Large-scale forest-based biofuel production in the Nordic forest sector: Effects on the economics of forestry and forest industries

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Abstract

Forest-based biofuel is a promising solution to increase the share of renewable and sustainable energy in the transportation sector. Large-scale implementation of biofuel, however, not only affects the energy and transportation sectors, but also the forest sector value chains. This study uses a partial equilibrium forest sector model to quantify how large-scale production of forest-based biofuel would affect forest owners and forest industries in the Nordic countries. In a scenario assuming that forest-based biofuels cover a 0–40% share of the current Nordic road transportation and domestic aviation fuel consumption, the model results show that the sawmill industry increases their profit slightly due to increasing prices for their sawmilling residues. The traditional pulp and paper industries, on the other hand, see a reduced profit by up to 3.0 billion €, corresponding to 8% of their annual turnover, due to the increase in the price of pulpwood. Due to the increasing wood prices, the forest owners benefit significantly from biofuel investments. According to the model, their gross revenue from harvesting increases up to 31% without the need to increase the harvest more than 15%. The overall profit in the traditional forest sector is reduced by 400–600 million €. The decrease in profit is largest when the biofuel production volume covers 20% to 30% of the liquid fuels in the Nordic countries. The reduction in overall profit is lower at 40% biofuel implementation, owing to the significant increase in revenue for the forest owner and the fact that the main reduction in pulp and paper industries happens at between 0% and 30% biofuel implementation. The study shows substantial economic spill-over effects from large-scale biofuel implementations to other parts of the forest sector.

Keywords: Biofuel; Forest-based biofuel; Forest sector modelling; Integration cost; Nordic countries; Partial equilibrium;

1 Introduction

The European Union (EU) has set the target of reaching a 10% share of renewable fuels for transportation by 2020 and, further, that 14% of the energy consumption in the transportation sector will be renewable by 2030 [1, 2]. Since the electrification of the transportation sector is a slow process, the EU member states need to produce or import large amounts of biofuel to reach this target. Currently, biofuel is mainly produced from food crops and palm oil, and thus the sustainability of using increased amounts of such feedstock for energy is questionable [3]. Second-generation (i.e., advanced forest-based) biofuels are often regarded as a sustainable alternative [4]. Such biofuels based on sustainably produced raw wood material may be available in large volumes around the world [5], with low indirect land-use implications [6].

Large amounts of biofuel are needed to fulfil the requirement for renewable fuel. One sustainable option is to produce forest-based biofuel. Large-scale implementation of forest-based biofuel production will affect not only the energy and transportation sectors, but also the forest sector, which includes forestry, wood-processing industries, and pulp and paper industries.

The forest sector has long traditions in the Nordic countries, and has undergone significant transitions since year 2000. Decreasing demand for some paper grades, together with the relocation of some forest industries to low-cost countries, have led to the closure of several mills over the last 20 years [7-9]. This in turn has led to a lower demand for pulpwood. Alongside the closure trend in the pulp and paper industries, which is being driven by digitalization, another trend also has started, driven by the increasing focus on GHG-related emissions from the production and use of fossil fuel and cement. Other products may therefore become more important in the future, such as sawnwood and biofuels. These changes may increase the demand for roundwood, by-products from the forest industry, and harvest residuals.

Although it may be of great importance when developing adequate policies for second-generation biofuel production, few studies have investigated the implications of significant forest-based biofuel production in the Nordic countries for the existing forest industries. One exception is a study by Trømborg et al. [10], which investigates how biofuel production may influence the Norwegian forest sector using a national forest sector model that covers Norway. They find that a production level of 500 million litres of biofuel yearly will lead to a small decrease in pulp production, a marginal increase in sawnwood production, and a significant decrease in biomass used to produce heat in Norway. The results are, however, highly sensitive to assumptions regarding international wood prices. Similarly, Kallio et al. [11] vary global demand for wood in bioenergy production, and investigate the influences on the global forest sector using a global partial equilibrium model. They report significantly higher harvest levels and prices for forest chips and pulpwood when increasing biofuel production up to 115 billion litres world-wide, while they find almost no change in the use of sawlogs in the European Economic Area (EEA). Kallio et al. [11] also find that there is a strong competition for feedstock between biofuel and bioheat, since they use the same feedstock. Lundmark et al. [12] investigate the effects of biofuel production implementation on the forest sector's profitability. They use three different models to investigate the implications of 0.5–3 billion litres of biofuel production in Sweden. Lundmark et al. [12] conclude that implementation of biofuel production in Sweden will have only a minor effect on the established forest industry, but the profitability of sales of by-products and harvest residuals will increase with increasing biofuel use.

Kallio et al. [13] study the Finnish chips market and conclude that an increase in sawnwood capacity is needed to make a significant increase in the use of chips and harvest residuals profitable. de Jong et al. [14] find an increase in profit for biofuel and sawnwood producers if they are co-located. These findings are supported by Mustapha et al. [15], who report a modest increase in sawnwood production volume in regions where biofuel is produced. Mustapha et al. [16] report a 12–35% increase in the price of chips in the Nordic countries if a 20% biofuel target is met.

Previous studies either apply models covering a single country or they use broad global models [17]. The national models have a simplistic modelling of international trade, while the global ones have a coarse regional resolution which means that the regional characteristics of raw material supply, production technologies, demand, and transportation costs are ignored. In addition, few (if any) studies provide a holistic overview of the effects on all the major stakeholders in the forest sector value-chain—forest owners, the sawmilling industry, pulp and paper industries, and biofuel producers.

In the present study, we apply a model covering the Nordic countries, which have a highly integrated forest products market [18-20]. This Nordic model includes modelling of sub-national regional markets and trade, which give a better representation of the forest sector than previously used national models. Mustapha et al. [15] used an earlier version of the model to study the optimal allocation of biofuel production in the Nordic region.

In this study, we quantify the economic effects of large-scale production of forest-based biofuel on forestry and forest industries in the Nordic countries—a region with considerable forest resources that may be utilized for biofuel production. We analyse the implications of different forest-based biofuel production levels ranging from 0% to 40% of total Nordic liquid fuel consumed within the transportation sector. The two main research questions in this paper are: a) what are the implications for the Nordic forest sector for different level of biofuel production? And b) which actors in the forest sector will gain or lose market shares with large-scale production of biofuel?

The paper is organized as follows: Chapter 2 describes the forest sector model used, along with the main assumptions regarding biofuel production in the model; Chapter 3 describes the scenarios that are used; Chapter 4 presents the results; Chapter 5 discusses the results; and finally, Chapter 6 provides the study's conclusions.

2 Method

2.1 Nordic forest sector model — NFSM

The Nordic Forest Sector Model (NFSM) is a spatial, partial equilibrium model covering forestry, forest industry, and bioenergy in Norway, Sweden, Finland, and Denmark. The model structure is built on the Norwegian Trade Model (NTM) [21-23], which in turn originates from the Global Trade Model (GTM) [24]. The NFSM has recently been used to identify optimal locations for biofuel production [15] and to estimate n^{th} plant total production costs in the Nordic countries [16] as well as the impacts of different conversion effectivities for different technologies [16].

The NFSM maximizes social welfare—i.e., consumer plus producer surplus—for each simulated period. The solution provides market equilibrium prices and quantities for each period, as shown by Samuelson [25]. In the NFSM, roundwood supply, industrial production, consumption of final products, and trade between regions are estimated simultaneously.

Roundwood supply is determined in the model by supply elasticities, the demand of roundwood by the industry, and growing stocks. Harvest of logging residues is related to the roundwood supply and the amount of harvest residuals is constrained up to 40% of the energy content in harvested roundwood in each region and period. The simulation of industrial production uses exogenous given input–output coefficients such as labour, energy costs, and feedstock requirements in combination with endogenous raw, intermediate, and final product prices. Consumption of final products is determined by regional demand, endogenous product prices, and price elasticity. Finally, trade between regions occurs until the price differences equal the transportation costs. Transportation cost is calculated with a fixed and variable per-kilometre cost between the assumed consumption, production, and harvest centre in each region. Transportation is chosen from the following options: truck, train, and ship. The model has 29 different products, including 6 types of roundwood supply (spruce, pine, and non-coniferous sawlogs and pulpwood), harvest residuals, 9 types of intermediate products, and 13 final products (3 sawnwood grades, 3 board grades, 4 paper grades, firewood and district heating, and biofuel). Norway, Sweden, and Finland are each modelled with 10 regions, while 1 region covers Denmark and 1 region covers the rest of the world. The latter is included to ensure that import and export to the Nordic countries is possible. The data used in the model are adapted from Mustapha [26]. The most important reference values for this study are shown in table 1.

A full description of the objective function and constraints of the NFSM is found in appendix 1. The model is solved as a Mixed Integer Linear Programming (MILP) problem, with the CPLEX solver using the General Algebraic Modelling System (GAMS) [27].

