Swedish Forest Harvest Level Considering Demand of Biomass for Energy Purposes

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Abstract: This paper presents the development and demonstration of an approach for incorporating decisions concerning forest management within the framework of a TIMES energy system model. The presented model explicitly incorporates a number of long-term applicable forest harvest trajectories, thereby endogenously linking decisions concerning harvest levels with the development of the energy system. The operation of the model is demonstrated by evaluating the optimal long-term harvesting level of Swedish forests for the development of the bioenergy and forest industry sectors. The experimental results suggest that in the short term (between 2010 and 2035), an increased national forest harvest level would be beneficial for the joint development of the two sectors. Such a short-term increase in harvest levels of forest biomass sources would ensure an adequate and reliable supply of biomass sources for the expansion of the two sectors. However, in the long term (between 2070 and 2100), the endogenously computed forest harvest level stabilized at a reference harvest level corresponding to a continuation of the current trend in forest harvest levels. While the emphasis of this paper is on the methodological development of the model, the experimental results highlights the importance of considering cross-sectorial implications when assessing the future developments of the bioenergy and forest industrial sectors.

Keywords: biomass, energy models, forest industry sector, land use, TIMES model

1. Introduction

Modern use of biomass for energy purposes commonly stems from a will to mitigate climate change and increase energy security. As biomass sources can substitute carbon-intensive fossil fuels such as coal, oil, and gas for heat, electricity and liquid fuel production, they are perceived as good sources for decreasing greenhouse gas (GHG) emissions. Numerous countries support the use of biomass as a means to achieve short-, medium- and long-term climate targets. Also, as biomass sources can be produced locally, they can decrease dependency on foreign commodity imports. The use of biomass for energy purposes is therefore widely recognized as a means to increase a country’s energy security in transportation, heat generation, and electricity generation, and thereby decrease vulnerability to severe supply disruptions and oil price shocks.

While political interest in promoting bioenergy production has increased, the scientific debate concerning the implications and consequences of large-scale bioenergy production continues. Three of the key factors in the debate concern: (i) whether or not bioenergy, and especially 1st generation biofuels, make a net contribution to GHG savings (Crutzen et al., 2008; Edwards et al., 2004; Farrell et al., 2006; Hill et al., 2006; O’Hare et al., 2009; Searchinger, 2010; Valin et al., 2014); (ii) the potential impact of large-scale biofuel production on price and security of food (Ajanovic, 2011; Banse et al., 2008; Havlík et al., 2011; Helling et al., 2008; Lotze-Campen et al., 2014; Mitchell, 2008; Mueller et al., 2011); (iii) the environmental side effects of large-scale bioenergy production (Anderson and Fergusson, 2006; Baum et al., 2009; Eggers et al., 2009; Fitzherbert et al., 2008; Forsell et al., 2016; Hartman et al., 2011; Semere and Slater, 2007). Even though the debate concerning bioenergy production continues, modern use of biomass is expanding rapidly in many parts of the world, particularly in countries with abundant biomass sources.

In Sweden, biomass and biofuels (including municipal waste, and biofuels such as tall oil, black liquor, ethanol, and biogas) supplied 10% (171 PJ) of the total national primary energy supply in 1980, and have since steadily increased to supply 24% (468 PJ in 2014) (Energimyndigheten, 2018).
Biomass sources are mainly used by the industrial sector including sawmills and pulp and paper mills (202 PJ in 2014), the district heating sector (160 PJ in 2014), private consumers (50 PJ in 2014) and for the production of biofuels (40 PJ in 2014) (Energimyndigheten, 2015). Most of the biomass sources employed in Sweden are currently produced domestically, however, 25% of the 352 million liters of the ethanol consumed in 2013 was imported or produced by imported feedstock (Energimyndigheten, 2014). Some of the pellets and peat consumed is imported. In all, some 16–33 PJ of biomass sources are imported per year, mainly for the district heating sector (Energimyndigheten, 2011).

