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Modelling effects of policies for increased production of forest-based liquid biofuel in the Nordic countries

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ABSTRACT

The Nordic countries have ambitious plans to reduce the use of fossil fuels. One possible solution is to blend biofuel into the liquid fuel mix. A large share of this biofuel could potentially be produced from forest biomass, which is an easily available resource in the Nordic countries. However, technologies for producing liquid biofuel from forest-based biomass are immature, implying high risk for biofuel investors. This study assesses six different support schemes that may increase the attractiveness of investing in forest-based liquid biofuel production facilities. Furthermore, the study simulates the likely effects of policy schemes on the future production of forest-based liquid biofuels using a partial equilibrium forest sector model. The study applies an nth plant estimate for the costs of various biofuel technologies and analyses investment support, feed-in premiums, quota obligations, increase in fossil fuel taxes, biofuel tax exemptions, and support for using harvest residues. According to the model results, a feed-in premium gives the lowest needed subsidy cost for production levels below 6 billion L (25% market share) of forest-based biofuel, while quota obligation is the cheapest option for production levels above 6 billion L. The necessary subsidy level is in the range of 0.60–0.85 €/L (82–116% of the fossil fuel cost in 2030) for realistic amounts of biofuel production. The pulpwood prices increase up to 24% from the base scenario due to increasing biomass demand.

1. Introduction

The European Union (EU) has set a target to reach 10% renewable energy in the transportation sector by 2020 and 14% by 2030 (European Commission, 2018a; 2018b; Wilson, 2019). In order to increase the renewable share, EU member states may introduce different kinds of policy mechanisms, such as feed-in tariffs, feed-in premiums, quota obligations, tax exemptions, tenders, and investment support (European Commission, 2018c). Neither the EU states nor the other participants in the European Economic Area (EEA), i.e. the EFTA member states Iceland, Liechtenstein, and Norway, have harmonized subsidies across member states. Instead, the European Commission leaves the member states to choose their own subsidy schemes and level of subsidy when it comes to environmental issues, as long as the subsidy conforms to the requirements set by the European Commission (2018c). However, the European Commission (2018c) considers feed-in premiums more appropriate than the other subsidy schemes since feed-in premiums encourage producers to be coupled with the market. The subsidy schemes mentioned above may all be feasible for increasing biofuel production in the Nordic countries, where incentives such as green certificates, tax exemptions, investment support, flexible grid tariffs, feed-in premiums, and feed-in tariffs are widely used in the heat and power sectors (Sandberg et al., 2018).

In the Nordic countries, several plans exist for producing forest-based liquid biofuel, but none have been implemented (Nyström et al., 2019). This may be partly because lack of technological maturity, which makes forest-based biofuel risky to investors. Another aspect is that the policy supporting biofuel consumption does not distinguish between locally produced biofuel and imported first- and second-generation biofuel. Although Norway has a separate target for using advanced biofuel (Lovdata, 2018), it is not directly targeting forest-based biofuel. Moreover, there is a raw material competition between traditional, new forest industry, high value forest products, energy, and biofuel, which makes the availability of low cost raw material suitable for biofuel production uncertain. All this may lead to reduced optimism and interest in biofuel plant investments. More targeted subsidies may be introduced, which may increase production. From a policy point of view, it is essential to find policy schemes that target the problem precisely and effectively, at the lowest cost to society.

The economic potential of investing in forest-based liquid biofuel is not only interesting from a climate mitigation viewpoint, but also for the economic development of the forest and forest industries as several

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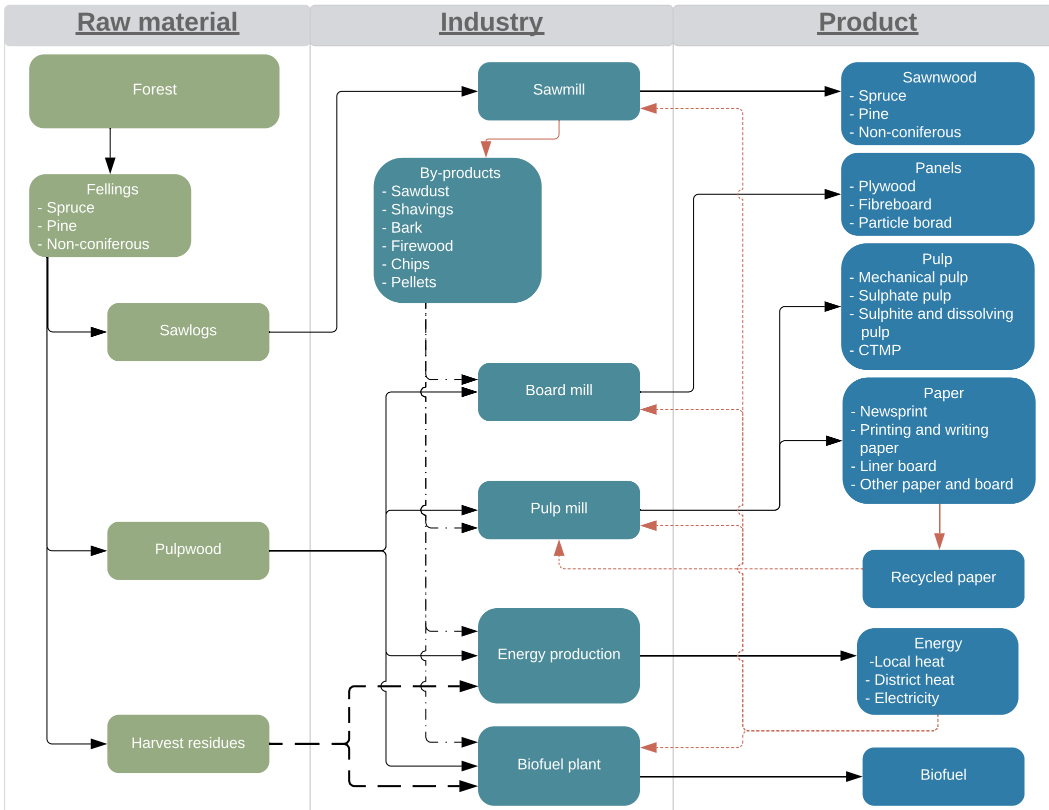

Fig. 1. Flowchart of the mass flow in NFSM, covering the raw materials, the main groups of industrial processes and the main final products.

studies have shown that large-scale biofuel production would heavily affect the Nordic forest sector markets (Jåstad et al., 2019; Kallio et al., 2018; Lundmark et al., 2018; Mustapha et al., 2017b; Trømborg et al., 2013).

Among previous studies analysing biofuel policies, Raymond and Delshad (2016) conclude that normative schemes are more influential than economic schemes for increasing the use of biofuel in the US. According to Khanam et al. (2016), a total biofuel subsidy equal to the ordinary emission taxes of fossil fuel decreases the consumer costs of purchasing biofuel by 7.7% and increases the biofuel consumption by 15%. Similarly, Ribeiro et al. (2017) conclude that the market share of advanced biofuel in the US could increase from today's level (2.01%) up to 27.4% with a 50% petrol tax and a 50% biofuel price subsidy.

Other studies have investigated the necessary level of subsidy that will make biofuel production profitable. For example, Zhao et al. (2016) calculate the breakeven price for a fast pyrolysis process in the US to be 0.74 ± 0.06 €/L. Similarly, Dimitriou et al. (2018) estimate the necessary subsidy for a Fischer-Tropsch biodiesel to become competitive with fossil fuel in Europe to be 12 €/ton of dried wood (0.14 €/$L_{biofuel}$). According to Dimitriou et al. (2018), there is a 14% probability that biofuel production cost would meet the market price of fossil fuel without subsidy by learning effects and optimum design of the plant, but if the tax on biofuel is reduced by 8%, the probability of profitable production increases to 50%.

While most of the abovementioned studies have focused on first-generation biofuel or the US market for biofuel, very few studies have addressed policy instruments for second-generation biofuel based on woody biomass, and, to our knowledge, no previous studies of forest-based biofuel policy impacts have accounted for the competition for biomass from the traditional forest industries. Hence, the main objective of the present paper is to quantify the level of subsidy needed for various policies to increase forest-based liquid biofuel production and thereafter the economic impacts of such an increase on the rest of the forest sector. For this purpose, we use a forest sector modelling approach wherein the interactions between the biofuel and forest industries are properly addressed.

The study quantifies the approximate biofuel subsidy levels needed to reach various biofuel market shares in the Nordic countries in a profitable way (for the producers). It also compares the costs of different types of support and how they affect the rest of the forest sector.

We have organized the paper as follows: Section 2 describes the method and main assumptions we have used; Section 3 describes the results; Section 4 discusses the results; and finally, Section 5 provides the study's conclusion.