		Norway	Sweden	Finland	Denmark
Production	Sawnwood [million m^3]	2.21	18.6	9.73	0.36
	Boards [million m^3/metric ton]	0.59	0.89	1.20	0.35
	Pulp & paper [million ton]	1.53	22.2	21.5	0.5
	Chips, briquettes, firewood [TWh]	4.79	39.4	40.3	15.3
Harvest	Sawlogs [million m^3]	4.63	34.5	19.5	0.80
	Pulpwood include chips [million m^3]	6.75	41.3	34.2	2.60
	Harvest residuals [TWh]	0	7.55	6.01	0.28
Price delivered gate	Sawlogs [€/m^3]	68	76	74	68
	Pulpwood [€/m^3]	36	48	49	38
Price elasticity of roundwood supply	Sawlogs	0.8	0.6	1.0	0.8
	Pulpwood	1.2	0.8	1.2	1.2

Table 1. The reference production, harvest, roundwood prices, and elasticity of roundwood supply [26].

2.2 Biofuel production

Different conversion routes can produce biofuel, and the routes have different levels of economic maturation, efficiency, and other technical parameters [28-31]. Biofuel production can have other chemical products as a main or side stream. Products that can be produced simultaneously with biofuel include a large variety of marketable products, such as methanol, ethanol, dimethyl-ether, methane, diesel, gasoline, paraffin, jet fuel, and other tradable biochemical products [32, 33]. Since the biomass to biofuel conversion effectivity is highly uncertain, we assume that biofuel production has an overall energy efficiency of 58% independent of feedstock used, which is within the scope of what may be reasonable in the future. As we focus on large production volumes in this study, some technology and raw materials may have different effectivity—however, we assume that 58% is valid as an average. The effectivity and input–outputs for the biofuel production are based on a techno-economic study carried out by Serrano et al. [34], and we have selected the technology route of hydrothermal liquefaction (HTL), which allows different raw materials and products. The assumed energy efficiency implies that about 8.6 m^3 solid wood is needed to produce 1 m^3 of biofuel. We further assume that biofuel production has the same effectivity for different raw materials. The model can choose the most economical solution from the following raw materials: spruce, pine, and non-conifer pulpwood; residuals from sawmills; harvest residuals; or a mix of these. The difference between the raw materials is only the energy content, which is adapted from Mustapha [26]. The model can invest in fixed-size production units, of which the sizes—adapted from Serrano et al. [34]—are set to 150, 300, 450, and 600 MW feedstock capacity. This equals 79, 157, 236, and 315 million litres as annual production volumes. Table 2 shows the main assumption for each production unit. The consumption of electrical energy is assumed to be 0.355 kWh/$L_{biofuel}$ and 4.2 kWh/$L_{biofuel}$ of natural gas used as hydrogen source under upgrading, for all production sizes. Table 3 shows the regional costs of labour and electrical power.

The Nordic countries have set ambitious targets for reducing their consumption of fossil fuel. Norway, Finland, and Demark have use mandates to this effect: by 2020, at least 20% of the liquid fuel used in Norway and Finland must come from biofuel [35-37], and the corresponding figure for Denmark is 10% [38]. Sweden has set their target for reducing transportation-related carbon emission at 2.6% for gasoline and 19.3% for diesel in 2018, and they plan to increase this target to 70% within 2030 [39]. For this reason, we assume that the future production of biofuel in the Nordic countries is equal to a certain share (i.e. use mandate) of the diesel, gasoline, and jet fuel consumed in the Nordic countries in 2017, which was about 29.1 billion litres [40-43]. The analysed scenarios of 0%, 10%, 20%, 30%, and 40% of current fuel consumption thus represent 0, 2.9, 5.8, 8.7, and 11.6 billion litres of biofuel produced annually. The amount of biofuel is implemented as quota obligations, and the model finds the most competitive location and plant size for each given production level—i.e., minimizing the costs of reaching the production target.

	150 MW	300 MW	450 MW	600 MW
Labour input [h/1000 L]	0.57	0.44	0.38	0.42
Fixed costs [€/L/year]	0.56	0.49	0.45	0.42
Investment costs [€/L/year]	0.40	0.34	0.31	0.29
Production [million L/year]	79	157	236	315

Table 2. Labour, fixed costs, investment costs, and production level for the different plant sizes [input feedstock]. Source: Serrano et al. [34].

	Denmark	Finland	Norway	Sweden
Labour [€/hour]	27	18	39	20
Electricity [€/MWh]	54.5	42.9	39.9	41.3
Natural gas [€/MWh]	36.1	36.1	36.1	36.1

Table 3. Costs of labour, electricity, and natural gas used for biofuel production in the Nordic countries [44-48].

3 Scenario description

3.1 Baseline scenario

In the base scenario, we mainly use data described in Mustapha [26]. However, we have made some changes to the NFSM, and the changes are described here, as well as in chapter 2 and the appendix.

We have doubled the price elasticity of roundwood supply compared to values found in Mustapha [26]. The reason for this is that different studies report different values of elasticity of roundwood supply. For example, Tian et al. [49] found high uncertainties for the level of elasticity of roundwood supply, while Bolkesjø et al. [50] found high price elasticity of roundwood supply. There are thus considerable uncertainties regarding the level of price effects on the roundwood supply in the Nordic countries; as such, this study assumes that the elasticity of roundwood supply may be higher than the level used in the data report for the NFSM [26].

Harvest residuals may be important as raw materials for biofuel production in the future; in Norway, harvest residuals are not currently used, but Finland and Sweden are utilizing some harvest residuals for energy purposes. In all scenarios, we allow the model to use harvest residuals for biofuel and heat production—within the constraint mentioned above.

3.2 Alternative scenarios

In addition to the base case, we analyse the effect of different alternative scenarios regarding techno-economic developments in the forest and bioenergy sectors. These scenarios are divided into five groups. In group A, we analyse the effect of changing the elasticity of roundwood supply: doubling (A3) and halving (A2) the elasticities compared with the base (A1) case. This is done because of the considerable uncertainty regarding the elasticity of roundwood supply and may actually have quite different level than that assumed in A1.

In group B, we test different levels of biomass consumption in district heating. The implications for the forest sector will likely be affected by competition over low-grade biomass usage (i.e., competition with the district heating sector). Biomass used for heating today may be used as raw material for biofuel plants in the future. For this reason, in scenario B1, we assume no use of biomass for district heating. On the other hand, increasing the CO_2 price may increase the utilization of biomass in district heating. For this reason, we double the biomass consumption from today's level in scenario B2.

Since year 2000, the Nordic pulp and paper industries has undergone a transition. For some paper grades, demand has reduced dramatically due to increased digitalization, while for other paper grades, demand has increased due to globalization. In group C, we cover both these cases, targeting what happens if the demand for Nordic pulp and paper reduces (C1) and increases (C2) by 50%, respectively.

Reducing GHG emissions from the construction sector may increase the production of sawnwood in the future. We therefore run a scenario with a 50% reduction (D1) and 50% increase (D2) in sawmill capacity.

Finally, in group E, we assume that each country has individual national consumption and production mandates for forest-based biofuel (E1). This means that there will be no trade of biofuels between the Nordic countries in these scenarios.

As mentioned above, all scenarios are run for five levels of biofuel production: 0%, 20%, 30%, and 40% of the total fossil fuel consumption. Table 4 shows a summary of the scenario used in this study.

Scenario name	Description	Changes
A1	Base	
A2	Low timber price supply elasticity	Halving the value of the price elasticity of roundwood supply
A3	High timber price supply elasticity	Doubling the value of the price elasticity of roundwood supply
B1	Low level of biomass use in district heating	No use of biomass in district heating
B2	High level of biomass use in district heating	Doubling the amount of biomass in district heating
C1	Reduced demand for pulp and paper	Reduced demand for pulp and paper by 50% in the Nordic countries
C2	Increased demand for pulp and paper	Increased demand for pulp and paper by 50% in the Nordic countries
D1	Reduced demand for sawnwood	Reduced demand for sawnwood by 50% in the Nordic countries
D2	Increased demand for sawnwood	Increased demand for sawnwood by 50% in the Nordic countries
E1	Each country has their own quota obligation	Each of the Nordic countries produces their own biofuel

Table 4. Summary of the different scenarios. All changes are relative to the base scenario (A1).

4 Results

4.1 Base scenario

4.1.1 Changes in biomass supply and biomass prices

The overall harvest level in the Nordic countries is about 145 million m^3 (table 1), of which 72 million m^3 is used by the pulp and paper industries [26]. Biofuel production corresponding to 40% of the current total fuel use in the Nordic region would require roughly 100 million m^3 of biomass. This represents a substantial increase in demand for wood (figure 1). As expected, the wood consumption for biofuel production comes from multiple sources: increased roundwood harvest, increased harvest of harvest residuals, and increased imports from other countries. In addition, increasing wood demand from the biofuel industry causes a significant reduction in wood use in the pulp and paper industries due to increasing wood prices (figure 1). Of the 98 million m^3 wood consumption in the 40% scenario, only about 25 million m^3 originates from increased domestic roundwood harvest in the Nordic countries. According to the model results, the average pulpwood price in the Nordic countries increases by 20–25%, while the total harvest increases by 17%. The combined effect of the increase in harvest and price significantly increases revenues for forest owners.