Numerous studies project that use of biomass for energy purposes will continue to grow in Sweden. Recent long-term projection by the Swedish Energy Agency (SEA) suggests that biomass and biofuels will supply 550 PJ by 2020, and 583 PJ in 2030 (Energimyndigheten, 2011). On the other hand, the RES2020 study (RES2020, 2009) projects a slower development in that biomass and biofuels will supply 506 PJ to primary energy production in Sweden by 2020. As the demand for biomass increases, a more diverse and wider spectrum of biomass feedstocks is being used to feed into the bioenergy sector. Logging residues, such as branches and tops traditionally left in the forest after harvesting are now commonly collected, chipped and sold for energy purposes. In the future, stump harvesting may also be used to further increase the supply of biomass feedstocks. However, national supply of biomass sources is limited. Increased demand for biomass sources for energy purposes has created sectorial competition over the biomass sources available. Pulpwood traditionally only bought by pulp and paper industries is now also to some extent being acquired for energy purposes (Routa et al., 2013). Recent years developments have also shown that demand from the bioenergy sector influences the management and harvest of biomass sources (Bisaillon et al., 2008). Harvesting operations, for example, have been noted to increase the minimum diameter for pulpwood, resulting in a larger crown and increased production of woody chips for bioenergy production (Räisänen and Nurmi, 2011). However, little is known about the optimal management of biomass sources for jointly developing the bioenergy sector and forest industries.

In Sweden, a high proportion of the biomass and biofuels consumed by the bioenergy sector comes from the forestry sector. In 2007, the agricultural sector only supplied 1% of the biomass and biofuels consumed by the bioenergy sector (Regeringskansliet, 2007). However, as short rotation crops grown on agricultural land makes it possible to produce high amount of biomass feedstocks for the bioenergy sector and as agricultural land is being freed up for other purposes, it is important to jointly consider the forest and agricultural sector. Furthermore, adapting the forest harvesting level to the development of the bioenergy sector may strongly impact the latter as the supply of woody biomass is highly dependent on the forest harvesting level and as the development of the bioenergy sector is highly dependent on the supply of biomass sources. However, in the previously described studies of the future development of the bioenergy sector in Sweden (Börjesson and Ahlgren, 2010; Energimyndigheten, 2011; RES2020, 2009), supplies of woody biomass sources were all exogenously defined in line with a predefined fixed forest harvesting level. Thus, the link and interconnections between the bioenergy sector and the forest harvesting level was not evaluated in these studies. Studies based on modelling frameworks that explicitly link the two sectors have earlier been performed at the global (Havlík et al., 2015; Kraxner et al., 2013; Lauri et al., 2017; Lauri et al., 2013; Popp et al., 2017) and EU aggregated level (Capros et al., 2016; Forsell et al., 2016), but not specifically for Sweden.

The aim of this study is to introduce an approach for incorporating decisions concerning forest management and forest harvest levels within the framework of a TIMES energy system model. The approach taken explicitly incorporates changes in forest management by endogenously considering a set of long-term applicable forest harvest levels and agricultural supply of biomass feedstocks within the energy system model, allowing the model to endogenously define the optimal harvest level. Thereby, the model makes it possible to examine the interaction and link between the bioenergy sector, forest industries, and harvest of forest and agricultural biomass sources. To evaluate the proposed method, we perform an explorative study of the optimal forest harvest level for developing the bioenergy sector and forest industries. In particular, we estimate how increased growth of the two sectors may influence the forest harvest level, as well as future changes in which biomass sources are used by the different industries.
2. Methodology