2. Method

2.1. NFSM

We use the Nordic forest sector model (NFSM), which is a spatial, partial equilibrium model covering forestry, the forest industry, and the bioenergy sector in Norway, Sweden, Finland, and Denmark. The model structure is built on the Norwegian Trade Model (NTM) (Bolkesjø et al., 2005; Trømborg and Solberg, 1995; Trømborg and Sjølie, 2011) that originates from the Global Trade Model (GTM) (Kallio et al., 1987). NFSM has recently been used to find optimal locations of biofuel production (Mustapha et al., 2017b), to estimate total production costs for biofuel production in the Nordic countries (Mustapha et al., 2017a), and to estimate implication for the Nordic forest sector if large investments in forest-based biofuel are made in the Nordic countries (Jåstad et al., 2019).

NFSM maximizes social welfare (i.e. consumer plus producer surplus) for each simulation period. The solution provides market equilibrium prices and quantities for each period and region as shown by Samuelson (1952). NFSM simultaneously estimates roundwood supply, industrial production, consumption of final products, and trade between regions. The model has 29 different products, including six types of roundwood (spruce, pine, and non-coniferous sawlogs and pulpwood), harvest residues, nine types of intermediate products, and 13 final products (three sawnwood grades, three board grades, four paper grades, local and district heating, and biofuel). Fig. 1 shows a flowchart of the main mass flow in NFSM. Norway, Sweden, and Finland are modelled with ten regions in each country, while Denmark accounts for one region, as does the rest of the world, see appendix B for regionalization details. For further explanation of the model, see appendix A.

The model is solved as a mixed integer linear programming (MILP) problem, with the CPLEX solver using the General Algebraic Modelling System GAMS (GAMS Development Corporation, 2017).

2.2. General model assumptions

In this study, we use data and assumptions from Mustapha (2016). The most important assumptions regarding the Nordic forest sector are shown in Table 1. In this study, we run the Nordic Forest Sector Model (NFSM) in a single-year mode (i.e. the reference year 2013) and we hence assume that all market adjustment, including new investments, as a result of new subsidies occur immediately. The currency in the model is euro and the average exchange rates for the reference year are assumed valid.

2.3. Biofuels – cost and technology assumptions

Biofuel can be produced by different conversion routes with different levels of economic maturity, efficiency, and other technical parameters (Mustapha et al., 2017a). In this study, we assume that the biofuel production unit uses 1.0 MWh of biomass, 0.021 MWh of electricity, and 0.25 MWh of natural gas in order to produce 35 L (0.33 MWh) of gasoline and 25 L (0.25 MWh) of diesel. These assumptions correspond to a biomass carbon efficiency of 58% and a total energy efficiency of 46%, which is in line with Serrano and Sandquist (2017). We also assume the same efficiency for different types of raw materials used for biofuel production in the model: spruce, pine, and non-coniferous pulpwood; residuals from sawmills; harvest residues; and a mix of these materials. The model will choose the cheapest available raw materials for producing biofuel. The model assumes that new investments are in fixed size production units with the following sizes 150, 300, 450, and 600 MW feedstock capacity. Table 2 shows the exogenous production costs for the different production unit sizes. All costs are estimated as yearly costs. We calculate the yearly investment costs – annuity – based on an interest rate of 10% p.a. and a payback time of 25 years. Table 3 shows the main exogenous product prices in NFSM and the total fossil fuel consumption in the Nordic countries.

In 2017, the total Nordic fossil fuel consumption was about 24.3 billion L (SCB, 2018; SSB, 2018; Statistics Denmark, 2018; Tilastokeskus, 2018). We assume a constant fuel demand, i.e. that the total demand does not depend on the fuel price. The model chooses the cheapest option of locally produced biofuel with or without subsidy and fossil fuel at a constant spot price; the model has to fulfil the total demand for liquid fuel. In practice, 100% of the demand is fulfilled with fossil fuel until the production cost of biofuel and subsidy falls below the spot price of fossil fuel. The production cost of biofuel increases with increasing biofuel volumes. We assume equal transportation costs for biofuel and fossil fuel.

2.4. Subsidy schemes analysed

As a way of stimulating biofuel producers, Norway, Finland, and Denmark have introduced quota obligations. In Norway in 2019, 12% of the fuel traded must be biofuel, of which 4.5% (with double counting) has to be so-called advanced biofuel (Lovdata, 2018). Norway will increase the biofuel share to 20% in 2020 (Lovdata, 2018; Ministry of Climate and Environment, 2017). Finland has set the quota obligation at 15% and plans to increase it to 20% in 2020 (Petroleum and Biofuels, 2018). Meanwhile, Denmark has set its quota obligation at 5.75% and plans to increase it to 10% by 2020 (Energistyrelsen, 2018). In 2018, Sweden has implemented obligations to reduce total carbon emissions from liquid fuel with 2.6% for gasoline and 19.3% for diesel compared the fossil alternative. The emission reduction obligations, in line with the renewable energy directive (European Commission, 2018b), correspond to a 23–51% share of biodiesel and a 3.7–5.3% share of bioethanol. The Swedish goal is to reach a 70% reduction by 2030 (Regeringskansliet, 2018). The EU has a goal of using a share of at least 6.8% biofuel in the liquid fuel mix, and a minimum of 3.5% of the liquid fuel mix has to be advanced biofuel (Wilson, 2019).

The assumptions for the subsidy schemes analysed are described in Table 4, and the implementation is shown in Appendix A.3.

2.5. Sensitivity analysis

We test the sensitivity of the results for some of the main parameters regarding biofuel production and the forest sector. These parameters are the following:

1. The conversion efficiency of biofuel production – which is 58% (base) in the base scenario – ranges from 42% (low) to 74% (high). The low and high levels are based on the range found in Serrano and Sandquist (2017).
2. The discounting rate used for calculating the yearly capital costs of a biofuel plant – which is 10% (base) in the base scenario – ranges from 5% (low) to 15% (high).
3. There is a cap on maximum allowed harvest in each country. The cap is set first at the reference harvest level shown in Table 1 (ref.) and then at the forest reference level (FRL). In Norway, the forest reference level for the period 2021–2030 is set to 14.5 million m^3 solid ub. as a yearly average (Klima- og miljødepartementet, 2019), in Finland to 68 million m^3 solid ub. (Jord- och skogsbruksministeriet, 2018), in Sweden to 77 million m^3 solid ub. (Miljödepartementet, 2019), and in Denmark to 3.65 million m^3 solid ub. (Johannsen et al., 2019).
4. The production capacity in pulp and paper production is 46 million tons (base) in the base scenario; this number is increased exogenously with two new chemical pulp mills that both consume 2 million m^3 solid/year[1] (increase).
5. The sensitivity of roundwood logging and transportation costs range from −25% (low) to +25% (high) relative to the base level.

3. Results

3.1. Required price of fossil fuels

For a given level of cost, biofuel investments may be triggered in one of the two following ways: (i) the price of fossil fuels increases above the cost level of biofuels, or (ii) the additional costs of biofuels are compensated for through policy.

We quantify the first mechanism in Fig. 2, which shows how the modelled biofuel production increases with increasing fossil fuel prices without any policy measures in place. According to these assumptions, a fossil fuel price of 1.3 €/L is needed for the first biofuel production units to produce. This is about three times the baseline price (see Table 3). Above this level, each € cent/L increase in the fossil fuel price will lead to about a 225 million L increase in the production of biofuels.

[1] The plants are located in Värmland in Sweden and in Karelia in Finland.

Table 1
The base production, harvest, roundwood prices, exchange rate local currency/€, and elasticity of roundwood supply adapted from (Mustapha, 2016).

		Norway	Sweden	Finland	Denmark
Production	Sawnwood [million m^3 solid]	2.21	18.6	9.73	0.36
	Fibreboards [million metric tons]	0.17	0	0.07	0.01
	Particle boards and plywood [million m^3 solid]	0.42	0.89	1.13	0.35
	Pulp & paper [million tons]	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 solid ub.]	4.63	34.5	19.5	0.80
	Pulpwood, including chips [million m^3 solid ub.]	6.75	41.3	34.2	2.60
	Harvest residues [TWh]	0	7.55	6.01	0.28
Exchange rate	Local currency/€	7.81	8.62	1.00	7.46
Price delivered at gate	Sawlogs [€/m^3 solid ub.]	68	76	74	68
	Pulpwood [€/m^3 solid ub]	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 2
Labour [h/1000 l], fixed and investment costs [€/L/year], and production level [million L/year] for the different plant sizes [input feedstock]. Source: Serrano and Sandquist (2017).

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

Table 3
Assumed prices for inputs and outputs, and observed consumption levels for transportation fuels, for the Nordic countries.

