NorFor is used to investigate how price effects for forest biomass and end-use products may differ depending on which feedstock mixes are used in the biofuel production. The results show that the choice of feedstock has an important effect on industrial impacts. It is found that the most economic biofuel feedstock mix is dominated by softwood chips which comprise 48% of total inputs in 2030 and increase in use up to 67% by 2055. The second largest component used for second-generation fuel production is hardwood chips at 34% initially, then substituted over time by softwood chips. The proportion of harvest residues is constant in the most economic feedstock mix (18%) and roundwood is not used at all for biofuel production. Despite the additional demand for chips, a single medium-scale biofuel plant is found to have only minor effects on existing forest industries and harvests in Norway, as the domestic impact is dampened by changes in foreign trade flows, especially of chips.

In *paper II*, the effects of EU's wood pellets imports from the Southeast U.S. (henceforth, SE) on SE timber prices, inventories, and carbon sequestration are analyzed. The sub-regional timber supply (SRTS) model is used to simulate market responses to changes in woody biomass consumption in the U.S. and EU between 2008 and 2038. Results indicate that the price of imported wood pellets in EU is sensitive to future U.S. renewable energy policies. The analysis shows that with the assumed bioenergy demands, prices increased for U.S. softwood roundwood from 25% to 125% by 2038, depending largely on U.S. domestic policy. Under all scenarios and for both the SE as a whole and for the part of the SE with the most active wood pellet market - the coastal plain, carbon storage increases because of a positive planting response among private forest owners to higher timber prices and due to a conversion of marginal agricultural land to forest. High wood demand gives a price signal for private forest owners to plant trees. This research highlights that at low EU's pellet import demand levels, the impacts of woody biomass from forests does not have large effects on timber markets and might even encourage carbon storage and planting of more forests.

In *paper III*, EFI-GTM, a global model of markets and trade of forest biomass and forest products is applied to examine the allocation of wood biomass between biofuels and heat and power production in the European Economic Area (EEA). The results show that policy choices might have strong impacts on the allocation of biomass use between heat and power production, and the production of liquid biofuels. Nevertheless, even assuming the goal of reducing the climatic warming to 2°C, the projections suggest that the European forest industry production is not expected to be much affected by the increased competition for biomass with the energy sector. This is because the rivaling regions would be facing similar biomass demand challenges and the relatively abundant wood biomass resources in Europe would help the forest industry in EEA to maintain its market shares. Thus, it is concluded that the policy makers must have very clear goals for the preferred ways to solve the shift from the present fossil fuel-based energy system to a less carbon-intensive one. This paper emphasizes that because large investments in biofuel production take time to plan and construct, and because the annual forest growth exceeds the harvests of wood in various parts of Europe, there is time to adjust the policies to control the market development.

Paper IV analyses the impact of carbon prices on forest management and marginal abatement cost curves in Europe using the new forest sector model EUFORIA (**E**uropean **FOR**est and **I**ndustry **A**ssessment model). This is a new bioeconomic model of the European forest sector which combines the information about the wood supply, determined based on harvest schedules of alternative management options, with data regarding wood demand coming from forest industrial production and consumption of forest products and trade. The model is described in the paper and then applied for analyzing the impacts of carbon pricing on the forest management in Europe and for estimating marginal carbon abatement cost curves by changing only forest management in Europe. The results indicate a decreasing area assigned to partial harvesting than to clearfelling with increasing carbon prices. The average age of clearfellings increases with increasing carbon prices, but the increase is rather small compared to a baseline scenario with zero carbon price, only 2-3 years. With a carbon price of 100 €/tCO_2 and use of 3% p.a. discount rate, there is a possibility to sequester around 20% more carbon annually than in the baseline scenario due to changed forest management across Europe.

In *paper V* possibilities to include risk in FSMs are analyzed by reviewing risk methods that have been incorporated in FSMs and in numerical models of other sectors as well as macroeconomic models, and by identifying and discussing promising approaches for including risk in FSMs. The analysis shows that there are many options for incorporating risk in model analyses, but only a few have been applied in forest sector modelling exercises. Nevertheless, many of the proposed methods are too demanding with respect to data availability and computer capacity to be applicable in large-scale numerical FSMs. The paper concludes that for incorporating risk in FSMs, fuzzy set theory and robust optimization techniques seem promising new approaches, alongside methods that already are in use, like Monte Carlo simulation and, in particular, scenario and sensitivity analysis.

Chapter 4 of the thesis provides discussion and synthesis. It is stated that bioenergy policies are important for the forest sector, whether reflected by legislation on a national level (Norway, United States) or internationally (European Union), and this situation is likely to prevail. Although most policies are tailored for specific geographical areas and have a direct impact on them, it has been shown that such policies may unintentionally affect forest resource utilization and markets in other regions. Nevertheless, articles I-IV in this thesis did not show overall dramatic effects on existing forest markets and industries created by new market actors and policies. Contrary, shocks, implied by policy incentives, are hampered by the “invisible hand” (Smith 1776) that makes the markets to adjust to policy changes by synergies, competition, and trade. This has implications for multi-level policy interrelationships where policy makers and policy designers should have very clear goal settings for the preferred ways to solve the shift from the present fossil fuel-based energy system to a less carbon-intensive one, and also should consider the market mechanisms across regions. Applications and future role of forest sector models are discussed in Chapter 4. It is concluded that FSMs have strengths and weaknesses, like all models, but are useful in certain studies and most likely will continue to be a principal instrument in forest sector impact analyses.

Regarding promising future research within this field it is inferred that more work should focus on: modelling climate change impacts on the forest sector using FSMs; examining future forest mitigation potential, for instance, by inclusion of carbon prices and consideration of the carbon cycle from forest growth to end-use; identifying the reasons behind data problems and improving parameter uncertainties, data collection procedures and statistical systems; developing new and updating existing FSMs, meanwhile assuring their integrity, transparency, and possibility for the replication of their outputs; investigating the impacts of new wood-based products on other parts of the forest sector; and finally, exploring methods in FSMs that lead toward robust solutions.

STRESZCZENIE

Unia Europejska (odtąd UE) jest na dobrej drodze, aby osiągnąć wyznaczone na 2020 rok cele w zakresie produkcji i zużycia energii odnawialnej. Także ostatnio, nowe ramy klimatyczne i energetyczne zostały zaproponowane na rok 2030. Zakłada się, że sektor leśny[1] ma znacząco przyczynić się do osiągnięcia celów zielonej gospodarki. Ponadto niezwykle istotne jest przeanalizowanie potencjalnych skutków unijnej dyrektywy w sprawie energii odnawialnej (RED 1 i trwająca RED 2) na sektor leśny w Europie i za granicą.

Aby zbadać globalne wyzwania dotyczące energii, zmian klimatu, skutków ekologicznych, rozwoju technologii oraz zrównoważonego użytkowania zasobów lądowych i naturalnych w nadchodzącej erze biogospodarki o obiegu zamkniętym (EEA 2018), potrzebne są ulepszone narzędzia analityczne. Wykorzystanie modeli sektora leśnego (odtąd MSL), łączących działalność w zakresie leśnictwa i przemysłu drzewnego, okazało się przydatne do oceny wzajemnych zależności między zasobami leśnymi a rynkami surowca drzewnego, z uwzględnieniem konkurencji i synergii między różnymi zastosowaniami drewna.

Niniejsza praca dotyczy wpływu zwiększonego wykorzystania bioenergii, opartej na drewnie, na zasoby leśne i rynki surowca drzewnego oraz analizuje mocne i słabe strony MSL. Praca składa się z pięciu artykułów:

Artykuł I analizuje wpływ biopaliw drugiej generacji wytwarzanych na bazie drewna na rynki surowca drzewnego, w tym wpływu na handel i rynki wyrobów z drewna, na podstawie norweskiego studium przypadku. Artykuł koncentruje się na pozyskaniu drewna, imporcie/eksporcie netto wyrobów z drewna oraz produkcji przemysłu drzewnego. Międzyokresowy model równowagi cząstkowej NorFor jest wykorzystany do zbadania, w jaki sposób efekty cenowe dla biomasy leśnej i drzewnych produktów końcowych mogą się różnić w zależności od składu surowców wykorzystywanych w produkcji biopaliw. Wyniki pokazują, że wybór składu surowca w produkcji biopaliw pociąga za sobą istotne konsekwencje gospodarcze. Stwierdzono, że najbardziej ekonomiczny skład, tworzy surowiec zdominowany przez zrębki z drewna iglastego, które w 2030 r stanowią 48% surowca wykorzystywanego do produkcji biopaliwa. Następnie ich udział rośnie do 67% w roku 2055. Drugim co do wielkości komponentem są zrębki drzewne pochodzące z drzew liściastych, które stanowią początkowo 34% całkowitego składu surowców

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[1] Sektor leśny w literaturze definiuje się jako sektor zawierający w sobie leśnictwo, przemysł drzewny oraz rynkowe interakcje pomiędzy nimi (Solberg 1986).

wykorzystywanych do produkcji biopaliwa a następnie zastępowane są z upływem czasu przez zrębki pochodzące z drzew iglastych. Udział odpadów pozrębowych jest stały (18%) w najbardziej ekonomicznym składzie surowców wykorzystywanych do produkcji biopaliwa, a drewno okrągłe nie jest wykorzystywane do jego produkcji w ogóle. Pomimo dodatkowego popytu na zrębki drzewne, jeden średniej wielkości zakład produkujący biopaliwo ma tylko niewielki wpływ na istniejący przemysł drzewny i pozyskanie surowca drzewnego w Norwegii. Krajowe następstwa gospodarcze hamowane są przez zmiany w przepływie handlu zagranicznego, w szczególności zrębek drzewnych.

W *artykule II* przeanalizowano skutki importu pelletu drzewnego z południowo-wschodnich Stanów Zjednoczonych (odtąd SE) do Unii Europejskiej pod kątem cen drewna, zasobów drzewnych i sekwestracji dwutlenku węgla. Model SRTS został wykorzystany do przeprowadzenia symulacji rynkowych reakcji na zmiany konsumpcji biomasy drzewnej w USA i UE w latach 2008-2038.

Wyniki wskazują, że cena importowanego pelletu drzewnego w UE jest wrażliwa na przyszłą politykę Stanów Zjednoczonych w zakresie energii odnawialnej. Analiza pokazuje, że przy założonych scenariuszach popytowych dla bioenergii, ceny iglastego drewna okrągłego w Stanach Zjednoczonych wzrosły z 25% do 125% w roku 2038, co było w dużej mierze spowodowane wewnętrzną polityką USA. We wszystkich scenariuszach, zarówno dla SE jako całości, jak i dla części SE z najbardziej aktywnym rynkiem pelletu drzewnego - Równiny Atlantyckiej, magazynowanie dwutlenku węgla wzrasta na skutek zwiększonego sadzenia lasów na gruntach prywatnych, co jest reakcją na wyższe ceny drewna oraz przekształcenie marginalnych gruntów rolnych w lasy. Wzmożony popyt na drewno, poprzez mechanizm cenowy, zachęca prywatnych właścicieli lasów do dalszych inwestycji. Badanie to podkreśla, że przy niskim poziomie popytu na pellet drzewny w UE, konsekwencje wykorzystania biomasy drzewnej z lasów SE, mają względnie niski wpływ na rynki drzewne, a nawet mogą zachęcać do sekwestracji dwutlenku węgla i sadzenia większej ilości lasów.

W *artykule III* zastosowano globalny model rynku leśno-drzewnego EFI-GTM w celu zbadania alokacji biomasy leśnej i drzewnej między produkcją biopaliw a produkcją ciepła i energii w Europejskim Obszarze Gospodarczym (EOG). Wyniki pokazują, że decyzje polityczne mogą mieć silny wpływ na alokację wykorzystania biomasy między produkcją ciepła i energii, a produkcją biopaliw ciekłych. Niemniej jednak, obierając cel ograniczenia ocieplenia klimatycznego do 2°C, wyniki modelowania sugerują, że zwiększona konkurencja o biomasę, pomiędzy przemysłem drzewnym i energetycznym, nie powinna mieć znacznego wpływu na produkcję produktów drzewnych w Europie. Wynika to z faktu, że konkurujące regiony borykają się z podobnymi wyzwaniami związanymi z zapotrzebowaniem na biomasę, a stosunkowo bogate zasoby biomasy leśno-drzewnej w Europie mogą pomóc przemysłowi drzewnemu w EOG utrzymać udział w globalnym rynku. Stwierdzono zatem, że decydenci polityczni muszą mieć bardzo jasne cele dotyczące preferowanych sposobów rozwiązania problemu przejścia z obecnego systemu energetycznego, opartego na paliwach kopalnych na system niskoemisyjny. Ponieważ duże inwestycje, związane z produkcją biopaliw, wymagają czasu, oraz bieżący roczny przyrost lasów przekracza roczne pozyskanie drewna w różnych częściach Europy, w artykule stwierdzono, iż decydenci polityczni mają czas na dostosowanie polityki w celu śledzenia zmian na rynku.

W *artykule IV* przeanalizowano wpływ cen emisji dwutlenku węgla na gospodarkę leśną i krańcowe krzywe kosztów redukcji emisji w Europie za pomocą nowego europejskiego modelu oceny sektora leśnego - EUFORIA (ang. **E**uropean **FOR**est and **I**ndustry **A**ssessment model). Jest to nowy bioekonomiczny model europejskiego sektora leśnego, który łączy w sobie informacje na temat podaży drewna, określone na podstawie alternatywnych planów pozyskania drewna wynikających z możliwości hodowlanych, z danymi dotyczącymi popytu na surowiec drzewny pochodzącymi z przemysłowej produkcji, konsumpcji i handlu produktów drzewnych. Model został opisany w artykule, a następnie zastosowany do analizy wpływu cen emisji dwutlenku węgla na gospodarkę leśną w Europie oraz do oszacowania krańcowych krzywych kosztów redukcji emisji CO_2, poprzez zmianę jedynie działań gospodarki leśnej w Europie. Wyniki wskazują, że wraz ze wzrostem cen emisji CO_2 zmniejsza się powierzchnia cięć pielęgnacyjnych (trzebieże) w porównaniu z powierzchniami przeznaczonymi do cięć końcowych (zrębu). Średni wiek rębności zwiększa się wraz ze wzrostem cen emisyjnych CO_2 o zaledwie 2-3 lata w porównaniu ze scenariuszem bazowym, który zakłada zerową cenę emisyjną dwutlenku węgla. Wyniki pokazują, że jeżeli cena emisyjna równa jest 100 €/tCO_2 a stopa dyskontowa utrzymuje się na poziomie 3% rocznie, istnieje możliwość sekwestracji około 20% więcej dwutlenku węgla rocznie niż w scenariuszu bazowym ze względu na zmienioną gospodarkę leśną w całej Europie.

W a*rtykule V* analizowane są możliwości uwzględnienia elementu ryzyka w MSL, poprzez dokonanie przeglądu metod, w których wzięto pod uwagę element ryzyka w modelach sektora leśnego, a także w numerycznych modelach innych sektorów, jak również modelach makroekonomicznych. Następnie określono i omówiono obiecujące koncepcje pozwalające na włączenie elementu ryzyka w MSL. Analiza pokazuje, że istnieje wiele możliwości inkorporacji elementu ryzyka w analizach modelowych, jednakże tylko nieliczne znalazły zastosowanie w pracach dotyczących modelowania sektora leśnego. Niemniej jednak wiele z proponowanych metod jest zbyt wymagających pod względem dostępności danych i komputerowych zdolności obliczeniowych, aby mogły być zastosowane w rozbudowanych numerycznych modelach sektora leśnego. W artykule stwierdza się, że dla uwzględnienia elementu ryzyka w MSL, teoria zbiorów rozmytych i techniki optymalizacji odpornej wydają się obiecującymi nowymi podejściami, obok metod, które są już w użyciu, takich jak symulacja Monte Carlo, a w szczególności analiza scenariuszy i wrażliwości.

Rozdział 4 niniejszej pracy stanowi dyskusję i syntezę. Stwierdzono, że polityka bioenergetyczna jest, a także prawdopodobnie dalej będzie istotna dla sektora leśnego, co odzwierciedlają przepisy prawne na poziomie krajowym (Norwegia, Stany Zjednoczone) lub międzynarodowym (Unia Europejska). Chociaż polityka jest dostosowana najczęściej do konkretnych obszarów geograficznych i ma na nie bezpośredni wpływ, w niniejszej pracy wykazano, że taka polityka może w niezamierzony sposób oddziaływać na wykorzystanie zasobów leśnych i rynki drzewne w innych regionach. Niemniej jednak artykuły I-IV zawarte w tej pracy, nie wykazały dramatycznych konsekwencji ekonomicznych na istniejących i rozwijających się rynkach leśno-drzewnych. Szoki gospodarcze, implikowane przez zachęty związane z polityką, są hamowane przez "niewidzialną rękę" (Smith 1776), która sprawia, że rynki dostosowują się do zmian politycznych poprzez synergie, konkurencje i handel. Ma to wpływ na wielopoziomową i wzajemną politykę, w której decydenci i osoby odpowiedzialne za kształtowanie programów politycznych powinni mieć bardzo jasno sprecyzowane cele dotyczące preferowanych sposobów rozwiązania problemu przejścia z obecnego systemu energetycznego opartego na paliwach kopalnych na systemy o niższej emisji dwutlenku węgla. Ponadto, powinni wziąć pod uwagę mechanizmy rynkowe w poszczególnych regionach. Zastosowanie i przyszłą rolę modeli sektora leśnego omówiono w rozdziale 4. Stwierdzono, że MSL mają mocne i słabe strony, jak wszystkie modele, ale są użyteczne w niektórych badaniach i najprawdopodobniej nadal będą głównym instrumentem badawczym w analizach wpływu na sektor leśny.

Jeśli chodzi o obiecujące przyszłe badania w tej dziedzinie, należy wnioskować, że więcej pracy naukowej powinno się skupić na: modelowaniu wpływu zmian klimatycznych na sektor leśny za pomocą MSL; badaniu przyszłego potencjału lasów w zakresie łagodzenia zmiany klimatu, na przykład poprzez uwzględnienie cen emisyjnych dwutlenku węgla i uwzględnienie pełnego cyklu węglowego od wzrostu lasu aż do jego końcowego wykorzystania; identyfikacji przyczyn problemów związanych z danymi i poprawie niepewności parametrów, procedur gromadzenia danych i systemów statystycznych; rozwijaniu nowych i aktualizowaniu istniejących MSL, zapewniając jednocześnie ich integralność, przejrzystość i możliwość powielania ich wyników; badaniach wpływu nowych produktów drewnopochodnych na inne części sektora leśnego; i wreszcie, odkrywaniu metod w MSL, które prowadzą do odpornych rozwiązań optymalizacyjnych.

LIST OF PAPERS

Paper I: Chudy R.P., H.K. Sjølie, G.S. Latta, B. Solberg (manuscript in review). *Effects on forest products markets of second-generation biofuel production based on biomass from boreal forests: a case study from Norway.*

Paper II: Chudy R.P., R.C. Abt, R. Jonsson, J.P. Prestemon and F.W. Cubbage. 2013. *Modelling the impacts of EU's bioenergy demand on the forest sector of the Southeast U.S.* Journal of Energy and Power Engineering 7 (2013) 1073-1081.

Paper III: Kallio A.M.I., R.P. Chudy, and B. Solberg. 2018. *Prospects for producing liquid wood-based biofuels and impacts in the wood using sectors in Europe.* Biomass and Bioenergy, vol. 108, no. November 2017, pp. 415–425.

Paper IV: Chudy R.P, G.S. Latta, A. Moiseyev, H.K. Sjølie, S. Härkönen, A. Mäkelä, B. Solberg (manuscript). *Analyzing the impact of carbon pricing on forest management and marginal abatement cost curves in Europe using the new forest sector model EUFORIA*

Paper V: Chudy R.P., H.K. Sjølie, B. Solberg. 2016. *Incorporating risk in forest sector modelling – state of the art and promising paths for future research*. Scandinavian Journal of Forest Research, 2016 Vol. 31, No. 7, 719–727.

CONTENTS

APPENDICES: PAPERS I-V

SYNOPSIS

1. INTRODUCTION AND OBJECTIVES

1.1 Renewable energy policy – a brief overview

Many countries around the globe recognize the necessity of renewable energy policies to address issues of energy security and greenhouse gas emissions. In December 2015, at the United Nations Framework Convention on Climate Change's 21st Conference of the Parties in Paris, 195 countries agreed to limit global warming to well below 2 degrees Celsius. In consequence, most countries committed to scaling up renewable energy and energy efficiency through their Intended Nationally Determined Contributions (INDCs). Out of the 189 countries that submitted INDCs, 147 countries mentioned renewable energy, and 167 countries mentioned energy efficiency. At present, renewable heat obligations exist in 21 countries, biofuel mandates in 66 countries and 114 countries have renewable energy regulatory policies in the power sector (REN21 2016).

In 2014, the average EU-28[2] energy import dependency was 53.4%, a share that has been steadily increasing over the last two decades. The highest import dependency was represented by oil (87.4%), followed by natural gas (67.2%) and solid fossil fuels such as coal (45.6%) (AEBIOM 2016). Such dependency on extra-Europe energy sources may significantly weaken the geopolitical influence of EU (Correljé and van der Linde 2006, Umbach 2010, AEBIOM 2016), and renewable energy is viewed as a potential solution to increase energy self-sufficiency.

The Renewable Energy Directive (RED) of 2009 requires EU to *"fulfill at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets"* (European Parliament 2009). Individual national renewable energy targets were set for each country, based on their starting point and overall potential for renewables, and were intended to drive significant improvements over business-as-usual national policies. By June 30th, 2010, EU's Member States had to establish National Renewable Energy Action Plans (NREAPs) in which they had to include national targets for the share of energy from Renewable Energy Sources (RES) in electricity, heating, and cooling, and transport. The transportation sector also has binding targets on its fuel mix (European Parliament 2009). Overall, EU-28 as a whole seems to be on track to reach the

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[2] The EU-28 is the abbreviation of European Union (EU) which consists a group of 28 countries (Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom) that operates as an economic and political block.

2020 renewable energy target of 20%. Some countries (e.g. Austria, Croatia, Denmark, Estonia, Finland, Italy, and Sweden) have already achieved or are very close to achieving their 2020 target, while others (e.g. Belgium, France, Ireland, the Netherlands or the United Kingdom) still need to take important steps to reach necessary reduction targets (IEA Bioenergy 2018).

EU's countries have agreed on a new 2030 Framework for climate and energy, including EU's wide targets and policy objectives for the period between 2020 and 2030 (European Commission 2014a). As stated, these targets aim to help EU achieve a more competitive, secure and sustainable energy system and to meet its long-term 2050 greenhouse gas reductions target. Targets for 2030 call for a 40% reduction in greenhouse gas emissions compared to 1990 levels, at least 27% share of renewable energy consumption and at least 27% energy savings compared with the business-as-usual scenario. More recently, in 2018, the European Union Parliament voted to increase the renewable energy goal for 2030 from 27% to a new target of 35%. The European Parliament also agreed on increasing EU's energy efficiency target to a minimum of 35% — binding for EU but indicative for national targets — and a move to ensure that 12% of the energy consumed in transport comes from renewable energy sources. These policies also aim to send a strong signal to the market, encouraging private investments, low-carbon technologies and electricity networks.

1.2 Role of woody biomass in meeting policy targets

Biomass is an essential renewable energy source in reaching EU's long-term decarbonization objectives (e.g. Lettens et al. 2003). Energy from biomass and the renewable share of waste contributes almost two-thirds (123 Mtoe, 63.1%) of the 28 Member States primary combined renewable energy production today and is expected to further increase through 2030 (PWC et al. 2017). In 2016, 23 out of the 28 EU's countries had more than 50% of bioenergy in their renewable energy share (AEBIOM 2016).

EU's forests have contributed to climate mitigation already for decades because they have been accumulating more timber volume (growing stock) than it was harvested (Nabuurs et al. 2013). Despite that, wood accounts for approximately two-thirds of the biomass used for renewable energy in EU (Bourguignon 2015). The European Commission's proposal is to maintain EU's position as a world leader in renewable energy (Dolzan et al. 2007). EU has declared that it will use wood from sustainable sources only (see e.g. European Commission 2016). Panoutsou et al. (2014) found that the overall EU-28 sustainable biomass potential is theoretically large enough to satisfy total projected bioenergy demand by 2020 and 2030, but costs for domestic biomass may be higher than for imported bioenergy, e.g. biodiesel or wood pellets. For instance, the targets for renewable energy set by EU have resulted in a surge in consumption of wood pellets. Consumption grew from 14.3 million tons (Mt) in 2012 (data are only available from 2012) to 20.5 Mt by 2015. During the same period, EU's production increased from 11 to 14.2 Mt (FAOSTAT 2017). Hence, reported net imports doubled in just three years. EU's demand for wood pellets is expected to increase further in the next decade (Jonsson and Rinaldi 2017). A report published by the USDA Foreign Agriculture Service's Global Agricultural Information Network (USDA 2016) provided an overview of European Union's wood pellet market. Main suppliers of wood pellets to EU are presented in Table 1. Overall, the biggest increase in imports from outside EU was coming from the U.S, which increased by 14% between 2015 and 2016. In the same period, intra EU-28 trade decreased by 12% (Forest Energy Monitor 2016)

Table 1. Main suppliers of wood pellets to EU (1000 metric tons)

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
United States	763	1001	1764	2776	3890	4287
Canada	983	1160	1346	1963	1259	1475
Russia	396	477	645	702	826	786
Belarus	90	101	112	116	122	158
Ukraine	57	150	217	165	136	149
Other	226	226	283	374	314	317
TOTAL	**2515**	**3115**	**4367**	**6096**	**6547**	**7172**

Source: USDA (2016) based on GTIS (HS Code: 44013020 and 440131 as from 2012)

Due to forest conservation policies in European countries (Thoroe et al. 2004, Verkerk et al. 2008, 2014), pressure on forests dedicated to timber supply may significantly increase locally or even outside Europe due to harvest leakage effects (Kallio and Solberg 2018a). The European Commission estimates that the majority of biomass can be supplied domestically, but the monitoring of imported biomass origin from outside EU is still recommended (European Commission 2014b) to ensure that it is produced in a sustainable way.

In 2017, more than 40 lignocellulosic biorefineries were operating across Europe, producing biofuel, electricity, heat, bio-based chemicals, and biomaterials (Hassan et al. 2018). While first-generation fuels will continue to dominate the market[3] for some time, it is expected that second-generation biofuels[4] will gain market share in the long term due to technological and production method improvements (Capital Economics 2018). EU's Indirect Land Use Change Directive (European Commission 2015) has established a limiting quota for first-generation biofuels and recently, the European Commission proposed a minimum share of 3.6% for advanced biofuels in transport by 2030 (European Commission 2016b). Koponen and Hannula (2017) estimated that the 3.6% share would require annually 48–62 million tons of woody feedstock without additional hydrogen input in the production process and 16–24 million tons with it. The possible increased use of wood in the production of liquid biofuels is expected to increase competition over biomass and thereby wood prices.

In sum, the use of wood for bioenergy is strong on the policy agenda, and it is of high interest to analyze the consequences of increased demand for wood-based energy and how various potential policy means may affect forest resources and wood products markets in Europe as well as in other regions affected by EU's policies. Several studies have already addressed this topic, and in the following section a brief overview of such studies is presented together with a few studies related to the topic.

1.3 Previous studies

During the last years, the global forest sector has been facing transitional changes that were reshaping many of its structures. Changes regarding climate change mitigation, energy policies, advancements in nanofiber and biochemistry technologies, the increasing role of services and values towards the use of forests have converted the forest sector into a more complex, interlinked and cross-sectoral entity (Hetemäki et al. 2010, Clark et al. 2012). As a result, scientists and policy makers are searching for new methods that may help them to better understand and navigate in the more complex forest sector environment, influenced by price regulations, subsidies and other political regulations. Higher attention towards forest products and services have made decision makers more conscious about possible impacts of increased pressure on forest resources, and their consequences on forest products markets.

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[3] In 2017, there were 224 biorefineries operating across Europe, in addition to several under construction (Nova-Institut 2017). However, 181 of these commercial biorefineries were classified as first-generation facilities.

[4] Biofuels produced from plant cellulose as well as animal and plant waste.

The utilization of forest sector models, which take into account both forestry and forest industries and the interaction between these two activities (Solberg 1986), has been found useful in providing consistent economic analyses during the last decades. Latta et al. (2013) give an overview of this kind of models and emphasize that including the main interactions between forestry and forest industries may provide more consistent analyses than those focusing solely on one subsector. Thus, FSMs are apt for analyzing the interplay between forest resources and wood-based products markets, as well as competition and synergies between different uses of woody biomass (see, e.g. Solberg 1986, Buongiorno 1996, Latta et al. 2013b, Jonsson and Rinaldi 2017).

Various FSMs have been applied for analyses related to environmental issues (e.g. Adams and Latta, 2005; Bolkesjø et al., 2005; Buongiorno and Gilless, 2003; Hänninen and Kallio, 2007; Kallio et al., 2006), some focused on bioenergy and products markets utilization (e.g. McCarl et al. 2000, EEA 2006, Kallio et al. 2011, Moiseyev et al. 2011, Lauri et al. 2012b, Trømborg et al. 2013, Latta et al. 2013a, Nepal et al. 2014, Galik et al. 2015, Jonsson and Rinaldi 2017, Mustapha et al. 2017), or climate change (e.g. Alig et al., 2010; Daigneault et al., 2012; Delacote and Lecocq, 2011; Lauri et al., 2012; F. Lecocq et al., 2011; Sjølie et al., 2011c; Solberg et al., 2003).

Several studies have also discussed the impacts of increased use of woody biomass for energy and its impacts on the forest sector for the whole EU and regions affected by EU's and national policies. For Norway, Trømborg et al. (2013) analyzed how second-generation biofuel based on wood may affect the competitiveness of more mature bioenergy technologies, such as bioheat, through competition for biomass. Regional variations in effects on biomass prices were found depending on local raw material availability and costs of transport and import. Sjølie et al. (2010) considered policies for promoting the use of wood fuel in heating and found that around 70% of the emissions from heating could be avoided in Norway if very high taxes on fossil fuels were introduced. Trømborg and Solberg (2010) analyzed the impacts of increased energy prices on the traditional forest sector in Norway. Their results show that an increase in the energy price of about 40% reduced production of particleboard by 12%, pulp (mainly sulfate) by 4%, while the production of fiberboard was unaffected.

The approach employed by Trømborg et al. (2013), Sjølie et al. (2010) and Trømborg and Solberg (2010) modelled the forest sector using a dynamic recursive method, where supply was based on econometric relations between harvest and regional roundwood prices and forest growing stock. Latta et al. (2013b) observed that timber supply response based on theoretical assumptions such as perfect information may lead to overestimation of the potential reactions to policies and market changes, while dynamic recursive models might be better suited for short-term predictions due to their limited variation from historical data. Thus, *papers I* and *IV*, included in this dissertation, consider forest inventory data together with different forest management options and analyse, among others, the economic optimal mix of species and feedstock categories for biofuel production, or the impacts of introducing a carbon tax/subsidy price system on all CO_2 emissions/sequestrations in the European forest sector.

Furthermore, many studies have investigated the impact of international or national bioenergy and carbon policies on the forest sector in Europe (e.g. Kallio et al. 2011, Moiseyev et al. 2011, Lauri et al. 2012, Trømborg et al. 2013) or United States (e.g. McCarl et al. 2000, Nepal et al. 2014, Galik et al. 2015). To the best of my knowledge, only a few studies (e.g., Kallio et al. 2015a, Jonsson and Rinaldi 2017, Kallio and Solberg 2018) have investigated the impact of increased biomass consumption within EU on regions outside EU. Lauri et al. (2017) looked at the impacts of increased demand for wood energy (biofuels + heat and power) on the forest sector and concluded that the global forest industry production is rather insensitive to increased wood demand in the energy sector even if bioenergy was to be produced in a scale required for the 2°C climate goal. The same findings are reported in Kallio et al. (2015) and Kallio and Solberg (2018a). Studies focusing on Norway (Trømborg et al. 2013), Finland (Kallio et al. 2011) and Europe (Moiseyev et al. 2014, Kallio et al. 2015, 2018) demonstrated that large-scale investments on second-generation wood-based biofuels would increase biomass prices and reduce bioheat generation.

1.4 Objectives

As shown in the previous section, many studies have been done regarding the impacts of wood-based bioenergy. However, many issues remain for further analysis. The main objective of this thesis is to investigate the impacts of increased use of wood-based bioenergy on forest resources and markets in Europe and US South and explore strengths and weaknesses of FSMs.

More specifically, the thesis addresses the following research questions:

- Q1: What are the main impacts on forest products markets in Norway of establishing a new medium-size, wood-based second-generation biofuel plant there?

- Q2: How much does a certain EU's renewable energy policy affect some key market variables and carbon storage in Southeastern U.S.?
- Q3: How strongly will various regulations and subsidies in EU influence the competition for woody biomass between biofuels and heat and power productions, and what are likely impacts on the traditional forest-based industries there?
- Q4: Is it possible (i) to develop an intertemporal forest sector model for Europe where the timber supply is based on detailed forest stand simulations of alternative forest managements and combine this endogenously with wood demand coming from forest industry productions, consumption of wood products, and trade; and (ii) apply this model for estimating forest sector carbon climate abatement cost curves for Europe?
- Q5: How are uncertainty and risk included in analyses made in the forestry, agriculture, fishery, and energy sectors, and can we identify promising methods for including risk in forest sector analyses?

These questions correspond respectively to the five scientific papers attached in appendices I-V. Compared to the existing literature these papers contribute in my opinion with new research knowledge or insights in several ways: *paper I*, addressing Q1, is the first study in Norway where an intertemporal forest sector model is used for estimating impacts of establishing a biofuel plant, thus making it possible to analyze to what degree choice of tree species and forest management may influence the results. *Paper II*, addressing Q2, is the first published research article which documents how EU's wood energy policies may impact the US forest sector. *Paper III*, where Q3 is addressed, is one of the first research papers to examine quantitatively how alternative combinations of biofuel and biomass prices would affect the production potential of liquid biofuels made of wood and allocation of wood biomass between biofuels, and heat and power production in the European Economic Area. The study also analyses the possible impacts of increased biofuel production on the forest sector. *Paper IV*, addressing Q4, documents the first intertemporal forest sector model for Europe, and provides the first estimate of carbon abatement costs published for the whole forest sector of Europe. *Paper V*, addressing Q5, is to my knowledge the first study reviewing risk methods applied in the agriculture, forestry, energy and fishery sectors and in full-equilibrium economic models, and based on the review, providing recommendations on types of risk methods that realistically can be included in FSMs.

Each of the research questions Q1-Q5 is addressed separately in the respective papers, but all papers deal with wood-based bioenergy and forest sector modelling, also *paper V* because the risk is fundamental in all kind of modelling. Seen together, the individual papers thus form a whole where various types of FSMs are applied for analyzing the impacts of increased use of wood-based bioenergy.

The remaining part of the thesis is structured in the following way: In chapter 2, methods and data are described more in detail. In chapter 3, the main results of each of the five papers are presented. In chapter 4, the results are discussed with a perspective view. In chapter 5, main conclusions are drawn, and finally, the five thesis papers are presented in appendices I-V.

2. METHODS

2.1. Modelling approaches and theoretical basis

In this chapter, I describe the various forest sector models used in the thesis. As EUFORIA is a new model, it is described more in detail than the other models.

During the last decades, the development and utilization of partial equilibrium forest sector models have increased. The use of FSMs started after the published work of Samuelson (1952) who introduced the theory of net social payoff represented as the basis for the interregional trade in spatial equilibrium models. According to this theory, it is possible to find the market clearing conditions by maximizing the sum of consumers' and producers' surplus minus transportation costs, thus providing quantities of demand, supply, and prices endogenously. The solution assumes competitive markets, i.e., that economic agents behave rationally, maximizing profit and utility as price-takers given the information they have about present prices and own production costs.

According to Latta et al. (2013), all FSMs in use today have their origins in four models that gave the beginning of forest sector modelling studies. These models were developed in the 1980s and include:

- TAMM – the Timber Assessment Market Model (Adams and Haynes 1980), covering North American solid wood products markets;
- PAPYRUS (Gilless and Buongiorno 1987), covering the North American pulp and paper markets;
- IIASA GTM the International Institute for Applied Systems Analysis Global Trade Model (Kallio et al. 1987), covering global forest products and trade;
- TSM – the Timber Supply Model (Lyon and Sedjo 1983)

These four models differ in their assumptions and optimization techniques. The first three models are classified as dynamic recursive meaning that they solve for the market equilibrium one-time period at a time, i.e., they take the model results in period t as model input in time period $t+1$ and then solve for this period. In that respect, it is assumed that market players considered in the model do not foresee the future. In contrast, TSM belongs to the category of intertemporal optimization models, meaning that it assumes that the agents possess full information about all future conditions, anticipate all market changes perfectly, and consequently solve the market outcome for all time periods simultaneously. This division on dynamic recursive optimization and intertemporal optimization models is kept up to the present day, and consequently new models on the market are often classified according to these two optimization types. Furthermore, all these models represent partial-equilibrium approach (contrary to general-equilibrium), which implies that other sectors of the economy than those related to the supply and demand of wood and forest-based products are considered indirectly, mainly through their connection to income measured as gross domestic product (GDP) using econometrically determined income elasticities based on GDP for each region and product, and exogenous assumptions on costs of labour, energy and other production inputs than timber.

In this thesis, intertemporal optimization models (NorFor, EUFORIA) and dynamic recursive optimization models (EFI-GTM, SRTS) have been used. Therefore, a motivation for using each model, together with their description and underlying assumptions, differences and similarities of modelling frameworks follows.

2.2. Description of the forest sector models

2.2.1 Intertemporal optimization models

The whole forest sector welfare or the net social payoff (NSP) is defined by the sum of all consumer surpluses and producer surpluses minus the total transportation costs of delivering products among regions. The NSP in a competitive market is presented in figure 1 below.

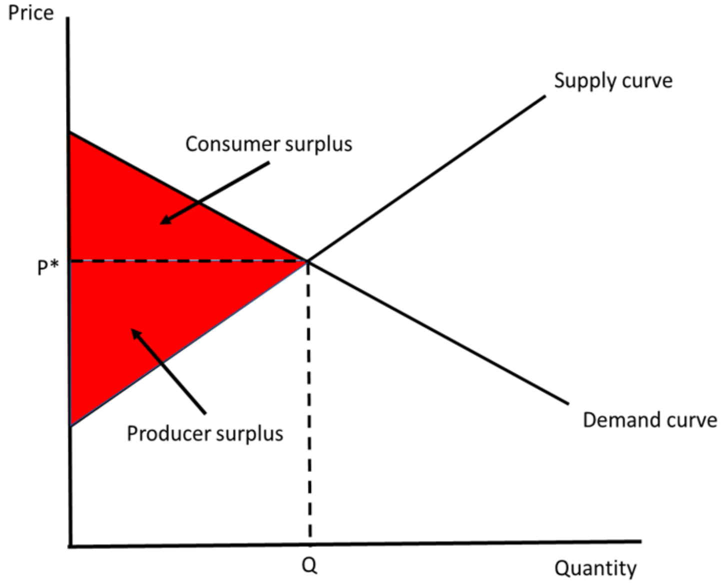

Figure 1. The forest sector welfare.