2.1. TIMES models

Computer-based energy system models are useful tools for representing and to gain crucial insights into the complex dependencies in an energy system. In this study a TIMES (The Integrated MARKAL-Efom System) (Gargiulo, 2009; Kanudia et al., 2005; Kanudia and Loulou, 1999) type model was used to study and analyze the development of a segment of the Swedish energy system. The framework of the TIMES models is developed and being maintained by the international ETSAP (Energy Technology System Analysis Programme) organization, under an implementation agreement with the International Energy Agency (IEA). The model is based on a demand-driven partial-equilibrium setting and expressed based on a linear programming approach. The framework assumes development of the energy system according to a perfect foresight, deterministic future development, non-competitive, and minimal total system cost (or maximal consumer and producer surplus if elastic end-use demands) setting. The energy system is represented over a short-, medium-, or long-term planning horizon, divided into multiple planning periods of variable length, during which the development of the energy system can be analyzed. The model is driven by the end-use demand of some commodities and is based on a technology-rich bottom-up approach in which typically a large number of technologies can supply the different demands. For a full detailed description of the mathematical formulation of the TIMES energy model we refer to Annex I and Loulou et al. (2016). For a range of applications of TIMES and the earlier MARKAL models, we refer to Blesl et al. (2007), Börjesson and Ahlgren (2010), Remme et al. (2008), RES2020 (2009), and Wright et al. (2010).

2.2. TIMES bioenergy model

In the present study, an Optimization of Forest Resources (OFR) model based on the TIMES framework was used for analyzing the link between the development of the bioenergy and forest industrial sectors, and the national forest harvesting level. Note that development of the two sectors is predefined in terms of end-use demands which are based on exogenous data sources. However, the model represents the whole production chain from harvesting of biomass sources to the end-use of commodities and it is the model that estimates the development of aspects such as: harvest of biomass sources, flow of commodities, investments, and use of conversion technologies. As the rotation age of trees in Sweden is relatively long (commonly 90 years), the development of the energy system was studied until 2100 so that long-term sustainable forest harvest scenarios could be considered. The planning horizon was divided into planning periods of variable length (1-5 years), with shorter planning periods at the beginning of the planning horizon and longer planning periods at the end. After 2040, only 5-year planning periods were used.

As both agricultural and forestry biomass sources may be used for bioenergy production, the OFR model considers a diverse set of biomass feedstocks such as: woody lignocellulosic plants (e.g. poplar, willow), herbaceous lignocellulosic plants (e.g. miscanthus, switch grass), oil crops (e.g. rapeseed), sugar crops (e.g. sugar beet), starch crops (e.g. wheat), agricultural residues, forestry residues (e.g. branches, tree tops), pulpwood, timber, and refined woody products (e.g. briquettes, pellets). To account for the sometimes high variance in harvest, cost, and supply of forestry biomass sources between regions, Sweden was divided into four regions (North, Mid, Central, and South Sweden) for which the harvest, potential supply, and cost of forestry biomass sources was expressed. As end-use demand of the bioenergy and forest industrial sectors is more evenly distributed over Sweden in comparison to supply of biomass sources, we selected to focus on representing regional differences on the supply side of forestry biomass sources. Supply and cost of forestry biomass sources was expressed for each region, while supply of agricultural biomass sources and end-use demand was expressed on an aggregated national level (see Figure 1). Thus, forestry biomass sources were harvested on a regional level, and then through a series of steps transported and converted to fulfill end-use demand on an aggregated national level.

In Sweden, forest industries are along with district heating plants both high users of biomass sources and large producers of bioenergy. The majority of the bioenergy produced by sawmills and pulp mills is used for driving internal processes while excess heat is commonly sold to the district heating network. The majority of the bioenergy produced by sawmills and pulp mills is produced
Figure 1. Regions of Sweden used to specify harvest, supply, and cost of forestry biomass sources. The regions are denoted as North (1), Mid (2), Central (3), and South (4) Sweden.

from woody by-products (e.g. black liquor, saw-dust, wood chips). However, the plants do not use all of the woody by-products produced internally, and a large quantity of woody by-products is also sold to district heating plants for bioenergy production. By considering the different sectors together, the flow of commodities and the different methods of bioenergy production could be jointly represented within the OFR model (see Figure 2 for an overview).