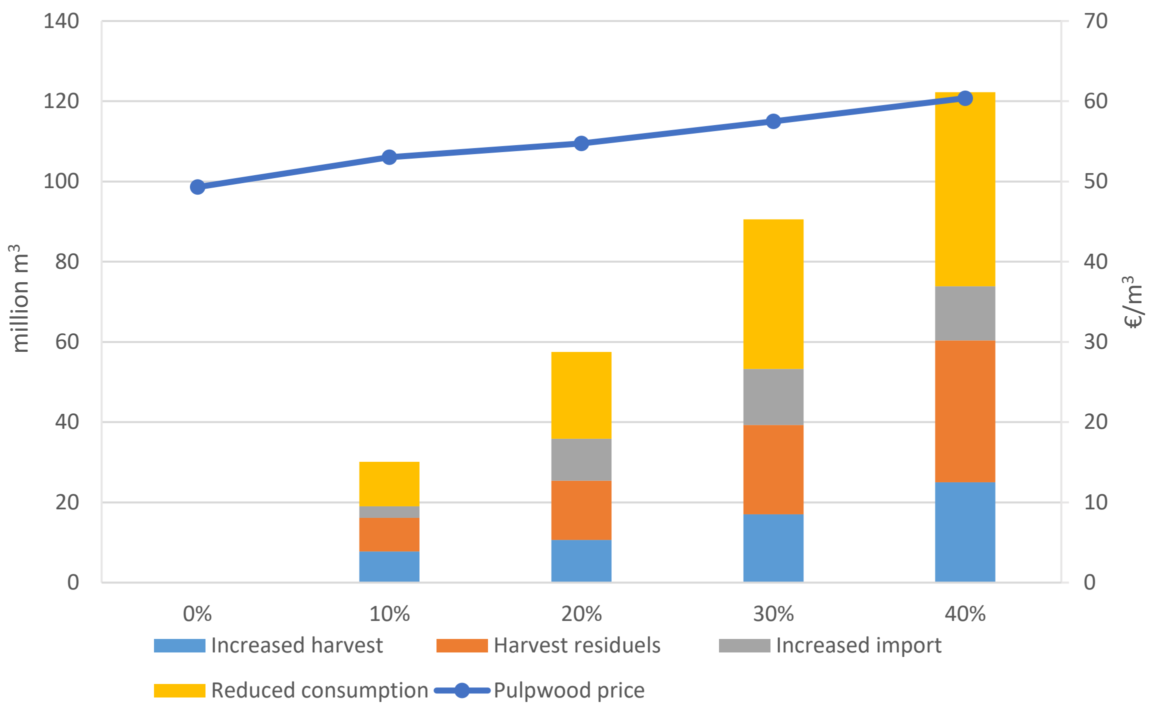

Figure 1. Modelled sources of wood consumption for biofuel production, values show increase from 0% scenarios for harvest (blue), harvest residual (orange), import (grey), and reduced consumption in other industries (yellow) (left axis) and corresponding pulpwood prices (right axis) in the Nordic countries for the five base scenarios.

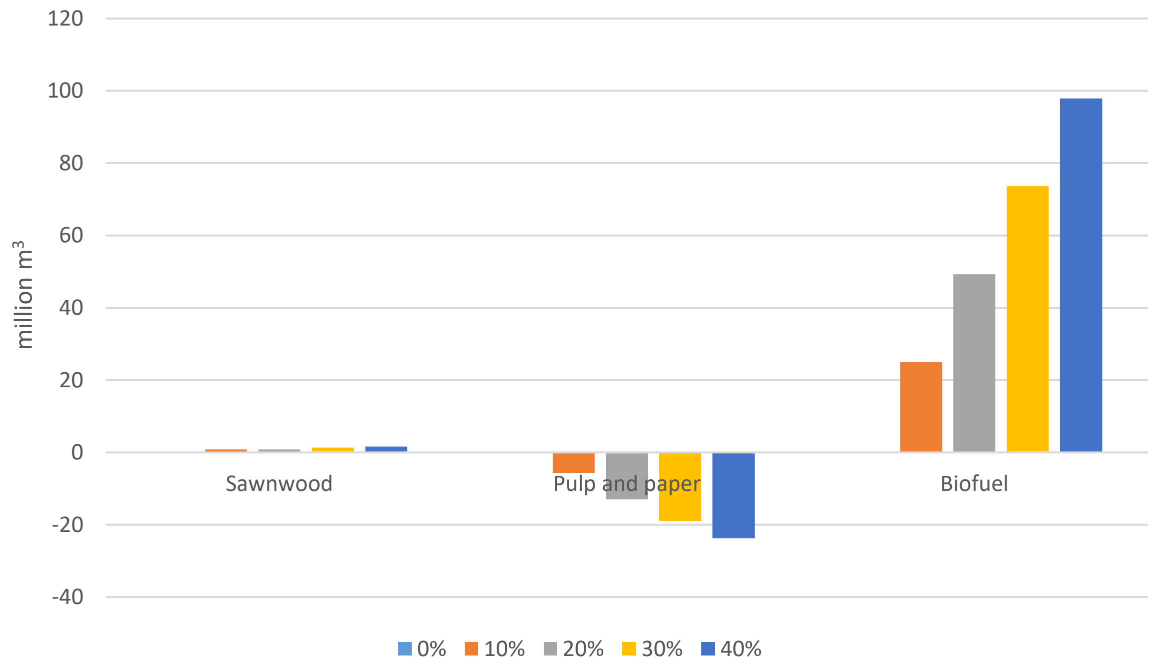

Figure 2. Modelled change of wood consumption in sawmills, the pulp and paper industries, and biofuel production in the Nordic countries, for the different base scenarios.

At 40% biofuel production, the increase in available roundwood in the Nordic countries (figure 1) is around 120 million m^3, while only 98 million m^3 is consumed for biofuel production (figure 2). The reduction in pulp and paper occurs simultaneously with an increase in the use of harvest residuals (figure 1). For this reason, the surplus of 20 million m^3 available roundwood from pulp and paper mill closures is higher than the actual need of roundwood for biofuel production. This is because biofuel producers use more harvest residuals than pulp and paper producers, which means that in the Nordic countries, traditional forest industry production becomes less competitive compared with the rest of the world due to increased pulpwood prices.

4.1.2 Economic effects to forest industries

Increased biofuel production affects the economy of sawmilling in multiple ways. The overall quantified effects on Nordic sawmilling profits are shown in table 5. Total sawnwood production increases by 2.8% and board production increases by 0.6% when the biofuel share increases from 0% to 40%. This is due to increased revenue from sale of by-products. The pulp and paper industries reduce their production by 32%, due to higher raw materials costs.

	0%	**10%**	**20%**	**30%**	**40%**
Sawlogs purchases	4 392	4 563	4 559	4 654	4 740
Sawnwood sales	7 010	7 103	7 061	7 105	7 095
Sales of by-products	1 009	1 111	1 163	1 247	1 347
Profit	1 969	1 969	1 979	1 991	1 993

Table 5. Modelled purchasing sawlogs costs, sales revenue of sawnwood and by-products, and changes in profit in the Nordic countries for the different base scenarios, in million €.

The market value of wood by-products from sawmilling increases rapidly with increased production of biofuel (table 5), whereas the market price for sawnwood decreases only slightly. In total, the sawmill profit increases by 24 million € when the biofuel production increases from 0% and 40%.

In the pulp and paper industries, the profit reduces by 3 billion € in the 40% scenario compared to the 0% scenario, due to a large reduction in sales revenue caused by a reduction in the production level. The reduction in cost is lower than the reduction in production due to the increasing pulpwood prices, while the market prices for pulp and paper only slightly increase.

	0%	**10%**	**20%**	**30%**	**40%**
Sales revenue	35 852	33 988	31 877	29 707	28 271
Cost of importing pulp and purchasing pulpwood	14 275	13 702	12 964	12 078	11 562
Profit	13 163	12 350	11 507	10 697	10 149

Table 6. Modelled cost of purchasing pulp and wood, sales revenue, and changes in profit for the pulp and paper industries in the Nordic countries for the different base scenarios, in million €.

4.1.3 Biofuel production

Table 8 shows how the modelled production of biofuel is distributed between countries. Sweden produces the largest amount of biofuel in all scenarios, followed by Finland. Some production is allocated to Norway in all scenarios, while biofuel production is only allocated to Denmark in the scenarios with more than 20% overall biofuel obligation. Norwegian production stabilizes at 10% biofuel production, while production in Finland and Sweden increases almost linearly.

4.2 Alternative scenarios

4.2.1 Changes in biomass supply and biomass prices

Table 7 shows the changes in harvest levels, use of harvesting residuals, import of sawlogs and pulpwood, reduced consumption of roundwood in other industries, and pulpwood prices for biofuel production from the base scenarios (A1) for each of the scenarios (A2–E1). For the scenario with low elasticity of roundwood supply (A2), we observe (as expected) higher pulpwood prices and lower harvest levels than in the base case. The reduction in harvest is substituted by harvest residuals and a larger reduction in consumption in the rest of the forest industry. High elasticity of roundwood supply (A3) provides lower pulpwood prices and an increase in consumption for other industries and thereby an increased harvest.