Technically, the NSP in EUFORIA and NorFor is formulated using the Samuelson partial equilibrium formulation (Samuelson 1952). One commodity simplified version is presented below. The optimal solution of demand (D*), supply (S*) and transported quantities ($Q_{i,j,t}$) has to satisfy the following equations:

$$\text{Maximize } NSP = \sum_t \left[\frac{\sum_i \left(\int_0^{D^*_{i,t}} P^d_{i,t}(q_{i,t}) dq_{i,t} \right) - \sum_j \left(\int_0^{S^*_{j,t}} P^s_{j,t}(q_{j,t}) dq_{j,t} \right) - \sum_i (Q_{i,j,t} * T_{i,j,t})}{(1+r)^{e_t}} \right] \tag{1}$$

subject to:

$$D^*_{i,t} \leq \sum_j \; Q_{i,j,t} \quad \forall i, t \tag{2}$$

$$S^*_{j,t} \geq \sum_i \; Q_{i,j,t} \quad \forall j, t \tag{3}$$

$$D^*_{i,t}, S^*_{j,t}, Q_{i,j,t} \geq 0 \tag{4}$$

where:

i - consuming region market,

j - producing region market,

r – discount rate,

t – time periods,

e_t – elapsed time from the first time period to time period *t*,

$D^*_{i,t}$ - quantity demanded in the market equilibrium in regional market *i* in time period *t,*

$S^*_{j,t}$ - quantity supplied in the market equilibrium in regional market *j* in time period *t,*

$Q_{i,j,t}$ - the amount of the commodity delivered from regional market *i* to regional market *j* in time period *t,*

$T_{j,i,t}$ - transportation cost from regional market *j* to regional market *i* in time period *t,*

$P^d_{i,t}(q_{i,t})$ - price dependent demand function for consumption in regional market *i* in time period *t*

$P^S_{j,t}(q_{j,t})$ - price dependent supply function for production of regional market *j* in time period *t*

Equation number 1 is the objective function of the model which maximizes the discounted sum of NSP less transportation costs across all time periods *t*. Equations 2 and 3 represent demand satisfaction at the *i-th* consumption market and supply limit at the *j-th* production market respectively for each time period *t*. The final requirement, equation 4, enforces non-negativity across markets and trade. In addition to Samuelson's theory about net social payoff maximization and its relationship to interregional trade and a spatial market equilibrium, a second important consideration in our simple example above is the effect of intertemporal dynamics. The balance of production, consumption, trade, and NSP is weighted across time through the denominator of the objective function (equation 1). At its simplest, these temporal dynamics are independent as in our example, while once supply or demand is affected by the previous or next time periods supply or demand a more complex formulation of the market model is required. A resulting model, such as NorFor and EUFORIA, would see the forest supply functions removed and replaced with a set of constraints governing forest growth dynamics introduced more akin to that of the theory for economically optimal harvest age (Faustmann 1849). These theories of Samuelson and Faustmann are pillars for the EUFORIA model, and consequently for NorFor model and other intertemporal optimization group of FSMs. Endogenous variables in the EUFORIA include forest management and harvest, processing of wood into sawnwood, pulp, paper, boards and bioenergy, and their consumption, and trade throughout the sector. Detailed data for all these segments are put together in the model, including country-level data for pulp, paper and board producers, county-level data for production and consumption and management and yields for National Forest Inventory (henceforth, NFI) plots in Norway or selected European countries.

NorFor

To address the potential consequences for the Norwegian forest sector of establishing a wood-based biofuel plant in Norway focusing on harvest, tree species use, net import/export, and forest industry production, NorFor (Sjølie et al. 2011a) was used in *paper I*. This model made it possible to simulate agent behavior in the sector with regard to investments in forestry, supply of timber and harvest residues for different tree species, forest industrial production, consumption of products and trade between Norwegian regions and foreign regions.

NorFor is an intertemporal partial, spatial equilibrium model, based on the assumption of perfect foresight and perfect competition. The intertemporal dynamics ensures that the model maximizes welfare for all periods simultaneously, rather than calculating separate optimal solutions recursively from year to year (see, e.g., Latta et al., 2013). NorFor maximizes the net-present discounted value over the time horizon, given the assumption that agents possess full information about the future conditions, i.e., anticipate all market changes perfectly and allocate forestland, wood resources, and industry capital accordingly. The model is partial as it is built on the assumption that the forest sector is small relative to other sectors in the economy so that changes in this sector do not significantly impact unit costs of labor, energy and other production inputs than wood products.

The spatial approach in NorFor is reflected in the 19 domestic and two foreign regions, transportation costs, and the fact that trade between regions is not fixed but determined endogenously. Finally, yet importantly, equilibrium means that the NorFor model has a set of equations which secure that supply equals demand for each product in each region and in each time period.

The NorFor model is divided into four parts such as forest management, industry, consumption, and products trade. The structure and data input of the forest industry portion of the model is derived largely from the NTMII (Bolkesjø 2004), with updated capacity data. The forestry part providing the timber supply depends on the management of forest; a set of options for all land is simulated with the stand simulator Gaya[5] (Hoen and Eid 1990) for each of the about 9000 sample plots in the Norwegian Forest Inventory. The data programming for incorporating forest yields into the harvesting schedules and their linking to the market module were to a large extent obtained from the regional models of Oregon (Adams and Latta 2005, 2007).

Endogenous variables in the NorFor model include many forest management alternatives for each NFI plots and endogenously decided harvest ages (including never harvest option), processing of wood into sawnwood, pulp, paper, boards and bioenergy and their consumption, trade, and greenhouse gas fluxes throughout the sector. Detailed data for all these product groups are put together in the model, including mill level data for pulp, paper and board producers, county-level data for production and consumption, and management and yields from the NFI plots. More details about NorFor and its data requirements (e.g. forest industry consumption) can be found in Sjølie et al. (2011), Trømborg and Sjølie (2011) or *paper I.*

EUFORIA

The **E**uropean **FOR**est and **I**ndustry **A**ssessment model (henceforth, EUFORIA) is a multi-regional and multi-periodic forest sector model that integrates forestry, forest industries, wood product demand and international trade of forest products. The model includes 32 European countries and 1 foreign region, 6 wood categories and 26 forest industry products. The model is developed in the General Algebraic Modeling System (McCarl et al. 2008).

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[5] Nevertheless, forestry data may be also supplied by another simulator (see, e.g., Latta 2013)

The three main subsectors of the model are (i) forest growth and management, (ii) industry and consumption, and (iii) transport and trade.

The forest stand model FORMIT-M (FORMIT 2014, Härkönen et al. 2018) is used as forestry sub-model, as it makes possible to include several forest management alternatives endogenously in EUFORIA and provides the future forest development for all main species present in NFI data in selected European countries (FORMIT 2014). Thus, the wood supply component in EUFORIA is based on forest inventory and forest management data, not econometric estimation of pre-determined wood supply elasticities. This approach distinguishes EUFORIA from other European forest sector models, such as EFI-GTM, EUFASOM or GFTM (Jonsson et al. 2015). The period length in EUFORIA is five years, and the optimization horizon may be adjusted by the user, depending on the objective of the study. FORMIT-M is described in detail in Härkönen et al. (2018), and here follows just a brief description of it. The growth model in FORMIT-M is defined in terms of stand mean-tree variables and stand density, which together define stand-level variables such as stem volume and component biomass. The state variables of the model comprise mean height (H), mean breast height diameter (D), stand density (N) and depending on the region, mean height to the crown base (H_c). Empirical functions are applied on these to derive auxiliary variables, including mean tree volume (V_{TREE}) and form factor (f_{FORM}), component biomasses (W_{x}) and litterfall (L_{x}), and leaf area index (LAI). The dynamics of the state variables in the growth model are derived from estimated Gross Primary Production (GPP) and its allocation to Net Primary Production (NPP) and further to stem growth. GPP is calculated using a semi-empirical, Light-Use Efficiency (LUE) based canopy level model (Mäkelä et al. 2008, Peltoniemi et al. 2015, Minunno et al. 2016) which uses daily weather data and LAI as inputs. An empirical model was derived using this GPP and NFI-based NPP for estimating the NPP:GPP ratio for different species and regions. Similarly, an empirical function was derived for species and regions for the ratio of stem growth to NPP. Stand level stemwood volume growth is obtained from the volume increment based on GPP and its allocation. This is divided by stand density to estimate mean tree growth, and empirically derived allometric functions are used to compute new values of H, D and H_c from new volume and stand density. The latter is updated on the basis of harvests and mortality, where mortality is assumed to occur if stand density exceeds the maximum density modelled using Reineke stand density index (Reineke 1933). Soil carbon dynamics are in FORMIT-M estimated using the Yasso07 model (Tuomi et al. 2009, 2011). Yasso07 takes tree litter fall and stand mean temperature and rainfall as inputs to estimate the development of soil carbon stocks. The initial soil carbon stock is estimated assuming the system is at steady state with respect to current litter input. FORMIT-M is a regional forest growth simulator responsive to management actions and climate change. The model combines a process-based carbon balance approach to forest productivity with a strong empirical component based on NFI data. The simulator uses basic stand level forest variables and aggregated meteorological variables as input data and produces estimates of carbon storage and fluxes at the forest site above and below ground, as well as wood production of roundwood in forest product assortments and forest biomass, under chosen climate scenarios. The model was parameterized using NFI data from 10 European countries and was extended to the rest of Europe based on remotely sensed data. The parameterization was done for 7 ecologically based species groups. Forest management schemes were defined for these groups in 6 different silvicultural systems in terms of harvest timing and intensity. A Business as Usual (BAU) scenario of forest management was defined as management that is currently considered as the typical forest management in the region and which retains the current proportions of the silvicultural systems by species. Alternative management scenarios were simulated as deviations from BAU, for 3 different silviculture options and endogenously determined clearfelling ages distributed on 5-year periods. More detailed information about the FORMIT-M simulation model can be found in Härkönen et al. (2018).

The product flow in the industry module in EUFORIA is presented in Figure 2.

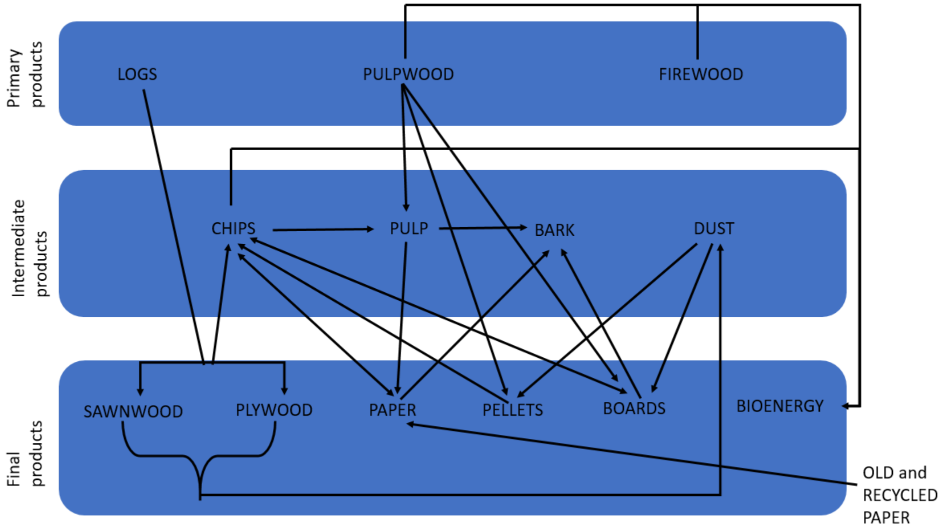

Figure 2. The product flow in the industry module in EUFORIA.

Regarding second and third subsectors, forest industry and transport data in EUFORIA are predominantly based on data from the EFI-GTM (Kallio et al. 2004a).

More details about EUFORIA, its structure, data requirements, and mathematical specification can be found in *paper IV*, where this model has been used.

2.2.2 Dynamic recursive optimization models

SRTS

To assess the impact of EU's energy consumption on wood pellet imports between 2008 and 2038, and determine the influence of U.S. and EU's bioenergy feedstock consumption on key market variables and carbon storage in the Southeastern U.S., the sub-regional timber supply model (SRTS) model was used. This model can project future timber inventories, estimate regional shifts, and compute price impacts at a sub-state level. The model can examine how different initial timber inventories, harvest patterns, and market characteristics affect future timber conditions and prices.

SRTS is a partial equilibrium market simulation model that can be used to analyze various forest resource and timber supply situations. Initially, the SRTS was developed to provide an economic overlay to timber supply models (Abt 1989). The model is a recursive dynamic model, meaning that changes in forest markets and conditions of the subsequent period are used to update the starting conditions of the subsequent period through the end of the projection period. Forest product and bioenergy feedstock supply is modelled as a function of stumpage price and inventory. Furthermore, price and harvest levels are simultaneously determined by the model's market equilibrium calculation for each product (hardwood vs. softwood, pulpwood vs. sawtimber), owner class (corporate vs. non-corporate), and subregion. In addition, changes in forest conditions are estimated by modelling the growth of forests using empirically based regional Forest Service data, harvest from the market equilibrium module and endogenous land-use change based upon commodity price differentials in underlying land uses. The framework for projecting forest inventory is summarized in Abt et al. (2000).

The objective function in SRTS differs from EFI-GTM in that the model's goal is to harvest across management types and age classes for each region-owner to achieve the projected target removals mix while harvesting consistent with historical harvest patterns for this region-owner. The ‘‘consistent with historical’’ requirement is defined as bounds around existing removal-to-inventory intensities. If the new product mix cannot be met with this constraint, the removal-to-inventory bounds are relaxed (Abt et al. 2009).

The model has been used in many studies. For instance, Pattanayak et al. (2002) used the SRTS model to explore the influence of non-market values on timber market decisions by non-industrial private forest landowners. Prestemon and Abt (2002) applied the SRTS model to project timber supply in the Southern Forest Resource Assessment. Schaberg et al. (2005) used SRTS to analyze the impacts of wood chip mills on timber supply in North Carolina. The latest extensions of SRTS model allow detailed analysis and user-defined product categories on a smaller area, such as a survey unit, and include the impact of land use change. For example, SRTS was used for evaluation of bioenergy policy (Galik et al. 2015, 2016, Costanza et al. 2017) or trade consequences of the wood pellet from the Southeast U.S. to EU (Chudy et al. 2013, Duden et al. 2017). A more detailed description of the updated SRTS can be found in Prestemon and Abt (2002b) or Abt et al. (2009).

EFI-GTM

To examine how alternative combinations of biofuel and biomass prices affect the production potential of liquid biofuels made of wood and allocation of wood biomass between biofuels and heat and power production in the European Economic Area, the EFI-GTM model has been used in *paper III*, as this model integrates forestry, forest industries, final demand for forest industry products and international trade in wood biomass and forest industry products. It includes 57 regions covering the whole world, but the regional disaggregation is most detailed in Europe as nearly all European countries are modelled as individual regions. The products modelled include 6 wood categories, 26 forest industry products, and 4 recycled paper grades and 3 technological options for the forest industries in Europe.

The EFI-GTM is a multi-regional and multi-period partial equilibrium model of the global forest sector. EFI-GTM calculates periodical production, consumption, import and export quantities and product prices for the forest sector products as well as periodical capacity investments of the forest industry for each region. The model finds the competitive market equilibrium prices and market equilibrium quantities of production, consumption, and trade for all products and regions included. The competitive market equilibrium is solved by maximizing the sum of consumers' and producers' surpluses of all regions and products (see Figure 1) minus the trading costs subject to market clearance. The model is solved in a recursive-dynamic fashion by one period at a time, updating the relevant data for the next period in each step.

In addition to *paper III*, EFI-GTM has been used in many studies related to the analyses in this thesis, among others, illegal logging policies (Moiseyev et al. 2010), export tariffs (Solberg et al. 2010), conservation policies (Kallio et al. 2006), renewable energy (Moiseyev et al. 2011), biofuels (Kallio et al. 2018), economic impacts of forest growth (Solberg et al. 2003) or wood use in the European construction sector (Eriksson et al. 2012). For more details about EFI-GTM, see Kallio et al. (2004) or *paper III*, where model structure and formulation are presented.

2.3 Intertemporal vs. dynamic recursive models – comparison

Usually, both intertemporal and dynamic recursive models are spatial, partial equilibrium models. Both have endogenous prices of timber and wood products but differ particularly with respect to the timber supply, applied time horizon, and assumptions related to the foresight of agents.

Intertemporal optimization models are usually characterized by having a larger set of forestry and forest management data. The degree of forestry detail in such models is made possible by simulating management-dependent growth on a diverse variety of sites, for example in NorFor on about 9000 plots of the Norwegian forest inventory. Thus, these models may simulate not only timber supply but also forest management. In contrast, dynamic recursive models are characterized with timber supply being decided by pre-determined supply elasticities and exogenous forest growth rates. In other words, annual timber growth is based on parameterization determined outside the FSM framework based on past and assumed future forest management, and timber supply curve shifts periodically, given these exogenous factors and the subsequent periods' harvest. Regarding the elasticity of supply, it is usually based on econometric studies and may vary between regions.

Intertemporal optimization models are applied up to 100 years and more in the future as they assume that agents have perfect foresight, while dynamic recursive models are myopic, employing static optimization, and assuming that agents do not possess any information about the future beyond the current period. Dynamic recursive models are generally applied for short-term projections (15-30 years).

Latta et al. (2013) noticed that timber supply response based on theoretical assumptions such as perfect information may lead to overestimation of the potential reactions to policies and market changes, while dynamic recursive models seem to be better suited for short-term predictions due to their limited variation from historical data. The dynamic recursive models lack the ability to endogenously adapt to expected future changes in forest management but provide realistic short-term projections as long as these are inside historical ranges. As such, one may argue that the intertemporal optimization models are better to use in long-term projection studies, regarding, e.g., potential climate changes and their long-term effects on the forest sector. The choice of discount rate in such models is very crucial as it weights all future time periods. The intertemporal optimization models usually produce short-term results that may not conform to recent market developments, but instead can give insights on the adjustments to expected future conditions. The differences between both models' types are described in detail in Sjølie et al. (2015) or *paper IV.* Sjølie et al. (2015) compared approaches of two Norwegian forest sector models (NorFor and NTMIII) and provided an overview of the data used in them, respectively. In *paper IV*, the main differences between EUFORIA and EFI-GTM, like the foresight assumptions and level of details regarding timber supply, are discussed.

3. RESULTS

3.1 Summary of Paper I: Effects on forest products markets of second-generation biofuel production based on biomass from boreal forests: a case study from Norway

3.1.1 Objective

The primary goal of *paper I* was to analyze the impact of wood-based second-generation biofuel on forest products markets based on a Norwegian case study, including the impact of trade on the wood industry market situation. This paper focuses on harvest, timber net import/export, and forest industry production. The secondary goal was to compare results to Trømborg et al. (2013) and determine the differences between two-different forest sector model approaches.

3.1.2 Method and main assumptions

To achieve this target, NorFor was applied across a range of scenarios limiting feedstock mixes used in biofuel production, to determine the impacts of the various feedstock mixes on domestic and foreign markets. In addition, it was quantified how much the traditional forest industries would benefit or lose from the new biorefinery production. To reflect possible biofuel technological options, it was assumed that the following feedstocks can be used, separately or in combinations: coniferous and hardwood roundwood, sawmill residues, and harvest residues. In the analysis, two main scenarios were modelled. The first was the business as usual (BAU) scenario, with no biofuel plants in Norway. The second scenario was called AF (Any Feedstock), and it assumed that one second-generation biofuel plant (SGBP) was installed and that it could use any combinations of the wood feedstocks mentioned above. In addition, three other scenarios with different fixed feedstock combinations were modeled, and results presented as sensitivity analyses against the AF scenario. The assumptions concerning the biofuel production were based on actual current plans to develop a second-generation biofuel in Norway, at Tofte, in Buskerud county by the end of 2020. The location was chosen as this was a site occupied by a previous pulp mill, and thus has an established infrastructure for wood supply logistics including deep-water quay to handle large quantities of timber (Dahle and Asbjørns 2015). It was assumed that the plant will begin biofuel production in 2025 and produce 150 000 tons of biofuel per year requiring one million cubic meters of woody biomass feedstock as an input. The NorFor model was solved for the 2010-2090 time period and results were generated for each 5-year period. The analysis was focused on the period between 2015 and 2055 representing the medium-term time horizon and thus avoiding any terminal condition influences that might affect later time period results.

3.1.3 Main results

Results showed that feedstock choice had a profound effect on the industrial impacts. We found the optimal biofuel feedstock mix to be dominated by softwood chips from pulpwood which comprise 48% of total inputs in 2030 and increase in use up to 67% by 2055. The second largest component used for second-generation fuel production was hardwood chips from birch at 34% initially then substituted over time by softwood chips. The proportion of harvest residues was constant in the feedstock mix (18%) and roundwood was not used at all for biofuel production. Despite the additional demand for chips, a single medium-scale biofuel plant was found to have only minor effects on existing forest industries and harvests in Norway. The domestic impact was dampened by changes in foreign trade flows, especially of chips. Forest sector models were found useful for this type of scoping analysis for new production processes as they include the main products flows, retain consistency across the sector, and are able to capture main complex mechanisms like inter alia choice of forest species, competition for wood fiber between various users, and vital production connections between sawmilling, mechanical pulp industry, forest owner behavior, and trade. Without exploring these potential interactions with existing markets, bioenergy policies may be less likely to succeed.

3.2 Summary of Paper II: Modelling the impacts of EU's bioenergy demand on the forest sector of the Southeast U.S.

3.2.1 Objective

The objective of *paper II* was to assess the impact of EU's renewable energy policy on the forest sector outside EU, particularly on key market variables and carbon storage in the Southeastern U.S.

3.2.2 Method and main assumptions

In *paper II*, the effects of EU's biomass imports from the Southeast U.S. on Southeast U.S. timber prices, inventories and production were analyzed. Each of the constructed demand scenarios consisted of three components. The first component was the demand for roundwood used in the traditional wood-using industries in the SE U.S., which assumed" V-shaped" recession with a sharp downward trend, a nadir at the depths of the housing market slump and then an equal and opposite upward trend that returns demand to pre-recession levels by the year 2014. Domestic (U.S.) bioenergy demand made up the second component, and included a high, a medium and a low domestic bioenergy demand scenario, projecting the demand for woody biomass into the coming decades. The focus of the study was on the third component, i.e., EU-27 wood pellet imports from the SE US. Based on literature review, analysis of public databases and calculations with respect to percentage of U.S. pellets among all pellets imported by EU-27 countries, and moisture content, it was determined how much of total EU's pellets imports were sourced in the U.S. SRTS was used to simulate market responses to changes in woody biomass consumption in the U.S. and EU between 2008 and 2038. The various biomass harvesting and residual factors and the U.S. and EU's renewable energy policy inputs to estimate the impacts of EU's biomass demand on multiple variables, such as SE U.S. timber inventory, supply and prices, carbon storage, and the number of forest plantations in the region, were analyzed.

3.2.3 Main results

Results indicated that the price of imported wood pellets in EU is sensitive to future U.S. renewable energy policies, the developments of which were uncertain at that moment of research. The analysis showed that with the assumed bioenergy demands, prices increased for U.S. softwood roundwood from 25% to 125% by 2038 depending largely on U.S. domestic policy. Under all scenarios and for both the SE U.S. as a whole and for the part of the SE U.S. with the most active wood pellet market - the coastal plain, carbon storage increases because of a positive planting response among private forest owners to higher timber prices and due to a conversion of marginal agriculture land to forest. High wood demand caused a price signal for private forest owners to plant trees. Moreover, newly established plantations compensated carbon loss from the exception for hardwood residues in the low scenario.

It was concluded that at low EU's pellet import demand levels, the impacts of woody biomass from forests did not have extreme effects on timber markets, and might have even encouraged carbon storage and planting of more forests. But if EU's pellet import demand were coupled with an aggressive U.S renewable energy policy, timber prices would increase substantially, which was not likely to be sustainable economically. Furthermore, it was concluded that the existing forest products industry sector might be adversely affected by much higher wood prices, and in consequence may oppose any renewable energy policies which induced these prices by predominantly increasing the demand on forest biomass. Because both U.S. and EU's policies regarding renewable energy are in states of flux, it was also concluded that future research should incorporate the latest policy developments.

3.3 Summary of Paper III: Prospects for producing liquid wood-based biofuels and impacts in the wood using sectors in Europe

3.3.1 Objective

Paper III analyses the competition between biofuels, and heat and power for woody biomass as well as the impact of increased production of wood-based biofuels, made from logging residues, wood chips and roundwood on traditional forest-based industries in the European Economic Area using EFI-GTM model.

3.3.2 Method and main assumptions

The analysis was done under two scenario settings A and B, reflecting the two main objectives of the study. In setting A, the impacts of varying global demand for wood bioenergy were compared. The scenario called "Bioinno"[6] was used as the reference point, but later it was modified with respect to deviations regarding the demand for energy biomass. In total, in setting A, three scenarios were analyzed. In the first modification, it was assumed that there was no increase in wood-based energy production after 2010, while in the other alternative, the increase in wood-based heat and power productions was allowed as in "Bioinno", but no increase in wood-based traffic fuel productions after 2010. In setting B, the economic potentials for increasing the production of wood-based liquid biofuels were explored under alternative bioenergy pricing schemes. For the forest industry, the background assumptions on the market demand developments were as in the "Bioinno" scenario above. The energy sector market assumptions were varied concerning (i) the producer price paid for liquid biofuels; and (ii) the maximum price that heat and power producers could pay for wood biomass to compete for that. These assumptions reflected the uncertain operating environment in the background, where the cost competitiveness of wood versus other fuels in alternative uses was subject to many aspects such as the subsidies and taxes for different fuels, the prices of alternative fuels that could be used, and the costs of using them. All above assumptions were used by the EFI-GTM (Kallio et al. 2004) - a global model for the markets and trade of forest biomass and products.

3.3.3 Main results

Results indicated that policy choices might have had strong impacts on the allocation of biomass use between heat and power production, and the production of liquid biofuels. Secondly, even assuming the strong goal of reducing the climatic warming to 2°C, the

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[6] The "Bioinno" scenario is described in more details in (Kallio et al. 2015), and assumes that long run global climate warming will be constrained to 20C and that biofuels will play an important role in achieving this goal.

projections suggested that the European forest industry production will not be affected much by the increased competition for biomass with the energy sector. This is because the rivaling regions would be facing similar biomass demand challenges and the relatively abundant wood biomass resources in Europe would help the forest industry in EEA to maintain its market shares. Regarding the first result, it was concluded that the policy makers must have very clear goal settings for the preferred ways to solve the shift from the present fossil fuel-based energy system to a less carbon-intensive one. With respect to the second finding, it was emphasized that because large investments in biofuel production take time to plan and construct, and because the annual forest growth exceeds the harvests of wood in various parts of Europe, there is time to adjust the policies to control the market development.

3.4 Summary of Paper IV: Analyzing the impact of carbon pricing on forest management and marginal abatement cost curves in Europe using the new forest sector model EUFORIA

3.4.1 Objective

Up to now, there was a lack of a model for Europe which could combine the information about the wood supply, determined based on harvest schedules of alternative management options utilizing existing NFI data, with data regarding wood demand coming from forest industrial production, consumption of products and trade. The objectives of *paper IV* were to: (i) develop an intertemporal forest sector model for Europe where the timber supply is based on detailed forest stand simulations of alternative forest managements and combine this endogenously with wood demand coming from forest industrial production, consumption of products and trade; (ii) apply this model for estimating forest carbon abatement curves and forest management for Europe at different carbon prices.

3.4.2 Method and main assumptions

EUFORIA has been developed to provide consistent analysis of the impact of external factors such as economic growth, carbon pricing, forest biodiversity protection, bioenergy development, trade regulations, exchanges rates, transport costs, consumer preferences and forest management strategies, on production, consumption, imports and exports of roundwood and forest industry products including wood-based bioenergy. The model assumes perfect foresight, perfect competition, and intertemporal optimization. Endogenous variables in the EUFORIA include forest management for NFI plots in selected European countries (regeneration intensities, thinning timing and intensities, harvest ages and quantities), production, consumption and price of sawnwood, pulp, paper, boards and bioenergy, and bilateral trade quantities for all products included in the model. Main exogenous data are alternative forest stand yields, initial forest growing stock, economic growth for each country, unit input requirements and corresponding production costs for each wood assortments and industrial products, and demand elasticities for each final product based on price and income. The model includes 32 European countries as separate regions and the rest of the world (ROW) region, which considers the trade between European and other countries. However, in the current version of EUFORIA, the actual wood industry production in ROW is not included, and trade between European countries and ROW is exogenously determined and equals the trade between these regions found in the base scenario by applying the EFI-GTM model. The timber supply component in EUFORIA was obtained by applying the forest management and growth simulation model FORMIT-M (FORMIT 2014, Härkönen et al. 2018) to provide future forest development alternatives for all main species present in NFI data in selected European countries. The period length in EUFORIA is five years. With respect to carbon price assumptions and scenarios, there were analyzed nine different carbon price scenarios: 1, 5, 10, 15, 20, 25, 50, 100 €/ton CO_2, which assumed the payment for carbon sequestration that was additional to the base scenario (0 €/ton CO_2).

3.4.3 Main results

Results indicated a greater reduction in the area assigned to partial harvesting than clearfelling across all carbon prices and time periods. At the beginning of projections, younger forests were selected for harvest as older forests contain more carbon stocks and thus would have to pay compensation for those larger emission as a carbon was introduced, but also that old forests having low growing stocks and low annual yields are harvested to give room for forests with higher average growth. However, the average age of clearfelling increases overall, with respect to the base, by 3.8% (2.7 years) as some of the stands that had been left standing are harvested at an older age than the baseline. With a carbon price of 100 €/tCO_2 and use of 3% p.a. discount rate, there is a possibility to sequester around 20% more carbon annually than in the business as usual scenario due to reduced harvests across Europe. It was concluded that EUFORIA model may provide many possibilities regarding analyses of impacts of future policies related to issues such as climate change mitigation, bioenergy production or forest conservation.

3.5 Summary of Paper V: Incorporating risk in forest sector modelling – state of the art and promising paths for future research

3.5.1 Objective

One of the weaknesses of nearly all currently used forest sector models is their deterministic approach, i.e., risks or uncertainties are not explicitly considered. In *paper V*, the possibilities of introducing risk component into deterministic forest sector models were explored, state of the art described, and promising paths for future research proposed. This study had also two sub-objectives. The first one was to review the risk methods that have been incorporated in FSMs and in numerical models in forestry, agriculture, fishery and energy, and macroeconomic models. The second one was to identify and discuss promising approaches for including risk component in FSMs. The main contribution of this research is to provide improved analysis of the impacts of increased use of woody biomass for energy using FSMs.

3.5.2 Method and main assumptions

Paper V was based on a literature review of more than 200 articles, extracted from the Science Direct database (journal articles) and Google Scholar (journal articles and other types of publications). Publications not written in English were excluded from this study, as well as publications that focused exclusively on scenario and sensitivity analyses.

3.5.3 Main results

Results showed that rather few large-scale model applications where risks were explicitly included, beyond scenario and sensitivity analyses, were identified. Also, except for scenario analyses, very few studies incorporated risk in sectors like energy and fishery, and in macroeconomic modelling. Studies in forestry that have incorporated risk applied a variety of methods, but most of them were at the single or multi-stand level using methods that are unsuitable to apply in FSMs. Additionally, the literature review showed that market agents' perception and attitude toward risk are relevant elements to consider in forest sector modelling. However, it is not an easy task, as human behavior belongs to the most complex risk factors in any type of modelling exercises and economic theory not always fully capture people's behavior. Finally, the analysis showed that there are many options for incorporating risk in model analyses. However, many of the proposed methods are too demanding with respect to data availability and computer capacity to be applicable in large-scale numerical FSMs.

Regarding the promising paths for the future research, it was concluded that for incorporating risk in FSMs, fuzzy set theory and robust optimization techniques seem promising new approaches, alongside methods that already are in use, like Monte Carlo simulation and, in particular, scenario and sensitivity analysis. At the end of the article, a procedure of incorporating risk component into FSMs was proposed, based on a combination of deterministic optimization, sensitivity analysis, Monte Carlo simulation, and scenario analysis. Although the procedure presents an ideal approach, it was underscored that in reality, one would most often have to make modifications according to available resources of data, model capacity, and human skills, but the procedure can still be useful with some adjustments.

4. DISCUSSION

The assumptions and results presented above in chapter 2 and 3 are discussed rather detailed in the respective *papers I-V*. This chapter, therefore, aims at giving a more overall, perspectively oriented discussion of the thesis results, concentrating on impacts of policies and increased bioenergy productions, the role of forest sector modelling, and future promising research.

4.1 Impacts of policies and bioenergy productions

The results in *papers I-IV* show varying impacts of bioenergy productions and policies on the forest sector.

Paper I results indicate that despite the additional demand for chips, a single medium-scale biofuel plant will have only minor effects on existing forest industries and harvests in Norway, but that the choice of tree species/wood assortments as biofeed is important.

Papers II and *III* indicate that specific policy changes in one region may significantly affect forest resources and markets elsewhere, mainly through trade. As policies regarding renewable energy are in states of flux, one main message from these papers is that future research should incorporate the latest policy developments, and policy makers should have clear goal settings for the preferred ways to solve the shift from the present fossil fuel-based energy system to a less carbon-intensive one. These results are in line with e.g. Jonsson and Rinaldi (2017) expressing the necessity of continuously market impacts assessments as effects vary over time and among different EU's members, as well as between EU and other regions.

Different forms of wood bioenergy and their impact on forest resources and wood markets have been analyzed, i.e. liquid wood-based biofuels (*paper I* and *III*) and wood pellets for heat and power (*paper II*). *Paper II* showed that at low EU's pellet import demand levels, the impacts of woody biomass from forests will not have extreme effects on timber markets, and may even encourage planting of more forests in the U.S. But if EU's pellet import demand were coupled with an ambitious U.S renewable energy policy, timber prices could increase substantially.

In *paper III*, it was found that increased competition for biomass from the energy sector does little to affect the European forest industry production. Interestingly, none of *papers I-IV* show dramatic effects (except for an aggressive U.S. renewable policy scenarios analyzed in *paper II*) on existing forest markets and industries created by new market actors and policies. One may say that potential shocks implied by policy incentives are to large degrees counterbalanced by market forces that adjust wood product markets through synergies, competition, and trade of wood-based products. This show the importance of considering multi-level policy interrelationships and that policy makers and policy designers have to take into account the market mechanism across regions where policies are supposed to operate.

Through *papers I-IV*, various types of forest sector modelling approaches have been applied, and the next section discusses the main challenges in forest sector modelling.

4.2 Forest sector modelling

During the last two decades, we have witnessed an increasing interest in the use of forest sector models, which have provided interesting insights and projections of prices and other fundamental market values into the future. One may say that the primary purpose of FSMs has been to make scenario analysis with special attention to underlying market dynamics of simulated policies, exogenous shocks and trade-offs between different objectives as economic and environmental goals (Latta et al. 2013b).

Although FSMs in the past have provided useful information, they have limitations, as all models. One limitation is that FSMs have not been created to calculate and evaluate the business profitability of new investments in forestry or forest industries. FSMs can be used to give valuable information for such evaluations, like shown for example in Mustapha et al. (2017) regarding which forest-based biofuel conversion pathways to choose, and in *paper I* regarding which biomass feedstock combinations are most economical. It seems that for business-oriented exercises, more detailed financial analyses are required.

One challenge is the choice of optimization technique in forest sector models. The pros and cons of intertemporal and dynamic optimization models have been outlined in section 2.3. It seems that these two different model types complement each other, rather than compete. This has some similarity to the discussion about using ‘gap’ models[7] and partial equilibrium

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[7] Wood balances or „gap" methods project demand and supply separately, and prices are not projected explicitly. In such models it is assumed that in making the demand and supply volume projections, prices in the future would continue to trend as they had in the past. The gap projections are related to estimates of future demand and supply volumes and the equilibrium price trajectory was not taken into account. Adams and Haynes (2007) argue that demand projections of such models are based usually on past trends or linkages between one or more end-use measures, such as housing activity or manufacturing output, and wood consumption. On the other hand, supply volumes (harvests) were projected by extrapolating trends or trends coupled with adjustments for changes in growth.

models (Chudy 2011). It is not possible to answer unanimously which approach is better, as it also depends on the research question asked. For example, Chudy (2011) concluded that wood resource balances can provide useful data about trends in wood production and consumption and differences between these two ('gaps'), while market models that distinguish demand, and supply are able to resolve the 'gap' by adjusting the price. One of the biggest weakness of 'gap' models is that these models do not take into consideration any market interactions through demand, supply and trade of wood biomass and forest industry products (Chudy 2011, Hänninen et al. 2018).

Another issue here is the use of numerical forest sector models instead of pure econometric models. As argued by, e.g., Buongiorno (1996), econometric models suffer from difficulties in incorporating structural changes in the markets and statistical problems in parameter estimation, while large forest sector models often may suffer from high complexity resulting in a lack of transparency, and are not necessarily better in handling structural changes in the forest sector (Toppinen and Kuuluvainen 2010). To overcome these issues, Buongiorno (1996) argues that sometimes simple models concentrating on a limited issue could be easily built, used and discarded, and might provide sufficient rigor of analysis with a further advantage of being highly transparent in use. Latta et al. (2013b) suggest that future modelling challenges may be overcome by hybrid models, which *"could move sequentially through time utilizing the intertemporal optimization model solution for harvest levels, manufacturing capacity additions, and silvicultural investment then use those outputs to guide the recursive dynamic models short-run solution which would then, in turn, update the starting conditions for the intertemporal optimization solution in the next time period"*.

There are ongoing discussions about appropriate model complexity and size (partial vs. general equilibrium models), basic assumptions (perfect vs. imperfect markets), assumptions of agents' behavior (perfect foresight vs. myopic) and optimization technique (dynamic recursive, i.e., static optimization vs. intertemporal, i.e., dynamic optimization), see for example Sjølie et al. (2015). Toppinen and Kuuluvainen (2010) concluded that the structure and parameters of applied numerical partial equilibrium models must consider multi-level, multi-region market issues to increase their credibility regarding results.

We should also bear in mind that forest sector modelling is susceptible to different factors of risks such as: model structure and its parameters (e.g. demand elasticities, input-output coefficients and forest growth parameters), the quality of data describing the past and current state of the world, exogenous assumptions such as population and GDP growth rates, or demand changes (Buongiorno et al. 2012). In addition, although FSMs vary considerably from nearly pure simulation models with no or weak market equilibrium assumptions to more complex spatial market equilibrium models that incorporate regional timber supply and forest industry products demand linked by interregional trade, nearly all of them share the common feature of being deterministic, i.e., risks are not explicitly considered (*paper V*). This is the case with all models applied in this thesis. Because long-term market forecasts are inevitably uncertain, through all the papers included in this dissertation, we applied sensitivity and/or scenario analysis to make the results more robust. In *paper V*, it is advised that techniques such as fuzzy set theory and robust optimization techniques seem promising new approaches, alongside methods that already are in use, like Monte Carlo simulation and, in particular, scenario and sensitivity analysis. Nevertheless, I think that even applying these techniques, the future projections and reality may differ significantly. Although we can be only certain that reality cannot take all scenarios, the FSMs are usually intended to contribute to system operations or policy development by helping to understand consequences if particular scenario may turn out to be a reality. Because future is uncertain, the modelling results, projections, and their potential realization are uncertain as well, and this is the common issue related to all forecasts and should be clearly understood by the users of any of these models.