2.3. Feedstock availability

Since the bioenergy sector may use biomass sources traditionally used for producing food, feed, and woody products, the development of this sector may induce competition for the available biomass sources. To avoid reduction in food and wood supply, restrictions concerning the sustainable use of biomass sources for bioenergy production were considered. For forest biomass sources it was assumed that the forest harvest could not increase to a level that would decrease the amount of standing forest in the long term. While the forest harvest level was endogenously computed by the model, only long-term sustainable harvest levels were considered. For the availability of agricultural biomass sources it was assumed that only freed-up agricultural land is available for growing crops dedicated to bioenergy production. Thus, only agricultural biomass sources that do not compromise food and feed production are considered for bioenergy production. While in the future structural changes in food and feed consumption, production, and increased international trade may lead to additional land being freed up from growing crops for conventional food and feed purposes, these types of changes are outside the scope of this assessment.

A key exogenous assumption for the OFR model is thus that Sweden will maintain its current production level of food and feed products. Furthermore, exports of agricultural and forestry biomass sources as well as intermediate commodities (e.g. pulpwood, wood chips, pulp, timber) were defined according to current levels and assumed to always having to be fulfilled. Imports of biomass sources and woody by-products were also defined according to current levels, but assumed to be able to increase to fulfill national demand. However, as the main aim of the model is to analyze the optimal national forest harvest level, the cost of increased imports was set to be higher than domestic biomass prices. Import prices were thus exogenously set so that domestic biomass sources would always be used before increased import levels.
2.3.1. Agricultural biomass sources

The potential land available for growing energy crops is considered as arable land and permanent grassland not used for producing food and animal feed. Improved productivity of food crops and technological progress have led to a decrease in the average European use of agricultural land for food and animal feed production (Ewert et al., 2005; Rounsevell et al., 2005). This trend has also been noted in Sweden during the last decade, where the number of small scale farms are decreasing and agricultural land is being abandoned (Johnsson, 2006). However, the debate concerning the implications and consequences of large-scale global use of agricultural land for bioenergy purposes is still ongoing (Ajanovic, 2011; Banse et al., 2008; Helbling et al., 2008; Mitchell, 2008; Mueller et al., 2011; Valin et al., 2015), and new political measures may quickly change the scene. To evaluate the influence of the assumption concerning availability of agricultural land for growing energy crops, a number of scenarios concerning land availability were constructed and assessed (see Section 2.6.2).

The baseline potential of agricultural crops and agricultural waste for energy purposes was defined according to data compiled in the REFUEL and RES2020 projects (REFUEL, 2008; RES2020, 2009), and specified on an aggregated national level in terms of oil crops (Rapeseed, Sunflower, Soy bean, Palm oil, and Jatropha), sugar crops (Sugar beet), starch crops (Maize, Wheat, and Triticale), wood crops (Eucalyptus, Poplar, Willow, and Locust trees), grass crops (Switch grass, Miscanthus, and Reed canary grass), agricultural waste, peat, and urban residues. Note that these studies are based on the assumptions of a constant self-reliance level of agricultural products on a European (EU27) scale and that only freed-up agricultural land was available for growing crops dedicated to bioenergy production. Although the methodology used in the REFUEL and RES2020 project to evaluate biomass potentials was developed to give consistent biomass evaluations between the EU27 countries, estimations were found to be consistent with national sources. Data on production costs of agricultural crops were gathered from an extensive literature review of the current costs of energy crops, and assumed to be fixed over the planning horizon (see Table 1).

2.3.2. Forestry biomass sources

The following woody biomass commodities were considered within the model: forest residues, pulpwood, timber, firewood, sawdust, wood chips, bark, black liquor, and refined woody products. As forest residues, pulpwood, and timber result from forest harvests, the availability of these woody biomass sources depended on the endogenously computed forest harvest level. Availability of these woody biomass sources was individually defined for each of Sweden’s four regions to reflect differences
in the supply of biomass sources. On the other hand, the availability of refined woody products and woody by-products (e.g. wood chips, sawdust, bark, black liquor) depends on the production level of the different industries. Production of woody by-products was expressed on an aggregated national level. As firewood is mainly acquired from private forests in Sweden, the cost was fixed at zero and the availability of firewood was assumed to be fixed over the planning horizon and to be independent of the endogenously computed harvest level.