Without the use of biomass in the district heating sector (B1), the use of harvest residuals is substantially reduced compared to the base scenario, especially at high biofuel production levels, due to the lower pulpwood prices. Harvest residuals are substituted by increased import. Simultaneously, the harvest and use of roundwood in the other industries increases compared to the base. When doubling the use of biomass in the district heating sector (B2), the use of harvest residuals increases in the 20% and 30% scenario at the expense of import and use of biomass in other industries.

As expected, when reducing the pulp and paper demand (C1), we observe a reduction in pulpwood prices and reduced use of harvest residuals. The new biomass for the 30% and 40% biofuel scenarios comes mainly from increased import. With increased pulp and paper demand (C2), we find increased pulpwood prices and increased harvest levels.

When reducing the sawnwood demand (D1), we find increased pulpwood import and more roundwood consumption in other industries, while increasing the sawnwood demand (D2) leads to reduced pulpwood prices. Finally, forcing each country to produce according to their own biofuel consumption (E1) causes minor effects only to the biomass balance compared to the base.

		Increased harvest	Harvest residuals	Increased import	Reduced consumption	Pulpwood price
0 %	A1					-
	A2					-
	A3					-0.2
	B1					-7.6
	B2					4.0
	C1					-1.1
	C2					0.3
	D1					0.5
	D2					-0.6
	E1					-
10 %	A1	-	-	-	-	-
	A2	-2.2	0.5	-1.3	2.7	1.4
	A3	0.7	-0.5	1.0	-0.8	-1.9
	B1	3.7	-7.6	3.3	-4.2	-3.9
	B2	-2.6	-0.3	2.6	-0.7	2.8
	C1	-0.5	-0.3	2.6	-1.5	-1.1
	C2	0.1	-0.5	-0.3	0.5	0.4
	D1	-0.7	-0.1	-0.1	0.8	0.5
	D2	-1.4	0.4	0.4	1.0	-1.0
	E1	0.1	-2.3	2.5	4.4	-
20 %	A1	-	-	-	-	-
	A2	-2.1	1.4	-4.2	8.1	2.7
	A3	2.8	-3.2	3.4	0.3	-1.9
	B1	6.5	-7.7	2.0	-5.7	-2.4
	B2	0.1	2.4	-4.8	6.4	4.0
	C1	0.3	-2.3	3.5	0.3	-0.8
	C2	0.8	-0.4	0.6	1.5	0.8
	D1	0.2	-1.7	1.3	2.6	1.0
	D2	-0.5	-1.9	2.2	1.8	-0.6
	E1	0.4	-	0.3	5.6	0.1
30 %	A1	-	-	-	-	-
	A2	-4.1	2.7	-1.6	4.3	3.3
	A3	3.2	-2.7	1.5	-2.8	-2.8
	B1	4.9	-9.9	5.8	-7.1	-3.4
	B2	0.9	5.5	-7.7	8.4	4.7
	C1	-0.7	-1.6	1.8	0.2	-1.3
	C2	1.0	1.0	-1.7	0.4	1.0
	D1	-0.2	-0.8	-2.0	2.8	0.7
	D2	-1.6	0.9	1.2	0.5	-1.0
	E1	-0.1	2.7	-0.2	0.4	-0.4
40 %	A1	-	-	-	-	-
	A2	-5.3	1.7	-0.3	4.6	4.2
	A3	4.4	-2.2	1.4	-3.8	-3.8
	B1	2.9	-11.6	10.3	-9.5	-4.4
	B2	2.0	1.3	-1.2	4.0	5.0
	C1	-1.2	-0.4	3.4	-0.9	-1.9
	C2	1.4	1.2	-0.8	-0.8	1.4
	D1	-	-1.8	2.4	-1.6	0.2
	D2	-1.4	0.4	1.4	0.8	-0.7
	E1	0.7	0.9	1.4	0.1	-0.2

Table 7. Modelled differences between base case (A1), and the other scenarios for wood consumption for biofuel production. Values represent difference for harvest, harvest residual, import, reduced consumption in other industries (million m^3), and corresponding difference for pulpwood prices (€/m^3) in the Nordic countries for the five different production levels for biofuel. "-" means no change from base.

4.2.2 Changes in biofuel production

Table 8 shows the changed biofuel production from the base (A1) for the different cases. Small changes occur, with the exception of cases where biomass is not used in district heating (B1), where more of the biofuel production is allocated to Finland. In the case of self-production of biofuel (E1), biofuel production in Norway and Denmark increases by 100% and 84%, respectively, compared to the base (A1) 40%. In the same scenario, production in Sweden and Finland reduces by 21% and 33%, respectively. Hence, according to this study, biofuel production in Finland and Sweden is more cost competitive than production in Norway and Denmark.

Country	Scenario	A1	A2	A3	B1	B2	C1	C2	D1	D2	E1
Norway	0%	0	-	-	-	-	-	-	-	-	-
	10%	0.32	-	-	-	-0.08	-	-	-	-	0.32
	20%	0.32	-	-	-	-	-	-	-	-	0.87
	30%	0.32	0.32	-	-	0.32	-	0.32	0.32	0.24	1.42
	40%	1.18	-0.08	-	-0.55	-	-0.08	-	-0.08	-0.08	1.18
Finland	0%	0	-	-	-	-	-	-	-	-	-
	10%	0.55	0.08	-	0.39	0.08	0.08	-	0.08	0.08	0.08
	20%	1.89	-0.32	0.08	0.32	-	-	- 0.08	-	-	-0.63
	30%	2.60	0.24	0.08	-0.08	0.08	0.39	0.16	0.39	0.32	-0.79
	40%	3.62	-0.16	-	0.39	-0.32	-0.24	-	0.08	-0.24	-1.18
Sweden	0%	0	-	-	-	-	-	-	-	-	-
	10%	2.13	-0.08	-	-0.39	-	-0.08	-	-0.08	-0.08	-1.02
	20%	3.70	-0.32	-0.55	-0.32	-0.63	-0.63	-0.24	-0.63	-0.32	-1.58
	30%	4.65	-0.55	-0.08	0.39	-0.71	-0.39	-0.47	-0.71	-0.55	-1.50
	40%	5.36	0.24	-	0.16	0.32	0.32	-	-	0.32	-1.10
Denmark	0%	0	-	-	-	-	-	-	-	-	-
	10%	0	-	-	-	-	-	-	-	-	0.79
	20%	0	0.63	0.63	-	0.63	0.63	0.32	0.63	0.32	1.50
	30%	1.26	-	-	-0.32	0.32	-	-	-	-	0.95
	40%	1.58	-	-	-	-	-	-	-	-	1.34

Table 8. Modelled production of biofuel in the base scenario (A1) and modelled changes from base for all scenarios and cases, in the different countries, all numbers are in billion litres annually. "-" means no change from base.

4.2.3 Harvest level and wood prices

The base scenario increases the pulpwood prices at mill gate from 50 €/m^3 with 0% biofuel to 61 €/m^3 with 40% biofuel. The prices deviate from -15% to 8% with 0% biofuel and from -7% to 8% with 40% biofuel: the highest is for high use of biomass in district heating (B2) and the lowest for low use of biomass in district heating (B1). Sawlogs prices increase from 74 €/m^3 to 78 €/m^3 for the base case (A1). The scenarios can be divided into three groups: group 1 has a high sawnwood demand (D2) that starts at 82 €/m^3 and ends at 84 €/m^3; group 2 has a low sawnwood demand (D1), starting at 68 €/m^3 and ending at 72 €/m^3; and the rest of the cases (group 3) have a maximum deviation of ±4% from the base case for all biofuel production levels. Generally, the modelled roundwood prices are robust to changes in the scenario parameters. The flexibility in wood supply from different wood sources (roundwood, harvest residuals, by-products, and imports), as well as changes in wood consumption from different wood consumer sectors, reduces the influence from the scenario parameters.

The modelled harvest levels follow the same pattern as prices. Again, we find that the pulpwood harvest is highest for high use of biomass in district heating (B2). For sawlogs, harvest is almost constant across scenarios. The highest sawlogs harvest is with high sawnwood demand (D2), at a constant level of +7% from the base level, while the lowest harvest is with low sawnwood demand (D1), with a harvest that deviates from -7% to -9%. The rest of the cases deviate at a maximum of ±2% from the base case.

4.2.4 Production levels

The scenarios affect different parts of the forest industry differently. The changes between the base (A1) 0% and the different cases for sawnwood production are shown in figure 3. In most cases, the production of sawnwood increases in Sweden, while the production in Finland slightly decreases for the cases with low use of biomass in district heating (B1). This shows that countries with high pulpwood demand also have high production of sawnwood. The largest changes appear for low sawnwood demand (D1) and high sawnwood demand (D2). The board production is almost unchanged across all scenarios and cases.