Furthermore, nearly all FSMs are part of partial equilibrium models, which means that they, ceteris paribus, take into consideration only a part of the market (forest sector in this case), to attain equilibrium. Therefore, these models share the advantages and disadvantages of all other partial equilibrium models. Compared to general equilibrium models (see, e.g., Solberg 1986, Narayanan et al. 2010, Chudy and Jonsson 2018), the main advantage of the partial equilibrium approach is that it incorporates more detailed forestry and forest industry data and requires less data on the other sectors. However, forest sector models have disadvantages related to being partial equilibrium models. For instance, since it is only a “partial” model of the economy, the analysis is often only done on a pre-determined number of economic variables, what makes it very sensitive to the estimated demand and supply elasticities (see, e.g., Buongiorno and Johnston 2018). Furthermore, due to being partial, these models may miss important interactions and feedbacks between the forest sector and other economic sectors, thus missing important inter-sectoral input/output (or upstream/downstream) linkages that are the basis of general equilibrium models (Chudy and Jonsson 2018). Finally, FSMs may miss the existing constraints that apply to the various factors of production (e.g., labor, capital, land etc.) and especially their movement across sectors.

However, against these weak points, it should be remembered that the forest sector's part of the economy in nearly all countries in the world is very small compared to total GDP, so what is happening in the forest sector has minor impacts on the total economy. When in FSMs including exogenously the costs of labor, energy and other production costs except costs of biomass and forest industry products (which are endogenously determined), it is therefore in most circumstances realistic to argue that one has a reasonably robust handling of the forest sector when the exogenously determined variables are clearly defined in the scenario specifications. In general, the assumed income and price elasticities together with the assumptions regarding GDP (income) and energy price developments are the main links between the forest sector and the other sectors in the economy. Some FSMs, like the FASOM and EUFASOM models, include also both the agricultural land base and commodity production, thus allowing endogenous land use change and commodity substitution between sectors (Latta et al. 2013b), but also these models are partial.

In the economics literature (e.g., Narayanan et al. 2010) there exists four main techniques how partial and general equilibrium models may be linked together:

- Feeding results from "structurally rich" partial equilibrium (PE) models into general equilibrium models (GE),
- Using econometric estimates to calibrate the parameters in GE models,
- Direct incorporation of specialized PE model into GE,
- Feeding the GE model results into a PE/econometric model.

One of the main strengths of FSMs is the level of data details they contain, regarding both wood industry (both in dynamic recursive and intertemporal optimization models) and forestry part (mainly in intertemporal optimization models). Very often such data comes from previous studies performed by research institutes, universities or even external parties (e.g., consultancy companies or directly from market players). However, while some data have high accuracy, other model parameters might be based on historical data with limited representativeness, or some parameters might have to be derived from the modelers' best judgment if no data are available. The needed accuracy level should be seen in the context of the problem being investigated. Thus, in the applied work, the choice of level of aggregation or disaggregation depends on many factors, such as the purpose of the exercise, the specification errors involved, the data available, and the need for simplicity and parsimony.

Which level of aggregation (e.g., partial vs. general equilibrium models) to choose in economic modelling is an important but difficult question. First, consistent aggregation may imply restrictions that are unlikely to hold in practice. Second, an aggregate approach may involve a loss of information and may also face an aggregation bias problem defined as the deviation of the macro parameters from the average of the corresponding micro parameters. On the other hand, measurement errors are most likely to be present, and the quality of the disaggregated data may be poor. Aggregation may reduce this problem if measurement errors at the micro level cancel each other out. Furthermore, since we, in general, do not know the data generating processes, we may face a trade-off between errors of misspecification in the disaggregated system and the aggregation bias problem. Also, if the purpose is forecasting, and sub-groups show large variations while the aggregate has smoother development, the aggregate may be easier to model and forecast than the disaggregated alternatives and maybe also easier to interpret as well.

In the forest sector, before deciding which level of aggregation to choose in empirical analyses, one should study the development in both endogenous and explanatory variables at a disaggregated level, if possible. If the development of corresponding disaggregated variables shows important asymmetric variation, this provides strong support for employing a disaggregated rather than an aggregate modelling approach.

The problem of uncertain future will always exist, even in situations where model structure and its parameters such as demand elasticities, input-output coefficients and forest growth parameters are determined by the highest reliability, and future policies are quantitatively well specified (no "empty formulas"[8], see, e.g., Chudy et al. (2016), or the quality of data describing the past and current state of the world is the highest. The problem of uncertain future in forest sector modelling framework may be related to exogenous assumptions such as macroeconomic indicators (e.g. Latta et al., 2018), growth rates or demand changes, but also to political changes (e.g. elections), forest disturbance occurrences, and land use changes. Finally, assumptions regarding human behavior belong to the most complex risk factors in any type of modeling exercise as a mainstream economic theory does not fully capture people's behavior (see e.g. Loewenstein 2000, Camerer and Fehr 2006).

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[8] "Empty formulas" demonstrate an agreement by a formula or a specific wording, and lack substance due to the use of vague and general terms. They are frequently used by political language and are extraordinarily effective in achieving approval. In legal programs they are so-called 'gray' legal concepts which require interpretation in each individual case. 'Sustainability' or 'multifunctional forest utilization' are often generally cited in forest programs without any detailed description of meaning (Krott 2005).

4.3 Future research priorities

The choice of model depends on many factors, like questions investigated, the timeframe looked into, geographical scope, assumptions regarding agent information, data quality and research resources available. Much time is today spent on building, testing, comparing and revising models, and considerable journal space is dedicated to introducing, applying and interpreting their results. Modelling is expected to be a principal instrument of modern science in the future, and it seems to me that numerical forest sector models are well suited for policy analysis and for forecasting the economic development of the forest sector. In short, forest sector modelling has many merits and few, if any, alternatives. Thus, it is of high interest to discuss research priorities and potential improvements within this field. Many issues could be mentioned here, see for example (Latta et al. 2013b), but the following are the most urgent ones in my opinion.

First, because the driving force behind expanding biofuel production is climate policy, future studies in forest sector modelling should closely consider climate mitigation impacts. One of such possibility would be to include carbon prices and follow the carbon cycle from forest growth to end-use. The use of carbon price would provide an important weighting factor for climate mitigation allowing an evaluation of optimal harvest and silviculture combinations as well as the total climate mitigation benefits of biofuel production.

Second, there should be more research effort spend on the improvement of parameter uncertainties, especially related to the supply and demand elasticities, which tend to dominate the uncertainty in the other parameters describing forest growth, manufacturing activities, and trade inertia (Buongiorno and Johnston 2018). For instance, in *paper II*, there was suggested that future research may be enhanced with studies of the price elasticity of biomass demand in EU. To show the scale of necessity, a study on impacts on resource efficiency of future EU's demand for bioenergy (PWC et al. 2017) was based on own price elasticity for woody biomass commodities published in Buongiorno et al. (2003), i.e. around 14 years in the past.

Third, Buongiorno (2018) and Kallio & Solberg (2018) recently found that FAOSTAT data show remarkable inconsistencies, even of the magnitude of millions of cubic meters between the apparent supply of wood (harvests + net imports) and forest industry production in many regions. It was noticed that errors and uncertainties of such magnitude have important consequences on the results of any analysis using the data and call for special attention by the data users. Thus, future research and work with respect to data reliability, accuracy and quality should focus on the identification of the reasons for the data problems, improvement of data collection procedures and statistical systems. Else, the results coming from FSMs will be biased and unreliable. In addition, new and more specific data on wood flows to and from different countries, connected with clear specification of product codes and relatively quick actualization of databases, would be an important step towards analytical improvements.

Fourth, new research questions should lead towards the development of new forest sector models, but also continuous update and improvement of existing ones. For instance, in *paper II* it was suggested that linking EU's demand models with U.S. supply models would help to explicitly incorporate inventory dynamics and domestic competition effects on biomass price, and consequently enhance further research. With respect to new models and update of existing ones, in my opinion, there should be more attention paid to their transparency and replication or reproduction possibility, which is "the cornerstone of science" (Simons 2014). The reproducibility crisis has been addressed by scholars, who have found that the results of many scientific studies are difficult or impossible to replicate or reproduce on subsequent investigation, either by independent researchers or even by the original researchers themselves (Schooler 2014). Thus, I think that forest sector modellers should address this problem, and when possible, should store their models, data, protocols, and findings in online repositories, making them possible to evaluate by public seek, and consequently improve the integrity and reproducibility of research.

Fifth, research about new wood-based products, including textiles, liquid biofuels, platform chemicals, plastics, and packaging, should continue. For instance, Hurmekoski et al. (2018) pointed that the assessment of market reactions to the diffusion of new products and the interlinkages between existing and emerging markets should be subjected to economic and physical constraints posed by industry structure, ideally by sector modelling. A sectoral approach was suggested as the one that could potentially capture the trickle/down impacts of increased production of new wood-based products on other parts of the forest sector by market adjustments through pricing and international trade.

Finally, more research about the robustness of FSMs′ results and risk factors associated with them should be investigated in future research, for instance, by applying the step-wise procedurę or new methods such as a fuzzy set theory or robust optimization, as suggested in *paper V*.

5. CONCLUSIONS

This thesis investigates the impacts of increased use of wood-based bioenergy on forest resources and markets, explores strengths and weaknesses of FSMs, and identifies promising future research directions.

Projections of forest sector developments are based on combining information from the past with a current understanding of present and future economic processes, development of the policy framework, and resource characteristics. The results of the research questions asked in section 1.4 are presented in chapter 3 and discussed in chapter 4, as well as in *paper I-V*. It is shown that FSMs are tools that can provide interesting results and improved understanding of complex mechanisms in the forest sector and its connections to bioenergy policies.

Government policies and technological development are probably the most important factors shaping the biofuel industry and its contribution in the new bioeconomy. There is a need for rather detailed tools to properly analyze the impacts of potential policy changes on forest resources and forest products markets. FSMs are in my opinion useful tools for such analyses.

The models presented in this thesis, differ considerably regarding scope and detailedness, but all include main forest products flows, retain economic consistency across the sector, and are able to capture major complex mechanisms. Nevertheless, modelers should also keep in mind that all models have their own limitations, and output results should be analyzed with care.

Future promising research regarding forest sector modelling includes: modelling climate change impacts on the forest sector; examining future forest climate mitigation potential; identifying the reasons behind data unreliability and improving parameter uncertainties, data collection procedures and statistical systems; developing new and updating existing FSMs, meanwhile assuring their integrity, transparency, and possibility for the replication of their outputs; investigating the impacts of new wood-based products on other parts of the forest sector; and finally, exploring methods in FSMs that lead toward robust solutions.

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Paper I

Effects on forest products markets of second-generation biofuel production based on biomass from boreal forests: a case study from Norway

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ABSTRACT

Second-generation biofuels are often seen as an essential element in the future bioeconomy strategy. Countries with extensive forest resources such as Norway often view wood as preferred bio-feedstock, yet the effects of wood demand on assortments of harvested wood and other wood-based industries are unclear. Focusing on the importance of feedstock choice, we analyze the impacts of establishing a second-generation medium-scale biofuel plant in Norway. For the analysis, a dynamic forest sector model where the choice of tree species, wood assortments, production of bioenergy, and forest industry products are explicitly included, was applied. We find the optimal biofuel feedstock mix to be dominated by softwood chips from pulpwood comprising 48% of total biomass inputs in 2030 and increasing to 67% by 2055, followed by hardwood chips from birch, comprising initially 34% of total biomass inputs and 16 % by 2055. The proportion of harvest residues remained constant at about 18% over time and roundwood was not used at all for biofuel production. Despite the additional demand for chips, the single medium-scale biofuel plant will have only minor effects on existing forest industries and harvests in Norway, as the domestic impact is dampened by changes in foreign trade flows, especially of chips.

Keywords:

Dynamic forest sector modeling, partial equilibrium, wood markets, bioenergy, NorFor

INTRODUCTION

The concept of a bioeconomy in which biologically-based energy, chemicals, and materials displace fossil-fuel intensive products and lead to a more sustainable low-carbon future has spurred a number of national and international strategies (Staffas et al. 2013). Biofuels and in particular second-generation (cellulosic) biofuels avoid the potential concerns regarding the food-versus-energy debate by focusing on the non-food portion of plants (Naik et al. 2010). As such, interest in second-generation biofuel plants (henceforth SGBPs) has increased worldwide, and SGBPs often figure prominently in bioeconomy strategies (e.g. OECD 2009, European Commission 2012, 2013). Biorefineries, including biofuel productions, may contribute to employment and development of rural areas, protection of the environment, and overall sustainability (EC BREC 2009). Continued demand declines in certain high-income country's pulp and paper markets (Latta et al. 2016) have led to increased interest in biorefinery developments particularly among the Scandinavian and North American forest industries (Näyhä & Pesonen 2012).

In Norway, where pulp and paper mills have been closed the last two decades, SGBP is high on the political agenda and several plans exist for building biodiesel plants. This is in line with the goal of the Norwegian Bioenergy Strategy (Norwegian Ministry of Petroleum and Energy 2008) to double the biomass use in energy production from 2008 to 2020. As agriculture comprises only 3% of Norway's land area the focus of this strategy is squarely on woody biomass. Meanwhile, the Norwegian National Renewable Energy Action Plan (Norwegian Ministry of Petroleum and Energy 2012) predicts only around twenty percent increase in direct supply from forest sources between 2006 and 2020 with no indirect supply from forest biomass in 2020. This discrepancy between strategy and action plan may lead toward confusion regarding potential future bioenergy supply in Norway (Lindstad et al. 2015). Trømborg et al. (2007) emphasized that wood fuel is of particular interest in Norway in part due to its physical potential but also based on its price competitiveness leading to a promising role in the Norwegian energy market in the coming decades. Trømborg and Solberg (2010) concluded that factors including forest industry capacities, regional wood supply potential, prices and technological development, international trade and the demand for forest industry products will determine the future Norwegian forest-based biomass supply for energy production.

Given the interest in national bioeconomy strategies and the role of SGBP within them, a number of studies focused on second-generation biofuels from woody biomass have been conducted. They can be broadly classified into three groups; those that explore the evolving technological potential (Naik et al. 2010; Sims et al. 2010; Stephen et al. 2010; de Wit et al. 2010), those that focus on the role of supply chain logistics specific to location (Leduc et al. 2010; Stephen et al. 2010; Wetterlund et al. 2012; Natarajan et al. 2014), and those that evaluate SGBP economic performance (Bioref-Integ 2010; Naik et al. 2010; de Wit et al. 2010; Laser et al. 2012). However, rather few studies have analyzed the impacts of SGPBs on the traditional forest industries and how these impacts vary based on feedstock characteristics such as tree species and wood assortment.

Kraxner et al. (2013) found that a higher global demand for bioenergy by mid-century will be satisfied by biomass resulting from the conversion of unmanaged forest into the managed forest, new fast-growing short-rotation plantations, intensification, and optimization of land use. Therefore, policies designed to increase the use of wood-based biofuels require careful crafting (e.g. Chudy et al., 2013; Moiseyev et al., 2010; Solberg et al., 2010), and potential compensating market responses should be investigated a priori to prevent excessive and harmful use of forest resources upon implementation. Kallio et al. (2018) analyzed the economic potential and possible impacts of increased production of wood-based biofuels on the forest industries and production of wood-based heat and power in the European Economic Area. The EFI-GTM was applied for the analysis, and results showed that policy choices have strong impacts on the allocation of biomass use between heat and power production and the production of liquid biofuels. Kallio et al. (2011) studied the use of forest chips for energy and found that in order to reach the governmental target for the increase in the use of forest chips for energy in Finland, investments in the new production capacity of the forest industry (particularly industries using sawlogs) are needed. Forsström et al. (2012) analyzed a biodiesel strategy based on domestic forest biomass. Using an integrated modelling framework, it was found that biodiesel proved not to be a cost-effective measure for attaining climate or renewables targets due to its low chain efficiency in displacing fossil diesel emissions. It was concluded that from the mitigation point of view, the direct burning of solid wood biomass in energy-efficient boilers should be favored. For Norway, Trømborg et al. (2013) analyzed how second-generation biofuel based on wood may affect the competitiveness of more mature bioenergy technologies such as bioheat through competition for biomass. Regional variations in effects on biomass prices were found depending on local raw material availability and costs of transport and import. This study did not find any significant impacts of trade on the wood industry market situation in Norway and did not consider forest management alternatives. Sjølie et al. (2010) considered policies for promoting the use of wood fuel in heating and found that around 70% of the emissions from heating could be avoided in Norway if very high taxes on fossil fuels were introduced. Trømborg and Solberg (2010) analyzed the impacts of increased energy prices on the traditional forest sector in Norway. Their results showed that an increase in the energy price of about 40% from the present level, reduced production of particleboard by 12% and pulp (mainly sulfate) by 4%, while the production of fiberboard was unaffected.

Many studies highlighted the benefits of second-generation fuels relative to the first generation and also suggest that both “good” and “bad” biofuels exist (Börjesson 2009), depending on energy balance as well as economic and social sustainability, and future deployments must focus on these issues (Taylor 2008; Kazamia & Smith 2014; Youngs & Somerville 2014). As a result, a lot of research focused on the bioenergy sector and its interaction with forestry and forest products has been conducted recently using both simulation and forest sector models across a range of spatial scales (global, national, regional and local scales).

The studies tend to focus on the optimal locations of potential SGBPs (e.g. Leduc et al., 2012, 2010; Luk et al. 2010; Natarajan et al., 2014; Wetterlund et al., 2012), technical and economic background (Wingren et al. 2003; Mabee et al. 2006; Festel 2008; Sassner et al. 2008; Wingren et al. 2008; Piccolo & Bezzo 2009; Sims et al. 2010; Stephen et al. 2010; Festel et al. 2014) and potential environmental impacts (Sunde et al. 2011a; Sunde et al. 2011b). However, these analyses generally did not consider markets and empirical work on specific biorefineries, nor did they include detailed forestry data and alternative forest management options. The approach employed in Norway by Trømborg et al. (2013), Sjølie et al. 2010 and Trømborg and Solberg (2010) modelled the forest sector using a dynamic recursive method, where wood supply is based on econometric estimated relations between regional income, roundwood prices and forest growing stock, and forest management alternatives are not considered.

On this background, the primary goal of our study is to analyze the potential impacts on the Norwegian forest sector of establishing a wood-based biofuel plant in Norway, focusing on the choice of tree species and wood assortments, timber net import/export, and forest industry production. Compared to previous analyses, our study differs primarily regarding its focus on the choice of feedstock and type of forest sector model used.

We apply a dynamic forest sector model (NorFor) with an intertemporal optimization method, where the supply is determined based on the optimal allocation of silvicultural management options for each of the about 9000 inventory plots in the Norwegian National Forest Inventory (including growing stock, silvicultural investment costs, and harvest costs). Thus, wood supply is endogenously determined in the NorFor model and is closely related to forest management options. This feature of the model makes it possible to identify scenario-specific optimal combinations of tree species and wood assortments as well as determine the effects of using non-optimal feedstock combinations. As noted in Latta et al. (2013), there are potential challenges with recursive models when analyzing policy or market changes (e.g. new players entering the wood market, like SGBP in our case) outside historical ranges, while intertemporal optimization approaches more easily handle such cases. The model is further described in the next section.

The paper continues with a description of the methods and data applied. Then the results are presented and discussed, and, finally, the main conclusions are drawn.

METHODS AND DATA

Biorefinery assumptions

Our assumptions related to biofuel production are based on actual current plans of Statkraft and Södra Cell, who have joined forces to develop a second-generation biofuel facility in Norway, at Tofte, in Buskerud county, by the end of 2020. The expected cost of this investment will be around 500 million Norwegian kroner (1 NOK is equal to ca. 0.10 Euro).

The location was chosen as this was a site occupied by a previous pulp mill, and thus has an established infrastructure for wood supply logistics including a deep water quay to handle large quantities of timber (Dahle & Asbjørns 2015). We assume that the plant will begin biofuel production in 2025 and produce 150 000 tons of biofuel per year requiring one million cubic meters of woody biomass feedstock as input with potential feedstocks including: coniferous and hardwood pulpwood, sawmill residues, and harvest residues. To reflect possible biofuel technological options, we assume that feedstocks can be used independently or in any combination. The plant will use hydrothermal liquefaction (HTL) biofuel conversion pathway, which is well-described by Mustapha et al. (2017). The NorFor model used does not distinguish hardwood pulpwood from hardwood chips in the final wood fiber mix.

Forest sector model description

NorFor (Sjølie et al. 2011) is an intertemporal partial, spatial equilibrium model, based on the assumption of perfect foresight and perfect competition. The intertemporal dynamics ensures that the optimal solution is found for the entire time horizon, rather than calculating separate optimal solutions recursively from year to year (see e.g. Latta et al., 2013). NorFor maximizes the net present discounted value over the time horizon, given the assumption that agents possess full information about the future conditions, i.e. anticipate all market changes perfectly and allocate forest land and wood resources accordingly. The model is partial, meaning that it is not covering all economic sectors, but is built upon the assumption that the forest sector (i.e. forestry, forest industries, and wood-based bioenergy) is small compared to the total Norwegian economy and therefore has very little impact on the rest of the economy, like costs of labor, capital and energy. NorFor is spatial because it includes 19 domestic and two foreign regions, transportation costs between all regions, and that trade between regions is not fixed, but determined endogenously. The two foreign regions are included to incorporate foreign trade. Due to extensive border trade between Sweden and Norway, Sweden is included as one region and "ROW" (Rest of the World) as the other, together representing all other foreign trade within the forest sector. The main trading partners are situated in Europe. Trade between two regions takes place as long as the price difference of the good in the two regions exceeds the transport costs, as shown by Samuelson (1952). As in this study, no binding constraint is imposed, the equilibrium prices in the regions differ by only the transport costs. The transport costs in NorFor are exogenous, and for each bilateral trade, the cheapest option among road, boat, and railway is chosen. No harvest or production are included for the foreign regions, only the trade with Norway. Finally, yet important, equilibrium means that the NorFor model has a set of equations that must be satisfied so that supply and demand for each product and in each region have to balance including the trade of each product. In the NorFor, the objective function is to maximize the present value of discounted net social payoff, i.e. producer surplus plus consumer surplus minus transport and capital costs. Samuelson's theory (Samuelson 1952) about net social payoff within interregional trade in spatial equilibrium models, as well as the theory for economically optimal harvest age (Faustmann 1849), are the fundamental pillars in NorFor.

Principally, the model is divided into four main parts - forest management including harvest, industry production, consumption, and trade. The structure and data input of the forest industry portion of the model is derived largely from the Norwegian Trade Model II

(Bolkesjø 2004), with updated capacity data. Forest growth and harvests depend on the management of more than 18 options for each of the about 9000 permanent sample plots in the Norwegian Forest Inventory, simulated with the stand simulator Gaya (Hoen & Eid 1990). Incorporation of forest yields into harvesting schedules and their linking to the optimization and market module were done as described in (Adams & Latta 2005; Adams & Latta 2007). Endogenous variables in the NorFor model include forest management and harvest (including never harvest option), processing of wood into sawnwood, pulp, paper, boards, and bioenergy products and their consumption, trade, and greenhouse gas fluxes throughout the sector. More details about NorFor and its data requirements (e.g. forest industry capacities and production costs, forest management options, transport costs, trade assumptions) can be found in Sjølie et al. (2011) and Trømborg and Sjølie (2011).

Scenarios

To explore the potential consequences of establishing a SGBP at Tofte, Norway we constructed a set of alternative feedstock scenarios defining different combinations of potential feedstocks. When compared with a business as usual (BAU) scenario with no SGBP at Tofte, each of the defined feedstock scenarios illustrates the Norwegian forest sector's response to the selected feedstock choice. Table 1 presents the scenarios along with allowable feedstocks: *CPW* using coniferous pulpwood only, *CSR* using coniferous sawmill residues only, *CPW/CSR* using coniferous pulpwood or sawmill residues, *OnlyC* using all coniferous feedstocks including their harvest residues, and *AnyFeed* using all feedstocks including non-coniferous sources. All SGBP production scenarios assume a production output of 150 000 tons of biofuel per year.

Table 1. Allowable feedstock combinations for biofuel production in Norway for each simulated scenario.

Scenario name	Description	Spruce pulpwood	Pine pulpwood	Spruce chips	Pine chips	Hardwood (chips/pulp wood)	Harvest residues
BAU	No biorefinery plant						
CPW	Coniferous pulpwood	x	x				
CSR	Coniferous sawmill residues			x	x		
CPW/CSR	Coniferous pulpwood or sawmill residues	x	x	x	x		
OnlyC	Only coniferous	x	x	x	x		x
AnyFeed	Any Feedstock	x	x	x	x	x	x

RESULTS AND DISCUSSION

The NorFor model was solved for the 2010-2090 time period and results are generated for each 5-year period. We focus our analysis on the period between 2015 and 2055 representing the medium-term time horizon, and thus avoid any terminal condition influences that may affect later time period results. We begin with the differences between BAU and AnyFeed, i.e., the scenario with no limitation on the second-generation biofuel plant feedstock choice. Then, we compare all other scenarios against the AnyFeed scenario results. To facilitate interpretation of the results, we have converted all production quantities to one unit – cubic meter (m^3) solid volume under bark - using the conversion factors listed in UNECE/FAO (2009).

Differences between the BAU and AnyFeed scenario

Impact on harvest area and volume

The expectation of actual SGBP demand increase leads to changes in harvest behavior across all time periods simulated. After the SGBP begins operation in 2025 up to the end of projection in 2055 an additional 10 500 ha of forest is harvested in AnyFeed compared to BAU, i.e., 3% more. We also see a reduction in the harvested area of roughly 500 hectares leading up to 2025 in AnyFeed as compared to BAU. This can be explained by the perfect foresight forest owner behavior assumption of the NorFor model, as forest landowners, foreseeing higher demand and thus higher future prices, reduce their harvests before the SGBP comes online. AnyFeed also results in an approximately 2 000 hectares (1%) increase relative to BAU of area thinned during the 30 years the SGBP is operating. Similarly, the area thinned in the 10 years before the plant is established decreases by over 800 hectares in AnyFeed compared to BAU.

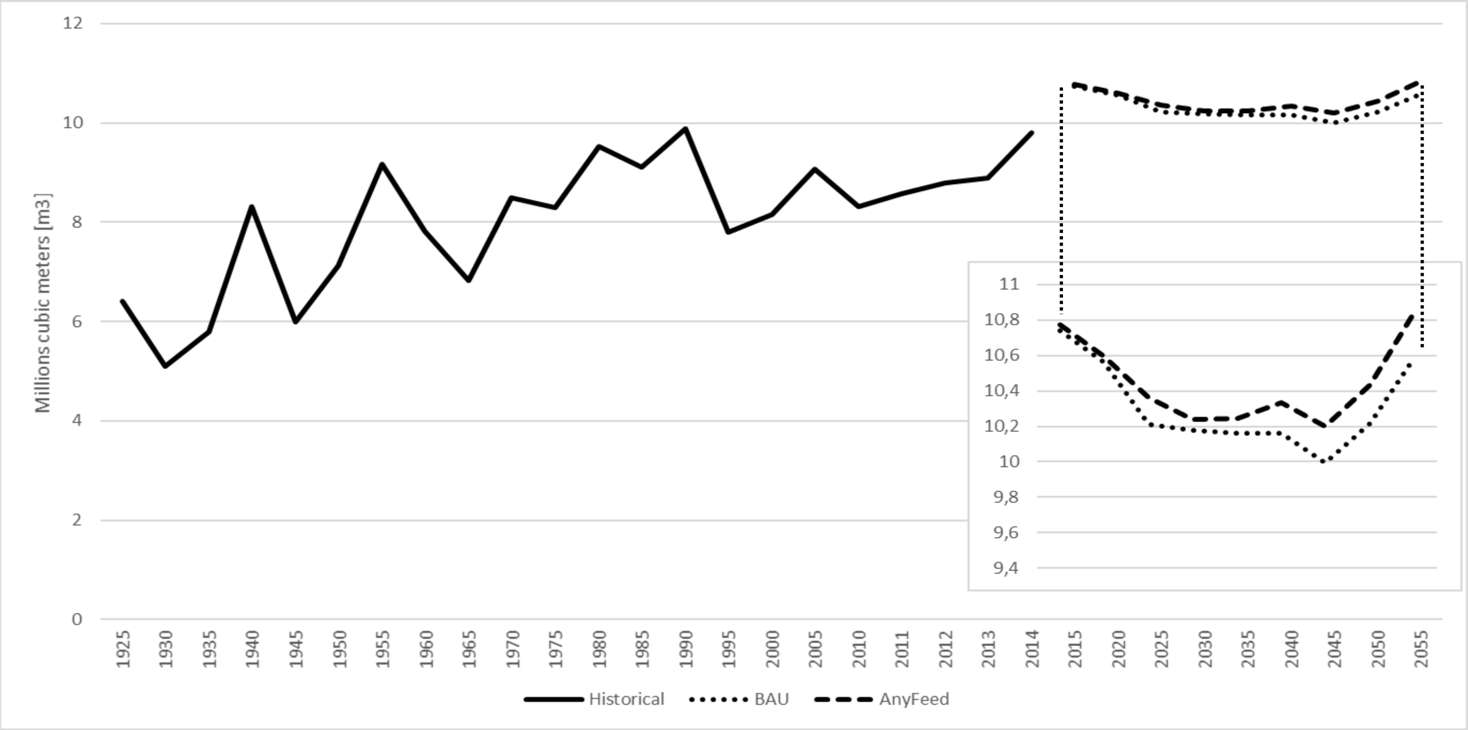

Figure 1. Historical and projected total harvest in Norway between 1925 and 2055 (million m3 per year).

Source: Historical harvest data (1925-2014): Statistics Norway (www.ssb.no)

Figure 1 presents the historical and projected AnyFeed and BAU total harvests for Norway between 1925 and 2055. Looking at the results over the whole projection period, the average annual total harvest between 2015 and 2055 is 10.3 and 10.5 million m^3 under the BAU and AnyFeed scenarios respectively. Thus, the presence of a SGBP leads to an additional harvest volume of about 9.8 million m^3 in Norway over the 40 years' time span. Out of these 9.7 million m^3, the majority (8.5 million m^3) will come as pulpwood. The increased harvest level of pulpwood, with a relatively smaller increase in sawlog harvests, suggests that the model favors harvest of younger stands and more thinnings in AnyFeed compared to BAU. Table 2 below presents the annual harvest levels for various wood assortments in the BAU scenario in the year 2030, 2055 as well as the averages for the 2015-2055 period, together with the differences between the harvests in the AnyFeed scenario and BAU (indicated by AnyFeed Δ m^3).

Table 2. Annual harvest volumes in Norway of different wood assortments under BAU scenario in 2030, 2055 and average 2015-2055, together with the differences between AnyFeed and BAU (in thousands cubic meters of solid volume under bark)

	2030		**2055**		**Average (2015-2055)**	
Harvested assortments	**BAU m3**	**AnyFeed Δ m3**	**BAU m3**	**AnyFeed Δ m3**	**BAU m3**	**AnyFeed Δ m3**
Birch Pulpwood	1,945	99	1,896	-107	1,917	43
Birch Sawlogs	12	0	12	0	12	0
Pine Pulpwood	1,328	80	1,575	134	1,422	71
Pine Sawlogs	1,226	-5	1,402	21	1,268	20
Spruce Pulpwood	2,853	73	2,857	111	2,882	76
Spruce Sawlogs	2,812	6	2,843	6	2,811	8
TOTAL	**10,176**	**253**	**10,585**	**165**	**10,312**	**218**

Table 2 shows that on average, the SGBP leads to an additional total annual harvest in Norway of approximately 218 000 m^3 per year, with the pulpwood component of this increase being almost seven times larger than that of sawlogs.

The addition of SGBP in Tofte also leads to different county-level harvest changes over the life of the plant. In 2025, the largest increases in harvest relative to BAU are a 19% increase in both Akershus and Buskerud counties totaling 170 000 and 147 000 m^3 respectively, while the largest reduction is 7% in Sogn og Fjordane and 6% in Vest-Agder (both around 24 000 m^3). In 2055, the largest expansion in harvest level occurs again in Buskerud with a 27% increase (230 000 m^3) and 8% increase in Hedmark (167 000 m^3), while an 18% reduction occurs in Akershus county (164 000 m^3).

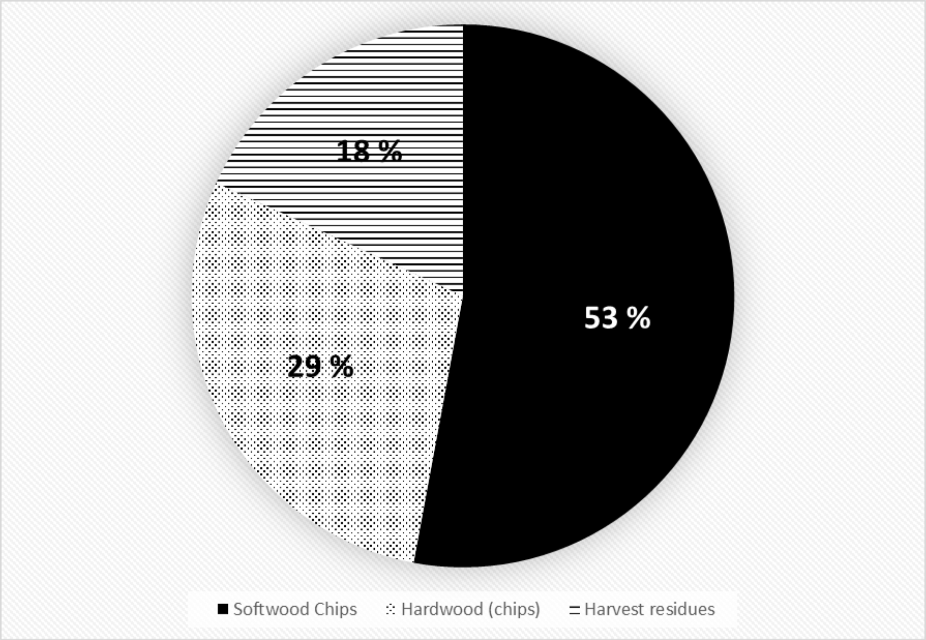

Figure 2. The average feedstock mix used for biofuel production between 2025 and 2055 in the AnyFeed scenario (% of total biomass used)

Figure 2 shows the optimal mix of woody feedstock used for biofuel production at Tofte between 2025 and 2055 with the largest component being softwood chips at 53%, varying from 48% in 2030 up to 67% in 2055. In the early years of SGBP production, the second most important feedstock for second-generation fuel production is hardwood chips, which decreases over time as it is substituted by softwood chips. The proportion of harvest residues remains constant in the feedstock mix at 18%, while roundwood was not used at all for biofuel production.

Given the relatively small harvest changes in comparison to the BAU harvest levels, the resulting pulpwood- and sawlog-price changes in the AnyFeed scenario are likewise found to be relatively small, about 1-2% increases over the SGBP lifetime.

Impact on wood industry

The increase in total sawlog harvest after 2030 in the AnyFeed scenario relative to BAU shown in Table 2 is caused by increased sawnwood production. The impact on the sawmilling industry is mainly a result of the increase in demand for sawmill residues for use in biofuel production. Market linkages in the Norwegian forest sector lead to a vertical cascading demand where increased demand for sawmill residues results in increased sawnwood production and consequently increased sawlog harvest. In addition, in NorFor, pulpwood and sawlogs are both complementary and substitute goods in timber supply (Sjølie et al. 2015), and thus higher demand for pulpwood result in more sawlogs brought to markets.

Production levels for selected forest products in NorFor under BAU and corresponding changes with respect to the AnyFeed scenario are presented in Table 3. It is generally seen that the addition of a medium-sized wood fiber user in Norway leads to only minor production shifts in the country. The impact is positive or negative depending on the biomass competition with the SGDP, and it also varies across counties. Looking at the last column with average values, the positive impact can be noticed for the production of sawnwood, while significant negative values are for space and water borne heat and energy wood, i.e. wood assortments that compete for chips and harvest residues with the biofuel plant.

Total sawnwood production in Norway between 2035 and 2055 is 42.9 million m^3 in BAU, while 43.5 million m^3 under AnyFeed. Out of this difference of 600 000 m^3, around 89% (534 000 m^3) is pine sawnwood, the rest being spruce sawnwood. At the local level, the largest increase in sawnwood production is seen in Buskerud county, where the SGBP is located. In the period 2035-2055, the total sawnwood production there increases by 26% from 3.4 million m^3 in BAU to 4.3 million m^3 in AnyFeed.

With respect to non-solid wood products such as fiberboard, pulp and paper products, and energy, the results showed very similar production levels in the two scenarios.

Table 3. Production of selected products in NorFor under BAU and corresponding changes with respect to AnyFeed scenario (thousand cubic meters of roundwood equivalent per year)

	2030		2055		Average 2015-2055	
Products produced	**BAU**	**AnyFeed Δ**	**BAU**	**AnyFeed Δ**	**BAU**	**AnyFeed Δ**
Sawnwood	3526.4	1.6	3724.0	24.8	3568.1	24.6
Particle board	150.3	0.4	150.3	0.4	150.3	0.4
Pulp (mechanical and chemical)	319.4	5.0	284.3	1.8	384.7	3.2
Linerboard	489.2	0.0	706.8	0.0	536.6	0.0
Paper products (newsprint, magazine papers)	4124.1	9.6	4338.8	-0.6	4178.4	-0.6
Fiberboard	541.3	0.0	661.0	0.0	566.4	0.4
Space and water borne heat	220.4	-6.3	241.5	-10.8	222.4	-4.2
Energy wood (firewood, chips, pellets)	323.2	-7.6	360.3	-12.0	328.5	-5.2

Trade

Result for net exports of selected wood products are presented in Table 4, where last column, shows that the assortments most affected by the SPDG plant under AnyFeed scenario were spruce and pine chips (higher net import), birch pulpwood (higher net imports), and pine and spruce sawnwood (higher net exports). In the 30 years period after biofuel plant installation (2025), the total net import of chips to Norway is increased by 47%.

The reduction of export comes from pine chips (see table 4). In the period 2015-2055, Norway was supposed to export in total 2.4 million tons of pine chips (75% to Sweden), while under the scenario with the biofuel plant the exported quantity falls to 1.3 million tons in total (around 80% with destination to Sweden).

Table 4. Net exports of selected wood products in 2030, 2055 and average 2015-2055 (in thousands cubic meters per year)

	2030		2055		Average 2015-2055	
Products produced	**BAU**	**AnyFeed Δ**	**BAU**	**AnyFeed Δ**	**BAU**	**AnyFeed Δ**
Pine Sawlogs	-3.3	-0.3	-3.3	0.0	-3.4	-0.1
Spruce Sawlogs	181.9	0.0	170.7	-0.4	176.4	1.1
Pine Pulpwood	-36.2	-0.5	-34.8	-0.7	-35.2	-0.4
Birch Pulpwood	-640.2	0.0	-753.6	0.0	-664.9	-9.0
Spruce Pulpwood	504.9	-2.1	432.6	0.0	469.4	-1.1
Pine sawnwood	-398.2	-5.0	-491.2	2.5	-399.5	13.2
Spruce sawnwood	-937.1	6.6	-1429.0	0.0	-1061.2	5.9
Pulp (mechanical and chemical)	-360.4	3.0	-444.1	1.8	-310.7	3.4
Paper products (newsprint, magazine papers)	-542.1	0.0	-1125.4	0.0	-670.7	-0.1
Fiberboard	-119.8	0.0	-165.1	0.0	-131.3	0.4
Linerboard	-60.4	0.0	-29.6	0.0	-52.5	0.0
Particle board	-399.0	0.5	-531.1	0.5	-428.8	0.4
Pine Chips	14.6	-6.9	17.4	-9.3	15.3	-5.6
Spruce Chips	-15.2	-8.2	-17.9	-9.7	-16.5	-5.6
Firewood	-6.6	-0.4	-8.2	0.0	-7.0	-0.2

These results suggest why the production of pulp and paper products is not significantly changed in Norway under the presence of the SPDG plant. The reason behind it can be related to increased net imports of pine and spruce chips as well as the increased harvest of birch pulpwood which can be used in the biofuel production, thus reducing the biofuel plant's impact on the rest of the Norwegian forest sector.