The bioenergy and forest industrial sectors were considered as competing for the available feedstock. However, there are significant variations in different industries’ choice and use of biomass sources. While district heating plants may rely on a variety of biomass sources (e.g. sawdust, bark, forest residues, pulpwood), sawmills only use timber to produce sawn wood. For example, all of the black liquor produced by a modern pulp mill is burned in recovery boilers to regenerate chemicals and produce heat and electricity, and sawmills commonly sell a portion of the wood chips they produce to district heating plants.

In the model, the production chain from resources to end-use products along with the associated flow of by-products was represented according to the current major flow of commodities as well as future development possibilities. Thus, changes in the flow as well as the proportional distribution of commodities were considered in the model. See Figure 3 for a simplified overview of the current flow of commodities between the different forestry industries. Note that the woody biomass resources in the model are also considered as available for biofuel production.

The production levels and transport costs of woody biomass sources were ascertained from an extensive literature review and assumed to be fixed over the planning horizon. The cost of forest residues was defined according to Athanassiadis et al. (2009) and it was assumed that the distribution of the volume on cost follows cost-supply curves that were aggregated to 10 steps per region. Thus, the supply of forest residues in each region is divided into ten cost classes, each containing one tenth of the total forest residue volume.

Table 1. Overview of the modeled potential and conversions of the biomass sources.

| Potential Conversion possibilities | Harvest cost | Generation of bio- | Bio- | FT | HVO |
|----------------------------------|--------------|-------------------|------|----|-----|
|                                 | (GTon DS)    | conversion technology | diesel |     |     |
|                                 | (2010 - 2000) | 139 | 139 | 139 | 139 |
|                                 | 2010 | 2000 | 2010 | 2000 | 2010 | 2000 | 2010 | 2000 | 2010 | 2000 |
|                                | 1st | Bio- |     |     |     |     |     |     |     |     |
|                                | 2nd | Bio- |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |
|                                |     |     |     |     |     |     |     |     |     |     |

2.3.3. Forestry harvesting trajectories

To account for possible changes in forest management due to competition and changes in demand of biomass sources, the OFR model endogenously computes the annual harvest level of forestry biomass sources from a set of exogenously developed forest harvest trajectories. This endogenously computed harvest level will here be referred to as the OFR harvest level. A harvest trajectory specifies the annual availabilities of pulpwood, timber, and forestry residues for each region and

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ii) 1st generation biofuels refer to fuels derived from food crops, such as grains, sugar beet and oil seeds. They are relatively easy to manufacture, and thus the main type of biofuels produced today. 2nd generation, or advanced, biofuels are produced from non-food biomass such as ligno-cellulosic materials or biogenic waste.
As the forest harvest level during one time period directly influences the possible harvest level during later periods, each harvest trajectory is a specification of annual harvest levels during the whole planning horizon. The OFR model computes which linear combination of the set of harvest trajectories is the most beneficial, or optimal, for developing the bioenergy and forest industrial sectors. Note that as each harvest trajectory is a specification over the entire planning horizon, the linear combination of harvest trajectories is the same for each planning period in order to keep the annual harvest levels within a long-term sustainable and feasible level. All linear combinations of the harvest trajectories are applicable and feasible as each region can be further divided into smaller management units, each managed according to different harvest trajectories. Furthermore, as there are no links between regions, the linear combination of trajectories can be different in the different regions.