Since the pulp and paper industries are major consumers of pulpwood, their production reduces with increased biofuel production (figure 4), especially in Finland and Sweden. The introduction of biofuel will directly compete with pulp and paper for the pulpwood, resulting in a reduction of pulp and paper production. In the simulations, the model is forced to produce biofuel to fulfil a given consumption or blending requirement. The competitiveness of pulp and paper versus biofuel production, or Nordic biofuel production versus imported biofuels, is not analysed in this study.

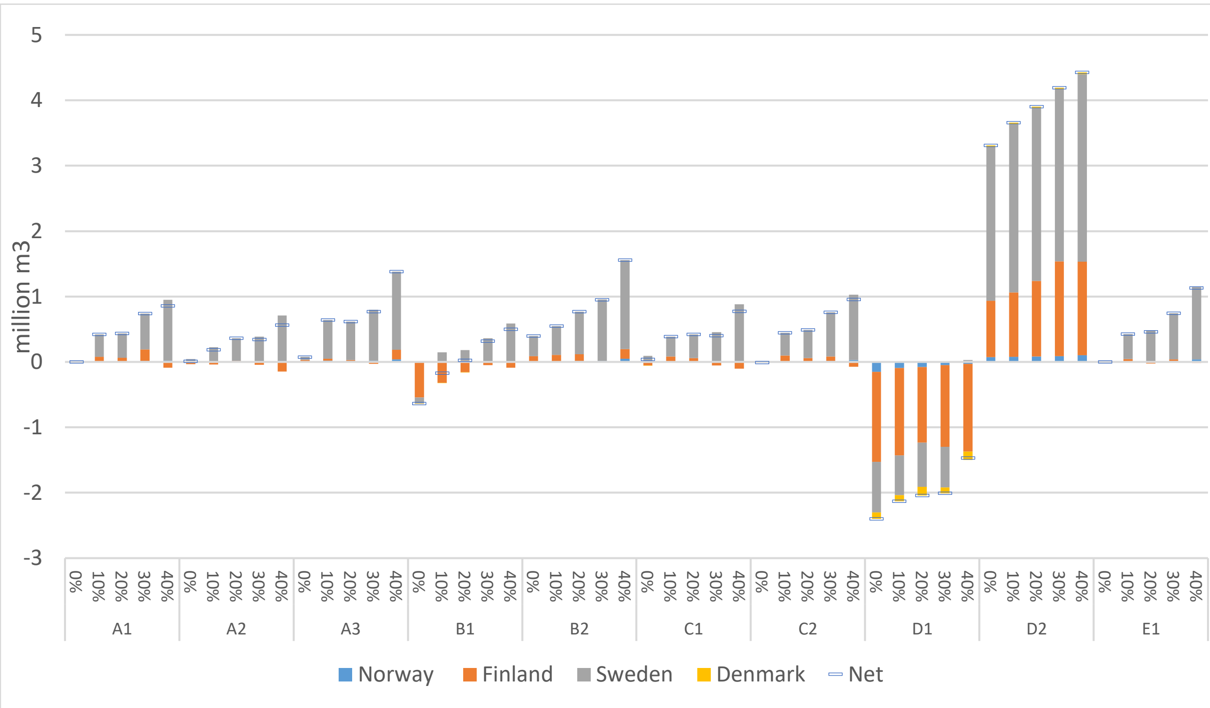

Figure 3. Modelled change in sawnwood production compared to base (A1) 0%, split by countries, for the different cases and scenarios.

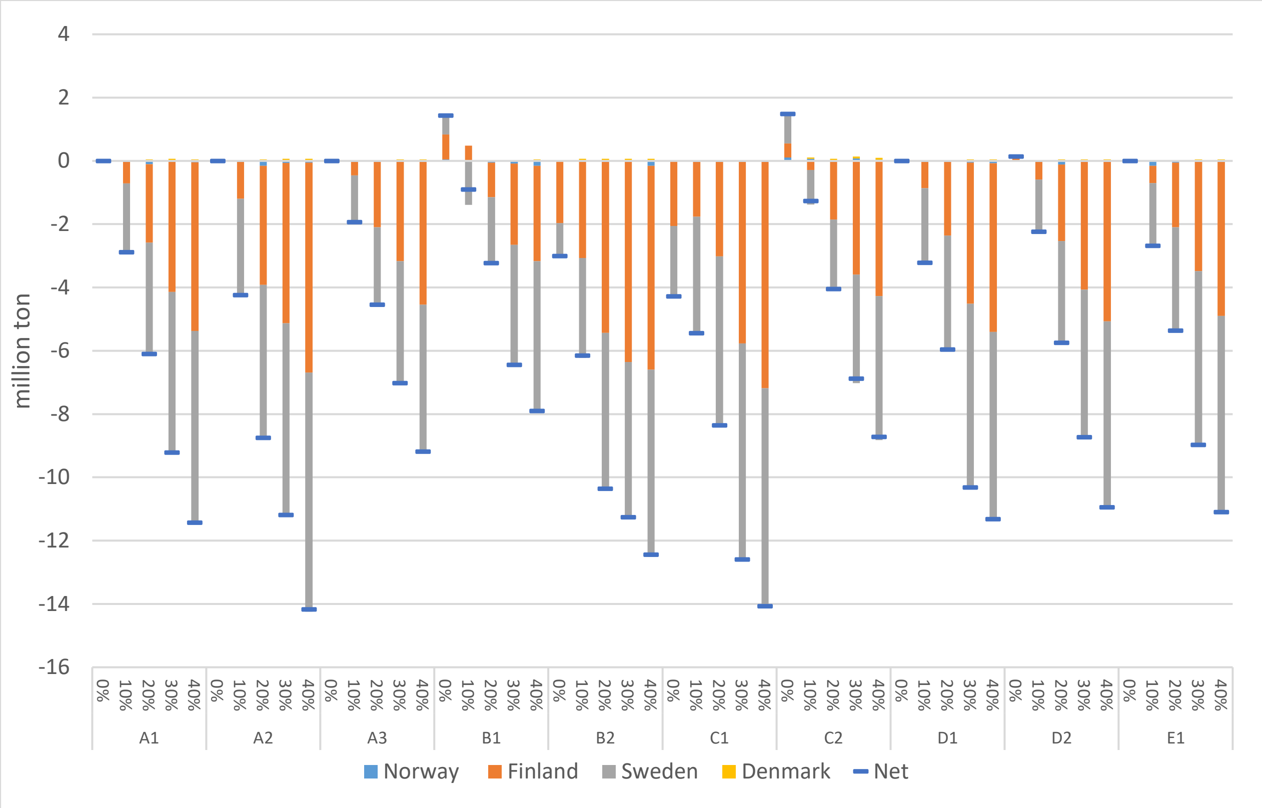

Figure 4. Modelled change in pulp and paper production compared to base (A1) 0%, for the different cases and scenarios, split by countries.

4.2.5 Cost, revenue and profit

Increased production of biofuel increases the market price of by-products from sawmills, which increases profits and production. The increased sawnwood production increases the consumption of sawlogs and therefore sawlogs unit prices, as shown in table 9. The highest sawlogs unit costs are observed when we also increase the demand for sawnwood (D2). Revenues from by-product sales (table 9) increase when more biomass is demanded in biofuel production. In total, the market price of sawnwood (table 9) is almost constant when increasing biofuel production—major changes happen only when we increase/decrease the sawnwood demand (D2, D1). Profit for sawmills (table 9) increase with the production and the market price of sawnwood. If the sawnwood demand increases by 50% (D2), we find the unit production profit increases by 7% compared to the base scenario.

The raw material costs for pulp, paper, and board industries rise with increasing biofuel production (table 9). The highest unit costs are in the cases where pulp and paper demand is also increased (C2) and/or there is an increased amount of biomass in district heating (B2) due to increased competition for biomass.

The average unit market price for pulp and paper products rises with increasing biofuel production (table 9), due to the increased competition for biomass between the pulp and paper industries and biofuel producers, which lowers production in the pulp and paper industries. The unit profit is relatively stable for all cases (table 9).