Table 4 shows that other wood assortments under biofuel plant operation are very close to the BAU scenario. Therefore, based on the above results one may assume that optimal feedstock mix is additional harvests in younger stands (pulpwood), imported wood chips from abroad (44% from Sweden, the rest from other countries), and finally from chips coming from Norway's domestic sawmilling industry.

The analysis of model results, with respect to relative changes to BAU in production, harvest, import and export under the biofuel production scenario, shows that the largest positive change will come from harvest level (65%), followed by import (10%), while production and export will be reduced in the analyzed period by 14% and 11% respectively.

Alternative feedstock scenarios

In this section, we compare results from scenarios designed to isolate different feedstock use for biofuel production by constraining biorefinery inputs. When compared against the BAU, this sensitivity analysis makes it possible to evaluate the degree to which feedstock choice affects the rest of the forest sector in Norway.

Impact on harvest area and volume

Results showing the difference in annual harvest levels from the AnyFeed scenario are found in Figure 3. The CPW scenario stands out from the other feedstock scenarios with the largest impact on harvest volume in Norway. This scenario uses spruce and pine pulpwood only, and therefore to satisfy the demand of the biofuel plant established in 2025 harvest has to increase. After 2025 in this scenario harvest increases annually 420 000 m^3, or about 4% more than in AnyFeed. The other scenarios lead to lower long-term harvest levels in Norway compared to AnyFeed, because they have higher costs caused by more restrictions regarding what kind of forest biomass which can be used.

Differences in harvest area between the feedstock scenarios follow the same pattern as the harvest levels. More detailed analysis of the model results shows that the largest increase in thinned area has CPW scenario (750 hectares or 1% more thinned than in AnyFeed), followed by reductions in thinning areas by 1300, 900 and 100 hectares for CSR, OnlyC and CPW/CSR respectively.

Figure 3: Annual harvest differences in Norway between AnyFeed scenario and each of the scenarios CPW, CPW/CSR, CSR and OnlyC during 2010-2055 (‘000 m3 per year)

When looking at the species and log assortments that make up the harvest, results indicate that the additional harvested volume in the CPW scenario is primarily comprised of pulpwood. Over the 2025-2055 time period of biorefinery operation, the species composition of the additional CPW scenario pulpwood harvest as compared to AnyFeed is found to be 66% and 42% higher for pine and spruce while the birch pulpwood harvest falls by 8%. For higher value sawlogs, over the same time frame, harvest falls by over 330 000 m^3 compared to AnyFeed, with this reduction consisting of about 40% pine and 60% spruce.

Looking at other scenarios, the harvest level is slightly higher than in AnyFeed scenario before the introduction of biofuel plant in Norway, and lower after the start of its operation. One explanation for such changes in harvest level for the scenarios that use wood chips, may be linked to wood trade changes, especially in wood chips, which may reduce domestic demand for wood chips (by e.g. lower chips exports from Norway) and in consequence harvests, and in the same time increase demand on foreign wood chips (higher imports from abroad to Norway).

Impact on wood industry

Results indicate that the sawmilling industry will see higher levels of production compared to AnyFeed under all scenarios in which sawmill residues can be utilized at the biorefinery (Figure 4). As in the AnyFeed scenario (see Figure 2) chip utilization is an important component of the biorefinery feedstock mix and therefore sawnwood production displays a complementary relationship with that of biofuel. As demand and prices of sawnwood chips increases, sawmill profitability follows leading to an increased demand for sawlogs. The obvious exception is that of the CPW scenario as it allows pulpwood use, thus breaking the complementary relationship between sawnwood and biofuel leading to a reduction in sawlog harvests and sawnwood production, making the sawmilling industry worse-off through the entire projection period.

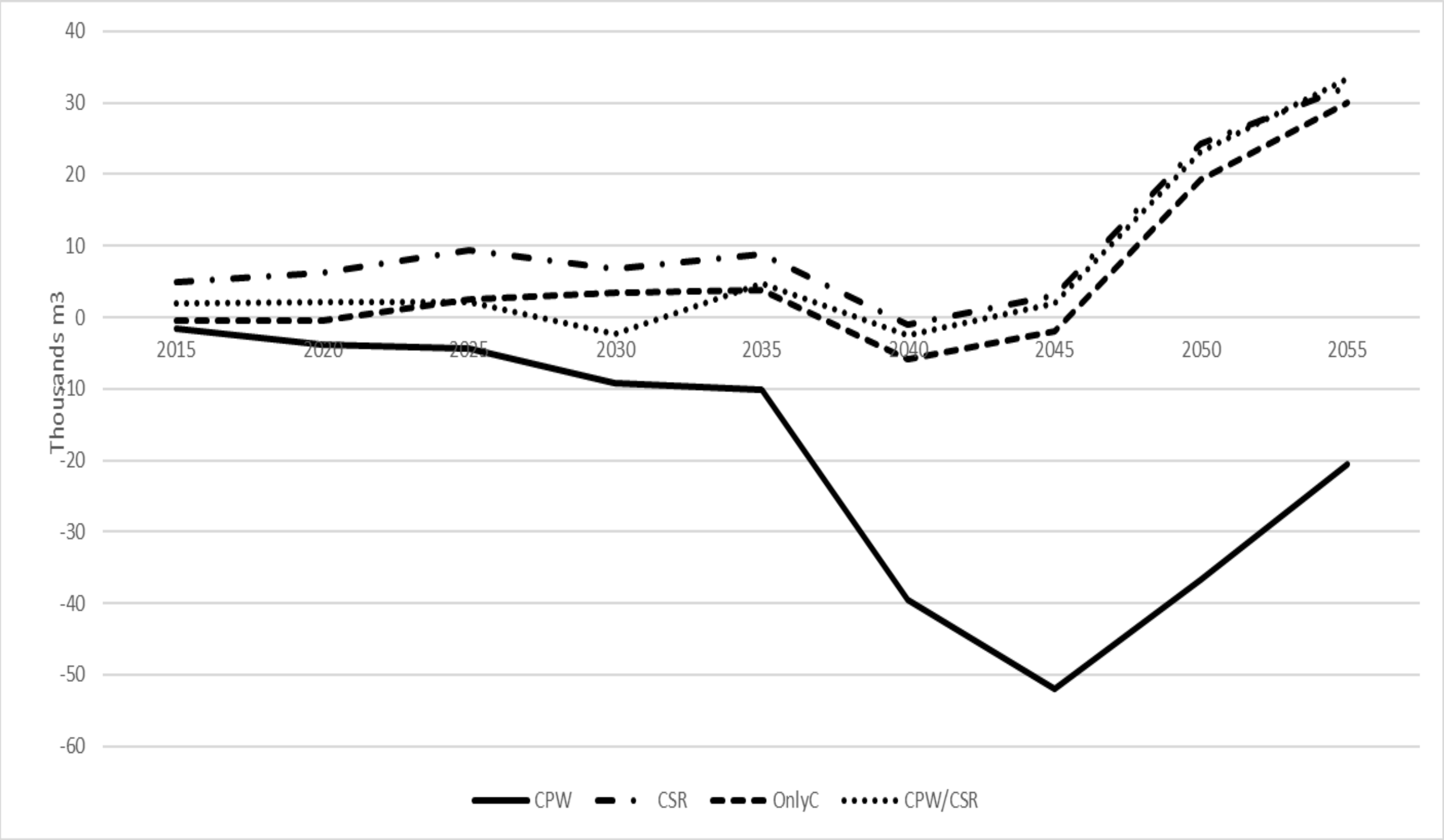

Figure 4. Annual differences of sawnwood production in Norway between AnyFeed scenario and each of the scenarios CPW, CPW/CSR, CSR and OnlyC during 2015-2055 (in thousand cubic meters per year)

When looking in more depth at this sawnwood production reduction in the CPW scenario we find that regional changes in production are largely confined to Buskerud county perhaps indicative of the localized advantages (and disadvantages) of sawnwood and biofuel plant co-location. The differences between feedstock scenarios and the AnyFeed scenario in pulp, paper, and fiberboard production are very small, and therefore not reported here.

Trade

As with the domestic forest industrial results, chips are among the most affected in forest product trade and pulp, paper, and board (fiberboard and particleboard) trade is less affected by biofuel plant. Figure 5 shows that in the CPW scenario, chips exports increase immediately in response to the establishment of the biofuel plant as chips are not allowed to be used there. The largest decrease in net export of chips relative to the AnyFeed scenario happens under CSR scenario, followed by CPW/CSR and OnlyC scenario (Figure 5). The change of the net export is coming from both the side of reduced export and increased import. For instance, in the CSR scenario in 2025, imports of spruce and pine chips increase by nearly 50%, while the export is reduced by almost 100%. For CPW/CSR scenario, these changes are 30% and 60%, respectively.

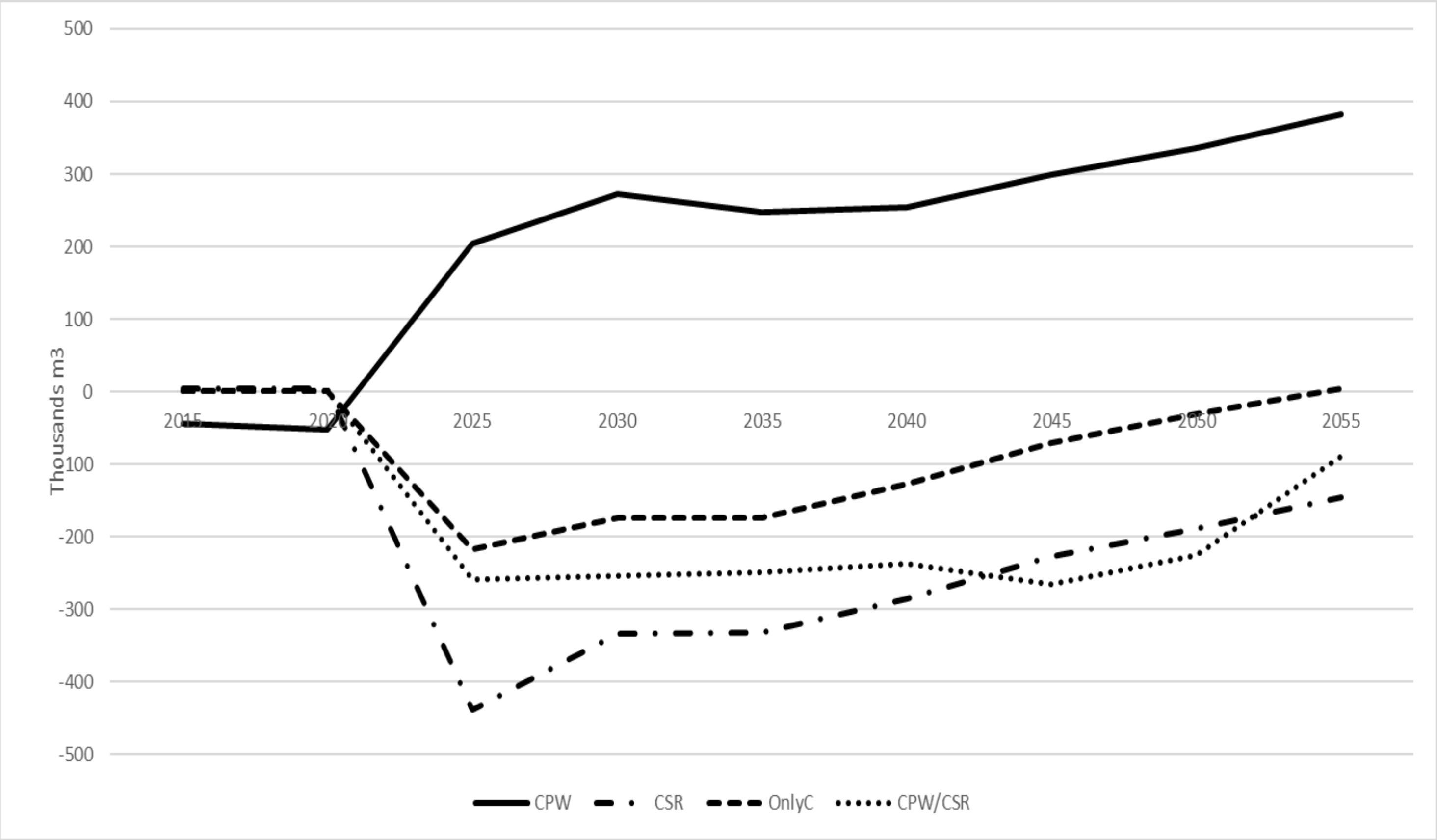

Figure 5: Annual differences in net exports of wood chips from Norway between AnyFeed scenario and each of the scenarios CPW, CPW/CSR, CSR and OnlyC during 2015-2055 (‘000 m3 roundwood equivalent per year)

It is interesting to compare our results with some of the findings in Trømborg et al. (2013). They analyze, among other issues, the impacts on biomass markets of three different locations of biofuel production in Norway, and impacts of feedstock choice in the biofuel production. Similarities between the present study design and that of Trømborg et al. (2013) include the scale of biofuel plant (one million m^3 biomass input per year) and the location in Buskerud county as one of the three location options analyzed. Also, the assumed demand for forest industry products, costs of transport and productions, as well as demand for forest industry products are on similar levels (although not identical). The main difference is regarding the type of forest sector models used. We apply a dynamic forest sector model meaning that we optimize over the whole time period of the analysis and thus assume perfect foresight behavior, whereas Trømborg et al. (2013) used a recursive dynamic forest sector model meaning that static optimization is used for each year. See Latta et al. (2013) and Sjølie et al. (2015) for a more detailed discussion of the differences and similarities between these two types of models. Other differences between the two studies are that Trømborg et al. (2013) focus on the impact on the other bioenergy industries as opposed to all forest industry productions and place a larger emphasis on price effects.

Regarding the effects of introducing a plant producing 100 million liters of biofuels annually, it is interesting to see that 10-15 years after the onset of biofuel production, the two studies have rather similar (although not exactly the same) results regarding decreased space and water borne heat production, slightly increased sawnwood production and negligible impacts on the pulp and paper industries. Both studies also confirm that a mix of tree species and log assortments results in lower impacts than restricting the biomass feedstock availability. However, regarding impacts on wood prices. Trømborg et al. (2013) showed 5-8% or higher pulpwood price increases for a 100 million biofuel plant, whereas we, using NorFor, find that prices for pulpwood differ less than 2%, even in the county where SGBP is installed. One reason for these differences between the two studies is most likely related to fundamental differences in how wood supply is modeled. In Trømborg et al. (2013) timber supply is determined using econometrically estimated timber supply curves based on historical harvest and price data, while in NorFor the timber supply is determined endogenously based on the assumption of perfect foresight using inventory data coming from over 9000 sample plots in the Norwegian National Forest Inventory, and taking into account many alternative forest management options for each plot. The pulpwood price results thus confirm the observation in Latta et al. (2013) that timber supply response based on theoretical assumptions such as perfect information may lead to overestimation of the potential reactions to policies and market changes, while dynamic recursive models might be better suited for short-term predictions due to their limited variation from historical data.

Another reason for the different results could be that unlike Trømborg et al. (2013) we did not hold the species composition fixed in our feedstock alternatives, thus, allowing the model to choose the optimal mix of species and feedstock categories. Finally yet equally important, differences in assumptions regarding trade between the two studies could be an important factor, as in our study wood products trade plays an important role in reducing price changes, in particular with respect to wood chips. Finally, while the driving force behind expanding biofuel production is climate policy, our study did not consider climate mitigation impacts. An interesting extension of this study in future research would be to include carbon prices and follow the carbon cycle from forest growth to end-use. The use of carbon price would provide an important weighting factor for climate mitigation allowing an evaluation of optimal harvest and silviculture combinations as well as the total climate mitigation benefits of biofuel production.

The results of our study demonstrate that a forest sector model like NorFor which accounts for the main products flows while retaining economic and production consistency across the sector including silvicultural alternatives, provides a useful tool for informing decision-makers of complex interlinkages across the forest sector. Compared to other forest sector models applied in Norway, the main strength of NorFor is its ability to capture in an economic consistent framework major complex mechanisms like alternatives for forest management and harvest, choice of tree species and assortments, connections between sawmilling, bioenergy and the other forest industries, and the competition for wood fiber between various users. Production of second-generation biofuels is high on the policy agenda in Norway as in several countries. Based on our results, we conclude that the mix of wood input is an important factor in determining the impacts on traditional forest industries, and depending on the particular feedstock options selected, different market players can benefit or lose. Our results also show that the pulp industry would see little changes due to the hypothetical new biofuel plant, while the sawmilling industry may to some extent benefit. A single medium-scale biofuel plant is not going to significantly affect the wood market in Norway, because trade is buffering. Although traditional wood markets will not be significantly affected, the effect on forest resources and carbon budget may be of higher importance, and should be investigated in future studies.

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Paper II

Journal of Energy and Power Engineering 7 (2013) 1073-1081

Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S.

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Received: July 02, 2012 / Accepted: October 31, 2012 / Published: June 30, 2013.

Abstract: The wood-pellet trade between the U.S. (United States) and the EU (European Union) has increased substantially recently. This research analyzes the effects of EU biomass imports from the Southeast U.S. on Southeast U.S. timber prices, inventories and production and on EU imports of feedstock. The SRTS (sub-regional timber supply model) was used to simulate market responses to changes in woody biomass consumption in the U.S. and the EU between 2008 and 2038. Results indicate that the price of imported wood pellets in the EU is sensitive to future U.S. renewable energy policies, the developments of which are so far uncertain. The analysis indicates that with bioenergy demands, prices increase for U.S. softwood roundwood from 25% to 125% by 2038 depending largely on U.S. domestic policy. Demand increases led to supply responses and increased carbon storage in Southeastern U.S. over time.

Key words: Pellets, forest product markets, international wood trade.

1. Introduction

Energy supply and greenhouse gas emissions are global concerns. The EU has set an ambitious target of 20% of the energy consumption to come from renewable sources by 2020 [1]. So far, every country in Europe has included bioenergy in its energy and climate policies [2]. Meeting national targets for renewable energy will require intense mobilization of domestic sources as well as increased imports [3].

The European Commission proposal is to maintain the EU's position as a world leader in renewable energy [4] and the EU has declared it would use wood from sustainable sources only. The federal government of the U.S. also has a number of policies in place to promote the use of bioenergy (e.g., the Energy Policy Act of 2005 (Public Law 109-58)). Currently, the merits of these policies and the impacts on biodiversity, climate change and land use are under discussion.

Studies indicate that woody biomass resources within the EU will not suffice to satisfy the demand if the targets for renewable energy are to be met [3, 5]. Indeed, international bioenergy trade is already growing rapidly, especially for wood pellets. The main wood-pellet trade routes are from Canada and the United States to Europe, in particular to Sweden, the Netherlands and Belgium [6].

An increasing demand for bioenergy in the EU would have implications for forest sectors in other countries. Large-scale bioenergy imports to mitigate domestic biomass scarcity in the EU brings to the fore among other issues, the question of potential global biomass scarcity relative to the future required levels of climate neutral energy [7]. Studies such as EFORWOOD (sustainability impact assessment of the forestry-wood chain) and EFSOS (European Forest Sector Outlook Study) II [5] have assessed the

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implications within Europe of an increased demand for bioenergy. However, there is as of yet no comprehensive analysis of implications outside Europe (except Ref. [8]).

Fast growing conditions, abundant forest resources, and low-cost transatlantic freight make the Southeast U.S. an attractive source of biomass imports for the EU. At present, there is a lack of knowledge as to how forest inventories, forest-product markets and forest carbon in the Southeastern U.S. could be affected by the EU energy sector. Hence, sustainable forest management and wood market in the Southeastern U.S. may face constraints in terms of satisfying domestic and EU bioenergy demand.

Thus, the objectives of this study are to: (1) assess the impact of EU energy consumption on wood pellet imports between 2008 and 2038; (2) determine the influence of U.S. and EU bioenergy feedstock consumption on key market variables and carbon storage in the Southeastern U.S. To meet the objectives of this study, the authors use the SRTS [9].

2. Materials and Methods

2.1 Modeling and Assumptions

The SRTS model [9] was used to simulate market responses to changes in woody biomass consumption in the SE U.S. (Southeast U.S.) and EU-27 member states. SRTS is a partial equilibrium market simulation model. SRTS uses detailed forest resource information on stand ages, forest types and growth rates to model changes in inventory by product. These inventory changes, which can arise from land use conversion and forest type conversion—e.g., through tree plantation establishment—are used to shift product supply curves.

To project timber supply trends based on present conditions and the economic responses in timber markets, the SRTS model uses a U.S. Forest Service, FIA (forest inventory and analysis) [10] dataset of inventory, growth, removals and acreage by forest type, private ownership category, species group and age class for multi-county areas. FIA data are the key biological forest resource drivers for the inventory by forest management type, age class and species groups [9]. The SRTS model provides a simulation environment for examining sub-regional timber supply dynamics and their impact on supply in the aggregate market. The potential price consequences consider sub-regional inventory and harvest shifts and changes in market demand.

Studies indicate that supply and demand price responses are inelastic [11, 12]. In this study, the authors assumed -0.5 and 0.5 for the elasticity of demand and supply respectively with respect to real price changes and an elasticity of supply with respect to inventory of 1.0 for all products implying that supply shifts are proportionate to product inventory change. The SRTS model assumes constant elasticity functional forms. The demand scenarios determined the demand curve shift in each year [13]. Biomass demand is met by both logging residues and industrial roundwood. The roundwood portion of this woody biomass demand quantity competes with the demand for roundwood used in the traditional forest products sector.

There are three components of each demand scenario. The first component is the demand for roundwood used in the traditional wood using industries in the SE U.S. Since the focus of this research was bioenergy, an assumption was made that demand for traditional forest products would fully recover from the most recent recession by 2014 and remain constant thereafter (Fig. 1). The rate of demand

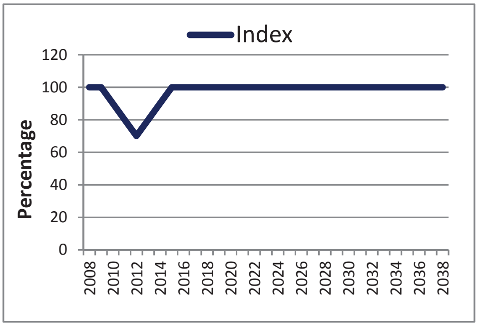

Fig. 1 Baseline domestic demand trend with a modeled recession and rebound.

change between these particular years will be equal to 33%. Recession and rebound will significantly influence the harvest level.

This recession is modeled as V-shaped with a sharp downward trend, a nadir at the depths of the housing market slump and then an equal and opposite upward trend that returns demand to pre-recession levels by the year 2014. While evidence is still lacking about actual (observed) harvest rates to the current year (2012), housing starts data from the U.S. Census Bureau (2012) indicate that the bottom was reached in 2009 but that recovery has not proceeded exactly in a V-shape but may be closer to a U-shaped recovery [14]. Stumpage prices for southern pine and mixed hardwood sawtimber and pulpwood have also failed to recover since the contraction in U.S. construction [15]. Nevertheless, a return to pre-recession long-term average demand levels, the authors contend, is a reasonable representation of long-run future market conditions.

Domestic (U.S.) bioenergy demand makes up the second component. Results from Ince et al. [16] were used for this component, which includes a high, a medium and a low domestic bioenergy demand scenario, projecting the demand for woody biomass into the coming decades. The United States is one of many countries where national energy policies have been enacted. Among the most important, the EISA (energy independence and security act), was introduced in 2007. This act and proposed legislation regarding national renewable energy goals for electric power can in the near future expand wood use dramatically for liquid fuel, electric power and thermal energy production [16].

Research by Ince et al. [16] used U.S. renewable energy projection from the 2010 U.S. Department of Energy Annual Energy Outlook, AEO (USDOE, 2010), which incorporates the impact of the U.S. Renewable Fuel Standard (under EISA). This study also incorporated the anticipated market impacts of a hypothetical national RES (renewable energy standard) for electric power.

The model used to evaluate the market effects of alternative scenarios was the USFPM (U.S. Forest Products Module), which was embedded in a global partial spatial equilibrium model of the global forest sector, the GFPM (Global Forest Products Model) [17]. The USFPM module provides a three-region, multi product of timber and wood residue markets.

Ince et al. [16] describe four scenarios that were used to project market impacts of alternative policies that affect U.S. wood energy demand. Scenarios differed from one another mainly in terms of assumptions about future expansion in U.S. wood energy consumption through 2030. Full description of all scenarios can be found in Ref. [16]. Generally, all scenarios include projected U.S. cellulosic biofuel output under the U.S RFS (renewable fuels standard policy) as projected by the 2010 AEO (annual energy outlook) [18]. The scenario labeled “HP” (C2) has a higher cellulosic biofuel demand projection from the AEO “HP” (High Oil Price) case, while the other three scenarios use the RFS biofuel projection from the AEO Reference Case. All scenarios include additional biomass energy consumption under hypothetical national RESs (renewable energy standards) requiring that either 10% (RES 10; Scenario A2) or 20% (RES 20; Scenario B2) of electric power be generated from non-hydro electric renewable energy sources by 2030. The last scenario, labeled “RES 20 + EFF”, includes a similar energy policy but allows half of the non-hydro renewable energy to be in the form of more efficient combined heat and power (EFF), therefore requiring somewhat less biomass input to attain the 20% renewable energy requirement [16].

The focus of our study is on the third component, i.e., EU-27 wood pellet imports from the SE US. Our EU estimates were based on Capaciolli et al. [19] and included three scenarios. Based on recent research, Eurostat and USITC databases [20, 21], it is concluded that wood pellets are the main bioenergy feedstock traded between North America and Europe. As total biomass consumption is predicted to increase in coming years, pellets are regarded as one of the important bioenergy commodities traded internationally that will contribute a significant share of total biomass consumption growth. To determine how much of total EU pellets imports are sourced in the U.S, it is necessary to distinguish the percentage of U.S. pellets among all pellets imported by EU-27 countries. Based on the Eurostat database, results show that U.S. contributes 30% to 56% of total imported wood pellets from third countries to EU-27. This discrepancy or range was caused because Eurostat provides two types of independent information about pellet import from third countries.

The authors therefore imputed this value at 40%, which while arbitrary, is simply a rounding to the nearest 10%, just slightly less than the midpoint. Scenarios are summarized in Table 1.

A critical variable to address in simulations is the moisture content of wood pellets. The most significant factor that relies on moisture is the amount of feedstock that is needed to produce one ton of pellets. Sikkema et al. [22] analyzed three conversion factors that can be used to determine pellets moisture. These authors examined three different types of wood pellets (bulk pellets for district heating in Sweden, bagged pellets for residential heating in Italy, and bulk pellets for power production in the Netherlands). To produce one ton of bulk pellets (8% moisture content) for district heating in Sweden, around 2.12 t of feedstock (average moisture content 55%) are required. To produce 1 t of bagged pellets (10% moisture content) for residential heating in Italy, around 1.78 t of feedstock (average moisture content 47%) are needed. And finally, to produce 1 t of bulk pellets for power production (6% moisture content) in the Netherlands, around 1.57 t of feedstock (average moisture content 36%) has to be used [22]. For all scenarios, the authors assumed a value of 1.78 to determine the amount of feedstock needed to produce 1 t of wood pellet (moisture 10%). Sensitivity analysis was performed using all conversion factors (1.57, 1.78, 2.12) to quantify the importance of pellet moisture content on natural resources demand and wood markets in the SE U.S.

The authors used SRTS, the various biomass harvesting and residual factors and the U.S. and EU renewable energy policy inputs to estimate the impacts of EU biomass demand on multiple variables. These include: SE U.S. timber inventory, supply and prices; carbon storage; and the amount of forest plantations in the region.

The authors focused on softwood pulpwood markets, which comprise the largest share of relevant harvest in the SE U.S. and an even greater share of wood used for wood pellets and chips exported to the EU. The different levels of EU demand depended on the four scenarios presented in Table 1.

2.2 Geographical Scope

The market and resource implications of increased EU imports of wood for energy were analyzed assuming demand was met by (1) the entire SE U.S., (2) only the coastal plain component which is closer to Atlantic ports. In this paper, only results for the entire SE U.S. are presented. Detailed results for the coastal plain, quite similar, can be found in Chudy [23].

This study defines the SE U.S. as the region comprised of the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia (Fig. 2).

Table 1 Combined scenarios of EU-27 pellet imports from the U.S. and wood fuel feedstock demand in Southeast U.S..

Scenario name	Wood fuel feedstock demand in the Southeast U.S.	Percent of U.S. pellets delivery to EU (%)
Baseline	no use of biomass for energy	0
A2 = Low	RFS + RES10	40
B2 = Medium	average of RFS + RES 20 and RFS + RES20 + EFF	40
C2 = High	RFS + RES20 + HP	40

The SE U.S. states are the main focus of the SRTS model and its relationship to the regions as defined in the FIA database. The SE U.S. has a large amount of forest resources available in this area and the potential for export of woody biomass to EU.

2.3 Species Supply Composition

One of the key assumptions is that 80% of wood for pellets will come from softwood. Harvest levels have historically been low in hardwood forest types across the South [9]. This is mainly due to lower growth rates, restricted availability (steep slopes or wet soils, small tracts) and because landowners of these management types traditionally have had other objectives for owning their land in addition to or in place of profits from timber production.

The 80% softwood fiber content that the authors assume is slightly at odds with recent historical experience, but the assumption withstands scrutiny for at least two reasons. Recent data [10] show that softwoods comprised roughly 65% of total harvest volumes in the SE U.S. and 77% to total harvest volumes in the coastal plain. However, recent growth rate information indicates that the plantation-based softwood species that manufacturers currently utilize will increase in productivity faster than the natural stand-based hardwood species that have made it into wood pellet furnish in recent years. Additionally, the analysis and assumptions accordingly focused on softwood timber harvests, based on the predicted higher demand of fast growing species devoted for biomass. Wood pellet plants use higher proportions of softwoods than hardwoods in pellet manufacture; some recently established plants using 100% softwood. This assumption takes account of slight changes in the pellet supply chain but also recognizes existing wood resource availability the SE U.S. One should bear in mind that hardwoods are composed of many different species (as compared to one-species softwood plantations), which can influence woody biomass quality.

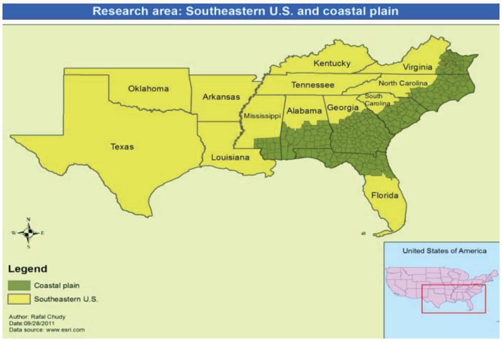

Fig. 2 Research area: the Southeastern U.S. and its coastal plain.

2.4 Harvesting Residue Rate and Recovery Rate

As far as the supply side is concerned, the recovery rate and the harvesting residue rate are the most important factors that determine how much biomass can be extracted from a harvest site. The harvesting residue rate quantifies the proportion of total wood biomass that remains after timber harvesting operations, in other words, which part of total stand yield will be left on the ground after harvest. On the other hand, the recovery rate also indicates how much of that residual biomass left on the ground can be extracted after timber harvest. In the literature there is wide variation in this rate. The biggest discrepancy in the research studies is the relation between theoretical and practical rates of biomass recovery rate for specific regions.

Some authors have not recognized an operational reality that the extraction of 90%-100% of biomass, while possible on some sites, is not likely to be attainable across whole regions. This derives from a large number of factors, including transportation costs, unfavorable site conditions, unfavorable tree species compositions, forest practice guideline constraints, legal limits related to wetland protection, limits on harvestability connected to threatened and endangered species and habitat protections, laws limiting rates of stream sedimentation, owner preferences, and the high cost of harvesting small residues. The technology to harvest a high amount of residue exists, but costs and environmental conditions play a significant role. For example, marshes or mountainous areas significantly decrease biomass removals. In the SE U.S. there are the huge variations in forest conditions.

To accommodate the practical limits on recovery and harvesting residue rates due to the above factors, two alternative values of the harvesting residue rate were used. The applicable value for a particular site was determined based on forest types (coniferous and broadleaves), as identified by the FIA data. According to FIA, the harvesting residue rate for coniferous stands is approximately 20%, while for hardwood stands it amounts to about 40% of wood removals. The difference between the values for coniferous and hardwoods can be understood by the circumstances that after harvest operation in hardwood stands, more branches, limbs and other woody parts will remain on the ground, compared to coniferous trees, which have fewer branches and straighter stems. The FIA define and reports biomass as the aboveground dry weight of wood in the bole and limbs of live trees ≥ 1 inch in diameter at breast height (d. b. h). According to FIA, tree foliage, seedlings and understory vegetation are excluded from above definition [24].

The assumption about recovery rate is derived from a study by Jurevics [25]. The main objective of that study was to estimate optimistic and conservative ranges of available logging residues. In this study the value of 60% is considered as the most suitable in terms of residue availability and policy-based goals based on Ref. [25]. Furthermore, removing residues can reduce the costs of site preparation and the risk of wildfire. Ince et al. [16] use the same recovery rate value (60%), which was the key to modeling U.S. wood fuel feedstock consumption in this study. Finally, empirical evidence suggests that a 60% recovery rate is realistic for harvesting operations using conventional equipment [26]. A study assessing the potential for biomass energy development in South Carolina reflects the plausibility of this rate of recovery [27]. More studies are needed in the future to determine the recovery rate and its influence on sustainable delivery of biomass to wood industry.

3. Results

In the baseline run of timber supply in the South, there was little change in the price of softwood pulpwood, as represented by the price index, which reflects net timber supply impacts in the market model (Fig. 3). After the initial dip in the price index during the V-shaped recession, there were only small differences in the softwood pulpwood price index between 2008 and 2038.

Under the three bioenergy demand levels, timber prices increased significantly at various rates, ranging from 25% to 125% by year 2038 (Fig. 3). High demand scenarios produced the largest impact on timber markets and prices. The low and medium scenarios were similar in terms of effect on market outcomes, increasing prices from 25% to 50%. There were modest impacts in all three scenarios up to 2020, with an approximate 25% increase in timber prices, but the highest demand levels increase the market effects dramatically after that.

Substantially increased timber prices in the SE U.S. due to increased U.S. and EU energy policy demand would also probably affect that policy. EU's wood pellet importers are sensitive to future U.S. renewable energy policies and prices, the developments of which are so far uncertain. U.S. domestic wood fuel feedstock utilization has the main impact on wood market in the SE U.S and its coastal plain.

Under all scenarios and for both the SE U.S. as a whole and for the part of the SE U.S. with the most active wood pellet market, the coastal plain, carbon storage increases because of a positive planting response among private forest owners to higher timber prices and due to a conversion of marginal agriculture land to forest (Figs. 4 and 5).

High wood demand causes a price signal for private forest owners to plant trees. Moreover, newly established plantations compensate carbon loss from

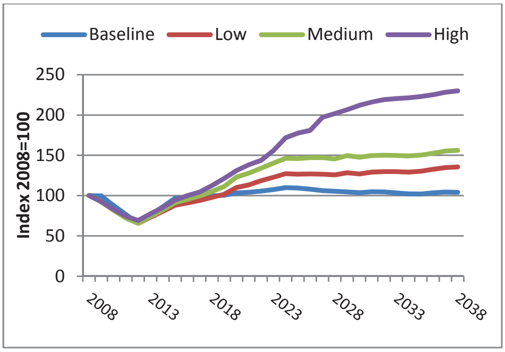

Fig. 3 Softwood pulpwood price in the Southeastern U.S. under different demand scenarios.

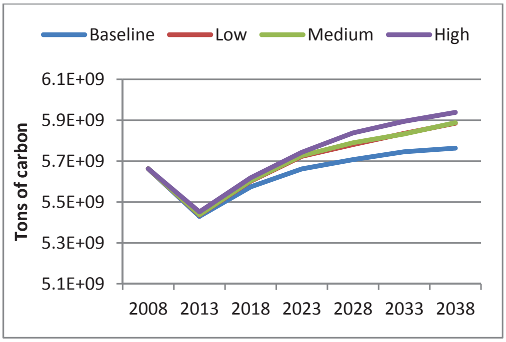

Fig. 4 Carbon storage in the Southeastern U.S. under different demand scenarios.

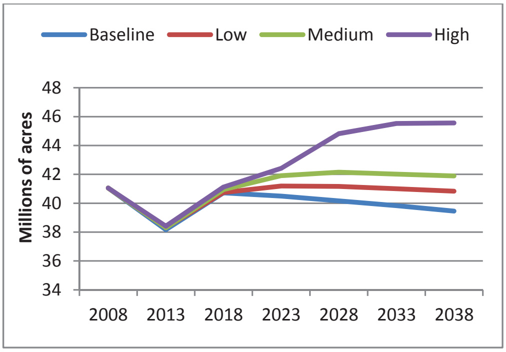

Fig. 5 Plantation acreage in the Southeastern U.S. under different demand scenarios.

higher harvest levels. A positive planting response may be advantageous, both to the regional economy and the environment.

All of the market impacts discussed above assume full utilization of available residues, with a minor exception for hardwood residues in the low scenario. This level of utilization may adversely affect site productivity, biodiversity and sustainable forest management. Separate research would be needed to address this issue.

4. Conclusions

This paper assesses the projected influence of EU wood biomass consumption and U.S. renewable energy policies on the forest market and carbon storage in the SE U.S. Both U.S. and EU policies are important with respect to sustainable use of natural resources, efforts to mitigating greenhouse gas accumulation, international timber product markets and trade. In this study, the authors find that the prices paid by EU importers for U.S. domestically produced wood pellets are sensitive to U.S. domestic renewable energy policies, whose future development is yet uncertain.

There is considerable evidence that biomass trade, especially in the pellet sector, will increase. Our results indicate that, at low EU pellet import demand levels, the impacts of woody biomass from forests will not have extreme effects on timber markets, and may even encourage carbon storage and planting of more forests. But if EU pellet import demand were coupled with an aggressive U.S renewable energy policy, timber prices would increase substantially, which is not likely to be sustainable economically. In this case, adverse impacts on natural resources could emerge. Furthermore, the existing forest products industry sector in the South would be adversely affected by much higher prices, and might therefore oppose such renewable energy policies.

Bioenergy policy seems to be the most influential factor on wood utilization and trade. Because both U.S. and EU policies regarding renewable energy are in states of flux, it is essential that future research into their forest sector impacts incorporate the latest policy developments. Such research could also be enhanced with studies of the price elasticity of biomass demand in the EU. Likewise, more specific data on wood flows to and from different countries, connected with clear specification of product codes and relatively quick actualization of databases, would be an important step towards analytical improvements. Linking EU demand models with U.S. supply models explicitly incorporates inventory dynamics and domestic competition effects on biomass price.

A better functioning bioenergy market is a matter of both time and policy reform. Increasing biomass demand will drive progressive infrastructure development while policy reforms can accelerate this process. Nevertheless, this research provides reasonable first-order estimates of the possible impacts of bioenergy demands on timber markets in the SE U.S., which can foster more discussion about the merits of the policies that the U.S. and EU adopt and revise.