	Norway	Sweden	Finland	Denmark	Source
Electricity [€/MWh]	39.9	41.3	42.9	54.4	Eurostat (2018)
Natural gas [€/MWh]	36.1	36.1	36.1	36.1	Serrano and Sandquist (2017)
Labour [€/h]	39	20	18	27	Eurostat (2017)
Fossil gasoline [€/L] – base year	0.43	0.43	0.43	0.43	Drivkraft Norge (2018a)
Fossil diesel [€/L]- base year	0.44	0.44	0.44	0.44	Drivkraft Norge (2018a)
Fossil fuel price 2030 [€/L] – used in scenarios	0.73	0.73	0.73	0.73	IEA (2017)
VAT [%]	25	25	24	25	Drivkraft Norge (2018b)
Special fuel taxes gasoline [€/L]	0.66	0.64	0.65	0.62	Drivkraft Norge (2018b)
Special fuel taxes diesel [€/L]	0.53	0.42	0.50	0.46	Drivkraft Norge (2018b)
Consumption diesel [million L]	3831	6197	3236	3048	SCB (2018); SSB (2018); Statistics Denmark (2018); Tilastokeskus (2018)
Consumption gasoline [million L]	1089	3400	1834	1673	SCB (2018); SSB (2018); Statistics Denmark (2018); Tilastokeskus (2018)

3.2. Required subsidy level

In the results presented below, the price of fossil fuel is kept constant at 0.73 €/L (corresponding to a crude oil price of $94/barrel), which is in line with the expectations of the IEA's New Policies Scenario for fuel prices by 2030 (IEA, 2017). The support level for the different policy instruments is gradually increased in the model runs. For the investment support alternative, we observe that due to high variable costs, even an investment support level of 100% does not cause any biofuel investments. Similarly, a complete tax exemption from the special fuel taxes is not sufficient to create profitable investments. In other words, investment support and tax exemptions alone are likely not sufficient to trigger biofuel production. Investment subsidies may, however, reduce investors' risk. Lower risk should reduce investors' required rate of return and hence may help make biofuel investments more attractive. This effect is, however, not included in the model.

For the other five subsidy schemes listed in Table 4, the model finds that biofuel investments and production are profitable for support over a specific threshold: feed-in premiums induce production at a subsidy level of 0.62 €/L; fossil fuel tax increases lead to production at 0.61 €/$L_{\text{fossil fuel}}$; harvest residues support results in production starting at 52 €/MWh_{input}, which corresponds to 0.86 €/L; and finally, quota obligations result in biofuel production both overall and in each of the Nordic countries (Fig. 3b).

3.3. Cost of subsidy schemes

The total direct costs of the different subsidy schemes are shown in Fig. 3a, while the unit costs are shown in Fig. 3b. The modelled total cost rises steadily with the amount of biofuel produced due to increasing raw material prices and transport costs. The support needed to reach a certain biofuel quantity is substantially higher for the harvest residues support scheme (cf. Table 4) than for the alternatives. For the four remaining subsidy schemes, there are only minor differences in the total impact on production levels up to about a 30% share of biofuel production. For larger volumes, quota obligations require less support than feed-in premiums and fossil fuel tax increases at high production volumes (> 25%). This is because quota obligations support the difference between producer cost (Fig. 3c) and fossil fuel price. One possible solution for reducing the gap between producer cost and fossil fuel retail prices is to increase the retail price. Meanwhile, feed-in premiums represent a fixed amount of subsidy producers get for producing. Quota obligations increase linearly with production cost, while the costs associated with feed-in premiums and increasing fossil fuel taxes do not increase linearly because of the increasing raw material costs.

Assuming renewable directives figures (European Commission, 2019) for savings from Fischer-Tropsch diesel based on farmed land, a subsidy level of 0.70–1.00 €/L equals a net carbon reduction cost of 256–366 €/ton CO_2. The total cost of reducing 10 million tons CO_2 (around 19% of the current Nordic emissions from transportation (Eurostat, 2019)) is estimated to be 2.7 billion €/year.

The unit production cost of biofuel always increases with increasing biofuel production (Fig. 3c) due to increased chips prices. Production costs are highest for national quota obligations due to higher labour costs and less accessible biomass in Norway and Denmark than in

Table 4
Assumptions regarding subsidy schemes, abbreviation, and modelled range.

Scheme	Abbreviation	Description	Min level	Max level
Feed-in premium	Feed-in	Biofuel producers get a premium when producing biofuel. Simulated as a flat value that is added to the market price.	0 €/L	1.1 €/L
Increase in fossil fuel tax	Fossil inc.	Increase in the fossil fuel tax. Assumed to result in the same increase in fossil fuel retail prices.	0.73 €/$L_{fossil\ fuel}$	1.8 €/$L_{fossil\ fuel}$
Investment support	Invest	Implemented as a reduction in the capital costs.	0%	100%
Quota obligation for all Nordic countries	Nordic quota	Forest-based biofuel has to cover a minimum share of the total fuel consumption in the Nordic countries.	0%	50%
Quota obligation each country independently	National quota	Forest-based biofuel has to cover a minimum share of the total fuel consumption in each of the Nordic countries.	0%	50%
Raw material support	Raw	Support for using harvest residues as raw material for biofuel production.	0 €/MWh_{input} (0 €/Lbiofuel)	75 €/MWh_{input} (1.25 €/Lbiofuel)
Tax exemption	Tax	Biofuels get tax exemptions for special fuel taxes.	0%	100%

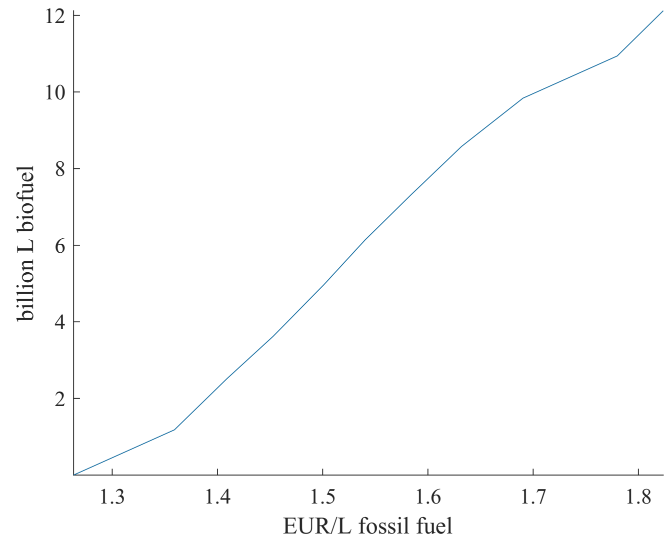

Fig. 2. Modelled biofuel production with increasing diesel and gasoline prices, assuming no policy support and no fossil fuel tax.

Sweden and Finland. The lowest unit costs are observed for harvest residues support due to the low demand for harvest residues in rest of the forest sector.

Harvest residues support has the lowest production costs (Fig. 3c) and highest subsidy costs (Fig. 3b) since the socioeconomic costs for the entire forest sector are highest for harvest residues support. The reason for this effect is that increased utilization of harvest residues, within limits, has few spillover effects on the rest of the forest sector. This means that the socioeconomic cost of harvest residues support is almost equal to the actual costs to the government since the market effects on the rest of the forest sector are relatively small. On the other hand, the other policies will lead to greater market gain and reduced need for governmental support since increased biofuel production will increase the roundwood prices, resulting in increased income for forest owners. The increased income for forest owners is higher than the decrease in production levels for pulp and paper producers; all together this increases the total welfare in the forest sector and reduces the need for governmental support.

3.4. Implications for the forest sector

Wood-based biofuel production implies an increase in demand for wood; hence, policies supporting biofuel will affect forestry and other forest industries. The modelled changes in harvest level and price for sawlogs and pulpwood for increasing subsidy levels are shown in Fig. 4. As expected, increasing subsidy levels, which is similar to increasing biofuel production levels, causes higher harvest levels and wood prices. Apart from the harvest residues support scheme, all subsidy schemes have more or less the same impact on harvest levels and prices. For the harvest residues support scheme, however, prices and harvests remain on the reference level up to a subsidy level of 75 €/MWh_{input} (1.25 €/L). From that point, harvest increases and price decreases rapidly because all easily available harvest residues are collected. From a harvest residues subsidy of 75 €/MWh_{input}, forest owners would harvest more roundwood in order to sell more harvest residues to the biofuel producers, and this additional roundwood would decrease roundwood prices.