		Sawmills				Pulp, paper, and board industries		
Case	Scenario	Profit	Sales revenue	Sales revenue by-products	Cost of sawlogs	Profit	Sales revenue	Cost of raw materials
A1	0%	63.5	226	32.5	142	270	737	293
	10%	62.6	226	35.3	145	270	742	299
	20%	62.9	225	37.0	145	270	749	305
	30%	62.7	224	39.3	147	271	753	306
	40%	62.5	223	42.3	149	272	759	310
A2	0%	61.9	226	32.6	143	271	737	293
	10%	62.2	226	36.3	147	270	746	302
	20%	63.1	226	38.8	148	268	749	306
	30%	62.9	225	41.7	150	269	759	314
	40%	62.2	224	45.5	154	273	767	316
A3	0%	63.1	226	32.4	141	271	737	293
	10%	62.6	226	34.1	143	269	740	298
	20%	62.9	224	35.6	143	271	744	299
	30%	62.9	223	37.2	144	272	745	299
	40%	63.2	222	39.6	144	272	748	301
B1	0%	61.5	229	25.5	140	276	725	276
	10%	61.9	227	30.5	142	270	737	294
	20%	61.7	226	32.4	143	267	740	299
	30%	62.1	225	34.8	145	269	746	303
	40%	62.1	225	36.8	146	271	748	302
B2	0%	62.8	225	35.8	145	270	744	300
	10%	62.8	224	37.8	145	270	750	306
	20%	62.9	224	40.4	147	270	756	310
	30%	62.9	222	43.7	149	275	771	318
	40%	64.6	224	46.6	152	281	781	323
C1	0%	62.1	226	31.8	142	266	726	287
	10%	62.4	226	34.7	145	268	738	296
	20%	63.1	225	36.4	145	272	740	294
	30%	63.9	225	38.4	146	273	747	298
	40%	62.5	223	41.2	148	274	753	303
C2	0%	63.5	226	32.7	142	274	746	297
	10%	62.6	226	35.6	145	272	752	306
	20%	62.9	224	37.5	145	272	757	310
	30%	63.2	224	40.1	148	270	766	319
	40%	63.0	222	43.4	149	273	772	321
D1	0%	59.4	209	32.6	129	270	737	293
	10%	59.6	208	35.5	131	272	743	298
	20%	59.4	206	37.6	131	271	749	304
	30%	59.5	206	39.6	133	268	752	308
	40%	59.7	208	42.1	138	272	759	310
D2	0%	67.7	246	32.0	156	271	736	293
	10%	68.4	246	34.5	158	268	741	300
	20%	68.8	245	36.4	158	271	747	301
	30%	69.2	244	38.6	159	269	748	304
	40%	70.0	243	41.9	160	271	759	312
E1	0%	63.5	226	32.5	142	270	737	293
	10%	62.6	226	35.4	145	268	743	302
	20%	62.6	224	37.2	145	269	748	305
	30%	62.8	224	39.5	147	271	749	303
	40%	63.2	222	42.8	148	274	758	309

Table 9. Modelled unit profit, sales revenue and main products and by-products, and cost of raw materials for sawmills and pulp, paper, and board industries in €/m³ or €/ton as Nordic average.

5 Discussion

This study demonstrates how biofuel production could influence the Nordic forest sector. One main finding is that the implementation of large-scale wood-based biofuel plants will significantly affect the forest and bioenergy sectors in the Nordic countries. The pulp and paper industries will reduce production volumes and profits, whereas sawmills will tend to increase their profit due to increased demand for their by-products. The forest owners will increase their revenue when biofuel production is introduced, as market prices for pulpwood and the use of harvest residuals will increase. The reduction in profit in the pulp and paper industries will be greater than the increase in profit for sawmills and the increase in revenue for forest owners combined. Added together, the net annual profit in the forest sector (excluding biofuels) will thus be reduced by 400–600 million € compared with the 0% biofuel production scenario. The effect is largest in the 20–30% scenarios and lowest in the 40% scenario. The results indicate that the least favourable production volume for the Nordic forest sector is around 20%, i.e., the same as the Norwegian 2020 goal for renewable fuel in transportation [36]. For levels above 30%, the increase in revenue for forest owners will occur faster than the reduction in profit for pulp and paper producers, giving a lower total loss in profit for the sector.

High levels of biofuel production, especially in the 40% case, will lead to a significant increase in demand for forest resources. A level of 40% biofuel will demand a 98 million m^3 pulpwood equivalent, which is two-thirds of the reference harvest in the Nordic countries (144 million m^3). The increased consumption for forest-based raw materials will be mainly sourced from import and harvest residuals, which is in agreement with Lundmark et al. [12]. The sawlogs consumption will be largely unaffected by the production level of biofuel, in line with

Mustapha et al. [15] and Lundmark et al. [12]. In the reference year (2013), the Nordic countries harvested 65% of the annual growth; with an increase of 98 million m^3, the utilization of roundwood will be 108% of the growth if we assume no changes in import and no reduction in consumption in other parts of the forest sector. This would not be sustainable; thus, the mass balance in the model is reached by increasing the net roundwood import and reducing the consumption in other industries—mainly in the pulp and paper industries. Forest owners in the Nordic countries and in the rest of the world will benefit from a high penetration of forest-based biofuel in the Nordic countries, while the Nordic pulp and paper industries will meet increased costs and decreased production. This result is supported by Schwarzbauer et al. [51], although they focus on the Austrian forest sector.

Pulpwood prices will increase by 22%, which is consistent with Mustapha et al. [15] but is lower than what was reported by Trømborg et al. [10] for the Norwegian market. The Norwegian roundwood market constitutes about 8% of the total Nordic roundwood markets, hence the significantly higher roundwood prices in Trømborg et al. [10], which were due to the lower available amount of roundwood. In the present study, we use a regionalized model covering all the Nordic countries that is capable of modelling trade across the borders. This gives a more realistic picture of the roundwood market than in a single country model.

Sawmills in the Nordic countries will tend to benefit from forest-based biofuel production through increased production and increased unit profit due to increased by-product prices. However, production of sawnwood will increase only marginally, as is shown in previous studies [10, 11]. Simultaneously, the pulp and paper industries will reduce their profitability and production volume, making the implementation of biofuel controversial. Since biofuel production is not competitive with fossil fuel at today’s costs, biofuel production must be subsidized. This will be highly controversial, since subsidizing biofuel will lead to reduced profit in other industries.

The results are stable across the different scenarios. In accordance with our expectations, the results tend to give higher pulpwood prices if the demand for forest products increases (B2, C2), while the price and use of harvest residuals decreases if the demand is reduced. Increased demand will not affect the allocation of biofuel production substantially. A reduction in demand (B1, C1) will move some production of biofuel from Sweden to Finland.

Increased production of forest-based biofuel will create a substantial reduction in the need for fossil fuel, but it will also reduce the profitability of pulp and paper producers. Reduced activity in the pulp and paper industries may reduce the forest sector's willingness and opportunity to invest in other types of biorefineries and thus in other green products. Several biorefinery technologies that use by-products from pulp and paper industries as raw materials have shown promising results [52, 53]. For those technologies, integration with the existing pulp and paper industries is essential. This study does not include possible synergy effects of such technologies. However, one assumption is that the pulp and paper industries will be unable to restructure from traditional mills into biorefineries with biofuel as a co-product. Pulp mills that manage this restructuring may not reduce their profit in the same magnitude as that mentioned in this study. We further assume that residuals from the pulp and paper industries (tall oil, kraft lignin, black liquor, etc.) will not be used to fulfil the biofuel mandate. At the moment, only some plants are using residuals from pulping in biofuel production [54]. Molinder et al. [55] estimate the total potential production of crude tall oil to be 600 000 ton/year in Scandinavia, while Backlund et al. [56] estimate a maximum of 5 TWh/year of lignin-based biofuel in Sweden. Together, lignin and tall oil will produce a maximum of 1.26

billion L biofuel in Sweden, which corresponds to 4.3% of the current fuel consumption in the Nordic countries. It is unlikely that the full potential will be reached since both tall oil and lignin have other higher-value applications than biofuel [57]; as such, we assume that the share of tall oil and lignin that would be utilized for biofuel production is limited, and therefore it is not considered in this study.

At present, there are no full-scale stand-alone biofuel plants, leading to uncertainties regarding the energy efficiency and choice of raw materials for commercial biofuel plants. Many different technology pathways are under development; however, to analyse the forest sector impacts we have chosen to use a generic technology in this study with an efficiency that may be realistic in the future but is still uncertain. A change in the efficiency within the modelling framework used in this study will only increase/decrease the amount of biomass needed for producing a certain amount of biofuel. The effects of a given amount of biomass consumption will be the same for the forest sector as those shown in this study. A significant strength of the way biofuel production is implemented in the NFSM is that the model can freely choose the location of the production unit and raw materials mix according to what is most economical. The assumption that the production unit has a fixed size is reasonable, since the investors will only consider plants of a certain size. In this study, we assume that biofuel can be consumed without being mixing with fossil fuel. This has led to 100% biofuel consumption in some regions, and 0% in others. This assumption might influence the location of the biofuel plants. As the cost of transporting roundwood exceeds the cost of biofuel transportation, the effect of this assumption will likely be small. In addition, this study assumes a fixed demand for biomass in district heating independent of biofuel production. Some studies have indicated that the integration of biofuel production and heat production has considerable effect on which technology that will be optimal [58]. However, Börjesson

Hagberg et al. [58] have shown that biofuel production only has a minor impact on heat production. It can be assumed that flexibility in the heat sector may dampen the price effects, but the potential influences of reduced bioheat and biopower (co-)generation are not considered here. Further development of the model will include better representation of the bioheat sector.