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Paper III

Biomass and Bioenergy 108 (2018) 415–425

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Prospects for producing liquid wood-based biofuels and impacts in the wood using sectors in Europe

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ARTICLE INFO

Keywords:
Climate change mitigation
Forest biomass
Energy wood
Bioenergy
Forest sector

ABSTRACT

Rapid decarbonisation of the transport sector calls for increased use of biofuels. Part of the increase may be covered by fuels produced from logging residues, wood chips and round wood. This article addresses the economic potential and possible impacts of increased production of such wood based biofuels on the forest industries and production of wood based heat and power in the European Economic Area. A global model for the markets and trade of forest biomass and products, the EFI-GTM was applied for the analysis. The results indicate, firstly, that policy choices will have strong impacts on the allocation of biomass use between heat and power production and the production of liquid biofuels. Hence, the policy makers must have very clear goal setting for the preferred ways to solve the shift from the fossil fuel based energy system to a less carbon intensive one. Nevertheless, because large investments in biofuel production take time to plan and construct, and because the annual forest growth exceeds the harvests of wood in various parts of Europe, there is time to adjust the policies to control the market development. Secondly, even assuming the goal of limiting the global warming to 2 °C, the European forest industry production is projected to be rather little affected by the increased competition for biomass with the energy sector. This is because the rivalling regions are facing similar biomass demand challenges. Also, the relatively abundant wood biomass resources in Europe help the European forest industry to maintain its market shares.

1. Introduction

The Directive 2009/28/EC on renewable energy sources [1] set a 10% mandatory target for a share of renewable energy in the transport sector in the EU by 2020. Various measures, including subsidies and obligations to blend biofuels into conventional petrol and diesel fuels have been implemented by the member states in order to achieve that goal [2]. That has led to an increase in the share of biofuels in transport fuels in the EU28 to 4.2% in 2015 [3]. Yet, the sector is still heavily dependent on fossil fuels. The need for immediate action to decarbonize the transport sector that consumes one third of the final energy in the EU28 [3] paves the ground for a further increase in the use of biofuels. They can be used in existing vehicle stock under existing infrastructure [4]. Furthermore, the biofuels are practically the only available renewable energy source, when it comes to aviation, heavy duty road vehicles, and marine transports.

Although the majority of biofuels is currently and may also in the future be made from non-lignocellulosic biomass, it is expected there will be increased demand for biofuels made of woody biomass too. The EU's Indirect Land Use Change Directive [5] establishes a limiting quota for first generation biofuels and recently, the European Commission proposed a minimum share of 3.6% for advanced biofuels in transport by 2030 [6]. As one option, such fuels can be made of wood. The 3.6% share would require annually 48–62 million tonnes of woody feedstock without additional hydrogen input in production process and 16–24 million tonnes with it [7]. The possible increased use of wood in the production of liquid biofuels is expected to increase competition over biomass and thereby wood prices. That might force some of the other users of wood, for instance heat and power plants, to seek for alternative fuels or technical solutions [8–10].

Only few studies consider the market development and impacts of wood-based biofuels production separately from the biofuels made from other biomass types, or wood based biofuels production separately from all energy wood use. Lauri et al. [11] look at the impacts of increased aggregated demand for wood energy (biofuels + heat and power) on the forest sector and conclude that the global forest industry production is rather insensitive to increased wood demand in the energy sector even if bioenergy was to be produced in a scale required for the 2° C climate goal. They project that 5000 $hm^3 \ y^{-1}$ of round wood and forest chips would be used for energy globally by 2100 in such case.

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https://doi.org/10.1016/j.biombioe.2017.11.022
Received 24 March 2017; Received in revised form 28 November 2017; Accepted 29 November 2017
0961-9534/

Studies focusing on Norway [10] and Finland [8] demonstrate that large-scale investments on second-generation wood-based biofuels would increase biomass prices and reduce bioheat generation. Also the prices of sawmill chips could increase following such investments despite the abundant supply of biomass in the Nordic countries [12]. That can generate a modest increase in sawnwood production [11,12].

This study aims to examine (i) how alternative combinations of biofuel and biomass prices affect the production potential of liquid biofuels made of wood and allocation of wood biomass between biofuels and heat and power production in the European Economic Area, and (ii) what are the possible impacts that increased biofuel production could cause to the forest sector. The study focuses on bioenergy produced from logging residues, sawmill chips and round wood.

Large uncertainty prevails regarding the future supply and market prices of woody biomass and biofuels made of it. These factors are affected by the consumers' behaviour (e.g. demand for biofuels, heat and power, and forest industry products), by the costs and availability of alternative energy forms, and by the policies (taxation, subsidies, and prices of CO_2 emission allowances, etc.). These issues affect the tightness of competition for biomass between the users and make the investment and operation environment unpredictable. To overcome some of this uncertainty, we consider alternative future markets environments, where we explore the development of wood based biofuels production, allocation of wood feedstock between heat and power production and biofuels, and the impacts of the increased use of wood for energy on the forest industries. In order to create and consistently quantify these market environments, we use a global forest sector model, EFI-GTM [13]. The EFI-GTM model includes the international trade in all main wood biomass and forest industry products. This approach enables us to take into account for the vision that the use of wood based energy is increasing also outside of Europe [11,14,15]. Due to international trade, Europe is not isolated from the global developments.

2. Material and methods

2.1. The global forest sector model, EFI-GTM

The EFI-GTM is a multi-regional and multi-periodic partial equilibrium model of the global forest sector. It integrates forestry, forest industries, final demand for forest industry products and international trade in wood biomass and forest industry products. It includes 57 regions covering the whole world, but the regional disaggregation is most detailed in Europe. Most European countries are modelled as individual regions. The updated version used in this study encompassed about 30 forest industry and energy sector products, 5 round wood and 3 forest chips categories, 4 recycled paper grades, and the by-products of the forest industries.

The partial equilibrium approach implies that the other sectors of the economy than those related to the supply and demand of wood and forest-based products are only considered indirectly. The model finds the competitive market equilibrium prices and market equilibrium quantities of production, consumption and trade for products and regions included. Concerning transport biofuels, we include the trade in wood biomass that can be used in production of biofuels in any region where profitable, but we do not include further trade in biofuels although such trade can take of course place in practise.

The competitive market equilibrium is solved by maximizing the sum of consumers' and producers' surpluses of all regions and products minus the trading costs. The model is solved in a recursive-dynamic fashion by one period at a time, updating the relevant data for the next period in each step. The general model formulation is presented in the Appendix, while more details concerning the functional forms and solving the model can be found from Ref. [13].

2.2. Scenarios considered

We consider two scenario settings A and B described in their own sections in more detail below. In setting A, the focus is to explore the impacts of the increased use of wood-based energy on the forest industry. Setting B focuses on wood-based biofuel production and allocation of wood biomass between biofuel and heat and power producers.

In defining the global demand drivers for the forest industry products in these two settings A and B, we followed the assumptions elaborated within a scenario “Bioinno” in a recent study by Kallio et al. [15]. The regional consumptions per capita of mechanical forest industry products were assumed to be 50% higher than their 2008–2012 averages by 2050. Demand for the printing and writing papers was assumed to decline gradually due ongoing substitution by the electronic media, being globally 18% lower in 2040 than in 2010. Assuming the future textile industries to increasingly favour wood based fabrics, the demand for dissolving and non-paper pulp was assumed to increase rapidly, in particularly after 2025, reaching 55 million tonnes by 2040. For the rest of the final forest industry products, the demand was tied to GDP growth employing the GDP elasticities from the econometric studies and expert estimates. The GDP growths were assumed to follow the IMF's forecast [16] for the regions it was available and then to converge to the OECD's [17] long run forecast by 2030 and stay at that level thereafter. The above assumptions were only used to specify the demand functions over time. The eventual demands projected by the model depend on the markets that are balancing supply and demand.

We also partly capitalized on the energy sector development in Ref. [15], as detailed below and summarized in Table 1. We considered the “Bioinno” scenario to be an interesting reference point for the present analysis because it includes the assumption that the global energy sector adapts to the goal of limiting climatic warming below 2° C. Consequently, the use of biofuels and production of bio-based heat and power increases considerably in Europe and globally. It is of interest to compare the quantities of wood-based heat, power, and biofuels in alternative biofuel and biomass price settings in this study to the quantities projected to be needed for the 2° C goal. Furthermore, because reaching the 2° C climate goal is challenging, we consider it to be somewhat unlikely that wood-based bioenergy would increase even more rapidly than in “Bioinno”. In the EFI-GTM version used in this study, we do not include alternative energy production forms competing with wood-based energy. Hence, it is convenient to use the “Bioinno” quantities as boundaries for wood based heat and power production in the scenarios when we address the biofuel production. In Ref. [15], the projections for the global energy system were made by Lehtilä and Koljonen with the global energy model TIMES-VTT which is based on widely used TIMES modelling framework [18,19]. The model is grounded in microeconomic theory and it mimics forward-looking market behaviour by the market participants in the global energy sector. The model is frequently used to support national energy and climate policy making in Finland [20].

More information on the main data and assumptions used in the modelling can, in addition to what is described below, be found from Refs. [13,15] and from the Appendix.

2.2.1. Setting A: comparing the impacts of varying global demand for wood bioenergy on the forest industry

Here, we compare three scenarios to examine the influence of potential future increases in the global demand for wood in heat, power and biofuel productions on the forest industry in Europe. We calculate two alternative cases to the “Bioinno” scenario [15]. In “Bioinno”, use of woody biomass is growing in all fronts: in the forest industry, in heat and power production, and in production of biofuels. In one alternative, we remove the possibility to increase production of wood-based transport fuels, but assume the heat and power production to increase as in “Bioinno”. In another alternative, we allow no increase in any wood based energy production after 2010, so that the forest industry

Table 1
Summary of the main scenario assumptions regarding the production of wood based biofuels and heat and power (h&p) in the settings A and B.

	Setting A			Setting B
	No increase of wood[a] based energy after 2010	Energy wood use increases in h&p production only	Energy wood use increases in h&p production and biofuels (< 2 °C)	12 combinations of prices that h&p plants can pay for wood at maximum and biofuel prices
Wood demand in h&p plants in 2040				
The EEA	150 TWh[b]	253 TWh[c]	253 TWh[c]	Constrained to be at most 253 TWh
The rest of the world	380 TWh	1067 TWh[c]	1067 TWh[c]	Constrained to be at most 1067 TWh[c]
Production of wood based biofuels in 2040				
The EEA	0	0	104 TWh	Constrained to be at most 1223 TWh[d]
The rest of the world	0	0	1149 TWh	Constrained to be at most 1149 TWh[c]
Price h&p plants can afford to pay for wood	endogenous	endogenous	endogenous	20, 30 or 40 €·MWh^{-1}
Price of liquid biofuel	not relevant	not relevant	Endogenous (median of the regional reference prices given to the model was 69 €·MWh^{-1})	70, 80, 90 or 100 €·MWh^{-1}

[a] Wood refers here to logging residues, sawmill chips and roundwood.
[b] In the EFI-GTM, we assumed that 1 m^3 of wood corresponds roughly to 2 MWh.
[c] Based on the projection of the quantity needed to satisfy the 2 °C climate goal in Ref. [15].
[d] 50% of the transport sector energy demand projected in National Energy Action Plans of the EU member states for 2020.

gets to be the sole user of the growing wood resources.

2.2.2. Setting B: comparing energy wood uses under alternative bioenergy pricing schemes

Here, we examine the supply of biofuels and allocation of wood biomass between biofuels and heat and power production in the EEA under alternative operations environments. We vary the energy sector market assumptions concerning (i) the producer price paid for liquid biofuels and (ii) the maximum price that heat and power producers can pay for wood biomass in order to compete for that with other users. The results will also be reflected against the wood energy quantities of "Bioinno" [15], to assess which market conditions make it possible to achieve the scenario path for "Bioinno" with the 2 °C climate mitigation target.

The price afforded by the heat and power producers to pay for energy wood is varied from 20 € to 40 € per MWh of wood feedstock and the producer prices of liquid biofuels is varied from 70 to 100 € per MWh of fuel. We consider the projected consequences of these alternative price settings but not the drivers or causes behind these prices. They can be interpreted to result from the alternative levels of technical development affecting the position of the producers in the feedstock market or they can result from and encompass various alternative configurations of taxes and subsidies applied to the energy sector. For instance, the price of 40 €·MWh^{-1} for wood corresponds to some 80 €·m^{-3} and can be regarded to be quite high compared to the current wood costs even in many industrial purposes, for instance pulp production. Yet, some existing subsidy systems for biobased electricity already lead to the situation where energy producers can pay relatively high prices for wood. Proskurina et al. [21] report subsidies for the biobased electricity of the magnitude up to 60 €·MWh^{-1} (Denmark), 53 €·MWh^{-1} (Estonia), and 56 €·MWh^{-1} (the United Kingdom), at least for some power plant installations. Even when converted to the feedstock level (e.g. assuming the fuel-to-electricity conversion efficiency of 30% [2]), these subsidies may raise considerably the price that can be paid for wood in power production and have a significant impact on the European wood based sectors [22]. Also, a price set on carbon, for instance in the form of emission allowance price, has impact on the price that heat and power producers can pay for wood.

In the model simulations, we constrained the wood based heat and power production in the EEA and the Rest of the World (hereafter RoW) to be at most in the level of the "Bioinno" [15] production. The wood-based liquid biofuel production in each EEA country was allowed be higher than in "Bioinno", but limited not to raise linearly more than to reach by 2050 the level of 50% of the *total* transport fuel use in 2020 estimated in the National Renewable Energy Action Plans of the EU MSs [23]. This allows a generous increase in European biofuels production. In RoW, we limited the liquid biofuel production not to exceed the "Bioinno" levels. These boundaries summarized in Table 1 were implemented as constraints into the EFI-GTM model.

2.2.3. Assumed available biofuel production technologies

Data on alternative technologies for biofuels production into the EFI-GTM model were formed or directly taken from McKeough and Kurkela [24], Hannula and Kurkela [25] and Hannula [26]. The data are summarized in Table A 1 in Appendix. In the model simulations, the regions chose almost solely a Fischer-Tropsch technology with biomass to biofuel conversion efficiency of 57% due to its more favourable cost structure concerning other inputs than biomass. Because there are no large scale plants making liquid biofuels from forest chips or roundwood in commercial operation, there is uncertainty over the eventual production costs. The alternative schemes for liquid biofuels prices in setting B can also been interpreted to cater for variations in marginal production costs.

3. Results and discussion

3.1. Impacts of increased biofuels production on the forest sector

Let us start by considering the impacts in the EEA related to wood harvests and prices and forest industry production (setting A).

3.1.1. Wood harvests and prices

The large quantities of energy wood (214 hm^3) projected in Ref. [15] to be needed in the EEA in 2040 for going towards the 2° C climate goal can be reached with forest chips and fuelwood as main biomass sources. Still, the European pulpwood harvests increase considerably compared to the case where there would not be any new liquid biofuel production (Fig. 1). The reason is that in the case where large quantities of biomass are used for decarbonising the global transport sector, biofuel production increases globally and not only in the EEA. This reduces considerably the possibilities of the EEA forest industry to import pulpwood from the rest of the world. Consequently, the wood harvests

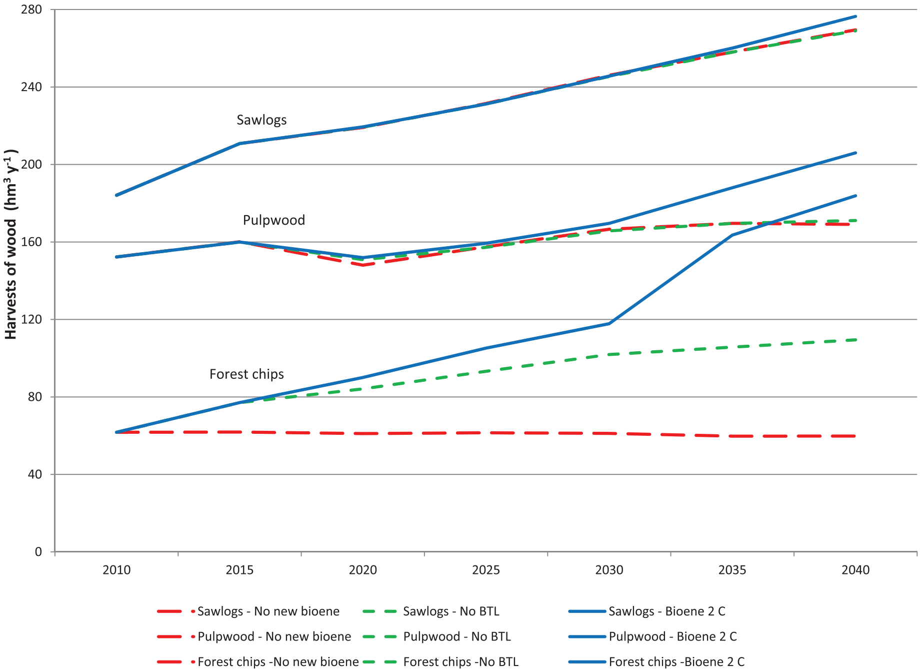

Fig. 1. Projected harvests of sawlogs, pulpwood and forest chips in the EEA when (i) demand for energy wood stays at 2010 level ("Now new bioene"), (ii) wood use increases in heat and power production but no wood based biofuels enter the market ("No BTL"), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C ("Bioene 2 C").

in the EEA are increased to compensate the cut in imports. In 2040, pulpwood harvests in the EEA are projected to be 20% (35 hm^3) higher in the case where wood-based liquid fuels are produced than in the case where modern energy wood only goes to heat and power production in increasing amounts. This also affects the prices of pulpwood and forest chips (Fig. 2) that are over 40% higher in the case where wood-based liquid biofuels enter the market than without them.

The price and demand increases for pulpwood and wood used for energy do not bring an important raise in the sawlog harvests in the EEA (Fig. 1), although that could be expected noting that the increasing value of sawmill chips could improve the profitability of sawnwood production and thus increase the sawlog demand. The difference in the sawlog harvests between the scenarios is about 7 hm^3 (less than 3%) in 2040 for the whole EEA region. Even this modest change is mainly due to reduced net imports of logs to the EEA, mostly hardwood, which calls for increased domestic harvests. The EU sawnwood production is not profiting more from the situation, because being a global phenomenon, the increase in the use of energy wood does not bring any particular advantage to the producers of sawnwood in the EEA.

If wood based bioenergy production remained in the 2010 level, prices of forest chips would decline in the long run (Fig. 2), because their supply would be higher due to increasing roundwood harvests from which they come as a side-product and because increasing amounts of household fuelwood could be used for more efficient modern energy relieving the pressure to harvest forest chips for that. Instead, pulpwood prices tend to be rising in any case due to increased forest industry production. Fig. 2 also shows that setting the biofuel production to match the biomass needed for meeting the 2 °C climate goal would cause high pulpwood price increases after 2030 in the EEA because of the consequent changes in world trade.

3.1.2. *The forest industry*

In the scenarios with increased wood based energy production for the 2 °C climate goal, this increase takes place globally. In such setting, the operating environment of the forest industries is affected everywhere and not only in the EEA. Therefore the forest industry production is not projected to be changed much in the EEA across the cases (Fig. 3).

The results also show that the impacts of bioenergy on the forest industries are not always obvious. The chemical pulp production in the EEA is projected to be 2–4% higher during 2025–2030 in the case where both wood based liquid biofuels and wood-based heat and power production are increased globally than in the cases with less bioenergy, although one would expect the pulp production to decline due to stronger competition for biomass. At the same time, the global total chemical pulp consumption is projected to be marginally lower than in the other cases. This is because the investments in new capacity in RoW take place more slowly in the case where there is strong competition over biomass between the energy sector and the forest industry. The forest resources in the EEA allow for increase in wood-based bioenergy production, while the forest industry production is somewhat stagnant due to mature product markets. Nevertheless, by 2040, the EEA pulp production is projected to be some 5% lower with biofuels than without them. The results indicate that the available forest resources in the EEA may bring some advantage to the region's forest industry in the next decades by improving its possibilities for meeting the tightening global competition in the longer run.

3.2. *Comparing the market outcomes under alternative biofuel pricing schemes*

Let us now look more closely at the production volumes of wood based biofuels in the EEA and the allocation of wood between liquid biofuels and heat and power under alternative pricing schemes (setting

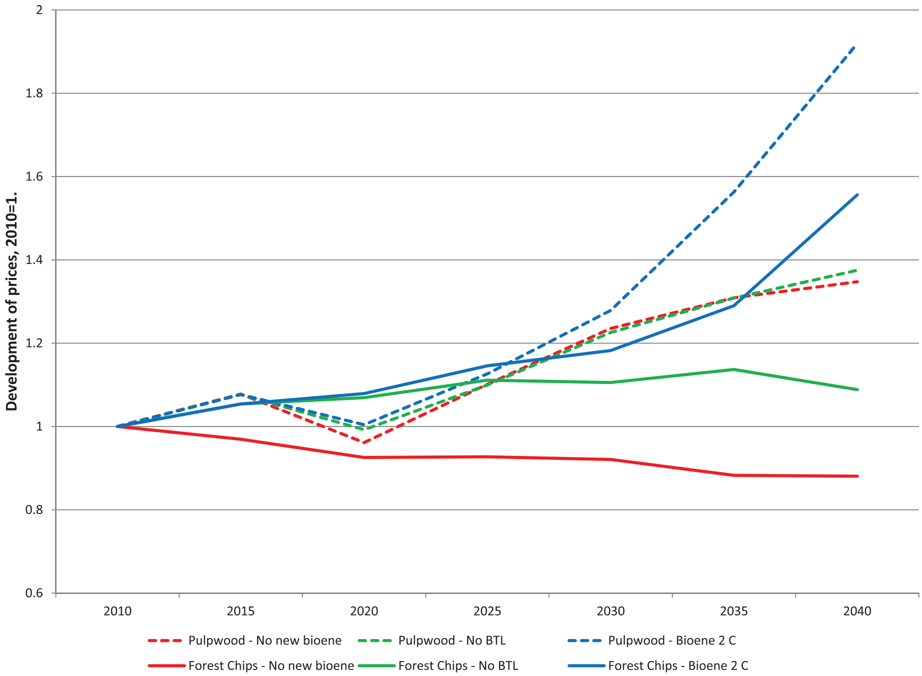

Fig. 2. Projected development of average market equilibrium prices in the EEA for softwood pulpwood and forest chips with 2010 = 1.0 when (i) bioenergy demand stays at 2010 level ("No new bioene"), (ii) wood use increases in heat and power production but no wood based biofuels enter the market ("No BTL"), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C ("Bioene 2 C").

B) as displayed in Figs. 4 and 5.

Across the pricing combinations considered, the highest quantity of liquid biofuels in the EEA can be expected under the setting where heat and power plants are able to pay at most 20 €·MWh^{-1} for wood and mill gate price is 100 €·MWh^{-1} for biofuels (Fig. 4a). Such combination leads to the production of 800 TWh of transport biofuels made out of wood in the EEA in 2040. Furthermore, no wood would be used for modern heat and power production after 2025, as then the price for energy wood is driven above the level of 20 €·MWh^{-1}. The average price of energy wood in the EEA exceeds 40 €·MWh^{-1} by 2035 and continues to increase after that due to increased competition for wood globally.

When we decrease the assumed biofuel price to 70 €·MWh^{-1} and let the heat and power plants pay at most 20 €·MWh^{-1} for wood (Fig. 4d), the quantities of wood used in heat and power plants are projected to decline to be only one third of the quantity in 2010 by 2040, whereas liquid biofuel production raises to about 160 TWh in the EEA. The projected average price for energy wood biomass remains below 25 €·MWh^{-1} in the EEA in this case. After 2020, the liquid biofuels production only increases in Nordic countries and in Eastern Europe, where biomass availability and costs make that possible.

At the price of 20 €·MWh^{-1}, the supply of energy wood is rather limited and it depends on the profitability of the alternative end uses where the supply is directed. Instead, if heat and power producers can afford to pay 30 €·MWh^{-1} or more, they can source considerably more wood (Figs. 4 and 5) despite the competition coming from the biofuel producers. It is to be noted, however, that at the regional level, also the local transport costs for forest biomass would affect the use of biomass [10]. The need for transporting the feedstock can make it possible for small heat producers to buy smaller quantities locally, as large liquid biofuel producers need to add transport costs both for feedstock and the end products.

In Ref. [15] it was projected that in order to meet the 2 °C climate goal the quantity of energy wood used in modern heat and power production in the EEA would need to increase from 150 TWh in 2010 to up to 250 TWh in 2030–2040. Fig. 5a–d shows that such energy wood quantities in modern heat and power productions are fully obtained in the cases where heat and power plants can afford to pay up to 40 €·MWh^{-1} for wood and where biofuel producers get 70 to 80 €·MWh^{-1} of their output. With higher biofuel prices of 90 €·MWh^{-1} or 100 €·MWh^{-1} examined in this setting, such 2 °C quantities for heat and power can only be obtained before 2030. After that the increased biofuel production drives the average price of energy wood to the level above 40 €·MWh^{-1}.

In the"Bioinno" scenario [15], the quantity of energy wood projected to be needed for liquid biofuel production in the EEA to match the 2 °C climate goal was roughly 100 TWh by 2040. Such production in 2040 is projected to be obtained for instance if heat and power producers can pay 30 €·MWh^{-1} for their wood feedstock and where biofuel producers get 70 €·MWh^{-1} for their output (Fig. 5). At several other settings with higher biofuel price or lower ability for heat and power producers to pay for biomass, the EEA production of liquid biofuels are projected to be considerably higher than 100 TWh.

Even in the cases where the heat and power plants are assumed to be able to pay up to 40 €·MWh^{-1} for wood biomass and the biofuel prices are not assumed to be very high, the liquid biofuel production is supported by path dependency. In the early years before 2030, wood biomass price is projected to be well below 40 €·MWh^{-1}, and much of the investment activities in biorefineries take place then (Fig. 5a–d). As the investments are irreversible the existing facilities will be kept in use even despite their poor profitability later on.

It is far from obvious that the most sumptuous biofuel quantities projected above could materialize even if shown feasible in the model

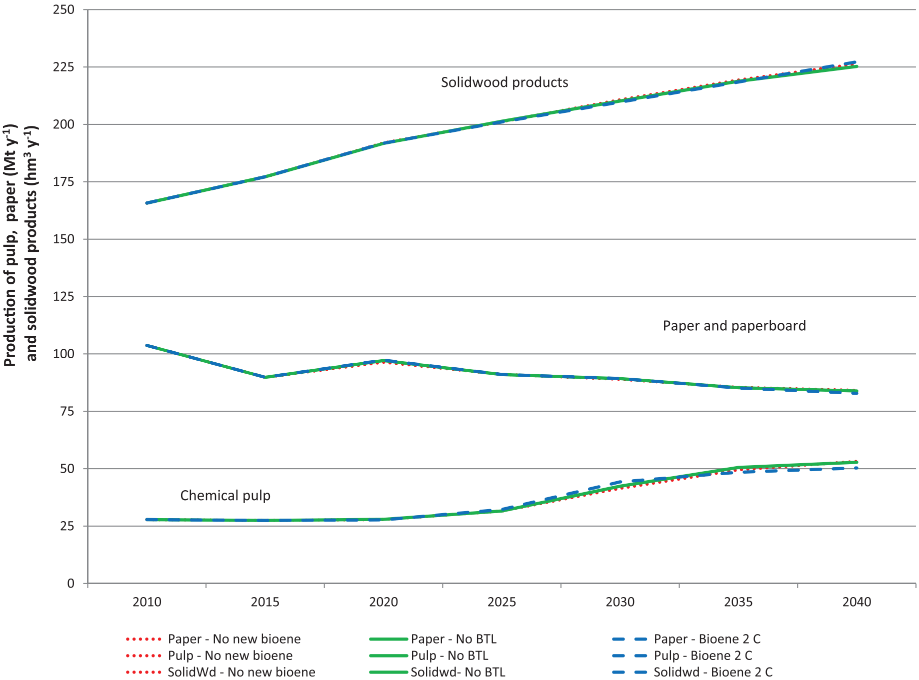

Fig. 3. Projected annual production of paper and chemical pulp (millions tonnes), and solid wood products (millions cubic metres) in the EEA when (i) bioenergy demand stays at 2010 level (“No new bioene”), (ii) wood use increases in heat and power production but no wood based biofuels enter the market (“No BTL”), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C (“Bioene 2 C”).

projections. The required investments into the production capacity would be large to take place in a decade or two. Delays in realizing the investments from the planning phase up to market operation and the uncertainties faced by the investors regarding future policies and the price and availability of biomass are considerable. Hence, the investors may go into large projects sequentially in order to see how the previous investments are being met in the market, and this process can be slow.

4. Conclusions

If wood-based heat, power and biofuels production are increased in order to respond to the goal of keeping the climatic warming below 2 °C, the production of bioenergy will increase globally. Our results indicate that under such setting the European forest industry production would not be affected much by increased competition for biomass, because the rivalling regions face similar biomass demand challenges. This and the relatively abundant biomass resources may help the European forest industry to maintain its market shares.

Our results suggests also that feedstock costs and prices of biofuels can have drastic impacts on the allocation of biomass use between the production of heat, power and liquid biofuels in Europe. Because these economic factors are affected by policies, the policy makers should have very clear goal settings for their preferred ways of solving the shift from fossil fuel based energy system to the system with less greenhouse gas emissions. The policies interfering with the markets should be designed so that biomass can be expected to go to the end uses providing the desired societal benefits. This means the challenge of setting the priorities between production of heat, power and fuels for alternative transport modes, also accounting for the other uses of wood and forests and environmental concerns.

In the short or medium term, when the production capacity of liquid biofuels is gradually accumulating, there is wood for both heat and power production and liquid biofuels. In the long run, the competition between them is projected to be more tight, and then the allocation of the use of biomass depends largely on the policies. Yet, because the investments for biorefinery capacities and the infrastructure are not taking place immediately and because in various parts of Europe the biomass availability is not yet of strong concern in the next decade, there remains room for the policy makers to adjust taxes, support mechanisms and restrictions governing the biofuel use in order to control the development.

Nevertheless, early assessment of the future biomass availability and decisions based on that are needed, because the investments in biorefineries, heat and power plants or forest industry production facilities are irreversible and shape the market demand for wood biomass for a long time. Particularly, the new heat and power plants can be rather flexible in their fuel use. Hence, in the regions where there is no cap for GHG emissions for the heat and power plants or where these plants can source the emission allowances from the market, the plants that are flexible in their fuel choices can switch to fossil fuels if biomass is not available at competitive prices. Such a situation with severe competition over biomass would not be good for climate or for the society that possibly have subsidized building these heat and power plants or biofuel plants.

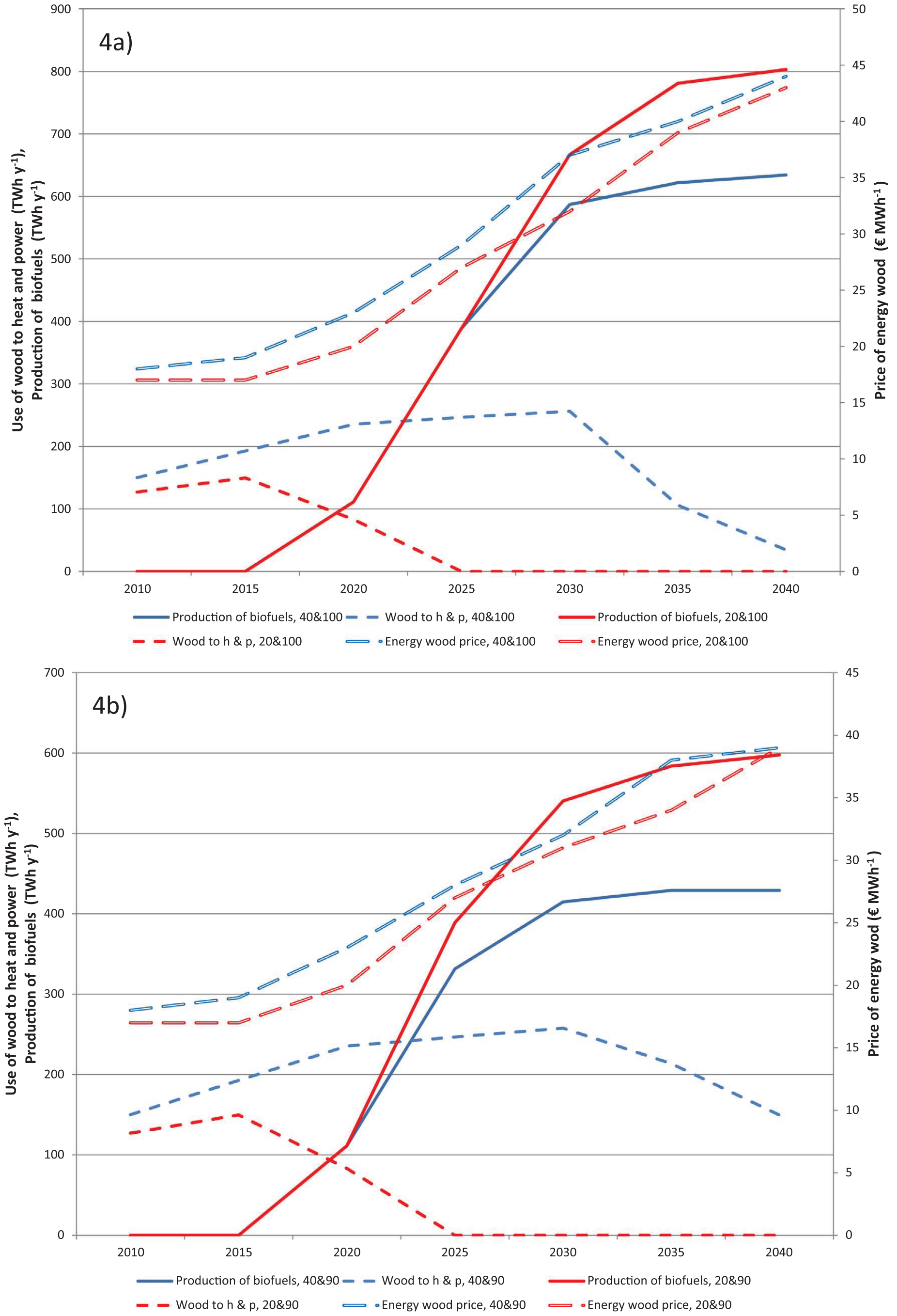

Fig. 4. a–d. Projected use of wood in heat and power production (TWh y^{-1}), production of wood-based liquid bi–ofuels (TWh y^{-1}), and market equilibrium price for energy wood (€·MWh^{-1}) in the EEA, when the heat and power plants can pay at maximum 20 €·MWh^{-1} (red) or 40 €·MWh^{-1} (blue) for wood and when the liquid biofuel price at mill gate is 100 €·MWh^{-1} (4a), 90 €/MWh (4b), 80 €·MWh^{-1} (4c) or 70 €·MWh^{-1} (4d). For instance 20&100 refers to the respective price combination of 20 €·MWh^{-1} and 100 €·MWh^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

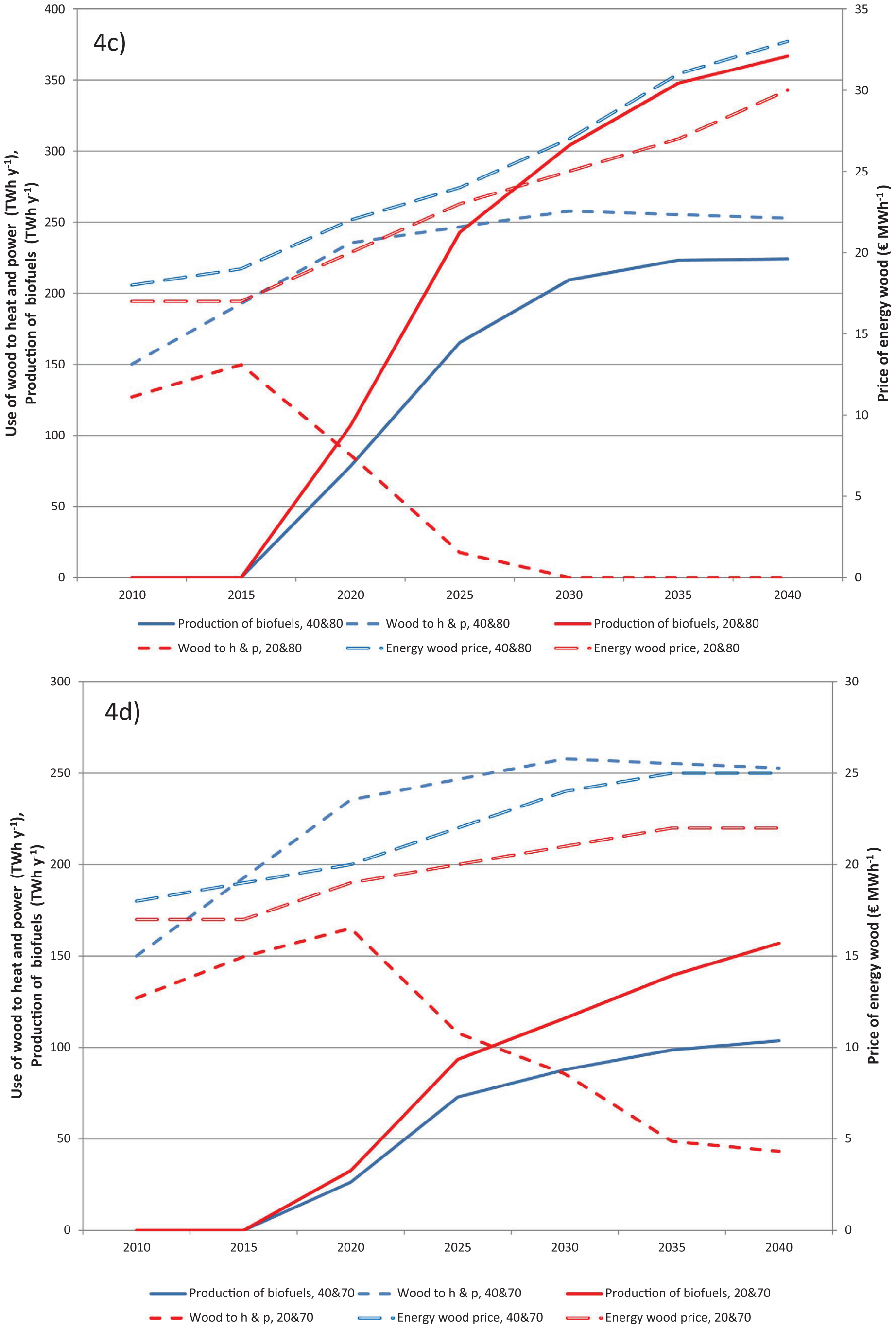

Fig. 4. (*continued*)

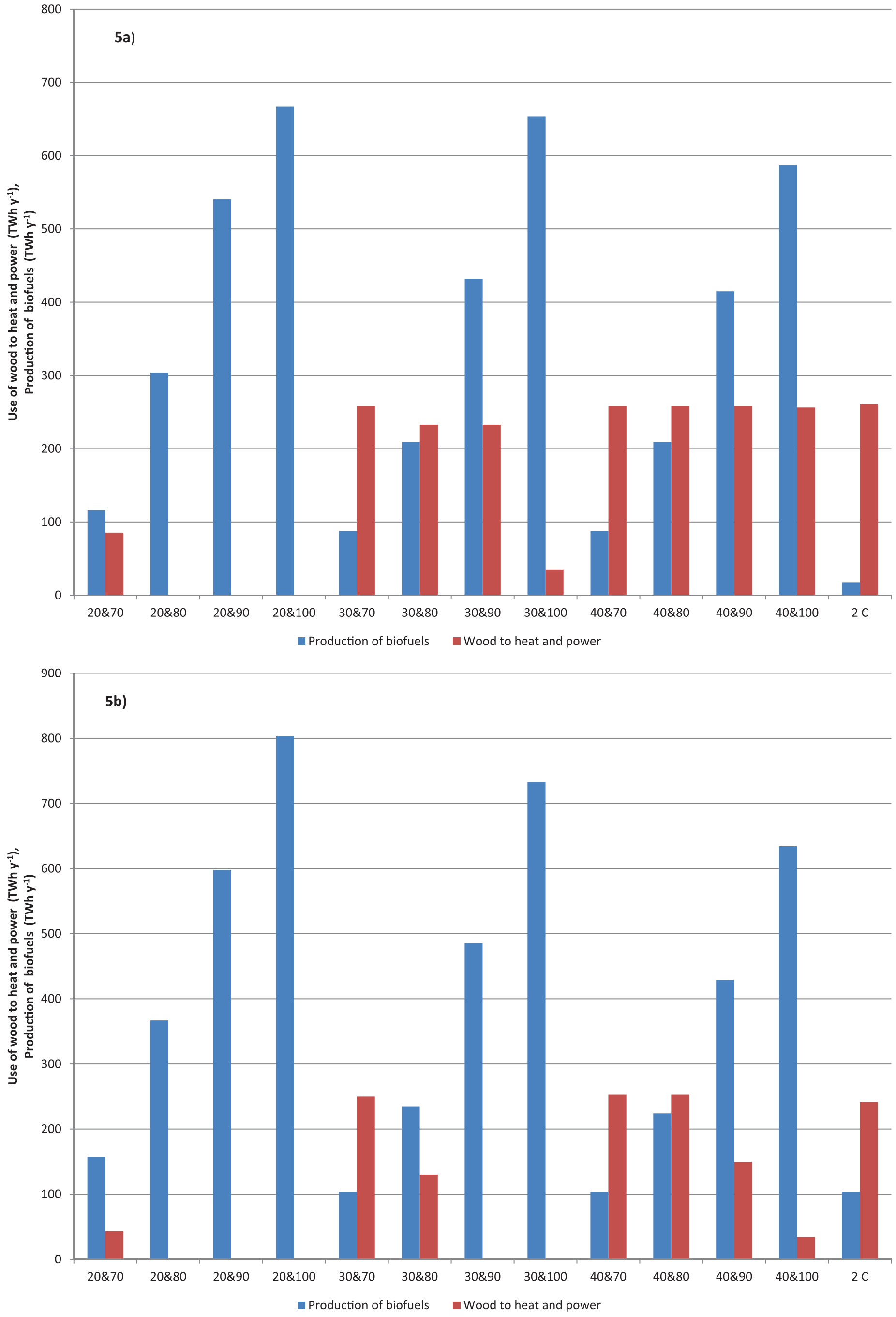

Fig. 5. a–b. Projected production of wood based liquid biofuels (TWh y^{-1}) and use of wood in heat and power plants (TWh y^{-1}) in the EEA in 2030 (5a) and 2040 (5b) with alternative combinations of prices that heat and power plants can pay for wood at maximum (€·MWh^{-1}) and the price of liquid biofuel at mill gate (€·MWh^{-1}). For instance 20&100 refers to the respective price combination of 20 €·MWh^{-1} and 100 €·MWh^{-1}, and “2 C” refers to quantities projected to be needed for 2 °C climate goal in Ref. [15].