For sawmills, the subsidy of biofuels would have two indirect impacts: (i) the sawlogs harvest level would tend to increase since the demand for pulpwood increases pulpwood prices, and (ii) the price received for sawmilling residues such as chips, dust, and bark would increase as these are used for bioenergy purposes. The overall impacts

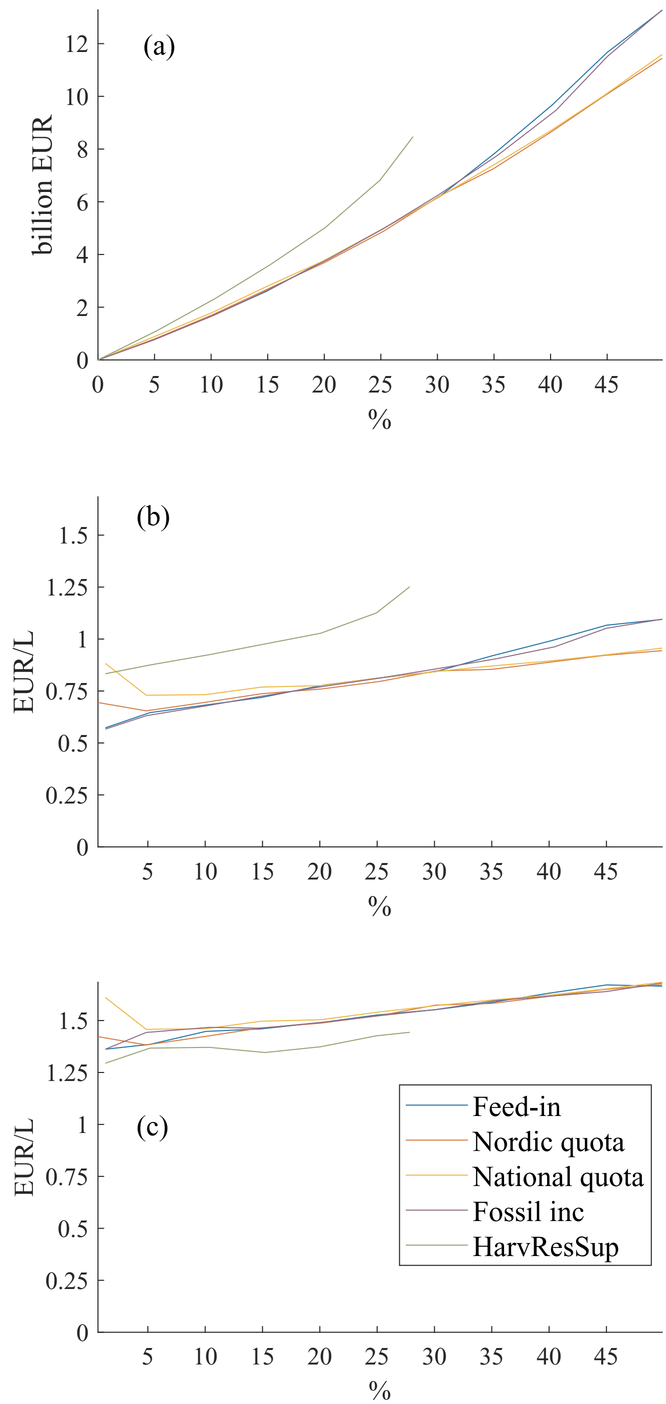

Fig. 3. Modelled total (a) and unit (b) subsidy amount needed for biofuel production, and the unit production cost (c), for the different support schemes, plotted against the volume share of biofuel in the Nordic countries (assuming 2017 consumption of liquid fuel), see Table 4 for scenario explanations.

are hence increasing sawlogs harvest levels and prices, increasing sawnwood production (Fig. 5a), and decreasing sawnwood prices (Fig. 5b).

While the impacts to the sawmill industry are rather modest, a more notable impact is seen for the modelled pulp and paper production (Fig. 5c) due to significantly increasing pulpwood prices. Moreover, pulp and paper prices increase slightly (Fig. 5d). Also, in terms of production and prices, the subsidy for harvest residues deviates from the rest of the case due to less competition for raw materials.

3.5. Regional results

Appendix B (Table B.1) shows modelled biofuel production at a regional level for the national and Nordic quota obligations scenarios at 20% biofuel production. According to these results, the biofuel production will mainly be located in central and southern Sweden and southern Finland. At a regional level, the highest production volume is found in the areas around Oslo (N2), Stockholm (S6), and Helsinki (F10). These areas have low, or no, pulp and paper production and are at the same time close to consumers. It should be noted that most of the production happens in the areas with high activity in the forest sector, e.g. regions in central Sweden and central Finland. When assuming national instead of Nordic quota obligations, the model solution has significantly lower production volumes in Finland, especially in the region around Helsinki, and an equal increase in production in Denmark. The harvest levels increase in all regions when biofuel investments are included. This increase is most significant in F2 and F8.

3.6. Sensitivity analysis results

All nine alternatives (sensitivities) described in chapter 2.5 are tested for feed-in premiums, fossil fuel tax increases, harvest residues support, and Nordic and national quota obligations. In order to make the results comparable, the subsidy level is kept constant within each of the five different policy schemes. The subsidy levels assumed in the sensitivity scenarios are feed-in premiums at 0.783 €/L, fossil fuel tax increases at 0.779 €/$L_{\text{fossil fuel}}$ (total fossil fuel price 1.51 €/$L_{\text{fossil fuel}}$), harvest residues support at 61.6 €/MWh_{input}, Nordic quota obligations at 19.5%, and national quota obligation at 19.9%. These subsidy levels resulted in close to a 20% biofuel share in the base scenarios (Fig. 3).

The biofuel production level (Fig. 6) for the Nordic quota obligation is not sensitive to any of the tested sensitivity parameters; the reason for this is that the quota obligations scheme ensures a constant minimum level of biofuel production. On the other hand, we find significant changes regarding the subsidy cost of using a quota obligations scheme (Fig. 7). The changes in the subsidy cost follow the changes in production cost when the raw material costs change.

The unit subsidy level (Fig. 7) is not sensitive to the tested parameters for feed-in premium and fossil fuel tax increase. The reason for this is that the subsidy is defined based on a unit of biofuel, making it sensitive to production volume (Fig. 6). The unit subsidy for harvest residues support is only sensitive to the conversion efficiency. This follows from the fact that the subsidy is based on the unit input of raw material.

The studied policy schemes almost do not change the production level of biofuel (Fig. 6) or the subsidy cost (Fig. 7) for the sensitivity parameters harvest restriction and increase in pulp and paper production capacities. The reason for this is that these restrictions only introduce a marginal change in the roundwood balance. The strictest harvest restriction lowers the harvest by only 7% (Fig. 8). For the increase in pulp and paper production capacities of total 4 million m^3 solid ub. pulpwood, however, the model will compensate by reducing the production capacities at other plants. The sensitivity of biofuel production and subsidy cost regarding harvest costs is also relatively low; consequently, when the cost of harvest increases by 25%, the market will reduce the demand for roundwood, which will stabilise the price. Biofuel production decreases by a maximum of 6% when the harvest costs increase by 25%, while the pulp and paper production decreases by 12% in the same simulation. This shows that the rest of the forest sector is more affected by change in harvesting costs than biofuel production. This stabilises the raw materials costs for biofuel producers.

The two parameters included in the sensitivity analysis that directly target biofuel production are those with largest changes in production level (Fig. 6) and cost of subsidy (Fig. 7). When changing the interest rate, the largest effect is found for Nordic quota obligations, which has a subsidy cost increase of 15% when the interest rate increases from 10%

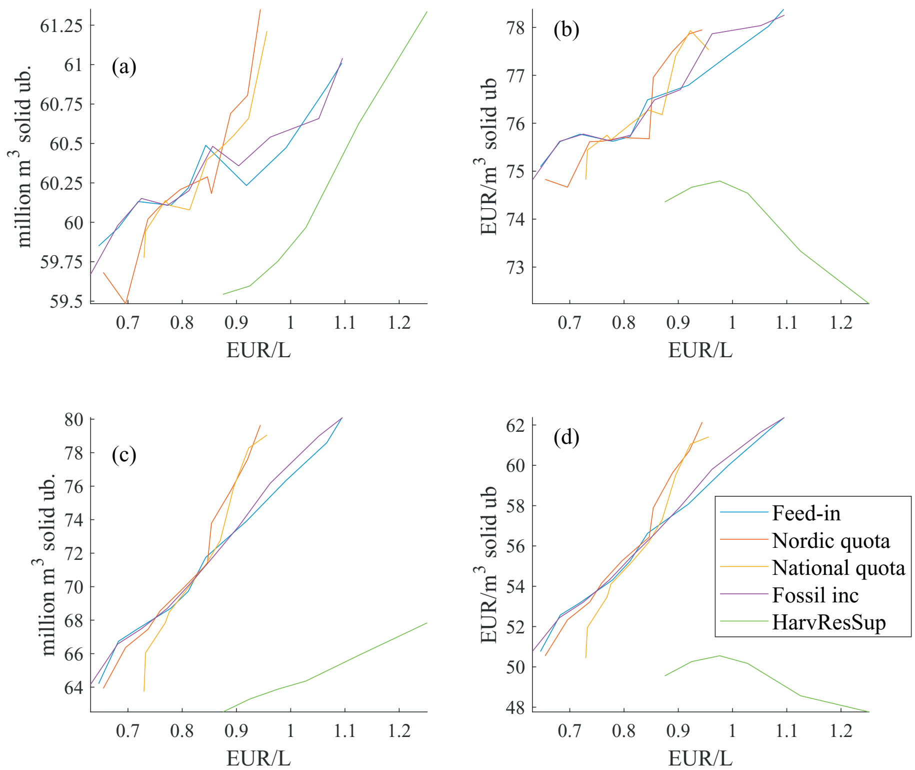

Fig. 4. Modelled sawlogs harvest (a), sawlogs prices (b), pulpwood harvest (c), and pulpwood prices (d) plotted against the unit amount of subsidy in the Nordic countries, see Table 4 for scenario explanations.