Since the NFSM is a partial equilibrium model, it has the same benefits and limitations as other partial equilibrium models. These include the fact that the model does not cover the raw material supply and cost precisely enough, since the model requires regional aggregation. Because of the aggregation, the NFSM is not able to model forest dynamics at the same detailed levels as forest models. But we are assuming that the NFSM can model the forest dynamics precisely enough for industrial studies. The NFSM models only the main industrial processes and products, because the larger variety in final products, similar products is aggregated to product groups with same market price. This simplification, together with the uncertainty in the techno-economic data for each mill, will make it impossible to determine exact implications for single mills, but on an aggregate level, the NFSM is able to provide robust result. As with every other partial equilibrium model, the NFSM is highly dependent on the input data. The NFSM uses the year 2013 as a reference year, but since the forest sector is under development, those input data may contain small inaccuracies, such as mill closures and investments that has happen from the reference year and until present. For example, in Finland, the harvest has increased by 7.2 million m^3 [59] since the calibration of the model, but such minor inaccuracies are not assumed to significantly affect the results of this study.

This is the first time that the biofuel data used in this study are used in a partial equilibrium model covering the Nordic forest sector. Together with the implementation of discreet production unit, this study yields new insights into the connection between the traditional forest sector and biofuel production.

6 Conclusion

This study shows that large-scale forest based biofuel production will substantially influence the economics of the forest sector. Sawnwood producers will increase their profit because they produce by-products that are suitable for use in biofuel plants, but the overall effects for sawmills are found to be minor. Forest owners, on the other hand, will benefit substantially from biofuel production since demand for chips, pulpwood, and harvest residuals will increase the wood prices. The model's results indicate an increase in roundwood prices up to 11% when assuming 40% biofuel implementation. On the other hand, implementation of biofuel will result in large reductions in the production (-25%) and profitability (-23%) in the pulp and paper industries and lead to mill closures, while harvest levels will increase up to 17% and the use of harvest residuals will increase by 56 TWh from current levels.

The different scenarios show that the total profit for sawnwood, pulp and paper producers, and forest owners will diverges ±7% from the base case for all scenarios in the Nordic forest sector, which suggests that the model results are quite robust with respect to the implications of the biofuel production.

Forest owners and sawnwood, pulp, and paper producers will reduce their total profit when biofuel production is implemented. The total profit in the Nordic forest sector will be reduced by 400–600 million € or 1.8–2.2% p.a. The greatest reduction in profit will occur with 20–30% biofuel implementation, due to a heavy reduction in the pulp and paper industries. This shows that policy makers should be aware of the reduction in profit for the traditional forest industry when implementing support schemes for biofuel producers. The total biofuel production volume in the Nordic countries will affect how much profit the forest sector loses. For higher volumes of forest-based biofuel, the Nordic pulp and paper industries will reduce their profit by 3 billion € p.a. This may reduce the traditional pulp and paper industries opportunities to research and develop new chemical products based on roundwood that, in the future, may reduce the use of fossil fuel.

7 Acknowledgements

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A Appendix

This appendix describes the objective function and constraints used in the Nordic Forest Sector Model (NFSM). NFSM is a linearized mix integer model with five special ordered sets of type 2 (SOS2) variable [60], one integer variable and six continues variables. The model consists of one objective function, 15 constraints used to handle the linearization, and 10 ordinary constraints. All indexes, variables, and parameters used in the model are shown in table A.1.

Table A.1, list of indexes, variables, and parameters used in the appendix

Indexes	
i, j	Region
k, k_2	All products, i.e., final products, intermediate products, and roundwood categories
f	Final products
w, w_2	Roundwood categories
l	Final and intermediate products
n	Linearization numbering
t	Production activity
ti	Time step
p	Pulp and paper categories
b	Biofuel product
tb	Biofuel production activity
r	Recycled paper grade
FS	Biofuel factory size
Variables used for linearization SOS2 variable	
λ^a	Consumption
λ^b	Harvest
λ^c	Harvest of harvest residuals
λ^e	Input of labour
λ^f	New investments
Integer variable	
δ	Counting number of biofuel production unit
Value steps	
x^a	Consumption
x^b	Harvest
x^c	Harvest of harvest residuals
x^d	Size of biofuel production unit
x^e	Input of labour
x^f	New investments
Variable	
γ	Consumption
φ	Production
θ	Harvest
ω	Interregional trade

ϵ	Harvest residues
Θ	Downgrading
Scalars	
N^a	Number of segments for linearization of consumption
N^b	Number of segments for linearization of harvest
N^c	Number of segments for linearization of harvest residuals
N^d	Number of segments for linearization of biofuel production
N^e	Number of segments for linearization of input of labour
N^f	Number of segments for linearization of new investments
An	Annuity factor
NP	Net present value of an investment
Parameters	
Γ	Reference price
ζ	Reference consumption
τ	Price elasticity
α	Roundwood supply shifts periodically according to changes in growing stock via this parameter
β	Econometrically estimated roundwood supply elasticity
η	Reference roundwood price delivered to gate mill
χ	Reference harvest
S	Growing stock
κ	Growing stock rate
μ	Intercept for harvest residuals
ν	Slope harvest residuals
D	Interregional cost for transportation
I	Investments costs
ι	Exogenous production costs
Λ	Input of products with exogenous costs
a	Input of product
R	Recycling rate
Ξ	The technical potential of harvest residuals
ξ	Labour costs for biofuel production
Π	Operation cost for biofuel production
ρ	Investments cost for biofuel production
ψ	Max fraction of pulpwood and sawlogs
υ	Binary parameter counting spruce and pine
Φ	Parameter with costs of new investments
ϖ	Unit labour costs

A.1 The objective function

NFSM is solved by maximising the objective function:

$$\max \Bigg[\sum_{i,f} Rconsume_{i,f} - \sum_{i,w} Charvest_{i,w} - \sum_{i} CharvestResidues_{i} - \sum_{i,b,tb} Cbiofuel_{i,b,tb} - \sum_{i,l,t} Clabour_{i,l,t} - \sum_{i,j,k} Ctrans_{i,j,k} - \sum_{i,l,t} Cproduction_{i,l,t} - \sum_{i,l,t} CNewInvestments_{i,l,t} \Bigg]$$

Where the first-term represents the inverse demand function, i.e., the consumers surplus. Second-term represent the harvest supply function. Third-term represents cost of harvesting harvest residuals. Fourth-term represents the cost of biofuel plants. Fifth-term represents the labour costs. Sixth-term represents the cost of interregional trade. The seventh-term represents the maintenance and other exogenous production costs. While the eighth-term represent the cost of increasing the industrial production capacity.

The values used in the objective function is solved with use of a piecewise linearization [60].

Calculation of sales revenue is shown in equation $(A.1 - A.3)$. Where $Rconsume_{i,f}$ is defined as the total revenue of final product f in region i. In the linearization of the revenue function, two dummy variable are in use: $x^{a}_{i,f,n}$ and $\lambda^{a}_{i,f,n}$, where $x^{a}_{i,f,n}$ is predefined range of possible consumption levels with N^{a} pieces in range from zero to the double of the reference value and $\lambda^{a}_{i,f,n}$ is a SOS2 variable. The SOS2 variable is used for ensuring one out of two outcome: (1) if the level of consumption $\gamma_{i,f}$ hit exactly a level in $x^{a}_{i,f,n}$, then only one number in $\lambda^{a}_{i,f,n}$, is different from zero (binary case). Or, (2) if the level of consumption $\gamma_{i,f}$ hit somewhere between the levels defined in $x^a_{i,f,n}$, than two neighbouring numbers in $x^a_{i,f,n}$ are different from zero (SOS2 case), with the constraint that they add up to 1 $(A.3)$.

$$Rconsume_{i,f} = \sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} * \left(\left\{ \Gamma_{i,f} - \frac{\Gamma_{i,f}}{\tau_f} \right\} * x^a{}_{i,f,n} + \frac{1}{2} \left\{ \frac{\Gamma_{i,f}}{\zeta_{i,f} * \tau_f} \right\} * \left(x^a{}_{i,f,n} \right)^2 \right) \ \forall\, i, f \ (A.1)$$

$$\gamma_{i,f} = \sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} * x^a{}_{i,f,n} \ \forall\, i, f \qquad (A.2)$$

$$\sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} = 1 \ \forall\, i, f \qquad (A.3)$$

Where $\Gamma_{i,f}$ and $\zeta_{i,f}$ are the reference price and reference consumption of final product f in region i, respectively, while τ_f is the price elasticity.

Cost of harvest $(A.4 - A.6)$, cost of harvesting harvest residuals $(A.8 - A.10)$, cost of labour $(A.13 - A.15)$, and cost of installing new capacities $(A.16 - A.18)$ are linearization in the same way as for sales revenue $(A.1 - A.3)$.