Acknowledgements

In addition to the home institutes of the authors, this work was supported by the Norwegian Research Council Project 193817 (Cenbio) and the Finnish Funding Agency for Technology and Innovation (TEKES) under the research program the Sustainable Bioenergy Solutions for Tomorrow (BEST). The authors are solely responsible for the results.

Appendix 1

The EFI-GTM model structure

The model structure is briefly presented below by introducing first the market agents and then the model. In the notations, the index referring to time *t* (year) is omitted for notational convenience, as the model is solved recursively, year after another. For more details regarding the functional forms and their specifications, we refer to [13].

Consumers

The consumers of the final forest industry products and biofuels, and heat and power plants buying wood for feedstock are represented in the model by inverse demand functions. Consumers are assumed to maximize their welfare, which is at greatest when consumers' surplus, defined as the area below the demand curve and above the market price is maximized for each product. In region *i*, let $q^i = (q_k^i)$ be a vector of the consumed quantities and let $P_k^i(q_k)$ be differentiable and non-increasing inverse demand function for product *k*. Let $\pi^i = (\pi_k^i)$ be a vector of product prices that consumers take as given, and let Q^i denote the closed, convex, and non-empty consumption possibility set.

Producers

Producers (e.g., timber growers, forest industry firms, biofuel producers) of a given region *i* maximize their profits, which can be defined as producer's surplus. Let $z^i = (z_k^i)$ be a vector of net output volumes for products *k* in region *i*, and let $C_k^i(z_k)$ be the marginal cost function for product *k*. The production possibility set V^i is assumed to a closed, convex, and non-empty. For the forest industry and biofuel producers, production with each production technology in region *i* is limited by a periodic capacity. Some production technologies (available capacity using certain technology) are already in use and therefore for them the capital costs related to investment made previously are sunk. For new production capacity (investments), full capital costs are included into marginal costs$C_k^i(z_k)$, but these costs are removed if the investment has been profitable and thus realized in the previous period. As discussed (Table 1), we also imposed scenario dependent constraints for the regional heat, power and biofuels production levels. Under competitive markets, the producers take product prices π_k^i as given.

Trade

Trade can be illustrated like a separable activity carried out by trade agents. To maximize the gain from trade, exporters buy goods at the domestic price, pay for the transportation, and sell at the price of the importing region. Similarly, importers buy at import prices and aim to make profits by selling at the domestic prices. Notation e_k^{ij} refers to the exports for product *k* from region *i* to *j*, whereasD_k^{ij} denotes the transportation cost for a unit of product *k* from region *i* to *j*. Bilateral export flowe_k^{ij} of a product matches the import flowe_k^{ji}.

Market equilibrium

For the markets to be equilibrium it must hold for every endogenous commodity and all regions that the consumption plus imports is equal to production and exports. Furthermore, all the agents (producers, consumers and traders) must be in their optimal solution given the market equilibrium prices and their own choice of production, consumption or trade quantities.

Model formulation

The profit or welfare maximization problems of the above agents are separable as all the agents are price takers. These problems can be aggregated and adding the condition that the market clears, the problem can be casted to one single convex optimization problem. There the competitive equilibrium is solved by maximizing sum of producers' and consumers' surpluses minus the transportation costs (Eq. (1)), subject to material balances (Eq. (2)), and constraints limiting production possibilities (mainly production capacities) (Eq. (3)) and constraints limiting consumption (Eq. (4)) and non-negativities related to activity variables (Eq. (5)) in all the regions.

$$Max_{q^i,z^i,e^{ij}} \quad \sum_{ik} \left[\int_o^{q_k^i} P_k^i(q_k^i)\mathrm{d}q_k^i - \int_o^{zi_k} C_k^i(z_k^i)dz_k^i \right] - \sum_{ijk} D_k^{ij} e_k^{ij} \tag{1}$$

$$q_k^i + \sum_j e_k^{ij} = z_k^i + \sum_j e_k^{ji}, \qquad \forall\ ki. \tag{2}$$

$$z^i \in V^i \quad \forall\ i. \tag{3}$$

$$q^i \in Q^i \quad \forall\ i. \tag{4}$$

$$q^i,\ x^i,\ e^{ij} \geq 0 \quad \forall\ ij. \tag{5}$$

The optimality conditions for the problem above equal the equilibrium conditions for regional competitive markets for one period *t*. The dynamic changes from year to year are modelled by recursive programming. That is, the long run spatial market equilibrium problem is broken up into a sequence of short run problems, one for each year. Hence, the decision makers in the economy are assumed to have imperfect foresight.

After each period, the data on market demand, timber supply and changes in production costs and available technologies and their capacities are updated. Between the periods, it is possible to introduce assumptions regarding for instance demand growth or exogenous input prices that may be assumed to change in the future. Thereafter, a new equilibrium is computed subject to the new demand and supply conditions, new technologies, and new capacities.

Appendix 2

Table A.1
Biofuel technologies specified into the model based on studies [7,24–26].

Input per 1 MWh of biofuel output (negative figure is by-product)	FT-Liquid fuels Tehc. integrated to pulp mill, adapted from Ref. [24]	FT-Liquid fuels Tech. LTFT-3 in Ref. [25]	FT-Liquid fuels Tech. LTFT-2 in Ref. [25]	Gasoline Tech. SG in Refs. [7,26]	Gasoline Tech. OG in Refs. [7,26]	Gasoline Tech. SG+ in Refs. [7,26]	Gasoline Tech. OG+ in Refs. [7,26]
Biomass, MWh	1.05	1.75	1.91	1.96	1.93	1.02	0.75
Power, MWh	0.20	0.01	−0.01	0.047	0.079	1.020	1.316
Heat, GJ	0	−1.0	−1.30	−1.47	−1.33	−1.21	−1.22
Other o&m costs, €	14.0	10.9	11.9	21.3	21.5	12.1	9.7
Capital costs, €	35	32.1	35.2	65.4	66.4	37.5	29.8

Notes: Tech. refers to technology. FT refers to Fischer-Tropsch. Possible output of LPG (Liquefied Petroleum Gas) is aggregated to heat output in gasoline technologies. SG and OG refer to steam and oxygen gasification, respectively. O&m refer to operation and management. In hydrogen boosted technologies (marked with +), electricity includes power needed for producing hydrogen. Wood biomass is measured wet with 50% water content.

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Paper IV

Analyzing the impact of carbon pricing on forest management and marginal abatement cost curves in Europe using the new forest sector model EUFORIA

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ABSTRACT

The design and implementation of effective climate change policies and their consequences for forestry and forest products markets are urgent issues in Europe. In this paper, we first describe a new dynamic spatial forest sector model of the European forest sector. The model has a detailed wood supply component based on alternative forest management options and includes production costs, demand, and trade of forest industry products. We then present an application of the model in a case study, analyzing impacts of introducing a carbon tax/subsidy price system on all CO_2 emissions/sequestrations in the European forest sector, and estimate marginal carbon abatement cost curves for this sector. The results indicate a greater reduction in the area assigned to partial harvesting than to clearfelling across all carbon prices and time periods. Average clearfelling age increases with increasing carbon prices, but no more than 3 years compared to the base scenario with zero carbon price. With a carbon price of 100€/tCO_2 and use of 3% p.a. discount rate, the model results show that there is a possibility to sequester around 20% more carbon annually over 2010-2090 time horizon in the European forest sector than without carbon pricing. We conclude that the model is promising for analyzing impacts on the forest sector of future policies related to, e.g., climate change mitigation, bioenergy production, and forest conservation.

Keywords: *forest sector, Europe, EUFORIA, bioeconomic modelling*

INTRODUCTION

The European Union (EU) countries have agreed on a new 2030 Framework for climate and energy including EU-wide targets and policy objectives for the period between 2020 and 2030 (European Commission 2014). As stated, these targets aim to help the EU foster a more competitive, secure, and sustainable energy system and enable it to meet its long-term 2050 greenhouse gas (GHG) reduction target. The Renewable Energy Directive (REDII) for 2021-2030 provides the structure for meeting the updated renewable energy target of at least 27% of EU's final energy consumption by 2030, and proposes harmonized mandatory sustainability criteria for solid, liquid and gaseous biomass along with a verification protocol to demonstrate compliance with the requirements (European Commission 2016).

The new strategy sends a signal to the market, encouraging private investment in low-carbon technology and electricity networks. In the REDII revision of previous renewable energy targets (European Parliament 2009), wood biomass is recognized as an important component among other renewable energy sources. These new targets also fit within the European Bioeconomy Strategy (European Commission 2012), recognizing and enhancing the essential role the forest-based sector plays as a source of renewable materials and energy[1] while reducing emissions through fossil fuel replacement (Ruter et al. 2016), and as a carbon sequestration sink (Yude et al. 2011), while simultaneously providing other important environmental, economic and social benefits.

In addition to the renewable energy targets and bioeconomy strategies, policymakers are also examining other ways the forest sector can contribute to climate change mitigation in effective ways. Three such possibilities are to stimulate additional forest carbon sequestration and reduced emissions through changes in forest management, product substitution, and storage in long-lived forest products. Inevitably, the diverse European policy goals lead to a variety of trade-offs and potentially policy incoherence, as well as consequences which are difficult to foresee. As such, studies utilizing model-based simulations have been used quite frequently to explore potential policy outcomes.

One attractive option for such a task is the use of theoretically consistent forest sector models (Solberg, 1986; Latta et al, 2013). This class of research tool is well geared toward the explicit representation of forest sector activities by combining information about the forest resource and wood supply with that of a cascading wood demand including forest industrial

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[1] Forest biomass accounted for around half of the EU's total renewable energy consumption (European Commission, 2013)

production, consumption of intermediate and final products, and trade. As briefly outlined below, several forest sector models exist for climate policy analysis in the EU and elsewhere, and they vary rather much regarding geographic coverage, spatial and sectoral detail, and temporal dynamics. For instance, Lauri et al. (2012) studied the effects of a fossil fuel CO_2 tax on the use of wood in Europe. The European Forest and Agricultural Sector Optimization Model (EUFASOM) was used, assuming that agents have perfect foresight (i.e. intertemporal optimization) regarding forest industries, but not regarding forest management (i.e. timber supply was calculated recursively). It was found that at the carbon price of 50 Euro per ton of carbon dioxide (henceforth, €/tCO_2) the use of wood for energy begins to compete with the use of wood in the forest industry. Moiseyev et al. (2013) examined the effects of carbon emission prices on the use of wood for electricity and heat production in the EU, applying the global forest sector model EFI-GTM (Kallio et al. 2004, Moiseyev et al. 2011). This model is solved in a recursive-dynamic fashion by one period at a time, updating the relevant data for the next period in each step, and having no alternative forest management options. The study found that at a carbon price of 100 €/tCO_2, around 31 million cubic meters (Mm^3) of industrial wood, in addition to 224 $Mm^3$of logging residues, would be used for electricity and heat in the EU region in 2030. The relatively low quantity of industrial wood used by the energy sector despite the assumed collapse of the use of coal was explained by the fact that under high CO_2 prices, other energy forms like natural gas, solar and wind energy become more and more competitive (Moiseyev et al. 2013). A follow-up study found that this wood could be sourced from the reduction of 12 Mm^3 going to wood products, 10 Mm^3 additional imports and 8 Mm^3 additional harvests (Moiseyev et al. 2014). Alig et al. (2010) examined the impacts of several scenarios about carbon prices in the United States and found that receipt of carbon-related payments by landowners in forestry and agriculture could have substantial impacts on future land use patterns, levels of terrestrial carbon sequestration, forest resource conditions, agricultural production trend, and bioenergy production. They used the Forest and Agriculture Sector Optimization Model-Green House Gases (FASOM-GHG) model (Adams and Haynes 2007, Lee et al. 2007, Adams et al. 2009), which is an intertemporal optimization model, to simulate both economic (market) and biophysical system in the U.S. forestry and agricultural sectors. Buongiorno et al. (2011) used the spatial recursive-dynamic economic model of the forest sector, GFPM - Global Forest Products Model (Buongiorno et al. 2003), to look at long-term effects of policies to induce carbon storage in forests. It was found that offset payments for carbon sequestered in forest biomass of \$15–\$50/tCO_2e (U.S. dollars per ton of carbon dioxide equivalent) applied in all countries, increased CO_2 sequestration in world forests by 5–14 billion tons from 2009 to 2030. The Global Timber Model (GTM) is a dynamic optimization model that optimizes the land area, age class distribution, and management of forest lands in 250 timber types globally (Sohngen et al. 1999, Sohngen and Mendelsohn 2003). The model does not include forest industries and has been applied, among others, to quantify potential GHG emissions reductions and costs. For example, Sohngen and Sedjo (2006), examined how different carbon price paths would affect reductions in deforestation. They found that an increase in the rate of growth of real carbon prices from 3%–5% per year would slow reductions in deforestation by 60%–85% over the next 20 years. This model does not include forest industry productions and trade between regions. Favero et al. (2017) used GTM to determine the most cost-effective mitigation methods to limit long-term radiative forcing. It was found that if carbon prices are low, forests are best used for sequestration (carbon storage), but if carbon prices are high, the role of forests for providing bioenergy and other forest products becomes more important.

Although both intertemporal optimization forest sector modelling (e.g., Alig et al., 2010; Lauri et al., 2012; Sohngen et al., 1999) and dynamic recursive (e.g., Buongiorno et al., 2003; Moiseyev et al., 2014, 2013); frameworks were applied to analyse carbon pricing and its impact on the forest sector in Europe, the forest supply side was based either on only econometric studies or on rather few forest management options regarding planting intensity, thinning types/intensities and clearfelling ages. Latta et al. (2013) noticed that models with exogenous forest growth seem best suited for short-term predictions, and their simulations of policies or market shocks outside historical ranges may prove difficult. These models usually employ a time horizon of 15–25 years. For instance, the results of Lauri et al. (2012) and Moiseyev et al. (2013, 2014) cover the period up to 2040 and 2030, respectively. Contrary, perfect foresight models tend to simulate forestry over a century or more into the future, emphasizing the long-term impacts of forest management changes. These models, thus, allow for more strategic analysis of forest sector developments where the choice of forest management becomes important.

Norway is one of the few countries in Europe having an intertemporal optimization forest sector model which includes detailed forest management options for each (of more than 9000) permanent forest sample plots in the National Forest Inventory (NFI). This model - called NorFor - is a partial, spatial equilibrium model of the Norwegian forest sector based on the assumption of perfect foresight and has been applied in several analyses related to carbon pricing. For instance, Sjølie et al., (2013a), simulating GHG fluxes and albedo impacts for a range of carbon prices, found that including albedo-induced climate effects into a policy scheme, strongly impacted optimal forest management and harvest levels. Sjølie et al. (2013b) analyzed the impacts of a dual discounting scheme on climate change mitigation efforts. It was found that discounting carbon values at the same rate as monetary values resulted in lower harvest level (11% reduction) over the model time horizon compared to the base scenario, and the carbon discount rate had great impacts on the harvest and management levels, and consequently the forest sector's contribution to climate change mitigation. Sjølie et al. (2013c) analyzed two sets of simulated carbon tax/subsidy policies, one crediting forest carbon sequestration while maintaining predetermined harvest levels and utilization of wood, and another targeting GHG fluxes in the entire forest industrial sector allowing harvest levels and wood markets to change in response to the policy. It was found that GHG emission reduction potentials differ substantially between the two policies, being several times higher for the latter than the former policy at a given carbon price. Sjølie et al., (2014) compared the forest sector's climate change mitigation potential in Norway under the Kyoto Protocol (KP) to unlimited carbon sequestration policy with no caps on forest carbon credits. Their results suggested that carbon offsets were higher in the short run under Kyoto Protocol policy than under unlimited policy but KP policy failed to utilize carbon sequestration potential in the long run.

Despite this rather comprehensive representation of forest sector models in the literature, there continues to be a need for additional tools and assessment frameworks in this sector to guide informed decision making. Particularly in Europe regarding the EU climate, energy, and forest policies, there is a need for forest sector models which, better than today, can include timber supply through detailed forest management options. The main objectives of this article are to fulfil this void by (i) developing a dynamic forest sector model for Europe where forest management and harvest is optimized utilizing NFI data and where production and trade of bioenergy and forest industry products are included in an economic consistent analysis framework; and (ii) using this model in a case study to estimate impacts of carbon prices on forest management, harvest and marginal carbon abatement cost curves in the European forest sector.

The model is named EUFORIA (**E**uropean **FOR**est and **I**ndustry **A**ssessment model). In the next section, we give an overview of its structure, assumptions and data requirements. Next, the results of the case study are presented. Finally, discussion and main conclusions are drawn.

METHODS AND MATERIALS

Overview of model structure and data

EUFORIA is an intertemporal, partial, spatial equilibrium forest sector model that integrates forestry, forest industries, wood products demand and international trade of wood and wood products. The model has been developed to provide consistent analyses of impacts of external factors such as economic growth, carbon pricing, forest policies, bioenergy development, trade regulations, exchanges rates, transport costs, consumer preferences and forest management strategies, on production, consumption, imports and exports of roundwood and forest industry products including wood-based bioenergy.

The model assumes perfect foresight and perfect competition, and performs intertemporal optimization, where the model's solutions are provided for all periods simultaneously. EUFORIA maximizes the sum of the net present value of consumer and producer surpluses net of transport costs. Partial means that the model does not include all economic activities, but only forestry and forest industries, assuming that the forest sector has little impact on other sectors of the economy. Spatial means that EUFORIA includes multiple regions, transportation costs, and that trade between each pair of regions is not fixed. Finally, equilibrium means that supply equals demand quantities for each product in each period and region modelled.

Endogenous variables in the model include forest management for National Forest Inventory plots in selected European countries (regeneration intensities, thinning timing and intensities, harvest ages and quantities), production, consumption, and price of sawn wood, pulp, paper, boards and bioenergy, and bilateral trade quantities for all products. Main exogenous data are economic growth for each country, unit input requirements and corresponding production costs for each wood assortments and industrial products, and demand elasticities for each final product based on price and income.

The model includes in total the following 32 European countries as separate regions (totally referred in this article as Europe or European region): Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Albania, Luxemburg and Montenegro. In addition, the rest of the world (ROW) is added as one region to take account of trade between Europe and other countries. The ROW region has been added as a pure trade region to balance the markets, and the actual wood industry production in ROW is not included in EUFORIA. Net import from ROW to Europe is assumed to be similar in all scenarios analyzed, and as estimated in the business as usual (BAU) scenario applying the EFI-GTM.

The wood supply part of EUFORIA is based on the NFI data available from the FORMIT project consortium (Austria, Czech Republic, Germany, Spain, Sweden, Finland, Norway, France, Italy, and Poland). For the rest of the European countries, the inventory data is taken from countries most similar in forestry conditions, as described in FORMIT (2014) and Härkönen et al. (2018).

The period length in EUFORIA is five years, and the analysis time horizon in this paper is 100 years, but is adjustable, depending on the objective of the study. Main three subsectors of the model are forest growth and management, industry and consumption, transport and trade. Their brief description follows.

The cost structure of forest industries and bioenergy production included in EUFORIA is similar to those in EFI-GTM (Kallio et al. 2004, 2018a), whereas the forestry part of EUFORIA is based on the forest stand simulation model FORMIT described below.

The appendix provides a mathematical description of the model.

Forest growth and management.

One of the most important components of EUFORIA that distinguish it from other European forest sector models such as EFI-GTM, EUFASOM or GFTM (Jonsson et al. 2015) is related to timber supply. The timber supply component in EUFORIA was obtained by applying the forest management and growth simulation model FORMIT-M (FORMIT 2014, Härkönen et al. 2018) for estimating future forest management development alternatives for all main species present in the NFI data in selected European countries.

FORMIT-M is a forest growth simulator responsive to both management actions and climate change. The model combines a process-based carbon balance approach to forest productivity with a strong empirical component based on NFI data. The simulator uses basic stand-level forest variables and aggregated meteorological variables as input data, and calculates carbon storage and fluxes at the forest site above and below ground, as well as wood production of roundwood in forest product assortments and forest biomass, under chosen climate scenarios.

According to the classification of Johnson & Scheurman (1977), the forest management model applied within EUFORIA is of Model I type, with some modifications. In the Model I type, each age class that contains hectares in the first period forms a management unit whose integrity is retained throughout the planning horizon. Each age class in the starting inventory is recognized as a management unit. In addition, each activity represents a possible management regime for a management unit, with its associated inputs and outputs, over the entire planning horizon.

In such a model type, an activity is needed for each possible regeneration and harvest sequence that can occur during the planning horizon within each management unit. These activities are generated by applying FORMIT-M. The growth model in FORMIT-M is defined in terms of stand mean-tree variables and stand density, which together define stand-level variables such as stem volume and component biomass. The state variables of the model comprise mean height (H), mean breast height diameter (D), stand density (N) and depending on the region, mean height to the crown base (H_c). Empirical functions are applied on these to derive auxiliary variables, including mean tree volume (V_{TREE}) and form factor (f_{FORM}), component biomasses (W_{x}) and litterfall (L_{x}), and leaf area index (LAI).

The dynamics of the state variables in the growth model are derived from estimated Gross Primary Production (GPP) and its allocation to Net Primary Production (NPP) and further to stem growth. GPP is calculated using a semi-empirical, Light-Use Efficiency (LUE) based canopy level model (Mäkelä et al. 2008, Peltoniemi et al. 2015, Minunno et al. 2016) which uses daily weather data and LAI as inputs. An empirical model was derived using this GPP and NFI-based NPP for estimating the NPP:GPP ratio for different species and regions. Similarly, an empirical function was derived for species and regions for the ratio of stem growth to NPP.

Stand-level stemwood volume growth is obtained from the volume increment based on GPP and its allocation. This is divided by stand density to estimate mean tree growth, and empirically derived allometric functions are used to compute new values of H, D and H_c from new volume and stand density. The latter is updated on the basis of harvests and mortality, where mortality is assumed to occur if stand density exceeds the maximum density modelled using Reineke stand density index (Reineke 1933).

Soil carbon dynamics are in FORMIT-M estimated using the Yasso07 model (Tuomi et al. 2009, 2011). Yasso07 takes tree litterfall and stand mean temperature and rainfall as input to estimate the development of soil carbon stocks. The initial soil carbon is estimated assuming the system is at steady state with respect to current litter input.

The model was parameterized using NFI data from 10 European countries and was extended to the rest of Europe on the basis of remotely sensed data. The parameterization was done for 7 ecologically based species groups. Forest management schemes were defined for these groups in 6 different silvicultural systems in terms of harvest timing and intensity. A BAU scenario of forest management was defined as management that is currently considered as the typical forest management in the region and which retains the current proportions of the silvicultural systems by species. Alternative management scenarios were defined as deviations from BAU to analyse the impacts of different management goals on forest production and carbon balance. These alternatives and BAUs are used as inputs in EUFORIA. More detailed information about the FORMIT-M simulation model is found in Härkönen et al. (2018).

Industry and consumption

In EUFORIA, a set of alternative production technologies for forest industry production (including bioenergy) is defined for each country separately. The amounts of the inputs used and outputs obtained are specified for each technology by input-output coefficients. Moreover, EUFORIA contains a set of inputs coming from exogenous sectors, which include net electricity (kWh/unit of main output), process heat (GJ/unit), labour (hours/unit), and the aggregate of other exogenous sector inputs, e.g., chemicals and other materials ($/unit). Maintenance costs for old capacity ($/unit) and investments costs for new capacity ($/unit) are accounted for in the total production costs. Next, there are three types of capacity costs in the model, e.g., capital rent, maintaining, and expanding capacity. The capacity is depreciated at a fixed rate; however, the industry may pay a maintenance cost to avoid this depreciation. Industrial agents have a possibility to invest in new capital stock, with all investment costs paid in the year of the investment. The adjustments of industrial capacity are weighted against all future discounted surpluses of the investment in EUFORIA. The demand for final products is a function of price and gross domestic product.

Transport and trade

According to Samuelson (1952), trade of a good takes place as long as the price difference between the two regions exceeds the transport costs. In EUFORIA trade between each pair of European regions is allowed as long as exogenously defined transport costs are covered.

EUFORIA selects the economic optimal option (road, boat or railway) to transport given forest product to destination market to maximize net social surplus. Trade between European countries and ROW is exogenously determined and equals the trade between these regions found in the BAU scenario (defined below) by applying the EFI-GTM model.

Carbon price scenarios and estimation of marginal abatement costs

European Climate Foundation (2010) and European Commission (2011) addressed the feasibility and implications of the 80% emissions abatement objectives and found that one of the consequences might be high CO_2 prices after 2030, at the level of above 100€/tCO_2 in 2040 and 200 €/tCO_2 in 2050.

Taking this into account, our first analysis with EUFORIA includes the following nine different carbon price scenarios: 1, 5, 10, 15, 20, 25, 50, 100 €/tonCO_2. These prices are assumed to be paid for carbon sequestration, i.e., for any fixation and emission of CO_2 which occur in addition to those in BAU, where the assumed carbon price is zero.

The mathematical estimation of marginal abatement costs is described in the appendix.

RESULTS

The model was solved for eighteen 5-year time periods between 2010 and 2095 for the baseline and eight carbon price scenarios. We focus on the 2015-2090-time period to minimize the effect of start-up and terminal conditions bias.

Forest management impacts

Table 1 shows the harvest and regeneration choices for three different years and three different carbon prices in relation to the baseline in which there was no carbon price.

Results indicate a greater reduction in the area assigned to partial harvesting than clearfelling across all carbon prices and time periods. At high €/tCO_2 prices, there are even cases at 2050 and 2090 where the reductions in partial harvesting area may have been offset by increases in acres assigned to clearfelling. The changes in area regenerated under carbon prices follow similar trends as all hectares clearfelled must be subsequently regenerated yet not all partial harvest regimes require a regeneration investment.

Table 1. Harvest and regeneration choices for three different years and three different carbon prices in relation to the baseline.

	2015				2050				2090			
	BAU	$\Delta 10_{\mathrm{EUR}}$	$\Delta 50_{\mathrm{EUR}}$	$\Delta 100_{\mathrm{EUR}}$	BAU	$\Delta 10_{\mathrm{EUR}}$	$\Delta 50_{\mathrm{EUR}}$	$\Delta 100_{\mathrm{EUR}}$	BAU	$\Delta 10_{\mathrm{EUR}}$	$\Delta 50_{\mathrm{EUR}}$	$\Delta 100_{\mathrm{EUR}}$
Clearfelling (1000 ha)	4,323	-1.67 %	-3.52 %	-3.34 %	4,337	0.81 %	-1.65 %	-5.32 %	4,542	1.54 %	-0.54 %	-1.34 %
Partial harvest (1000 ha)	10,638	-2.60 %	-5.41 %	-7.77 %	10,550	-2.69 %	-4.03 %	-5.73 %	9,253	-3.85 %	-6.77 %	-9.89 %
Regeneration (1000 ha)	10,862	-1.71 %	-5.56 %	-7.18 %	11,937	1.83 %	-3.15 %	-7.34 %	12,774	1.00 %	-2.52 %	-2.97 %
Age at clearfell (years)	70	-0.09 %	-1.41 %	-1.66 %	73	0.19 %	2.39 %	-2.25 %	71	-0.13 %	1.76 %	3.82 %
DBH of standing forest (cm)	21	0.09 %	0.22 %	0.58 %	22	0.24 %	0.63 %	1.56 %	23	0.93 %	1.83 %	3.62 %

The average age at which clearfelling occurs shows temporal variation but differs never more than 3 years from BAU (in table 1 maximum 3.62 % at carbon price 100 €/tCO_2 in 2090). In 2015 we see that younger forests than in BAU are selected for harvest when the carbon price increases. This indicates that on average, old forest having relatively low marginal growth, are harvested earlier than in BAU to give room for new forests with higher mean annual growth.

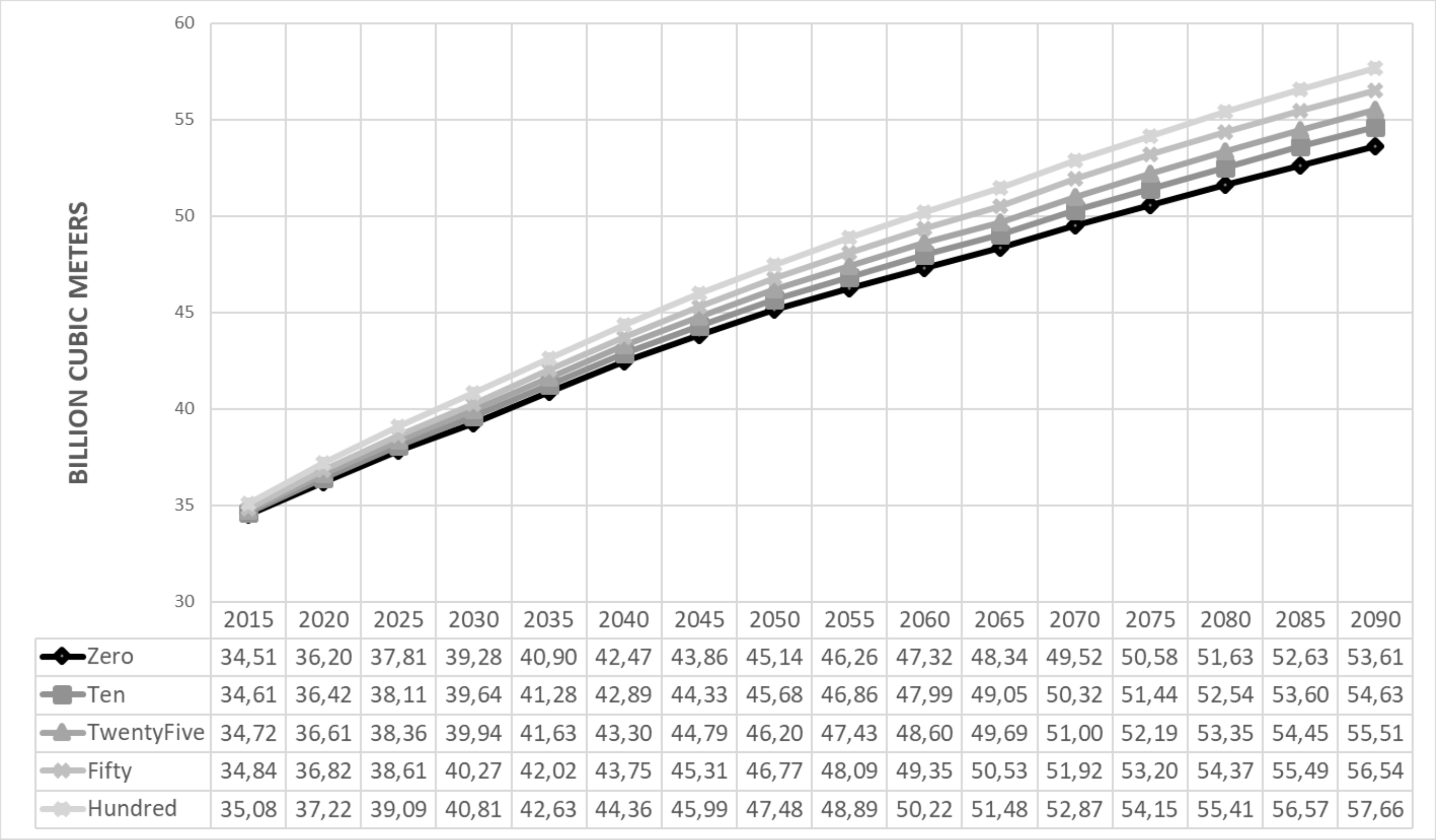
Total growing stock and harvests in Europe

The forest management responses to the carbon price scenarios lead to changes in both total growing stock and harvest in Europe. Figure 1 presents changes in total growing stock in Europe, between 2015 and 2090 under different carbon prices, and the resulting change in the average diameter of those growing stocks can be found in Table 1.

In the baseline, the total growing stock of forests in Europe amounts to 34.51 billion m^3 in 2015 and is expected to increase by 55%, to reach 53.61 billion m^3 in 2090 (see Figure 1). Over the same time period, the average diameter at breast height (DBH) of the forest is projected to increase 2 centimeters (cm) from 21 cm in 2015 to 23 cm in 2090.

Increasing carbon price results in larger forest inventory over time in Europe. Between 2015 and 2090, the total growing stock increases by 58%, 60%, 62%, 64% for carbon price equal to 10, 25, 50 and 100 €/tCO_2 respectively. This higher inventory is also comprised of larger trees. While the baseline projection was for the average diameter to increase 2 cm over the time period, with a 100 €/tCO_2 carbon price the average diameter of European forests is 3.6% larger (0.83 cm) than in BAU in 2090.

With a carbon price equal to 100€/tCO_2, the total forest growing stock is expected to increase by almost 40 billion m^3 in Europe from 2015 to 2090. Carbon prices equal to 50, 25 and 10 €/tCO_2 result in 2.9, 1.8 and 0.9 billion m^3 higher forest growing stock over the 75-year time horizon, respectively.

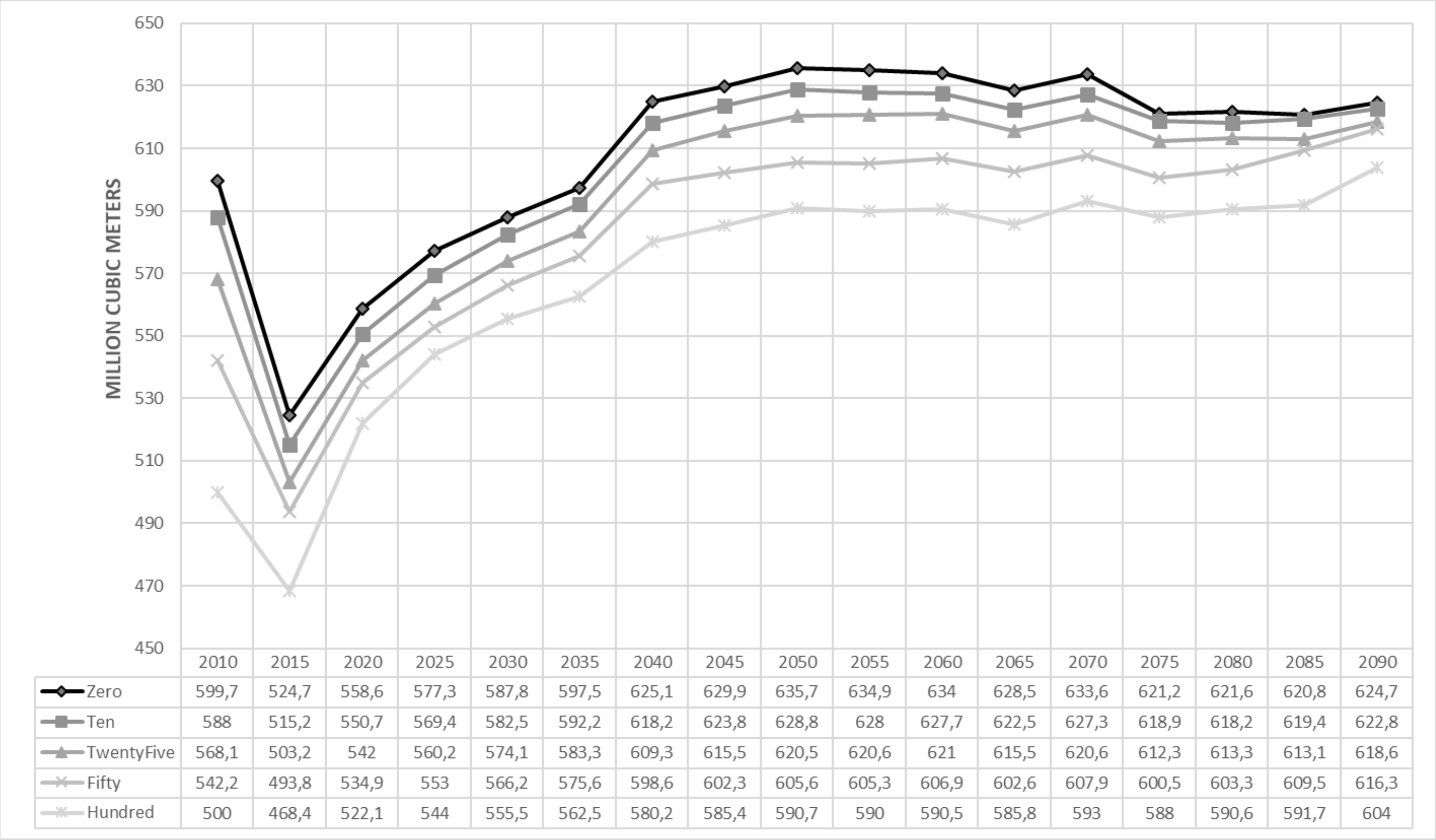


	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090
Zero	34,51	36,20	37,81	39,28	40,90	42,47	43,86	45,14	46,26	47,32	48,34	49,52	50,58	51,63	52,63	53,61
Ten	34,61	36,42	38,11	39,64	41,28	42,89	44,33	45,68	46,86	47,99	49,05	50,32	51,44	52,54	53,60	54,63
TwentyFive	34,72	36,61	38,36	39,94	41,63	43,30	44,79	46,20	47,43	48,60	49,69	51,00	52,19	53,35	54,45	55,51
Fifty	34,84	36,82	38,61	40,27	42,02	43,75	45,31	46,77	48,09	49,35	50,53	51,92	53,20	54,37	55,49	56,54
Hundred	35,08	37,22	39,09	40,81	42,63	44,36	45,99	47,48	48,89	50,22	51,48	52,87	54,15	55,41	56,57	57,66

Figure1. Total growing stock in Europe under different carbon prices.