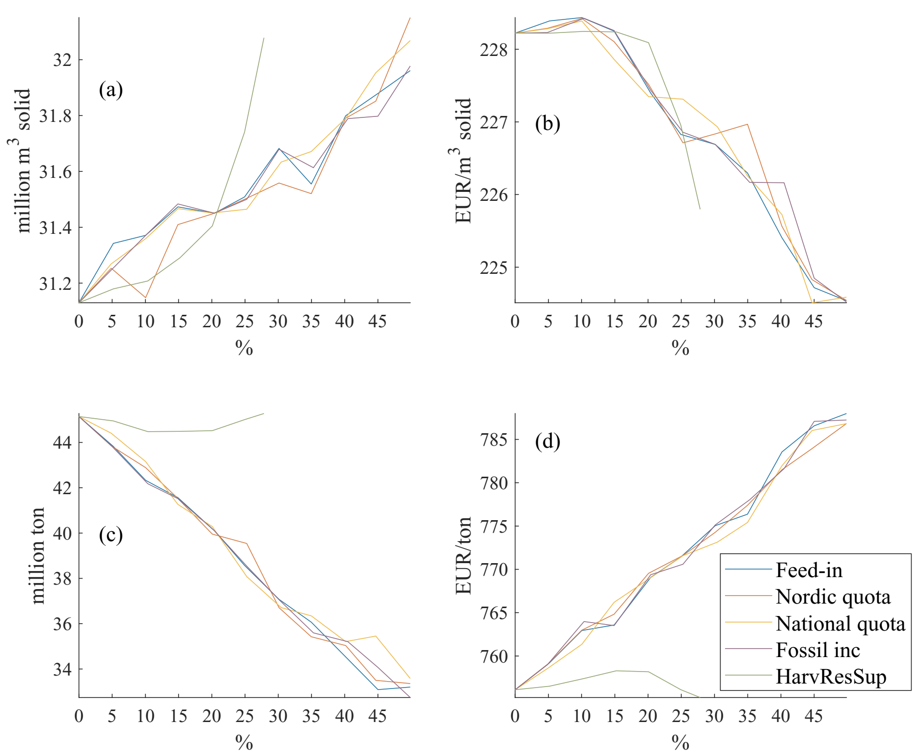

Fig. 5. Modelled sawnwood production (a), sawnwood prices (b), pulp and paper production (c), and pulp and paper prices (d) plotted against the volume share of biofuel in the Nordic countries (assuming 2017 consumption of liquid fuel), see Table 4 for scenario explanations.

to 15%; the production level for feed-in premiums and fossil fuel tax both decrease to 9% blend-in to fossil fuel for the same interest rate. The model is sensitive to conversion efficiency; if the conversion efficiency is reduced from 58% to 42%, the production with feed-in premiums and fossil fuel tax becomes zero, while an increase to 74% efficiency results in an increase in biofuel production to 55% blend-in to fossil fuel.

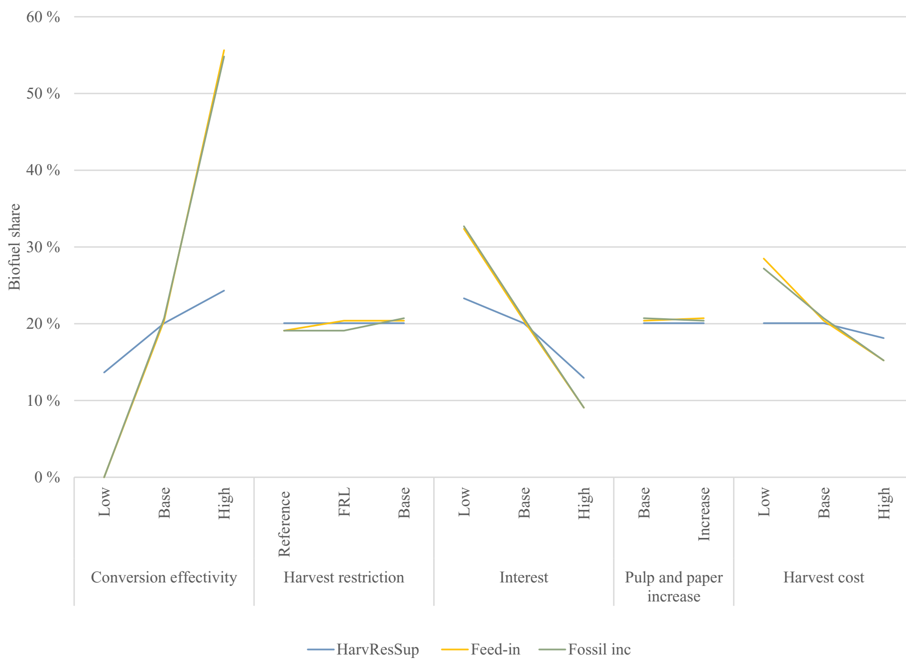

Fig. 6. Modelled fraction of biofuel production (assuming 2017 consumption of liquid fuel) for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in percentage of total liquid fuel consumption. The subsidy schemes for Nordic and national quota obligations are uninfluenced by the different sensitivities regarding biofuel production levels and are omitted in the graphical representation.

4. Discussion

This study uses a partial equilibrium modelling framework. The results show that the breakeven price for forest-based biofuel produced in the Nordic countries is around 1.3 €/L (price for fossil fuels + subsidy). This level is 75% higher than the breakeven price estimates from Zhao et al. (2016). A major reason for higher costs in the present study, compared to Zhao et al. (2016), is that converting roundwood to fuel is a more challenging process than converting corn stover. Another reason may be that labour and construction costs are higher in the Nordic countries than in the US. Hagos et al. (2017) found that a subsidy of 0.43 €/L is enough to promote biofuel production in inland Norway. This is almost half the subsidy level we found for biofuel production (0.7 €/L). The main reason for this difference is a the assumed willingness to pay a higher price for biofuel than fossil fuel (Lanzini et al., 2016), which was included in Hagos et al. (2017) but was not considered in the present study. Baral and Rabotyagov (2017) reported the willingness to pay for forest-based biofuel to be 6% of the fossil fuel price, while Lim et al. (2017) estimate the willingness to pay a premium for bioethanol may be as high as 15.6% of the gasoline retail price, which will reduce the need for subsidies only slightly.

According to the model results, feed-in premiums and increased fossil fuel taxes have similar effects on the optimal biofuel production level. Feed-in premiums lower production costs, while an increase in the fossil fuel tax increases the alternative fuel price. Although these two policies may influence the market similarly, their distributional

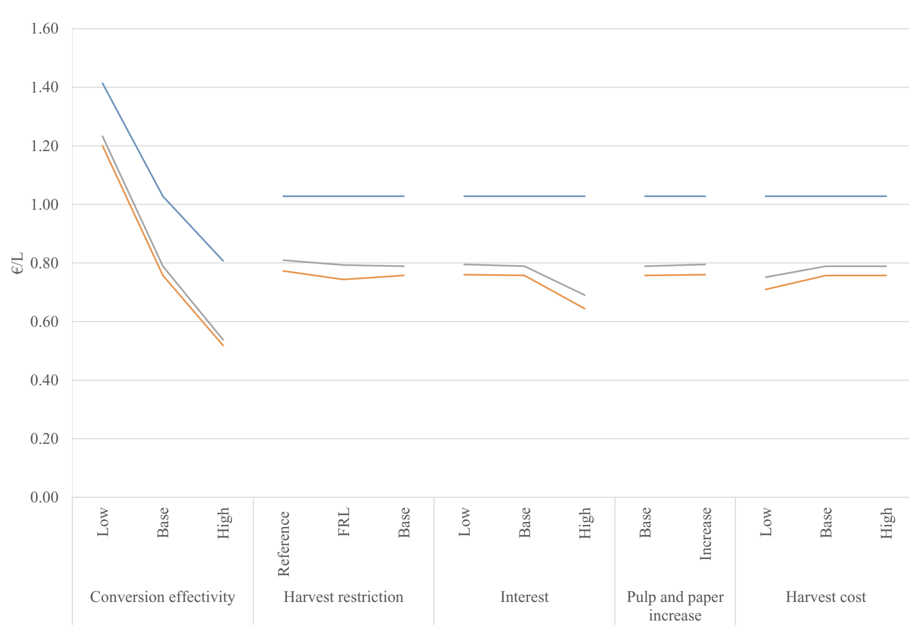

Fig. 7. Modelled unit subsidy cost for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in €/$L_{biofuel}$. The subsidy schemes for feed-in premium and increasing fossil fuel tax are uninfluenced by the different sensitivities regarding subsidy cost and are omitted in the graphical representation.