The cost of harvesting roundwood ($Charvest$) is calculated using SOS2 variable $\lambda^b{}_{i,w,n}$ and range $x^b_{i,w,n}$ with N^b segments. $\beta_{i,w}$ is econometrically estimated roundwood supply elasticity for roundwood category w in region i. $\alpha^t_{i,w}$ is estimated with use of equation $(A.7)$, for the first year (ti=1) $\alpha^{ti}_{i,w}$ is calculated using reference price $\eta_{i,w}$ and reference harvest $\chi_{i,w}$. For the second year (ti=2) $\alpha^{ti}_{i,w}$ is calculated using reference standing stock $S_{i,w}$ and for the subsequent years (ti>2) $\alpha^{ti}_{i,w}$ is calculated with use of the modelled standing stock $S^{ti}_{i,w}$. The standing stock is growing at a rate $\kappa_{i,w}$ and reduced by harvesting $\theta_{i,w}$. For more detailed description of α and β are found in [22].

$$Charvest_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * \left(\frac{\alpha^t_{i,w}}{\beta_{i,w}+1}\right) * \left(x^b_{i,w,n}\right)^{\beta_{i,w}+1} \;\; \forall\, i,w \qquad (A.4)$$

$$\theta_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * x^b{}_{i,w,n} \;\; \forall\, i,w \qquad (A.5)$$

$$\sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} \; = \; 1 \; \forall\, i,w \qquad (A.6)$$

$$\alpha^{ti}_{i,w} = \begin{cases} \dfrac{\eta_{i,w}}{\chi_{i,w}{}^{\beta_{i,w}}} \,, if\ ti = 1 \\ \alpha^{ti-1}{}_{i,w} \Big/ \left(\dfrac{\left[\left\{\left((1+\kappa_{i,w}) * S^{ti-1}_{i,w}\right) - \theta^{ti-1}_{i,w}\right\} + S^{ti-2}_{i,w}\right]/2}{S^{ti-2}_{i,w}}\right)^{\beta_{i,w}} \,, if\ ti \geq 2 \end{cases} \,, \forall\, i,w \; (A.7)$$

Cost of collection harvest residuals ($CharvestResidues$) is estimated with use of $\lambda^c{}_{i,n}$ and range $x^c_{i,n}$ with N^c segments. Where μ_i and ν_i is the intercept and slope of harvesting harvest residuals in region i, while ϵ_i is the amount of collected harvest residuals.

$$CharvestResidues_i = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * \left\{\mu_i * \; x^c_{i,n} + \frac{1}{2} * \nu_i * \left(x^c_{i,n}\right)^2\right\} \forall\, i \qquad (A.8)$$

$$\epsilon_i \; = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * x^c{}_{i,n} \;\; \forall\, i \qquad (A.9)$$

$$\sum_{n=1}^{N^c} \lambda^c{}_{i,n} = 1 \; \forall\, i \qquad (A.10)$$

Cost of producing biofuel ($Cbiofuel$) is estimated using the integer variable $\delta_{i,tb,FS}$ where tb is the technology used in production of biofuel (b) and FS is the name of the discrete biofuel unit production volume with size $x^d_{i,b,tb,FS}$ and N^d is the total number of factory sizes NFSM can choose between. Each discrete factory size has their own labour costs ($\xi_{i,b,tb,FS}$), operation costs ($\Pi_{b,tb,FS}$), and investment costs ($\rho_{b,tb,FS}$), NP is used to calculate the net present value of the biofuel investment, while $\varphi_{i,b,tb}$ is the production level of biofuel.

$$Cbiofuel_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * \left(\xi_{i,b,tb,FS} + \Pi_{b,tb,FS} + NP * \rho_{b,tb,FS}\right) \forall\, i, b, tb \qquad (A.11)$$

$$\varphi_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * {x^d}_{i,t,tb,FS} \,\forall\, i, b, tb \qquad (A.12)$$

Cost of labour input ($Clabour$) is estimating using the SOS2 variable ${\lambda^e}_{i,l,t,n}$ and range $x^e_{i,l,t,n}$ with N^e segments. Labour costs ($\varpi_{i,l,t,n}$) is divided in to 4 segments with the first segment represent zero production which lead to zero labour cost, second segments represent 1% of the reference production capacity for product (l), produced with technology (t) in region (i). The third segment represents the reference production, for production between the second and third segment lead to a unit labour cost equal to the reference unit labour costs. Finally, the last segment represent production above the reference value, this will give a linearly increased unit cost from the reference labour cost with 1% increase in unit labour cost when 1% increased production above the reference quantity. $\varphi_{i,l,t}$ is the production of product (l) with production activity (t) in region (i).

$$Clabour_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * \varpi_{i,l,t,n} \; \forall \, i, l, t \qquad (A.13)$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * x^e{}_{i,l,t,n} \; \forall \, i, l, t \qquad (A.14)$$

$$\sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} = 1 \; \forall \, i, l, t \qquad (A.15)$$

The costs of new production facility ($CNewInvestments$) is estimated with use of the SOS2 variable $\lambda^f_{i,l,t,n}$ and range $x^f_{i,l,t,n}$ with N^f segments. The range $x^f_{i,l,t,n}$ consists of the reference production capacity for production of l with use of technology t in region i or the new production capacity with the previous period investment. $\Phi_{i,l,t,n}$ is zero for segments (N^f) that represent production less than 120% of reference production for pulp and paper industry and 140% for rest of the model. For production over the threshold, $\Phi_{i,l,t,n}$ is estimated as a unit increase cost. If the production level for two subsequent year is far below the installed capacity will the model, assume that the production unit has been partly or fully closured, it will then have a cost to increase the production level in a following year.

$$CNewInvestments_{i,l,t} = An * \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * \Phi_{i,l,t,n} \; \forall \, i, l, t \qquad (A.16)$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * x^f{}_{i,l,t,n} \; \forall \, i, l, t \qquad (A.17)$$

$$\sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} = 1 \; \forall \, i, l, t \qquad (A.18)$$

In addition to the linearized costs, the objective function include two parts which are calculated directly, this is (1) $Cproduction$ $(A.19)$ that represent the annuity (An) of the investment cost (I_l) of product (l) and exogenous given production costs, where ι_i and $\Lambda_{i,t}$ represent the exogenous price and input of exogenous product in region i, respectively, produced with use of technology t. In addition to (2) $Ctrans$ $(A.20)$ that represent the transportation cost of transporting quantity $\omega_{i,j,k}$ with unit costs $D_{i,j,k}$ for product (k) between region i and region j.

$$Cproduction_{i,l,t} = \left[An * I_l + \iota_i * \Lambda_{i,t}\right] * \varphi_{i,l,t} \; \forall \; i,l,t \qquad (A.19)$$

$$Ctrans_{i,j,k} = \omega_{i,j,k} * D_{i,j,k} \; \forall \; i,j,k \qquad (A.20)$$

A.2 Constraint

The objective function is solved with following constraints:

$$\theta_{i,k} + \sum_{k_2} \Theta_{i,k,k_2} - \sum_{l,t} \varphi_{i,l,t} * a_{k,l,t} - \gamma_{i,f} + \epsilon_i + \sum_j \omega_{j,i,k} - \sum_j \omega_{i,j,k} = 0 \; \forall \; i,k \quad (A.21)$$

$$\sum_{k,k_2} \Theta_{i,k,k_2} = 0 \; \forall \; i \qquad (A.22)$$

$$\theta_{i,w} * \upsilon_{w,w} \leq \psi_{i,w} * \sum_{w_2} \upsilon_{w,w_2} * \theta_{i,w_2} \; \forall \; i,w \qquad (A.23)$$

$$\sum_{i,p,t} \varphi_{i,p,t} * a_{r,p,t} \leq \sum_{i,p} R_p * \gamma_{i,p} \; \forall \; r \qquad (A.24)$$

$$\epsilon_i \leq \Xi \sum_w \theta_{i,w} \; \forall \; i \qquad (A.25)$$

$$\varphi_{i,l,t}, \gamma_{i,f}, \theta_{i,w}, \epsilon_i, \omega_{i,j,k} \geq 0 \; \forall \; i,j,f,l,k,w \qquad (A.26)$$

Where $a_{k,l,t}$ is the input of product k in production of product l with use of technology t. $\Theta_{\mathrm{i,k,k_2}}$ is the amount of product k that are downgrading to product k_2 in region i. $v_{w,w}$ is a binary parameter that relates spruce sawlogs and pulpwood and pine sawlogs and pulpwood. $\psi_{i,w}$ are the max amount of sawlogs and pulpwood allowed in each region i, while R_p is the assumed recycling rate of paper grade p.

Equation $(A.21)$ ensure that every product and roundwood have to be used as either input in industry, consumption by final consumer, downgraded, or traded with other regions. Equation $(A.22)$ ensure that the amount of original product is equal the amount of the downgraded product. Equation $(A.23)$ ensures that harvest of pulpwood and sawlogs not exceed the possible fraction of each of the quality. Equation $(A.24)$ ensure that the use of recycling paper grade (r) not exceed a predefined recycling rate. Equation $(A.25)$ ensure that the harvest of harvest residuals not exceed the theoretical limit (Ξ) as a function of harvest, and finally $(A.26)$ ensure that every variable is non-negative. In this study, the total production of bioheat and biopower assumed equal to the reference demand in each regions.

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