Figure 2 shows harvest in Europe between 2010 and 2090, including sawlogs, pulpwood, and fuelwood assortments altogether.

In all model runs, due to the model's assumption of perfect foresight, the adaptations begin at once by harvesting more in the first period (2010) than in the next period. The main reason for this is that there is a lot of mature forest in the standing stock. Overall, higher carbon prices trigger lower harvest levels. By increasing the carbon price, forest owners are encouraged to keep more of their forests unharvested. With a carbon price of 100€/tCO_2, between 2010-2090, on average around 42 million cubic meters are harvested less than in the baseline scenario. For the carbon price of 10€/tCO_2, this value is reduced to around 6 million cubic meters.



	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090
Zero	599,7	524,7	558,6	577,3	587,8	597,5	625,1	629,9	635,7	634,9	634	628,5	633,6	621,2	621,6	620,8	624,7
Ten	588	515,2	550,7	569,4	582,5	592,2	618,2	623,8	628,8	628	627,7	622,5	627,3	618,9	618,2	619,4	622,8
TwentyFive	568,1	503,2	542	560,2	574,1	583,3	609,3	615,5	620,5	620,6	621	615,5	620,6	612,3	613,3	613,1	618,6
Fifty	542,2	493,8	534,9	553	566,2	575,6	598,6	602,3	605,6	605,3	606,9	602,6	607,9	600,5	603,3	609,5	616,3
Hundred	500	468,4	522,1	544	555,5	562,5	580,2	585,4	590,7	590	590,5	585,8	593	588	590,6	591,7	604

Figure 2. Total harvest in Europe under different carbon prices between 2010-2090.

Wood products demand

Demand for wood products in the EUFORIA expresses the quantity consumed in Europe. It is calculated as the amount of wood produced there plus the net imports from other European countries and exogenous imports to Europe from ROW minus the exogenous exports from Europe to ROW. In this chapter, we focus on sawnwood and boards, and pulp and paper demand in the European region.

Sawnwood

Figure 3 shows the sum of softwood and hardwood sawnwood consumption in Europe.

The sawnwood consumption in Europe increases over time until 2050, and then decrease some during 2050-2090. In BAU it increases by 17% between 2015 and 2090, from 95.6 Mm^3 to 112 Mm^3. The consumption decreases with increasing carbon prices, mainly because sawnwood prices increase as a consequence of higher sawlog prices. However, increasing carbon emission prices up to the high 100€/tCO_2 has a relatively minor impact (about 4% reduction in 2050, and 3% reduction on average over the period 2015-2090.

Figure 3. Total sawnwood (hardwood and softwood) consumption in Europe

Table 2 shows demanded volume quantities for baselines in the year 2015, 2050 and 2090, together with relative changes with respect to carbon prices. In 2015 and 2050, demand reduction in hardwood sawntimber will be higher than for softwood in terms of percentage changes. In 2015, the reduction in demand is equal to 191, 632 and 1,210 thousand m^3 under 10, 50 and 100 €/tCO_2 carbon prices, respectively, while in 2050 reduced demand volume correspond to 100, 830 and 1,277 thousand m^3 for respective carbon prices. On the other hand, it is expected that under a carbon price of 100 €/tCO_2, demand reduction for softwood sawnwood will be 4.5, 3.9 and 2.2 million cubic meters in 2015, 2050 and 2090, respectively.

Table 2. Demand for forest products under different carbon prices for 2015, 2050 and 2090. Numbers for BAU are in thousand cubic meters (sawnwood and wood-based panels) or thousand metric tons (pulp and paper products).

	BAU	Δ10EUR	Δ50EUR	Δ100EUR	BAU	Δ10EUR	Δ50EUR	Δ100EUR	BAU	Δ10EUR	Δ50EUR	Δ100EUR
Softwood Sawnwood	82,341	-0.7 %	-3.7 %	-5.5 %	100,589	-0.6 %	-2.3 %	-3.9 %	96,908	-0.1 %	-1.5 %	-2.3 %
Hardwood Sawnwood	13,320	-1.4 %	-4.7 %	-9.1 %	16,247	-0.6 %	-5.1 %	-7.9 %	15,109	-0.2 %	-0.9 %	-1.2 %
Plywood	11,131	-1.7 %	-5.4 %	-9.0 %	13,747	-1.2 %	-3.8 %	-7.1 %	12,840	-0.8 %	-2.9 %	-4.0 %
Particle board	25,294	-0.8 %	-2.6 %	-4.1 %	37,238	0.0 %	-0.4 %	-0.4 %	41,395	0.0 %	0.2 %	0.1 %
Other particle board	7,313	0.0 %	-0.2 %	-6.3 %	5,451	0.0 %	-0.4 %	-1.3 %	5,657	0.0 %	-0.3 %	-0.5 %
Oriented strand board (OSB)	3,145	-1.3 %	-5.1 %	-9.1 %	4,278	0.0 %	-0.9 %	-1.2 %	4,664	-0.2 %	-0.6 %	-0.6 %
Medium-density fibreboard (MDF)	6,782	-1.7 %	-3.5 %	-6.8 %	9,935	-0.9 %	-1.5 %	-1.8 %	10,882	0.3 %	0.0 %	0.0 %
Hardboard	2,540	-0.2 %	-1.4 %	-2.4 %	3,873	0.0 %	-0.2 %	-0.4 %	4,539	0.0 %	-0.4 %	-0.5 %
Pulp	30,892	-0.7 %	-2.3 %	-10.4 %	36,522	-0.3 %	-2.3 %	-4.0 %	39,349	-0.1 %	-1.4 %	-2.2 %
Newsprint	5,339	-0.6 %	-4.3 %	-7.6 %	5,032	-0.3 %	-1.9 %	-4.7 %	4,369	0.4 %	-1.4 %	-2.1 %
Printing and writing paper	23,738	-0.3 %	-1.9 %	-6.6 %	22,074	-0.3 %	-4.0 %	-7.1 %	21,296	0.1 %	-3.3 %	-5.2 %
Packaging	35,360	-0.4 %	-2.4 %	-5.6 %	35,392	-0.1 %	-0.8 %	-1.9 %	36,116	-0.1 %	-1.3 %	-1.7 %
Tissue	5,682	-1.3 %	-3.0 %	-7.7 %	8,674	-0.4 %	-1.7 %	-2.6 %	9,915	0.0 %	-0.4 %	-1.0 %

Wood panels

Figure 4 presents total demand for wood-based panels, i.e. plywood, particleboard, OSB, MDF, and hardboard. In the baseline scenario with zero carbon price, the demand for wood-based panels increases by 42%, starting at 56.2 Mm^3 in 2015 and ending up at nearly 80 Mm^3 level in 2090. Adding a carbon price, only small reductions in demand are observed.

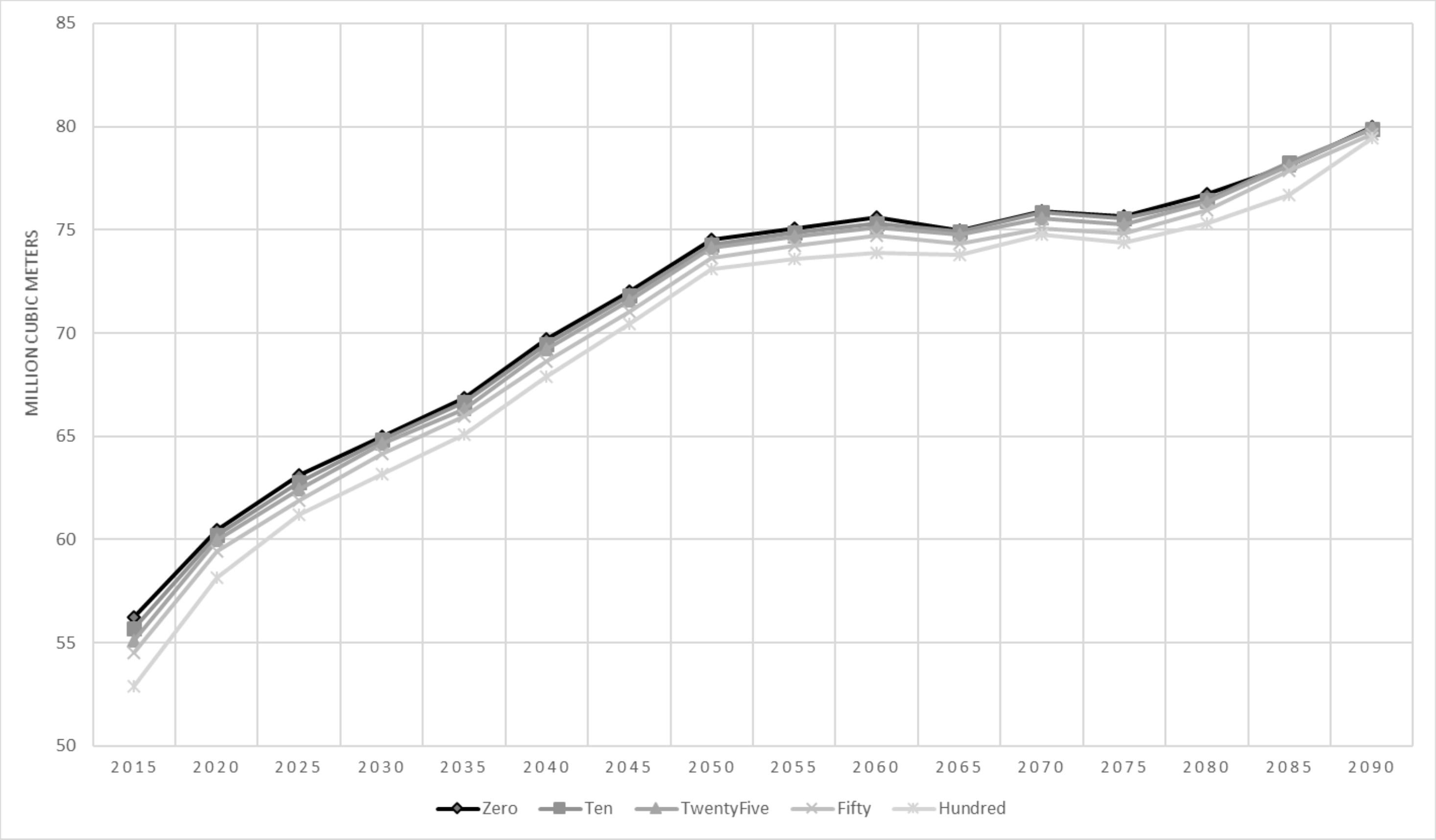


Figure 4. Total wood-based panels demand in Europe.

Pulp demand

Figure 5 shows the total pulp demand in Europe. The total pulp demand consists of four different pulp types, i.e., bleached softwood kraft pulp, bleached hardwood kraft pulp, unbleached kraft pulp and dissolving pulp. Overall, pulp demand increases over the projection period for all scenarios. For the baseline, the pulp demand in Europe is expected to increase by ca. 27%, from 30.9 up to 39.3 million metric tons. Increased carbon prices result in only modest pulp demand reductions. For instance, in 2050, the pulp volume demanded is expected to be reduced by 125.3 (-0.3%), 831 (-2.3%) and 1,466 (-4.0%) thousand metric tons under 10, 50 and 100€/tCO_2 carbon price, respectively (Table 2).

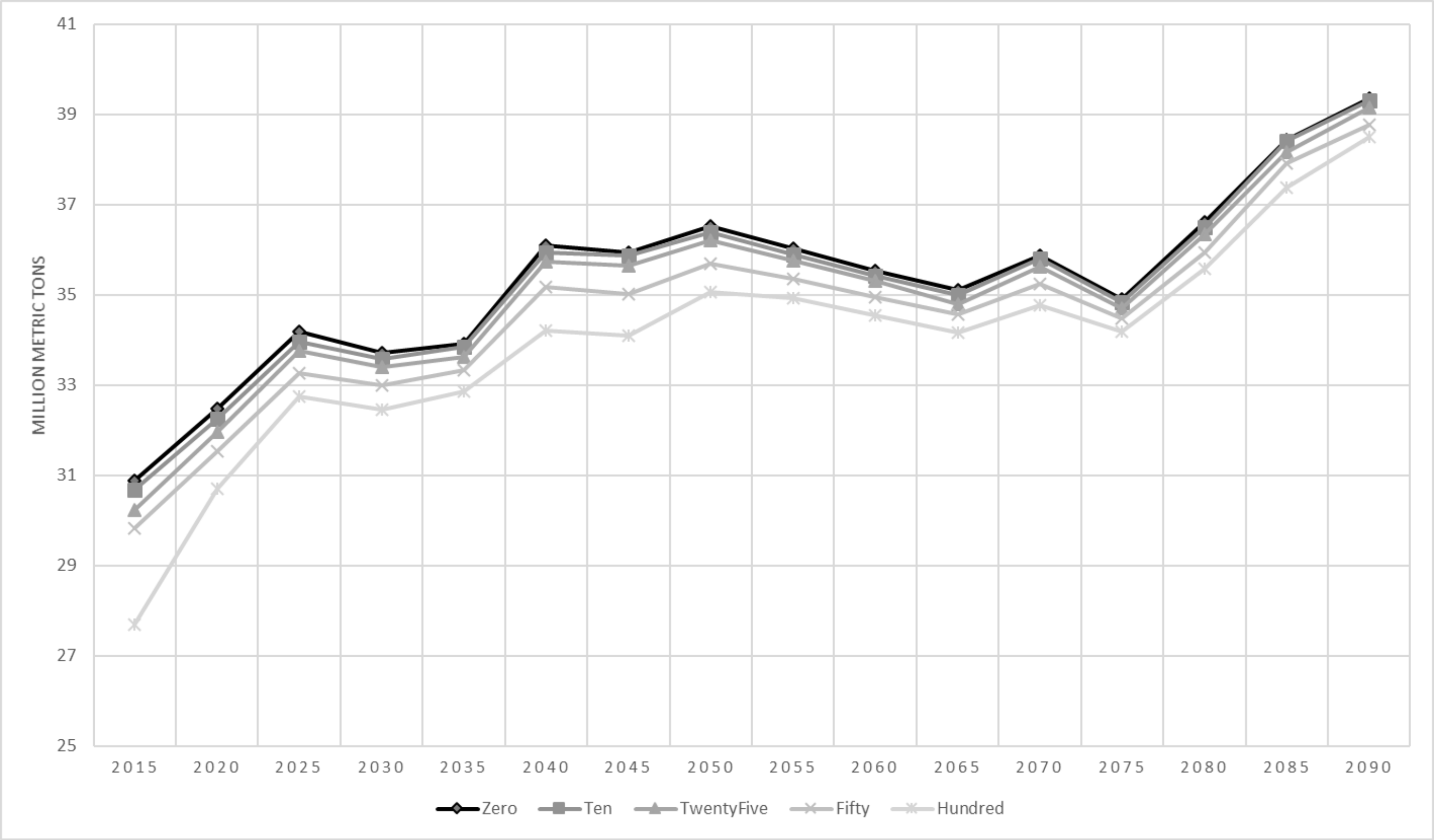


Figure 5. Pulp demand in Europe.

Paper products demand

Figure 6 presents the total paper products demand in Europe between 2015 and 2090. Within total paper products there are included following sub-categories: newsprint, printing and writing paper, packaging and sanitary paper (tissue).

Overall, up to 2045, there can be observed an increasing trend in the demand for paper products in Europe, followed by a decline period up to 2075, and again "V-shape" rebound until the end of the projection. Similarly, to other wood product categories, higher carbon prices imply lower demanded quantities for paper products. Based on Table 2, in 2015, it can be observed that at 100€/tCO_2 carbon price, the most impacted paper product is sanitary paper (-7.7%), followed by newsprint (-7.6%), printing and writing paper (-6.6%) and packaging paper (-5.6%). This order changes over the years, but noticeably in 2050 and 2100, the biggest demand reduction is observed for printing and writing paper.

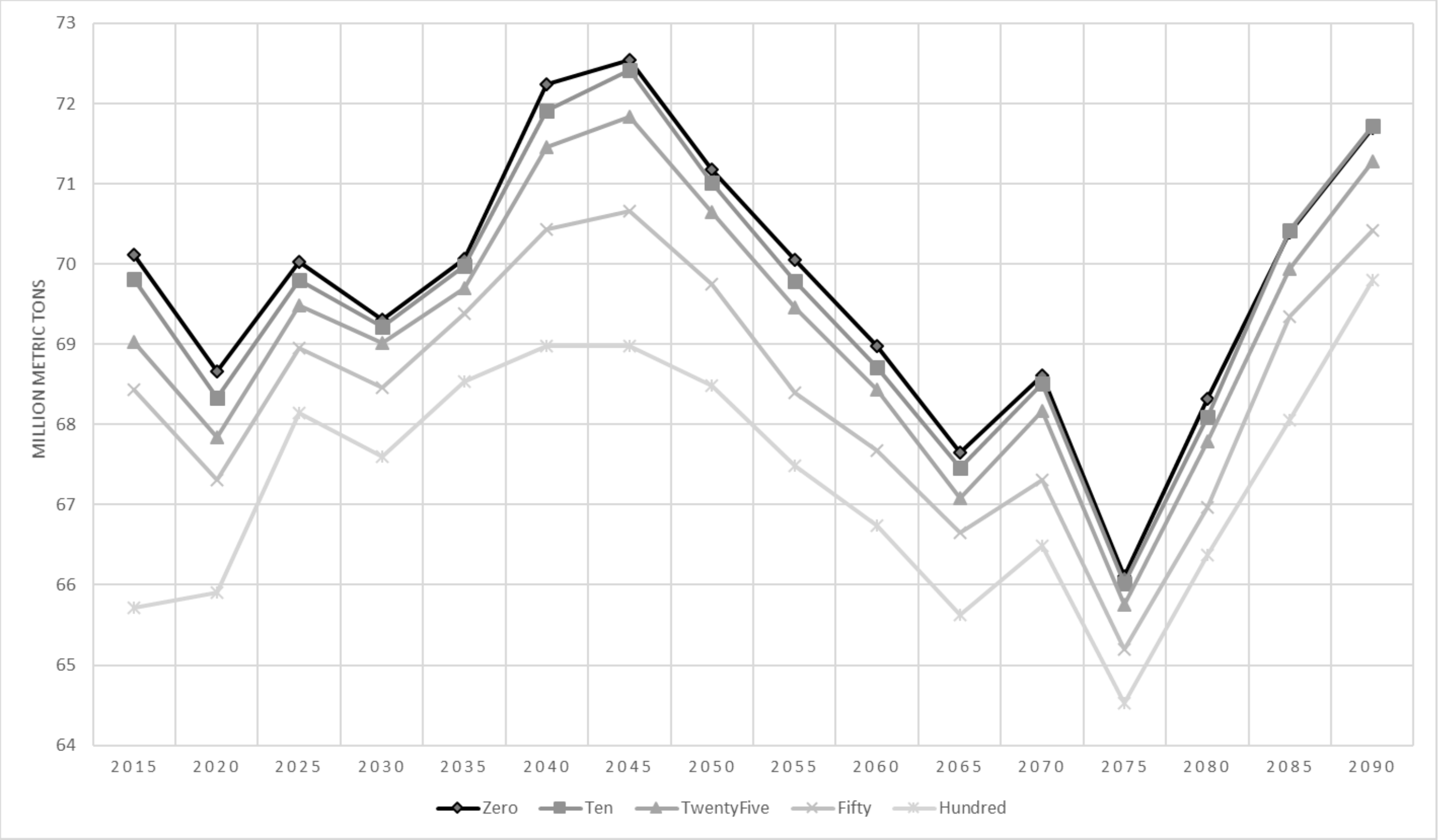


Figure 6. Demand for paper products in Europe.

Carbon stock changes and marginal abatement cost curve

Figure 7 shows the distribution of carbon stock change between 2015 and 2090 under carbon price zero and hundred. The biggest part of carbon stock is stored in trees' stems, followed by harvested wood products (HWP), HWP substitution, roots, and branches.

Based on figure 7, in general, the distribution of carbon stock under carbon price zero and hundred did not change much. Nevertheless, at price €/tCO_2, there is an observed increase in carbon stock in tree parts (stems, roots, branches etc.), while there is a decrease in harvested wood products and their substitution effect. This is caused by lower harvest at high carbon prices.

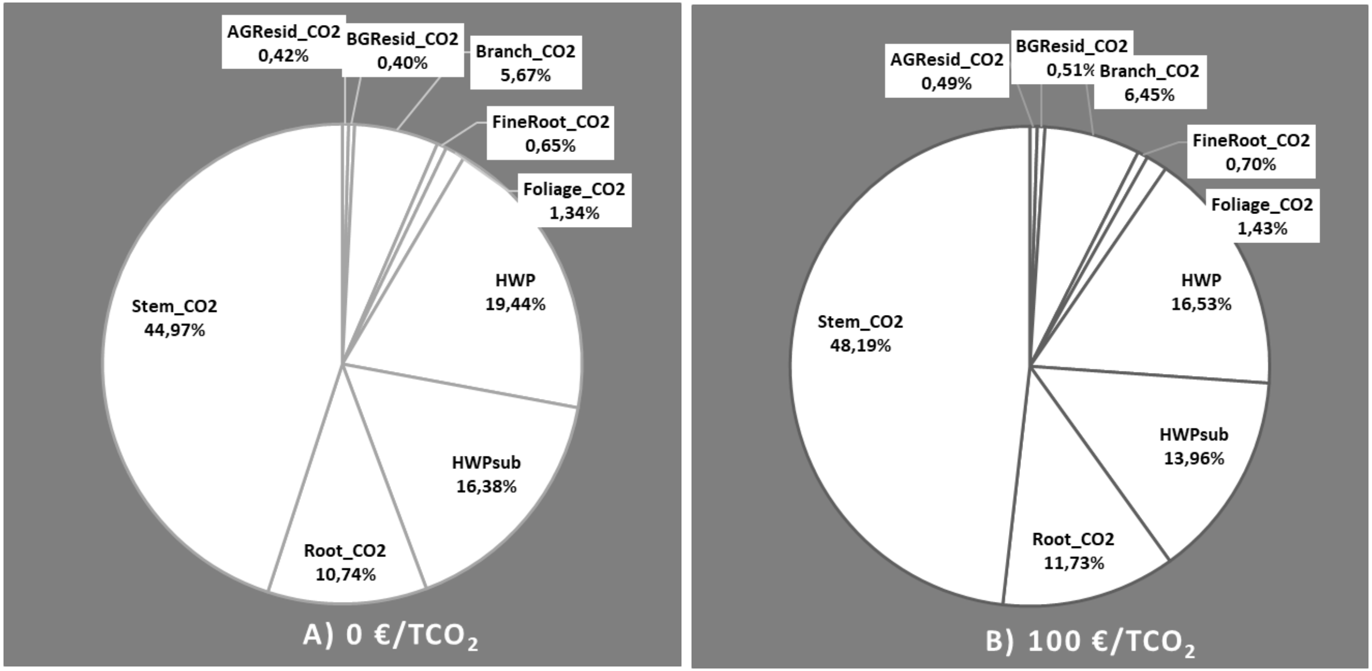


Figure 7. Carbon stock distribution between 2015 and 2090 under carbon price zero and hundred

Figure 8 shows how much additional CO_2 may be sequestered under different carbon prices and assumed discount rates.

For instance, with a discount rate of 3% per annum (p.a.) and a carbon price of 100€/tCO_2, forests in Europe are capable to sequester 84 Million tons of additional CO_2. Today, annual carbon sequestration in forestry in Europe is equal to around 400 Mt CO_2. Therefore, by applying a carbon price of 100€/tCO_2 and a discount rate of 3% p.a, forests in Europe may sequester 21% more carbon dioxide than without such carbon price policy.

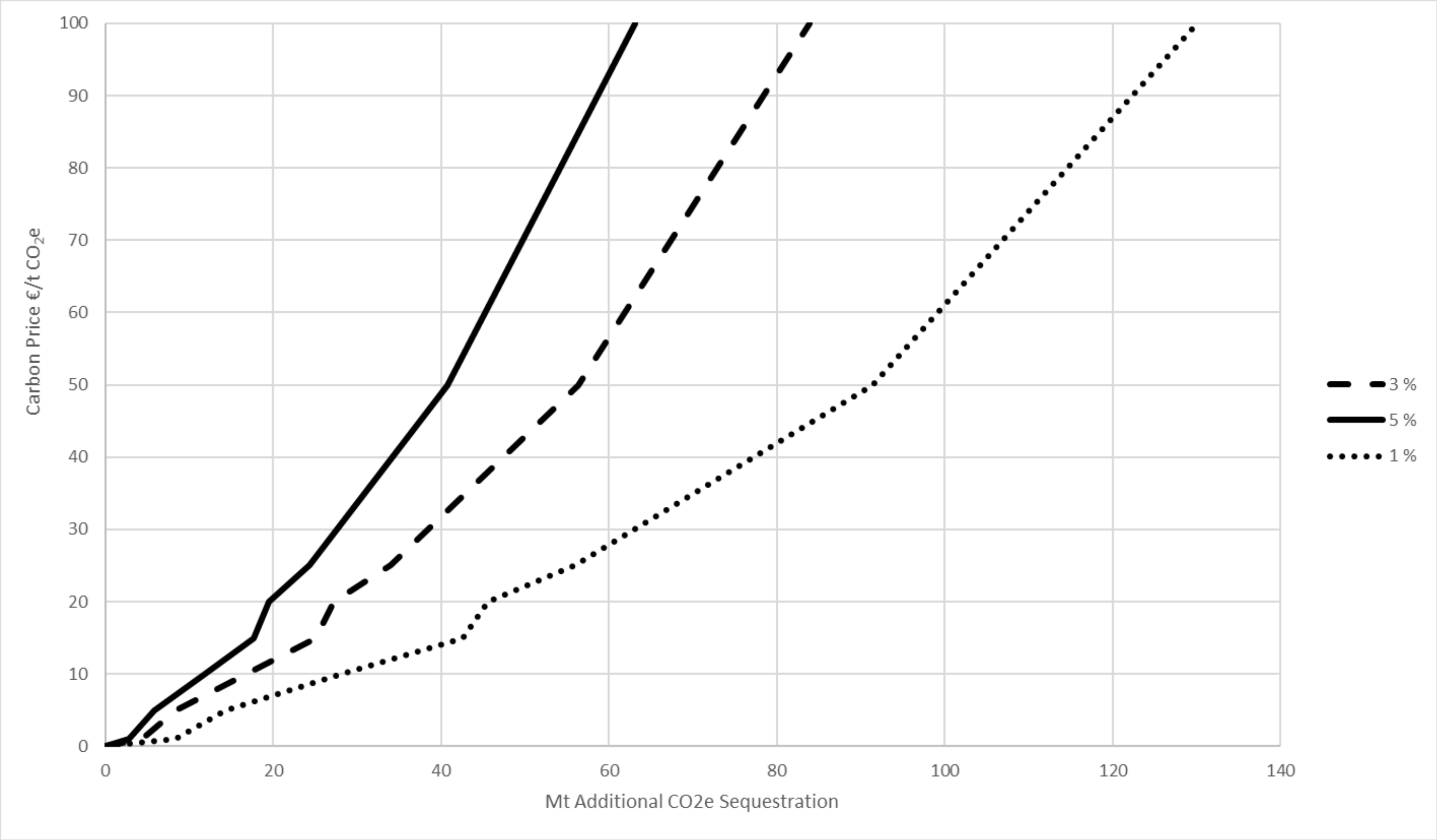


Figure 8. Marginal abatement cost curves under different discount rates (1, 3 and 5% p.a.) calculated as the relation between carbon price (€/tCO_2) and annual CO_2 sequestration (Mt per year) which comes in addition to the sequestration with zero carbon price

DISCUSSION

The net carbon sequestration in the European forest sector depends on the sequestration in forests (caused by harvest and silvicultural decisions), and on what happens in forest products markets regarding, for example, the length of time that carbon remains sequestered in the various forest products, and the degree to which their consumption substitutes more carbon intensive products, such as steel or concrete.

The results of this study show that increasing carbon price paid for sequestration, which is additional to the BAU scenario (0 €/CO_2), leads to decrease in harvest levels and increased investments in forest primary production, resulting in an increase of forest growing stock and average DBH of standing forests across the European region. The analysis of total harvests showed that the application of 100 €/CO_2 carbon price will result in 42 Mm^3 (7%) lower wood removals from European forests compared to BAU, and that this reduction will be predominantly caused by greater harvest reduction in areas assigned to partial harvesting than to clearfelling. Moiseyev et al. (2014) reported that carbon price of 100€/tCO_2 had a relatively marginal impact on EU harvest resulting in 2% increase in 2030. Under the same carbon price, our results show a 5.5% reduction in harvest level in 2030. Although both results represent relatively modest harvest impacts of such high carbon price, the difference in sign is interesting and reflects primarily the basic differences regarding how timber supply and trade are modelled. In EUFORIA perfect foresight is included so forest management and harvest adapt fully to the assumed carbon prices over the whole time period considered, whereas in EFI-GTM timber supply is included through exogenously determined price and growing stock elasticities.

With a price of 100 €/tCO_2 and 3% p.a. discount rate, around 20% more carbon can be sequestered annually (84 Mt additional CO_2) in the forest sector, compared to the BAU. This is consistent with results reported by Backéus et al. (2005), Alig et al. (2010), and Sjølie et al. (2013c), who found that assigning carbon storage a monetary value increases carbon sequestration in the forest and decreases harvest levels.

Storing carbon has been found a cost-effective mitigation method to limit climate change (Lecocq et al. 2011, Favero et al. 2017). However, the choice between policies that favor carbon sequestration in biomass, and policies that favor fossil-fuel substitution is still under debate and depends on the time horizon analysis, but also optimization method. For instance, Favero et al. (2017) used the GTM model with intertemporal static optimization to make projections up to the year 2100 and found that the most effective choice is to use carbon storing together with supplying woody biomass for burning in power plants with carbon capture and storage.

The FORMIT-M used in EUFORIA for forest modelling includes impacts on carbon sequestration in soil, but we have not investigated these effects in this paper. Some studies suggest that carbon stocks can be increased by 200–500% in forest floors and by 40–50% in top mineral soil by tree species change (Vesterdal et al. 2013). Research about targeted use of tree species may enrich further analyses about the interactions between forest sector and carbon dynamics in the context of climate change mitigation policies. Furthermore, the relation between the rotation length, timber prices and site quality carbon stock in trees and soil, but also carbon stocks in wood products should be considered in future research. For instance, Liski et al. (2011) found that shortening the rotation length decreases the carbon stock of trees but increases the carbon stock of soil due to the increased production of litter and harvest residues. Sohngen and Brown (2008) noticed that timber prices may have also an important influence on the marginal costs of carbon sequestration, with site quality being of secondary importance.

Our results show that the average age of clearfelling, compared to the baseline, increases by only 1.6% (0.5 years) and 3.8% (2.7 years) with carbon prices 50 and 100 €/tCO_2, respectively. Van Kooten et al. (1995) examined the implications of carbon subsidies and taxes on economically optimal harvest decisions and the supply of carbon removal services in the forest sector, and discussed how the optimal financial rotation age (Faustmann harvest) is affected by the inclusion of carbon sequestration benefits. It was found that in general, the inclusion of the external benefits from carbon uptake results in rotation age only a bit longer than the financial (Faustmann) rotation age, what is consistent with our results. It should also be mentioned that longer rotation age might be favorable to carbon sequestration, but the costs may involve decreased harvests and revenues of landowners (Liski et al. 2011), negative impacts on consumer welfare (Lecocq et al. 2011) or reduction in wood-based industry productions (Moiseyev et al. 2014).

Our results showed that decreased timber harvest increase prices and reduces consequently the consumption of wood products. However, the impact of carbon pricing on the wood industry in Europe is found to be relatively marginal between 2015 and 2090. Assuming carbon price of 100 €/tCO_2, the demand reduction will be on average within the range 2-4% for sawnwood, wood-based panels, and pulp and paper industry with a tendency to lower demands at the beginning of the projection period. Moiseyev et al. (2014) reported that by increasing carbon emission prices up to the high 100 €/tCO_2 level, the impact on the wood-based industry production will be relatively marginal (about 2% reduction in 2030).

In this research, we have not analyzed changes in the carbon stock of wood products, which may vary with tree species depending on volumes and timber sorts harvested, manufacturing processes and products manufactured (Liski et al. 2011). Also, we did not consider the use of wood for liquid biofuels as there are currently no commercially operative liquid biofuel production units utilizing woody biomass on a large-scale. However, their role might increase in the future and might result in intensified competition over wood (Kallio et al. 2018a).

To check the accuracy, we compare also baseline harvest level to other studies (Table 3). We also tried to approximate harvest level in some countries (e.g. Serbia or Switzerland) in 2010 to see how EUFORIA results fit into this context. It seems that EUFORIA results for total harvest levels in Europe are within the range reported by other studies.

Table 3. Comparison of projected harvest levels for EUFORIA model and similar studies.

Year	Jonsson et al. 2018			Eurostat[2]	EFI-GTM (Kallio et al. 2018)[3]	EUFORIA – BAU (Zero Carbon Price)[4]
	CBM-GFTM BAU[5]	EU Ref. Scenario 2016	ReceBio Baseline scenario			
2010	498 (523.5)	492	556	519 (529.2)	500 (515.1)	600
2015					518	525
2030	517	565	616		605	588

[2] Without Bosnia and Herzegovina (5.6 Mm3 – estimated based on Stanojcic-Eminagic (2010) and Serbia (4.6 Mm3 in 2009, reported by Jović (2009)

[3] EU + Norway (10.4 Mm3 in 2010). Number in the bracket includes Bosnia and Herzegovina, Serbia, Switzerland.

[4] EU + Norway + Switzerland (4.9 Mm3 in 2010, reported by Eurostat database (accessed 2018) + Bosnia and Herzegovina + Serbia

[5] Without Bosnia and Herzegovina, Serbia, Switzerland, Norway, but with Luxemburg. Number in the bracket includes before-mentioned countries, except Luxemburg.

Furthermore, our modelling results indicated that the total growing stock of forests in Europe equals to 34.51 billion m^3 in 2015, with an expected increase by 55% up to 2090. According to MCPFE (2015), the total growing stock of forests in Europe was equal to 35 billion m^3 in 2015, what shows a relatively good match.

There is not much published information in the literature about the FORMIT simulator or its application, what makes it difficult to compare our results with other similar studies regarding changes in forest management behavior or model assumptions. EFI-GTM model is well-documented and has its own history in forest sector modelling exercises, and in this short paragraph, we would like to point to main differences between EUFORIA and EFI-GTM, like the foresight assumptions and level of details regarding timber supply differently. The EUFORIA model uses the intertemporal optimization framework, while EFI-GTM is characterized as dynamic-recursive. Moreover, one of the advantages of EUFORIA model is the level of details regarding timber supply side, obtained by the FORMIT simulator (FORMIT 2014). The wood supply component in EUFORIA is based on forest inventory data, not econometric estimation of the wood supply curve as it takes place in EFI-GTM model. EUFORIA shares common weaknesses with other forest sector models, and it is of interest here to discuss factors which could be decisive for the results we obtained. EUFORIA belongs to the group of partial equilibrium models which means that ceteris paribus, it takes into consideration only a part of the market (forest sector in this case), to attain equilibrium. Since it is only a "partial" model of the economy, the analysis is often done on a pre-determined number of economic variables, what makes it very sensitive to the estimated demand and supply elasticities (see, e.g., Buongiorno and Johnston 2018). Another consequence of being partial for EUFORIA is that this model may miss important interactions and feedbacks between the forest sector and other economic sectors, thus missing important inter-sectoral input/output (or upstream/downstream) linkages. For instance, EUFORIA may miss the existing constraints that apply to the various factors of production (e.g., labor, capital, land etc.) and especially their movement across sectors that are the basis of general equilibrium models (Chudy and Jonsson 2018). Next, the problem of an uncertain future in forest sector modelling framework may be also related to exogenous assumptions such as macroeconomic indicators (e.g., Latta et al. (2018), growth rates or demand changes, but also to political changes (e.g. elections), forest disturbance occurrences, land use changes or finally, human behaviour.

Furthermore, it should be noticed that the data quality applied in the EUFORIA varies due to representativeness issues and/or uncertainties. Representativeness issues in the model include aggregation of prices, products, regions, industrial conversion technologies, transport costs, trade and consumption of industrial products. For instance, EUFORIA contains only inventory data for a limited number of countries in Europe. More data coming from national forest inventories should help to reduce uncertainty. Further, although the trade in forest products in Europe is allowed, one of the drawbacks of the current version of EUFORIA is its assumptions regarding exogenous and similar trade over time with countries outside Europe. Regarding trade, there are many uncertainties, inter alia, in relation to the development of the Russian forest and energy sectors, which might affect the EU in a manner not straightforward to anticipate (Lauri et al. 2012). But also, about the harvest leakage effect on regions outside Europe (Kallio and Solberg 2018, Kallio et al. 2018b), which analysis might be helpful to avoid the overestimation of the climate benefits of policies that decrease or increase roundwood harvests. Our analysis showed that harvest level in Europe will be reduced by 42 Mm^3, compared with the baseline. Although it is not a relatively large number, Kallio and Solberg (2018) reported that about 60-100% of the harvest change in a small open economy – Norway, may be offset by an opposite change in the rest of the world. Such high leakage also implies that the marginal abatement costs shown in Figure 8 most likely overvalue the climate impacts of carbon sequestration potential in the European forest sector.

As pointed by Chudy et al. (2016), one of the weaknesses of nearly all, currently used forest sector models is their deterministic approach, i.e., risks or uncertainties are not explicitly considered. This weakness refers to EUFORIA as well, especially regarding supply and demand elasticities, which could dominate the risk in the other parameters describing forest growth, manufacturing activities, and trade inertia (Buongiorno and Johnston 2018). Because EUFORIA belongs to the group of deterministic models, the risk component in such models can be incorporated through methods that already are in use, like Monte Carlo simulation and, in particular, scenario and sensitivity analysis (Chudy et al. 2016). In this study, we applied a scenario analysis to show how results can vary, depending on the carbon price. However, a possible improvement of the model is related to the modelling of uncertainty in the economic development of the European forest sector, for instance, by testing the sensitivity of the model to different factors. Similar studies were already done for EFI-GTM model (Kallio 2010) or NTMIII (Jåstad et al. 2018).

CONCLUSIONS

This paper presents an overview of EUFORIA, its structure, assumptions and data requirements. In addition, it shows a practical application of the model analyzing impacts of carbon pricing on forest management and marginal abatement cost curves in Europe.

An important comparative advantage of EUFORIA in the long-term analysis is the incorporation of endogenously determined forest management and harvest, based on rather detailed forest inventory data. The case-study of carbon price scenarios provide insight into how agents in the European forest sector might react to a sudden exogenous policy change under perfect foresight assumptions. This treatment of agent information utilization is important to emphasize, as the estimated resulting allocation of resources and market outcomes should be viewed as a sort of maximum market potential reactions rather than an actual forecast. Also, the emphasis should be placed on differences between scenarios, rather than the results of the individual scenarios.

Despite several shortcomings, scenario analysis using such a model provides decision-makers with relevant information not possible to get with other types of market models.