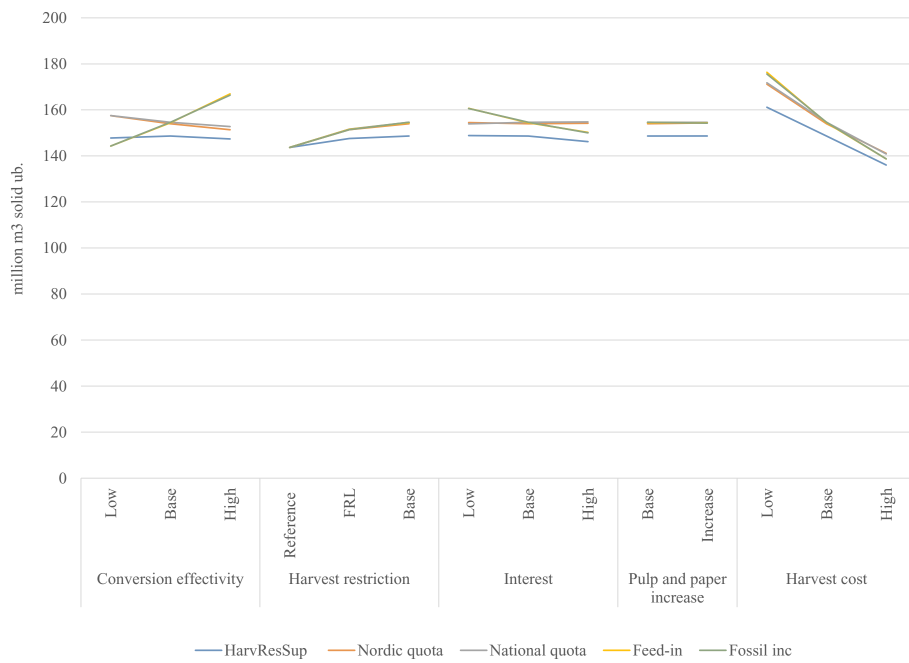

Fig. 8. Modelled harvest level for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in 1000 m^3 solid ub.

effects are different. For feed-in premiums, the government supports the producers directly for each unit of biofuel produced. This means that the costs of the policy are shared among all taxpayers. For increased fossil fuel tax, the fuel consumer pays via increased fuel prices. When interpreting the results, it should be stressed that the model assumes fully rational and informed producers and consumers, and that the economic valuation of the climate benefits of reducing the use fossil fuel or costs of indirect land use are not included in the economic benefits. A possible impact of increasing fuel taxes is a lower total demand for liquid fuel and increased use of fossil fuel substitutes such as electric cars. The model does not cover this effect.

Harvest residues have barely been used to this end for applications other than district heating. In this study, we assume harvest residues can be used as a raw material in biofuel production. Our results show that harvest residues support schemes may increase biofuel competitiveness, but their feasibility depends on the support level. If the support is too low (< 50 €/MWh_{input}, according to this study) no harvest residues will be used for biofuel production, while if the support is too high (exceeds 75 €/MWh_{input}, according to this study), forest owners will increase roundwood harvest to increase their residues supply. This in turn might lead to lower roundwood prices. For lower subsidy levels, it will be possible to utilize harvest residues for biofuel production without interfering with the traditional forest sector. Luke (2019) reports a selling price for logging residues in the Finnish market of 17.7 €/m^3, which means that a subsidy of 60 €/MWh_{input} is 3.4 times higher than the market price. Thus, subsidising harvest residues makes sense if the goal is to support forest owners, but it is not the most effective means of increasing production of forest-based biofuel. It should, however, be noted that the short and long run climate impacts of bioenergy from long rotation crops are widely debated (Cintas et al., 2017; Guest et al., 2013; McKechnie et al., 2011; Norton et al., 2019). The use of harvest residues for energy purposes is regarded favourably in this perspective since the alternative leads to a rather rapid decay of the stored carbon in the tops and branches. Simply put, this will shift the emission from decaying harvest residues to the time of combustion. Support of harvest residues relative to virgin wood fibre in biofuel production may hence be optimal from a climate viewpoint although the cost per litre produced is higher.

The model results show that the needed policy costs for quota obligations, feed-in premiums, and fossil fuel tax increases are at similar levels for the range of 0–30% biofuel implementation. Above 30%, feed-in premiums and fossil fuel tax increases have higher total costs than quota obligations. Both feed-in premiums and fossil fuels taxes should be relatively easy to implement since feed-in premiums are already in use in the power sector and fossil fuel tax already exist, but politically they may be difficult to introduce. However, to reach a renewable share target for transportation, increasing the fossil fuel tax is likely to be more effective than feed-in premiums since higher fossil fuel prices will not only stimulate investments in forest-based biofuel but also increase the use of electric cars and other renewable fuel alternatives. On the other hand, introducing a feed-in premium will make it possible to target forest-based biofuel, which is equal to stimulate the production of forest-based biofuel at the expense of food-based biofuel. This will not be possible with an increase in the fossil fuel tax without further regulations. Feed-in premiums may also support less mature technologies and ultimately boost technology learning since the premium may vary between technologies. Regardless of which type of subsidy is used to increase the implementation of biofuels, a long time horizon is important, as is the predictability of the subsidy.

From a governmental point of view, quota obligations may be the most profitable scheme since they ensure that the production of biofuel continues, even with significant changes in the production cost or alternative fuel cost, but the consumer price may change dramatically. The main drawback with quota obligations is that the produced volume of biofuel will be reduced with reduced liquid fuel demand. Thus, with this approach, biofuel producers will bear the risk of increased use of electric cars. On the other hand, a feed-in premium will ensure a stable production of biofuel even if the use of liquid fuel decreases, as long as the production cost and fossil fuel spot price is almost stable. This shows that over time the different schemes will give rise to different risk takers.

All kinds of subsidy schemes have transaction costs, and these costs vary between different types of subsidies (Coggan et al., 2010; Rørstad et al., 2007). Some subsidy schemes may have rather high transaction costs, while others have low costs. Transactions costs are not part of this study, but they may have a large impact on the economic ranking of the subsidy schemes. For instance, increasing fossil fuel prices may have a lower transaction cost than harvest residues support since the method of increasing fossil fuel prices through taxes is already widely used in the Nordic countries and the marginal cost of increasing the tax from 0.66 €/$L_{\text{fossil fuel}}$ to, for example, 1.3 €/$L_{\text{fossil fuel}}$ is relatively low. For harvest residues support, a new reporting system has to be built up, which has (new) operational costs.

There are other types of subsidy besides the ones shown in this study that may lower producers' risk; one option may be reverse auction. Since NFSM is a deterministic model, it is close to impossible to model reverse auction in a satisfactory manner, but the pattern for reverse auction will probably follow the feed-in premium scheme modelled in this paper. Bittner et al. (2015) estimate that the probability of biofuel producers losing money for reverse action is lower than for capital subsidy and that the probability of loss is > 50% for capital subsidy for shorter contracts. This is in accordance with our study since we do not get any investment under the investment subsidy scheme.

For the most part, the sensitivity analyses in this paper did not lead to significant changes in the production of biofuel or subsidy costs. The exceptions to this are conversion efficiency and interest rate. One conclusion that may be drawn from this it that the results are sensitive to the assumption regarding biofuel production but not sensitive to changes in the forest sector. A reason for this is that the chosen level of sensitivity is largest for the biofuel production parameters, but this also reflects the uncertainties in the model quite well. The assumed biofuel plant in this study is yet to be built. There is hence a high uncertainty regarding the ‘real’ conversion efficiency of a commercial biofuel plant.

The NFSM is a regional model which divides the Nordic countries into a total of 31 regions. Although the regionalization gives a proper representation of the current industrial production and harvest, when we introduce biofuel production with endogenously defined location it becomes more uncertain. Since the model maximizes total welfare, the location of a biofuel plant could be decided by its having only marginally better economic conditions than other locations. Since we use fixed size production unit, a marginal change in the biofuel cost may lead to significant changes in the entire forest sector for a given region. When a biofuel producer decides on a location for a biofuel plant, factors besides the availability of raw materials and synergic effects for the traditional forest sector will also be considered. These may include access to educated labour, local taxes or subsidies, price of land, access to existing infrastructure, possibility of using a side stream from existing industry (including non-forest industry), and many other aspects that are not covered by this model.

The model used in this study is a spatial partial forest-sector model; as is the case with all models, the NFSM is a simplification of the real world. The Nordic forest sector is the only part of the economy covered in the study, which leads to assumptions regarding the different intersections. The most important assumption in this study is the assumption regarding demand for fossil fuel. We have assumed constant demand for liquid fuel in the transportation sector; but the demand for liquid fuel will likely decrease if retail prices increase, which may be the case with implementation of large biofuel subsidies. Dahl (2012) found that the demand for gasoline and diesel in the Nordic countries is quite price inelastic (−0.05 to −0.40); for simplicity, we assume that the fuel demand is constant. In the model, we assume that harvest, production, and consumption happen in the regional centres. For this reason, pulp mills, sawmills, and biofuel plants may be co-located in the modelling framework. The reference year used in the NFSM is 2013, and all results depend on the assumptions regarding the forest sector that year.