Further studies with EUFORIA could preferably focus on the impacts of potential European policy changes regarding the increased use of wood-based bioenergy, forest conservation, and the role of forestry in the new bioeconomy. As FORMIT-M is a process model, EUFORIA can also rather easily be used for analyzing long-term impacts of climate change.

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APPENDIX

This appendix lists symbols used in the paper and has been organized into three groupings; sets, parameters, and variables. Sets, for which we have used lower case letters, are collections of things over which the model is defined. Parameters, again designated by lower case letters, represent exogenous data which may or may not be defined over a group of sets. Finally, upper case letters indicate endogenous variables determined by the model which may or may not be defined over a group of sets. Following the objective function and constraints that comprise EUFORIA follow.

Sets

a	is the set of 8, 20-year forest age classes
c	is the set of countries *(32 in Europe and a rest-of-world trading region)*
e	is the set of 100 equal steps over which the area under forest products demand is broken into
f	is the set of forest types which vary by European subregion
i	is the set of forest product manufacturing input mixes
j	is the set of carbon pools *(Stem, Branch, Foliage, Root, Fine Root, Above Ground Residuals, Below Ground Residuals, Harvested Wood Products in use, Wood Products use Substitution)*
m	is the set of forest product manufacturing technologies
p	is the set of forest products either produced or consumed within the model
r	is the set of 100 different thinning and regeneration harvest timings for each forest strata (country c, silvicultural system s, forest type f, and age class a combination) including a never harvest option
s	is the set of silvicultural regimes which vary by European subregion
t	is the set of 18, 5-year time periods, t^{-1} would indicate the prior time period
w	is the subset of forest products that are logs *(coniferous sawlogs, pulplogs and fuelwood, and nonconiferous sawlogs, pulplogs, and fuelwood)*

Parameters

$b_{p'cmip}$	parameter indicating forest product manufacturing coefficient indicating the amount of forest product p required to produce one unit of product p', in country c, using manufacturing technology m and input mix i
d	parameter indicating 5-year forest product depreciation rate (set at 2%)
$g_{t'tpj}$	parameter indicating harvested wood product carbon remaining stored in use from forest product p originally used in time period t' remaining stored in carbon pool j in time period t.
h_{cr}	parameter indicating the per unit forest harvesting costs in country c for management regime r
k_{cp}	parameter indicating the per unit forest product capacity costs of expanding manufacturing capacity for product p in country c
l_{csfatr}	parameter indicating carbon stored in carbon pool j, in country c, silvicultural system s, forest type f, age class a, in time period t, enrolled in harvest regime r
n_{cr}	parameter indicating the per unit reforestation costs in country c for regime r
$o_{c'cp}$	parameter indicating the per unit operating costs of transporting product p from country c' to country c

q_{pcm}	parameter indicating the forest product non-wood costs of manufacturing product *p* in country *c* using manufacturing technology *m*
u_c	parameter indicating the recovery rate for recycled paper in country *c*
v_{cw}	parameter indicating the wood product *w* allocation of the total harvest yield in country *c*
x_{csfa}	forest area parameter for EUFORIA strata (unique country, silviculture, forest type, and age class
y_{csfatr}	parameter indicating harvest yield in country *c*, silvicultural system *s*, forest type *f*, age class *a*, in time period *t*, enrolled in harvest regime *r*
$z_{c'ctp}$	parameter indicating the trade of forest product *p* outside of the EU from country *c'* to country *c* in time period *t*
α_{pj}	parameter indicating wood product substation carbon pool *j* associated with the use of forest product *p*.
β_{pcte}	parameter indicating the area of each rectangle associated with of the *e* equal steps that are used in the piece-wise integration of the area under the demand curve for forest product *p* in country *c* in time period *t*
η_c	parameter indicating the discount rate (%) in country *c*
θ	parameter indicating carbon price in €/tonne
λ_{ctj}	parameter indicating the baseline (0 €/tonne) carbon stock in carbon pool *j* in country *c* in time period *t*

Variables

A_{csfar}	variable indicating acres in country *c* using silvicultural system *s* in forest type *f* of age class *a* assigned to harvest regime *r*
B_{ctpm}	variable indicating the building of manufacturing capacity for forest product *p* in country *c* using manufacturing technology *m* in time period *t* beyond periodic depreciation
C_{ctj}	variable indicating the carbon stock in carbon pool *j* in country *c* in time period *t*
D_{ctp}	variable indicating the annual demand for forest product *p* in country *c* in time period *t*
G_{ctpm}	variable indicating an expansion of manufacturing capacity for forest product *p* in country *c* using manufacturing technology *m* in time period *t* limited to the periodic depreciation of that capacity
H_{ctw}	variable indicating the annual harvest of wood product *w* in country *c* in time period *t*
K_{ctpm}	variable indicating manufacturing capacity for forest product *p* in country *c* using manufacturing technology *m* in time period *t*
M_{pcmit}	variable indicating manufacturing of wood product *p* in country *c* using manufacturing technology *m* and input mix *i* in time period *t*
$T_{c'ctp}$	variable indicating the trade of forest product *p* inside of the EU from country *c'* to country *c* in time period *t*
W_{pcte}	variable indicating the proportion of each of the *e* equal steps that the area under the demand curve for forest product *p* in country *c* in time period *t*

Mathematical depiction of EUFORIA model

The EUFORIA model consists of an objective function that implements piecewise integration of the forest product demand curves allowing for a solution as a linear programming problem and thirteen sets of constraints controlling area allocation, harvest calculation, supply and demand balancing, and cost accounting.

Objective function

The objective function (Equation A1) used in the linear program involves the maximization of the discounted sum of the net social payoff plus a payment/cost for carbon sequestration/emission in excess of a baseline carbon sequestration/emission determined by solving the model with a carbon price of zero.

$$MAX \quad \sum_{c}\left(\sum_{t}\left(\left(\sum_{p}\sum_{e}\left(W_{pcte} * \beta_{pcte}\right)-\sum_{p}P_{ctp}-F_{ct}\right)+\theta * \frac{\sum_{j}\left(\left(C_{ct^{+1}j}-C_{ctj}\right)-\left(\lambda_{ct^{+1}j}-\lambda_{ctj}\right)\right)}{5}\right) * (1+\eta_c)^{-(t-t^{\sim})}\right) \tag{A1}$$

Constraints

$$\sum_{r} A_{csfar} = x_{csfa} \quad \forall c,s,f,a$$

Allocation of all available area (A2)

$$\sum_{s}\sum_{f}\sum_{a}\sum_{r}\left(A_{csfar} * y_{csfatr} * v_{cw}\right) = 5 * H_{ctw} \quad \forall t,c,w$$

Annual harvest calculation (A3)

$$\begin{aligned} & H_{ctp} + \sum_{c'} z_{c'ctp} + \sum_{c*} T_{c*ctp} + \sum_{p'}\sum_{m}\sum_{i}\left(M_{p'cmit} * b_{p'cmip}\right) + R_{ctp} \\ & = \sum_{p'}\sum_{m}\sum_{i}\left(M_{pcmit} * b_{pcmip'}\right) + \sum_{c'} z_{c'tp} + \sum_{c*} T_{cc*tp} + D_{ctp} \quad \forall c,t,p \end{aligned}$$

Supply balance (A4)

$$D_{ctp} = \sum_{e} W_{pcte} \quad \forall c,t,p$$

Demand balance (A5)

$$R_{ctp} \le D_{ct^{-1}p} * u_c \quad \forall c,t,p$$

Recycling limitation (A6)

$$\sum_{i} M_{pcmit} \le K_{ctpm} \quad \forall c,t,p,m$$

Capacity limitation (A7)

$$K_{ctpm} \le K_{ct^{-1}pm} * (1-d) + G_{ctpm} + B_{ctpm} \quad \forall c,t,p,m$$

Capacity dynamics (A8)

$$K_{ctpm} * d \geq G_{ctpm} \quad \forall c, t, p, m$$

Capacity maintenance limitation (A9)

$$\sum_{m} \sum_{i} \left(M_{pcmit} * q_{pcm} \right) + \sum_{c'} \left(T_{c*ctp} * o_{c'cp} \right) + \sum_{m} \left(K_{ctpm} * \frac{k_{cp}}{100} G_{ctpm} * \frac{k_{cp}}{10} + B_{ctpm} * k_{cp} \right) = P_{ctp} \quad \forall c, t, p$$

Industry costs (A10)

$$\sum_{s} \sum_{f} \sum_{a} \sum_{r} \left(A_{csfar} * y_{csfatr} * h_{cr} \right) + \sum_{s} \sum_{f} \sum_{a} \sum_{r} \left(A_{csfar} * n_{cr} \right) = F_{ct} \quad \forall c, t$$

Forestry costs (A11)

$$W_{pcte} \leq 1 \quad \forall c, t, p, e$$

Demand integral step limit (A12)

$$\sum_{s} \sum_{f} \sum_{a} \sum_{r} \left(A_{csfar} * l_{csfatrj} \right) + \sum_{t' \leq t} \sum_{p} \left(D_{ctp} * g_{t'tpj} \right) + \sum_{p} \left(D_{ctp} * \alpha_{pj} \right) = C_{ctj} \quad \forall c, t, j$$

Carbon calculation (A13)

Paper V

SCANDINAVIAN JOURNAL OF FOREST RESEARCH, 2016
http://dx.doi.org/10.1080/02827581.2016.1212089

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REVIEW ARTICLE

Incorporating risk in forest sector modeling – state of the art and promising paths for future research

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ABSTRACT
The use of numerical forest sector models (FSM) for economic and policy analyses has strongly increased in the last decades. Nearly all of these models are deterministic; however, long-term market projections are inevitably uncertain. The main objective of this article is to explore the possibilities of introducing risk in such models. For that we (i) review how risk has been incorporated in FSM, forestry and equilibrium models in adjacent sectors (agriculture, fishery, energy) and in macroeconomic models, and (ii) based on the review, identify and discuss promising approaches for including risk in FSM. Rather few large-scale model applications where risks were explicitly included beyond scenario and sensitivity analyses were identified. For incorporating risk in FSM, fuzzy set theory and robust optimization techniques seem promising new approaches, alongside methods that already are in use, like Monte Carlo simulation and, in particular, scenario and sensitivity analysis.

ARTICLE HISTORY
Received 16 December 2015
Accepted 7 July 2016

KEYWORDS
Partial equilibrium modeling; market analyses; forest industries; numerical modeling

Introduction

During the last two decades, we have witnessed an increasing interest in the use of forest sector models (FSM). Generally, one may define FSM as models that include forestry, forest industries and market interactions between them (Solberg 1986). As such, FSMs represent a large variety, from pure simulation models with no or weak market equilibrium assumptions, to more complex spatial market equilibrium models that incorporate regional timber supply and forest industry products demand linked by interregional trade (see Latta et al. 2013 for an overview).

Although FSM vary considerably, nearly all of them share the common feature of being deterministic – i.e. risks or uncertainties are not explicitly considered. However, without exception, every model is by definition a simplification of reality, and as pointed out by Kallio (2010), large-scale FSM have thousands of parameters which have varying degrees of inaccuracy. While some base year data have high accuracy, other model parameters are estimates based on statistical analyses, and some parameters might be derived from the modelers' best judgment if no data are available. The needed accuracy level should be seen in the context of the problem to be solved. FSM share this challenge with modeling in all other economic sectors, and for improving risk assessments in the forest sector it may therefore be of high interest for developers and users of FSM to learn about the model experiences gained in adjacent economic sectors like agriculture, fishery and energy, besides macroeconomic modeling and forestry.

Following this, the main objective of this paper is to explore the possibilities to include risk in FSM. The study has two sub-objectives: (i) Review the risk methods that have been incorporated in FSM and in numerical models in forestry, agriculture, fishery and energy and macroeconomic models, and (ii) based on this review identify and discuss promising approaches for including risk in FSM.

The remaining parts of the article are organized as follows. First, the methodology is described, the scope of the study clarified and the concept of risk defined. Second, the sector-wise review is presented, focusing on the methods applied and main experiences gained that seem relevant for FSM. Third, the results are discussed and main conclusions drawn.

Method and scope

The article is based on a literature review of more than 200 articles. The Science Direct database (journal articles) and Google Scholar (journal articles and other types of publications) were the main sources of information. We excluded publications not written in English. As we were interested in studies that in their risk and uncertainty explorations go beyond scenario or sensitivity analyses, we have omitted studies that only used these approaches. Only one FSM study has incorporated risk beyond scenario and sensitivity analyses and was therefore included explicitly in the review. Although we studied original papers for the other sectors, our review of these sectors is mostly based on previous reviews as they provided the most comprehensive overview for our study.

The study is not exhaustive, but shows in our opinion the main possibilities and challenges for incorporating risk in FSM.

FSM have been designed to analyze various kinds of economic and policy problems. Four models TAMM – the Timber

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Assessment Market Model (Adams & Haynes 1980), PAPYRUS (Gilless & Buongiorno 1987), International Institute for Applied Systems Analysis Global Trade Model (Kallio et al. 1987) and TSM – the Timber Supply Model (Lyon & Sedjo 1983) have served as cornerstones for most of the FSM in use today (Latta et al. 2013). However, the present models differ in aspects such as geographical scope, assumptions regarding agent information, degree of detail and size (Latta et al. 2013). The focus of the article is on partial, spatial equilibrium models that cover several regions; in practice, the geographical scope is minimum in a country or state. These models maximize the social surplus based on Samuelson (1952) and secure spatial equilibrium solutions by incorporating interregional trade.

In this study, we use the classical definitions of risk and uncertainty by Knight (1921). In objective risk situations, the odds of outcomes are known based on objective probability, i.e., the outcome can be described by sure probability functions. Subjective risk situations, on the other hand, are characterized by subjective probability formed by personal judgment, information, intuition or other subjective evaluation criteria (Aczel & Sounderpandian 2008). Using the risk concept, one accepts that lack of objective probability can be replaced by subjective probability. However, in uncertainty situations, we do not even know how to describe the outcomes (Runde 1998; Guerron-Quintana 2012). We are aware that discussions about these concepts have been ongoing for decades and that there exist several definitions of risk and uncertainty (Leroy & Singell 1987; Langlois & Cosgel 1993; Runde 1998), but we use this established distinction as we believe that it creates a suitable and reasonable basis for our study on numerical models. It would make no meaning in numerical models to include parameters which we have no information about and cannot quantify. Risk as defined above, on the other hand, covers all cases where a probability distribution of the variable in question can be assumed.

Although we have limited the scope to focus solely on risk in the Knightian sense, we have included articles on uncertainty in the review when they offer relevant insight with regard to risk. The papers that we reviewed applied various definitions of risk and uncertainty. To avoid confusion, we have used our definition in the review of the papers, and stated explicitly when they have used the term “uncertainty” as defined by us.

Literature overview

Forestry

Kangas and Kangas (2004) gave a broad overview of risk[1] theories and approaches to consider risk in forestry decision analyses. They classified risk theories into five main classes labeled frequentist probability theory, Bayesian probability theory, evidence theory, fuzzy set theory and possibility theory. Major sources of risk in forestry decision-making were then discussed. Finally, forestry decision applications were divided into two main model types – those using optimization or heuristics solutions techniques and those using multi-criteria decision analyses in a probabilistic or non-probabilistic framework.

The following issues emphasized op. cit. as important aspects regarding risk consideration in forestry studies are in our opinion relevant for model exercises in general, including FSM:

- In the future, risk analysis will probably be an integrated part of most decision analyses.
- Several approaches are needed to deal with risk, as we need decision support tools suited for different situations.
- The Bayesian methodology seems promising, in particular in situations where there are subjective risks.
- Fuzzy set theory seems promising in certain types of forestry modeling.
- Involving social aspects (like stakeholders’ preferences, attitudes and values) implies new challenges regarding obtaining knowledge about these aspects.

Hanewinkel et al. (2011) gave an overview on how to integrate risk assessment in forest management, divided into five points: (i) specification of major disturbances to forests and their future importance (storm, snow, fire, insects), and review of studies exploring these disturbances; (ii) methods for assessing and modeling risk; (iii) spatial and timing aspects of the disturbances; (iv) how to reduce risk and damages and (v) inclusion of economic aspects in risk analyses.

We find the following issues emphasized in that study relevant for FSM, in particular models that include forest management:

- Models should be applied only when the users of the model have thorough understanding of their limitations and uncertainties.
- Regarding forestry modeling, the integration and combination of models that include climate change and relevant downscaling are important.
- Equally relevant is to incorporate the interaction between various types of hazards, like storm, insect attacks and fire.
- Variables that cover degree of vulnerability and resilience could attract high interest for inclusion.

Yousefpour et al. (2011) reviewed 112 studies of complex decision problems in adaptive forest management under climate change uncertainty. The studies were classified depending on the sources of risk (price, interest rate, climate change, fire, wind, biotic, society); risk models applied (e.g. Markov chains, Ito calculus, Bayesian statistics, geometric Brownian motions, vector autoregressive processes, expected value, Poisson processes, binomial tree); variables considered in the objective functions (timber, water, biodiversity, carbon, amenity, recreation) and analytical and operation research method used (real options, information gap, expected value, Ito calculus, Quasy optimum, dynamic programming, non-linear programming, fuzzy set theory, simulation, analytical hierarchy processes, heuristics).

The following issues emphasized op. cit. are in our view of particular interest for FSM:

- There is an inherent risk associated with the probability distributions of future climate changes, which implies that proper forest model development will need to handle non-stationarity and perhaps even belief-based parameters of stochastic processes and probability distributions, like Bayesian updating.
- There is a need for simple but valid forest growth models that (i) can provide good estimates of timber production and preferably also other goods and services as functions of stand characteristics, (ii) are sensitive to climate change, (iii) are able to link various stand output functions to form forest and landscape levels models, (iv) are simple enough to provide good conditional predictions of key state variables and flows at low computational costs, hence allowing for appraising numerous decision alternatives.

Hildebrandt and Knoke (2011) gave first an overview of financial techniques they consider are of interest for decision-making under risk[2] in forestry, concentrating on the expected utility framework (stochastic dominance, downside risk, mean-variance analysis), option pricing models (binominal and Black–Scholes models) and robust optimization (information-gap decision theory). Secondly, they reviewed how these techniques had been used in forestry studies, and analyzed their pros and cons.

We think that the following points from this study of risk consideration in forestry may apply also to FSM:

- Even though it is intuitively clear that many long-term decisions should consider risk, adequate financial valuation is not sufficiently developed within the forest science.
- Robust optimization techniques seem promising for analyzing many long-term decisions in forestry, and should be developed further for applications related to forestry.

Pasalodos-Tato et al. (2013) reviewed different methods to handle risk[3] in forest planning at three spatial levels (stand, forest/landscape and regional) and looked into participation processes, the objectives dimensions and the goods and services addressed.

Of the issues they emphasized, we think the following are important to keep in mind for FSM developers and users:

- The technical implementation of risk in forest planning models may lead to very large-scale optimization problems difficult to solve, and when solved difficult to interpret.
- Robust optimization has until now been used in only relatively small-scale analyses, and needs in forestry planning to be expanded to larger applications.
- There is a trade-off between simplicity and increased complexity when considering risk in forest planning. So far, the decisions about considering or ignoring risk have generally been in favor of simplicity.
- The knowledge about and estimation of risk may in many cases be very limited, including current and future preferences for non-timber variables like recreation, biodiversity and water catchment.
- In order to enhance the inclusion of risk into practice, certain aspects need special consideration:
    - (a) A good understanding of the main risk factors and their effects.
    - (b) A clear notion about the potential gain by including risk.
    - (c) The methods and tools chosen to include risk should be suitable for the decision problem in question, sufficiently easy to implement and use and possible to communicate to the relevant users of the model results.

FSM studies

Buongiorno et al. (2012), using the Global Forest Products Model to project the development of the global forest sector up to year 2060, mentioned in the context of FSM three sources of risk[4]: (1) model structure and its parameters such as demand elasticities, input–output coefficients and forest growth parameters, (2) the quality of data describing the past and current state of the world, (3) exogenous assumptions such as population and GDP growth rates or demand changes.

To the best of our knowledge, Kallio (2010) is the only FSM study that has explicitly included risk[5] beyond sensitivity and scenario analyses. She applied Monte Carlo simulation in an FSM for Finland, consisting of 15 regions (of which 14 were domestic), 12 wood fiber categories and 32 forest industry products. The following factors were given probability functions (either lognormal, normal or uniformly ones): initial growing stock, annual forest growth, wood supply elasticity with respect to growing stock and price, harvest costs, prices of imported eucalyptus, energy prices, other production costs, product prices, export demand of sulfate pulp and transportation costs. Random samples were drawn from the assumed probability functions of uncertain parameters and used as inputs for each model run until the sample means and variances of the products' manufacturing levels and roundwood prices converged within the desired tolerances.

We found the following results op. cit. of particular importance for our study:

- The risk in basic parameters only moderately affected the projections, whereas the cyclicality in world market prices had much higher impacts on the Finnish forest sector.
- The robustness of the model results are important for the users of the results. Allowing for price cyclicality gave large projection variance, whereas it was lower in the single sensitivity events or policy studies done.

In global FSM, world prices are endogenous, i.e., derived from where demand equilibrates with supply, and not exogenous as for one country. Thus, log or product prices do not enter the parameter set of global models, but are determined endogenously based on data, assumptions and structure in the models. Exchange rate is, however, an important and highly volatile parameter in local as well as global FSM. To the best of our knowledge, no systematic analyses of the risk related to exchange rates in global versus local models have been carried out, and the Monte Carlo method is one way for exploring the impacts of such risk. However, Monte Carlo applications can be very time-consuming, especially for larger models. Therefore, techniques that save time and are similar to Monte Carlo in terms of stochastic component generation seem preferable, and we discuss some of these approaches in the next chapter.

Sjølie et al. (2011a) provided insight into what could be labeled risk regarding structural model assumptions in FSM. They studied how agents in the Norwegian forest sector would react to a sudden future exogenous change under the assumptions of perfect, imperfect and no foresight. Their main result was that these foresight assumptions significantly influenced the impacts of a future change.

Another type of structural model assumptions was analyzed by Kallio (2001), who investigated how assumptions about the wood markets influenced the FSM results. She simulated the wood buyers' behavior under alternative competition structure (perfect competition, Cournot oligopsony and monopsony) in Finland during 1988–1997. The results suggested that noncompetitive behavior of the buyers was possible during the recession years in that period, and that the conclusions depended strongly on the size of the assumed pulpwood price elasticity.

Toppinen and Kuuluvainen (2010) reviewed 47 European papers published during the 1998–2007 period, divided into econometric models and numerical FSM. They underlined that numerical FSM depend on supply and demand elasticities provided by econometric studies and that these models in particular encounter the following challenges:

- The lack of theoretically well-founded numerical descriptions of forest age–class dynamics.
- The lack of description of forest owners' preferences for the production of timber, non-timber and non-market goods.
- Incorporation of technological change related to the development of existing and new products.
- Inclusion of global perspectives regarding structural changes, products dynamics and location of new production capacities.
- The stochastic nature of the real world.

Hurmekoski and Hetemäki (2013) reviewed how different outlook approaches have taken into consideration structural changes, and questioned whether outlook studies based on FSM are informative enough for today's decision-makers and other stakeholders. According to the authors, the global forest sector is becoming more complex, interlinked and cross-sectoral. They argue that existing outlook studies and FSM have not been able to sufficiently capture the structural changes in the forest sector and its operating environment as seen in global paper markets, and it may be assumed that the models have difficulties in considering the possible changes in other markets as well (Hurmekoski & Hetemäki 2013).

Agriculture

Starting from the review paper of global models applied to agricultural and trade policies (Van Tongeren et al. 2001) we paid closer attention to model applications that incorporated risk. Burrell and Nii-naate (2013) found that introducing stochastic features into baseline projections is a relatively new concept in large-scale agro-economic models and that presently there are only three modeling systems which contain stochastic functionality: Food and Agricultural Policy Research Institute (FAPRI), European Simulation Model and AGLINK-COSIMO. All these models can be used to analyze risk based on multivariate distribution that generates the stochastic components (see Table 1). These multivariate distributions were obtained by techniques such as Gaussian Quadrature (European Simulation Model (ESIM)), Latin Hypercube (FAPRI) and Monte Carlo (Burrell & Nii-naate 2013). When models become large, Monte Carlo simulation becomes impractical. The Gaussian Quadrature technique saves computational capacity and provides a practical mean to include risk in large models, obtaining results very similar to Monte Carlo. Latin Hypercube is a stratified sampling method that became very popular in the 1980s when computers were less powerful, but has becomes less popular due to improvements in computer capacity and sampling techniques.

The following issues that were emphasized as important future research needs are in our opinion particularly relevant for considering risk in FSM:

- Incorporation of market agents' views and attitudes toward risk may bring valuable qualitative information to the modelers on how to improve models.
- Choice of insurances reflects attitudes toward risk and show what market agents are most afraid of.
- Due to complex systems, integrated risk assessment models which allow combining qualitative with quantitative data into one consistent modeling framework seem better suited for holistic risk evaluation than applying multiple models that are not integrated.
- Identifying risk attitudes among different types of land owners may contribute toward better models.
- Including stochasticity may contribute to a better understanding of asymmetric effects of policies.
- Deterministic large-scale agro-economic models have been updated in order to include variability in exogenous factors (e.g. yield). Techniques such as Latin Hypercube, Gaussian Quadrature and Monte Carlo have been applied. Nevertheless, application of these techniques is not always straightforward.

Fishery

Charles (1998) distinguished three main categories of uncertainties in fisheries, i.e. random fluctuations (e.g. survival rate of fish in the ocean, price for fish in the market), uncertainties due to imprecise parameter estimates and unknown states of nature, and fundamental structural uncertainties (e.g. spatial complexity, fish–fish interactions, technological

Table 1. Selected agriculture sector models that consider risk.

Model	Main characteristics	Objective function	Time horizon	Main risk factors considered	Technique of risk incorporation
FAPRI stochastic model (Westhoff et al. 2005; Meyer 2007)	Recursive dynamic, non-spatial framework that consist of a set of partial equilibrium models covering, e.g., US crop model, international cotton, dairy, livestock or sugar models	Maximization of social surplus	The models provide 15-year projections	Crop yields, energy and cost variables, demand shocks, animal stocks and trade	Latin Hypercube, Monte Carlo
ESIM (Artavia et al. 2009)	Comparative static, net-trade, partial equilibrium multi-country model	No information[a]	Up to 2020	Crop yields	Gaussian Quadrature, Monte Carlo
AGLINK-COSIMO (Burrell & Nii-naate 2013)	Recursive dynamic composed of two modules: AGLINK –supply–demand model of world agriculture and COSIMO – commodities simulation tool	Maximization of social surplus	Models 10 years into the future	Macroeconomic indicators (e.g. exchange rate, GDP, prices), crop yields, world crude oil prices	Sensitivity analysis, Monte Carlo

[a] Both FAPRI and AGLINK-COSIMO are based on the Samuelson (1952) approach defined as maximization of the social surplus. However, we are not sure about the ESIM model due to lack of transparency in the description of the examined agriculture sector models.

changes, fisher objectives or fisher response to regulations). There is a significant amount of studies related to risk and uncertainty in fishery that analyze stock assessment and harvest decisions (Hannesson 1987; Hilborn et al. 1993; Singh et al. 2006), fishery management (McAllister & Kirchner 2002; Sethi et al. 2005; Doyen et al. 2012), fisher behavior and optimal fish quota (van Dijk et al. 2014) and climate effects on fisheries (Torralba & Besada 2015). However, to our knowledge, there are no large-scale fishery sector models that explicitly include risk. Based on the review of regional economic models for fisheries in the US such as Input–Output models, Fishery Economic Assessment Models, Social Accounting Matrices and computable general equilibrium (CGE) models (Pan et al. 2007), we found that these models include no stochastic elements.

Energy

Risk assessments have long traditions in energy sector analyses. In the energy sector, risk research has focused on the availability of natural resources (e.g. Speirs et al. 2015) financial aspects and investments (e.g. Sadorsky 2001) and energy planning and modeling (e.g. (Crousillat 1989; Mirakyan & De Guio 2015). Energy models are highly relevant for FSM as both model classes are characterized by long planning horizons and large optimization problems. We have selected the articles within the energy sector that we believe are particularly relevant for FSM.

Mirakyan and De Guio (2015) described the modeling process, starting from mental models to applied models and proposed a framework that can identify and classify different risk types at subsequent model development phases. In the context of the energy sector, it was found that most of the studies in energy planning were deterministic and no risk analysis was performed or even mentioned. It was highlighted that only a couple of studies took into account variability among model inputs, while other risk factors such as model context or risk in ignorance situations were not discussed in integrated energy planning. Model inputs and parameters were usually analyzed, but similarly other risk types in the modeling framework were often neglected and not mentioned in results.

Lee (2014) analyzed energy supply planning and supply chain optimization, with special attention to risks[6] in market, politics and technology. It was concluded that if risks can be captured by a relatively small number of scenarios, the two-stage stochastic programming framework could be sufficient. However, for problems that are more complex, approximate dynamic programming (ADP) was mentioned to be a promising technique. ADP is a method that relies on algorithmic strategies for solving large and complex problems, and helps to overcome the "curse of dimensionality" problem – i.e. situations where the size of a state space grows exponentially in a number of state variables. ADP is assumed to achieve near-optimal solutions for large deterministic models with long time periods and can deliver robust solutions to stochastic problems as well.

Cai and Sanstad (2015) focused on fundamental model risk[7] in the study of CO_2 emissions abatement from the energy system. They stressed that technological change appears crucial in terms of model reliability.

Connolly et al. (2010) and Jebaraj and Iniyan (2006) analyzed existing energy models distinguishing between energy planning models, simulation models, scenario models, equilibrium models and optimization models. As our focus is on large-scale equilibrium models, we have scrutinized whether risk was considered in the partial equilibrium models such as the PRIMES model (E3MLab 2014), the LIBEMOD model (Aune et al. 2001) and the Balmorel model (e.g. Kirkerud et al. 2014) (see Table 2). We consider the scenario aggregation technique that was used in the LIBERMOD model to be a potentially interesting approach for FSM. This technique allows the users to obtain individual scenario solutions and thereafter, by analyzing intermediate solutions, to identify at an early stage factors that play significant or insignificant roles in the construction of the overall solution (Rockafellar & Wets 1987; Brekke et al. 2013).

Based on the above-mentioned energy studies, we believe the following issues are particularly relevant for risk consideration in FSM:

- ADP seems to be an interesting optimization technique as it may overcome the "curse of dimensionality" problem of dynamic programming and uses learning and

Table 2. Selected energy sector models that consider risk.

Model	Main characteristics	Objective function	Time horizon	Main risk factors considered	Technique of risk incorporation
PRIMES (E3MLab 2012, 2014)	Partial equilibrium, dynamic, non-spatial model that assumes perfect foresight for energy demand and supply sectors. Includes EU28 member states and i.a. Western Balkans countries and Norway	Maximization of social surplus. Separate objective functions per energy agent are formulated	Designed to provide long-term energy system projections and system restructuring up to 2050	Macro and global assumptions (e.g. fuel prices), policy assumptions and technological development	Scenario analysis
Stochastic version of LIBEMOD (Brekke et al. 2013)	Numerical multi-market equilibrium model of the Western European energy market. Represents 7 energy goods (e.g. electricity, natural gas or biomass)	Maximization of social surplus	2000–2030	Economic risk (e.g. fossil fuel prices, GDP) Political risk (e.g. climate policy)	Scenario aggregation Monte Carlo
Balmorel (Kirkerud et al. 2014)	Partial equilibrium, dynamic model with emphasis on the electricity and combined heat and power sectors in the Baltic Sea region	Maximization of social surplus	Long term (one year) or short term (week)	Capacity of electric heat-producing units	Scenario analysis

approximation mechanisms to analyze complex and large problems.

- Scenario aggregation techniques appear helpful to indicate the most influential factors.
- Close dialogue between policy-makers and modelers is needed for the modelers to identify main uncertainties in the models and for the modelers to understand how the model results are being used.
- Careful attention should be given to every step in the model development, as different uncertainties appear during the way of this process.
- Scenario analysis reflects contrasting evolution of vital exogenous assumptions, and is a common practice in the energy sector, giving satisfactory results.
- Brekke et al. (2013) compared deterministic results with Monte Carlo and scenario analyses. They found that in certain cases, Monte Carlo gave similar results to scenario analyses and both these approaches often gave more accurate estimates of the outcome under risk than the simple deterministic solution. However, in some cases Monte Carlo failed to produce a good approximation to the true optimal policy under risk.

Macroeconomic modeling

Macroeconomic models are designed to describe the whole economy of a region, country or even group of countries, including vital relationships between sectors. Pratt et al. (2013) identified the following main categories of risks in this type of modeling: Model risks,[8] economic risks that contain unknown future states of the world, policy risks and technology risks.

In the following, we give a short overview on how risk has been treated in macroeconomic modeling, paying special attention to some global macroeconomic models.

Pratt et al. (2013) made an exhaustive review of risk incorporation in CGE models. Some authors have tried to overcome the shortcomings of deterministic CGE models by applying different implicit techniques. Burniaux (2000) extended previous OECD analyses on greenhouse gas emissions using the GREEN model (Burniaux & Truong 2002), illustrating the risk by two extreme cases (Burniaux 2000).

Some CGE models have explicitly incorporated risk based on the fact that the economy is affected by random fluctuations and shocks. This approach was used by Smets and Wouters (2003), who analyzed the euro area. In order to account for the stochasticity in the empirical data, they introduced various market shocks to the dynamic stochastic general equilibrium model. Thereafter, they estimated by using Bayesian technique the sources of business cycle dynamics in the euro area.

Based on the above-mentioned macroeconomic studies, the following issues seem particularly relevant for taking risk into account in FSM:

- When input data are regarded as robust, risk analysis of input data is less important.
- The use of extreme cases (scenarios) may bring valuable and robust outputs when the decision-maker wants to know the boarders of possible states of the world.
- Scenario analysis seems to be the most applicable and straightforward technique to incorporate risk in a deterministic modeling framework.

Discussion and conclusions

Although risk has been subject to considerable attention in the literature, no consensus seems to exist on which methods are most appropriate to significantly increase the level of model output reliability.

Our review shows that risk has been included in only one FSM study; in addition risk has been recognized through scenario analyses in many studies (Buongiorno et al. 2012; Chudy et al. 2013; Moiseyev et al. 2014; Sjølie et al. 2015). Also, except for scenario analyses, very few studies have incorporated risk in sectors like energy and fishery, and in macroeconomic modeling. Studies in forestry that have incorporated risk applied a variety of methods, but most of them were at the single or multi-stand level using methods that are unsuitable to apply in FSM.

Risk components play important roles in modeling practices in all the reviewed sectors. Each sector is characterized by its own specific risk factors. For instance, in fishery the risk related to biomass supply caused by limited knowledge about growing stocks seems higher than in forestry, where in many countries forest inventories are relatively accurately assessed compared to inventories of fish stocks. Nevertheless, there is a need for simple but valid models that are able to maintain the realism of forest growth models when aggregating forest dynamics to, e.g., regional level. Sectors share characteristics regarding risk factors, in particular related to exogenous changes in policies and markets alongside catastrophic events.

The review shows that market agents' perception and attitude toward risk are relevant elements to consider in forest sector modeling. However, human behavior belongs to the most complex risk factors in any type of modeling exercise as economic theory does not fully capture people's behavior. Risk perception and attitude might potentially be incorporated in stochastic simulation models by using the stochastic efficiency with respect to a function Stochastic Efficiency with Respect to a Function framework to include how agents may behave given possible choices, as applied by e.g. Lien et al. (2007) and Ogurtsov et al. (2008). However, this method has significant limitations, in particular when decisions are complex or non-discrete. Research on including insurance in forest sector modeling seems an interesting subject for further analysis.

According to Smith & Heath (2001), deterministic models are "first-pass attempts" in assessment modeling, and are often missing quantitative risk descriptions important for decision-making. Some authors, such as Kay (2012), emphasize that despite models being consistent in the mathematical sense, the discrepancy between the real world and theory may be problematic.

There are ongoing discussions about appropriate model complexity and size, basic assumptions (perfect vs. imperfect markets), assumptions of agents' behavior (perfect foresight vs. myopic) and optimization technique (dynamic recursive vs. intertemporal, see, for example, Sjølie et al. 2015). There is no clear answer to the question of which of these approaches, assumptions and methods are best. Nearly all of the reviewed deterministic FSM studies discussed risk factors and their potential impacts on the results. However, most of those discussions look into risk related to model inputs and parameters, whereas other types of risks related to, e.g., model structure and assumptions about agent behavior are rarely discussed. Increased cooperation between model developers and model users seems important here. The forest sector is definitely susceptible to structural changes, and decision-makers may help modelers to identify the most vital risk factors in a given modeling and policy framework.

We have shown that many options exist for incorporating risk in model analyses. However, many of the proposed methods are too demanding with respect to data availability and computer capacity to be applicable in large-scale numerical FSM.

Taking into consideration that our focus in this article is on large-scale numerical partial equilibrium modeling, we are of the opinion that a combination of deterministic optimization, sensitivity analysis, Monte Carlo simulation and scenario analysis is a promising avenue to pursue, e.g. by using the following step-wise procedure:

(A) Define the problem to be analyzed, the main variables which have to be considered and as well as possible their structural relations and risk in the real world.
(B) Make necessary model simplifications to incorporate A as well as possible in a deterministic optimization model. Here, other model structural elements have to be clarified, like product and regional details, degree of trade inclusions and agent behavior assumptions.
(C) Use the deterministic model for sensitivity analyses to identify the decisive factors of those found in A and included in the optimization.
(D) Provide probability distributions (using subjective probabilities if satisfactorily empirical distributions are not available) on the factors identified in C. Here Bayesian probabilities can be used to include conditional probabilities between variables and structural factors.
(E) Use the Monte Carlo method and deterministic optimization in combination, to:
    (1) Draw from the probability distributions in D a time-consistent set of estimates and use this set in the deterministic optimization model in B.
    (2) Repeat E1 until pre-specified convergence criteria are reached.
    (3) Write out the distributions of output and input variables that are important for decision-makers involved in the model exercise.
(F) Use scenario analysis to define a new set of basic assumptions under A, B, C or D (for example another scenario regarding economic growth or climate change) and repeat the procedures A–E with the new assumptions. Scenario analysis seems to be the best currently feasible way that shows the range of possible outcomes and can serve as a valuable decision-making tool at the forest sector level.

This procedure could then be supplemented by introducing robust optimization (Ben-Tal & Nemirovski 2000; Palma & Nelson 2009), the information-gap decision theory (Ben-Haim 2006, 2010) or fuzzy-set theory (Mendoza et al. 1993; Ells et al. 1997). Robust optimization could, for example, be incorporated in step C above through constraints regarding fulfilling certain ecological qualities or certain resilience criteria with a pre-specified probability. Fuzzy set theory might be part of the probability quantifications in step D. In a dynamic partial equilibrium model like NorFor (Sjølie et al. 2011b) it is also possible *ex ante* in the forestry sub-model to use stochastic programming for generating forest management treatments, and then use these alternatives as input in the overall forest sector optimization.

The above-described A–F procedure presents an ideal approach. In reality, one would most often have to make modifications according to available resources of data, model capacity and human skills, but the procedure can still be useful with some adjustments.

Notes

1. The term “uncertainty” was used in the paper, which according to our definition is “risk”.
2. See Note 1.
3. See Note 1.
4. See Note 1.
5. See Note 1.
6. See Note 1.
7. See Note 1.
8. They used the term “uncertainty” besides “risk”.

Disclosure statement

No potential conflict of interest was reported by the authors.

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ISBN: 978-82-575-1553-9
ISSN: 1894-6402

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