5. Conclusion

This study assesses the impacts of various energy policies targeted at increasing wood-based liquid biofuel production in the Nordic countries. According to the model results, the fossil fuel spot price plus unit subsidy has to be above 1.3 €/L for wood-based biofuel production to be profitable. Furthermore, to reach a forest-based biofuel share of 20% of the Nordic liquid fuel consumption, a total subsidy level in the area of 3.9–5.3 billion €/year is needed, assuming a fossil fuel price of 0.73 €/L. This support corresponds to a support level of 0.77–1.0 €/L produced biofuel. Correspondingly, to reach 10% and 40% targets, the costs would be 0.67–0.91 €/L and 0.86–0.98 €/L, respectively. For a forest-based biofuel share in the range of 15–25%, quota obligations, feed-in premiums, and increased fossil fuel taxes will have almost the same economic effectiveness according to the present study.

According to the sensitivity analysis, the results are relatively stable for parameters related to the traditional forest sector and more dependent on the assumption when it comes to biofuel production cost. Harvest residues support tends to be more stable than the other schemes when it comes to the tested sensitivities due to lower consumption of harvest residues in other parts of the forest sector.

The study finds that biofuel production will interfere with and reduce the profits of the traditional forest sector. The different subsidy schemes have, to some extent, different implications for forest owners and forest industries; quota obligations, feed-in premiums, and increased fossil fuel taxes will increase pulpwood prices and hence increase forest owners' revenues, as well as raw material costs in the pulp and paper industry. Support of harvest residues, however, will hardly interfere with the traditional forest sector but will instead increase the use of harvest residues. Increased biofuel subsidies will increase the profitability of biofuel production and are important for changing from fossil fuel to biofuel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Nordic forest sector model

This appendix describes the objective function and constraints used in the Nordic Forest Sector Model (NFSM). NFSM is a linearized mixed-integer model with five special ordered sets of type 2 (SOS2) variables (Lin et al., 2013), one integer variable, and six continuous 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
h	Harvest residues
F	Fossil fuel
m	Countries

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

(*continued on next page*)

Table A.1 (*continued*)

Parameters	
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
M	Matrix that represents which regions are included in which country

Biofuel subsidy parameters	
σ	Feed-in premium given in €/L
Ω	Subsidy for use of harvest residues €/MWh
Δ	Fraction of investment support
ς	Increase in fossil fuel taxes
Ψ	Level of quota obligations

A.1. The objective function

This Section (A.1) is adapted from Jåstad et al. (2019).

NFSM is solved by maximising the objective function:

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

where the first term (*Rconsume*) represents the inverse demand function, i.e., the consumers' surplus. The second term (*Charvest*) represents the harvest supply function. The third term (*CharvestReduidues*) represents the cost of harvesting harvest residuals. The fourth term (*Clabour*) represents the labour costs. The fifth term (*Ctrans*) represents the cost of interregional trade. The sixth term (*Cproduction*) represents the maintenance and other exogenous production costs. The seventh term (*CNewInvestments*) represents the cost of increasing the industrial production capacity. The eighth term (*Cbiofuel*) represents the cost of biofuel plants. Finally, the ninth term (*BioSubsidy*) represents the biofuel subsidy that is directly relevant for the objective function, see section A.3 for detailed description.

The values used in the objective function are solved using piecewise linearization (Lin et al., 2013).

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 used, $x_{i,\ f,\ n}{}^{a}$and $\lambda_{i,\ f,\ n}{}^{a}$, where $x_{i,\ f,\ n}{}^{a}$is predefined range of possible consumption levels with N^{a} pieces ranging from zero to double the reference value and $\lambda_{i,\ f,\ n}{}^{a}$ is an SOS2 variable. The SOS2 variable is used for ensuring one out of two outcomes: (1) if the level of consumption $\gamma_{i,\ f}$ hits exactly a level in $x_{i,\ f,\ n}{}^{a}$, then only one number in $\lambda_{i,\ f,\ n}{}^{a}$ is different from zero (binary case); or (2) if the level of consumption $\gamma_{i,\ f}$ hits somewhere between the levels defined in $x_{i,\ f,\ n}{}^{a}$, then two neighbouring numbers in $x_{i,\ f,\ n}{}^{a}$ are different from zero (SOS2 case), with the constraint that they add up to 1 ($A.\ 3$).

$$Rconsume_{i,f} = \sum_{n=1}^{N^{a}} \lambda^{a}{}_{i,f,n} * \left(\left\{\Gamma_{i,f} - \frac{\Gamma_{i,f}}{\tau_{f}}\right\} * x^{a}{}_{i,f,n} + \frac{1}{2}\left\{\frac{\Gamma_{i,f}}{\zeta_{i,f} * \tau_{f}}\right\} * (x^{a}{}_{i,f,n})^{2}\right) \quad \forall \quad i, f \tag{A1}$$

$$\gamma_{i,f} = \sum_{n=1}^{N^{a}} \lambda^{a}{}_{i,f,n} * x^{a}{}_{i,f,n} \quad \forall \quad i, f \tag{A2}$$

$$\sum_{n=1}^{N^{a}} \lambda^{a}{}_{i,f,n} = 1 \quad \forall \quad i, f \tag{A3}$$

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 linearized 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 $x_{i,\ w,\ n}{}^{b}$ with N^{b} segments. $\beta_{i,\ w}$ is the econometrically estimated roundwood supply elasticity for roundwood category w in region i. $\alpha_{i,\ w}{}^{t}$ is estimated using the equation ($A.\ 7$). For the first year (ti=1) $\alpha_{i,\ w}{}^{ti}$ is calculated using reference price $\eta_{i,\ w}$ and reference harvest $\chi_{i,\ w}$. For the second year, (ti=2) $\alpha_{i,\ w}{}^{ti}$ is calculated using reference standing stock $S_{i,\ w}$, and for subsequent years, (ti > 2) $\alpha_{i,\ w}{}^{ti}$is calculated using the modelled standing stock $S_{i,\ w}{}^{ti}$. The standing stock grows at a rate $\kappa_{i,\ w}$ and is reduced by harvesting $\theta_{i,\ w}$. A more detailed description of α and β can be found in (Bolkesjø et al., 2005).

$$Charvest_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * \left(\frac{\alpha_{i,w}^{t}}{\beta_{i,w} + 1}\right) * (x_{i,w,n}^{b})^{\beta_{i,w}+1} \quad \forall \quad i, w \tag{A4}$$

$$\theta_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * x^b{}_{i,w,n} \quad \forall \quad i, w \tag{A5}$$

$$\sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} = 1 \quad \forall \quad i, w \tag{A6}$$

$$\alpha_{i,w}^{ti} = \begin{cases} \dfrac{\eta_{i,w}}{\chi_{i,w}{}^{\beta_{i,w}}}, \; if \; ti = 1 \\ \alpha^{ti-1}{}_{i,w} \Big/ \left(\dfrac{[\{((1+\kappa_{i,w}) * S_{i,w}^{ti-1}) - \theta_{i,w}^{ti-1}\} + S_{i,w}^{ti-2}] / 2}{S_{i,w}^{ti-2}}\right)^{\beta_{i,w}}, \; if \; ti \geq 2 \end{cases} \quad \forall \quad i, w \tag{A7}$$

Cost of collection harvest residuals (*CharvestResidues*) is estimated using $\lambda^c{}_{i,n}$ and range $x_{i,\ n}{}^c$ with N^c segments, where μ_i and ν_i are the intercept and slope of harvesting harvest residuals in region i and ϵ_i is the amount of collected harvest residuals.

$$CharvestResidues_i = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * \left\{\mu_i * x_{i,n}^{c} + \frac{1}{2} * \nu_i * (x_{i,n}^{c})^2\right\} \quad \forall \quad i \tag{A8}$$

$$\epsilon_i = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * x^c{}_{i,n} \quad \forall \quad i \tag{A9}$$

$$\sum_{n=1}^{N^c} \lambda^c{}_{i,n} = 1 \quad \forall \quad i \tag{A10}$$

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 $x_{i,\ b,\ tb,\ FS}{}^d$, and N^d is the total number of factory sizes NFSM can choose between. Each discrete factory size has its 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.

$$Cbiofuel_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * (\xi_{i,b,tb,FS} + \Pi_{b,tb,FS} + NP * \rho_{b,tb,FS}) \quad \forall \quad i, b, tb \tag{A11}$$

$$\varphi_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * x^d{}_{i,t,tb,FS} \quad \forall \quad i, b, tb \tag{A12}$$

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

$$Clabour_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * \varpi_{i,l,t,n} \quad \forall \quad i, l, t \tag{A13}$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * x^e{}_{i,l,t,n} \quad \forall \quad i, l, t \tag{A14}$$

$$\sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} = 1 \quad \forall \quad i, l, t \tag{A15}$$

The cost of a new production facility (*CNewInvestments*) is estimated with use of the SOS2 variable $\lambda_{i,\ l,\ t,\ n}{}^f$ and range $x_{i,\ l,\ t,\ n}{}^f$ with N^f segments. The range $x_{i,\ l,\ t,\ n}{}^f$ 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 < 120% of reference production for the pulp and paper industry and 140% for the rest of the model. For production over the threshold, $\Phi_{i,\ l,\ t,\ n}$ is estimated as a linear unit increasing cost. If the production level for two subsequent years is far below the installed capacity, the model assumes that the production unit has been partly or fully closed, and there will then be a cost to increase the production level in the following year.

$$CNewInvestments_{i,l,t} = An * \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * \Phi_{i,l,t,n} \quad \forall \quad i, l, t \tag{A16}$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * x^f{}_{i,l,t,n} \quad \forall \quad i, l, t \tag{A17}$$

$$\sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} = 1 \quad \forall \quad i, l, t \tag{A18}$$

In addition to the linearized costs, the objective function includes two parts that are calculated directly: these are (1) *Cproduction* (*A*. 19), which represents 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*, and (2) *Ctrans* (*A*. 20), which represents 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*.

$$Cproduction_{i,l,t} = [An * I_l + \iota_i * \Lambda_{i,t}] * \varphi_{i,l,t} \quad \forall \quad i, l, t \tag{A19}$$

$$Ctrans_{i,j,k} = \omega_{i,j,k} * D_{i,j,k} \quad \forall \quad i, j, k \tag{A20}$$

A.2. Constraints

The objective function is solved with following constraints:

$$\theta_{i,k} + \sum\nolimits_{k_2} \Theta_{i,k,k_2} - \sum\nolimits_{l,t} \varphi_{i,l,t} * a_{k,l,t} - \gamma_{i,f} + \epsilon_i + \sum\nolimits_{j} \omega_{j,i,k} - \sum\nolimits_{j} \omega_{i,j,k} = 0 \quad \forall \quad i, k \tag{A21}$$

$$\sum\nolimits_{k,k_2} \Theta_{i,k,k_2} = 0 \quad \forall \quad i \tag{A22}$$

$$\theta_{i,w} * \upsilon_{w,w} \le \psi_{i,w} * \sum\nolimits_{w_2} \upsilon_{w,w_2} * \theta_{i,w_2} \quad \forall \quad i, w \tag{A23}$$

$$\sum\nolimits_{i,p,t} \varphi_{i,p,t} * a_{r,p,t} \le \sum\nolimits_{i,p} R_p * \gamma_{i,p} \quad \forall \quad r \tag{A24}$$

$$\epsilon_i \le \Xi \sum\nolimits_{w} \theta_{i,w} \quad \forall \quad i \tag{A25}$$

$$\varphi_{i,l,t}, \gamma_{i,f}, \theta_{i,w}, \epsilon_i, \omega_{i,j,k} \ge 0 \quad \forall \quad i, j, f, l, k, w \tag{A26}$$

where $a_{k,\ l,\ t}$ is the input of product k in production of product l with use of technology t. $\Theta_{i,\ k,\ k_2}$ is the amount of product k that is downgraded to product k_2 in region i. $\upsilon_{w,\ w}$ is a binary parameter that relates spruce sawlogs and pulpwood and pine sawlogs and pulpwood. $\psi_{i,\ w}$ is the maximum 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) ensures 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) ensures that the amount of original product is equal to the amount of the downgraded product. Equation (A. 23) ensures that harvest of pulpwood and sawlogs does not exceed a certain fraction of each possible quality grade. Equation (A. 24) ensures that the use of recycled paper grade (r) does not exceed a predefined recycling rate. Equation (A. 25) ensures that the harvest of harvest residuals does not exceed the theoretical limit (Ξ) as a function of harvest. And finally, (A. 26) ensures that every variable is non-negative. In this study, the total production of bioheat and biopower are assumed equal to the reference demand in each region.

A.3. Biofuel policies

A.3.1. Feed-in premium

When the feed-in premium subsidy is activated, the *BioSubsidy* element in the objective function is as shown in (A. 27), where σ is the unit feed-in premium given in €/unit biofuel and $\varphi_{b,\ tb,\ i}$ is production of biofuel b in region i with use of technology tb. The subsidy σ varies between 0 and 1.1 €/L biofuel produced.

$$BioSubsidy = \sigma \sum_{b,tb,i} \varphi_{b,tb,i} \tag{A27}$$

A.3.2. Increase in fossil fuel tax

For the fossil fuel tax increase policy scheme, the cost consumers are willing to pay for biofuel is $\Gamma_{i,\ b}$ in region i, changed to $\Gamma_{i,\ b} = \Gamma_{i,\ b} + \varsigma$ in function (A. 1), where ς is the unit fossil fuel price increase.

A.3.3. Investment support

In the investment support policy scheme, the investment cost $\rho_{b,\ tb,\ FS}$ for biofuel b produced with technology tb and factory size FS is changed to $\rho_{b,\ tb,\ FS} * (1 - \Delta)$ in function (A. 11), where Δ is the fraction of investment support.

A.3.4. Quota obligation for all Nordic countries and for each country independently

For the quota obligation policy scheme, the constraint (A. 28) is added for Nordic quota obligations and the constraint (A. 29) is added for national quota obligations, where $\zeta_{F,\ i}$ is the reference consumption of fossil fuel F in region i and the quota obligation level is Ψ. $M_{m,\ i}$ is a binary parameter that represents the connection between region i and country m and ensures that the quota obligations level Ψ is fully met in each region.

$$\Psi \sum_{F,i} \zeta_{F,i} \le \sum_{b,tb,i} \varphi_{b,tb,i} \tag{A28}$$

$$\Psi \sum_{F,i} \zeta_{F,i} M_{m,i} \le \sum_{b,tb,i} \varphi_{b,tb,i} M_{m,i} \quad \forall \quad m \tag{A29}$$

A.3.5. Harvest residues support

For harvest residues, the support scheme is the *BioSubsidy* element in the objective function as shown in (A. 30), where $\varphi_{b,\ tb,\ i}a_{b,\ tb,\ h}$ is the input of harvest residues h when producing biofuel b with use of technology tb in region i. The unit input subsidy Ω is defined in €/input harvest residues, in this study is the subsidy in ranges 0–75 €/MWh.

$$BioSubsidy = \Omega \sum_{b,tb,i,h} \varphi_{b,tb,i} a_{b,tb,h} \tag{A30}$$

Appendix B. Regional results

The regional harvest and biofuel production are shown in Table B.1. There some regional differences between the Nordic quota and national quota scenarios. In all regions, the harvest level increases when biofuel is included, and there are only small differences between the two scenarios with biofuel production.

Table B.1
Overview of the different regions in the model and the production of biofuel and total regional harvest for the Nordic quota and national quota scenarios. The policy level is 20% quota obligations for both scenarios. Regional harvest without biofuel production is also included for comparison.

NFSM Regions	Regions	**Biofuel production [million L]**		**Harvest [1000 m^3]**		
		Nordic quota	National quota	Without biofuel	Nordic quota	National quota
N1	Østfold	0	0	769	882	882
N2	Akershus, Oslo	315	315	919	1046	1037
N3	Hedmark	0	79	3930	4577	4526
N4	Oppland	0	0	1254	1456	1444
N5	Buskerud, Vestfold	0	315	1276	1435	1442
N6	Telemark, Aust-Agder	0	0	1066	1176	1173
N7	Vest-Agder, Rogaland	0	0	462	505	501
N8	Hordaland, Sogn og Fjordane	0	0	311	332	335
N9	Møre og Romsdal, Sør-Trøndelag	0	0	560	609	619
N10	Nord-Trøndelag, Nordland, Troms, Finnmark	0	315	836	881	881
S1	Norrbottens län	0	0	3980	4123	4143
S2	Västerbottens län	315	315	6533	6953	6978
S3	Jämtlands län	236	0	5008	5304	5325
S4	Västernorrlands län	0	0	6698	7021	7041
S5	Gävleborgs län, Dalarnas län	315	315	11,313	11,933	11,852
S6	Västmanlands län, Uppsala län, Stockholms län, Södermanlands län	630	315	8173	8375	8376
S7	Örebro län, Värmlands län	315	315	8587	9085	8998
S8	Västra Götalands län	315	0	6381	6892	6884
S9	Kalmar län, Kronobergs län, Gotlands län, Jönköpings län, Östergötlands län	315	315	11,826	12,623	12,622
S10	Hallands län, Skåne län, Blekinge län	236	315	7498	7583	7709
F1	Lappi	0	0	3640	3775	3828
F2	Kainuu, Pohjois-Pohjanmaa	315	315	7913	9284	9277
F3	Keski-Pohjanmaa, Pohjanmaa, Etelä-Pohjanmaa	0	0	4691	4879	4879
F4	Keski-Suomi	0	0	4695	4810	4869
F5	Pohjois-Savo	0	0	5434	5542	5583
F6	Etelä-Karjala, Kymenlaakso, Pohjois-Karjala	0	0	8700	9108	9127
F7	Satakunta, Varsinais-Suomi, Åland	315	315	3969	4216	4226
F8	Päijät-Häme, Pirkanmaa, Kanta-Häme	315	315	8955	10,198	9982
F9	Etelä-Savo	0	79	5505	5829	5766
F10	Uusimaa	945	0	1148	1326	1179
D1	Denmark	0	945	3593	3783	3957
Sum		4880	4880	145,627	155,541	155,444

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