The harvest trajectories are developed with the Markov forest model developed by Sallnäs (1990). In the core of the model formulation, the states of the Markov model defines the area of the forest as within a specific age- and volume-class, and the transition probabilities expresses the potential transition of area between states as a result of different natural processes and management regimes. In this approach, the country is stratified according to region, ownership type, site index, and forest species. For each strata, an individual Markov chain model is computed by: first, determining the optimal forest management action for each state of the forest; second, allocating each state’s forest land to the optimal action, registering the ensuing volumes and sum over all states; and, third, projecting the state of the forest for one 5-year period with the transition probabilities of the Markov forest model. This procedure is repeated until the end of the planning horizon is reached (for further details we refer to Eriksson et al. (2007)). Optimality corresponds to the maximum net present value under an infinite horizon. The value of a trajectory is subsequently the net present value of that trajectory. The initial state of the forest is based on a classification of sample plots from the National Forest Inventory from 1996, 1997, and 1998 corresponding to 21.0 million hectares, i.e. all productive forests in Sweden excluding reserve areas and forests with modified management amounting to about 1.5 million hectares (Skogsstyrelsen, 2010). Prices for resources for harvesting and silviculture refer to year 2007 (for further details we refer to Eriksson et al. (2007)).

A total of 8 trajectories were developed for each region by varying the timber price level and discount rate (see Table 2). Each trajectory was calculated assuming harvest flow constraints and sustainable forest management constraints not allowing for a depletion of the forest stock. The aim was to produce a set of trajectories that distinctly showed different harvest profiles over time. Among the trajectories created, one was named business as usual (BAU) as it was the one that, in terms of the profile over time, represented a continuation of the current trend regarding forest harvesting (Claesson et al., 2008). The BAU trajectory was developed using prices for timber and
pulpwood of year 2007 and an annual discount rate of 2%. The projection should cover a 90 year period beginning in 2010, assuming that the state of the forest in 2010 would stay about the same as at the end of the 1990’s. The trajectories were computed for each region separately, meaning that the model had a total of 32 trajectories to combine, whereas Table 2 shows the sum over the 4 regions for each set of timber prices and discount rate. It can be noted that while the harvest levels of the different trajectories vary over the time periods, all harvest trajectories result in almost the same volume of standing timber at the end of the planning horizon even though this requirement was not explicitly imposed.

Table 2. The sum over the 4 regions of annually harvested volume in million m$^3$ standing volume (trunk volume above stump) for each trajectory. The first 10 year period is fixed and with the harvest level set to the same value as BAU for all trajectories.

| Trajectory | Periods | 2000- | 2010- | 2020- | 2030- | 2040- | 2050- | 2060- | 2070- | 2080- | 2090- | 2100 |
|------------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| BAU        |         | 73.98 | 73.98 | 75.80 | 80.10 | 77.52 | 80.72 | 82.57 | 90.57 | 91.20 | 94.21 |
| Trajectory 1|         | 73.98 | 41.52 | 51.53 | 60.91 | 75.99 | 86.01 | 95.39 | 105.99| 111.82| 112.47|
| Trajectory 2|         | 73.98 | 60.29 | 59.29 | 65.93 | 73.48 | 77.90 | 83.35 | 97.62 | 106.82| 111.49|
| Trajectory 3|         | 73.98 | 97.22 | 81.15 | 74.15 | 67.94 | 76.43 | 78.96 | 87.93 | 86.98 | 90.72 |
| Trajectory 4|         | 73.98 | 97.22 | 93.11 | 70.95 | 71.37 | 76.29 | 80.51 | 90.03 | 89.56 | 91.46 |
| Trajectory 5|         | 73.98 | 97.22 | 93.11 | 70.95 | 71.37 | 76.29 | 80.51 | 90.03 | 89.56 | 91.46 |
| Trajectory 6|         | 73.98 | 97.22 | 93.11 | 70.95 | 71.37 | 76.29 | 80.51 | 90.03 | 89.56 | 91.46 |
| Trajectory 7|         | 73.98 | 97.22 | 93.11 | 70.95 | 71.37 | 76.29 | 80.51 | 90.03 | 89.56 | 91.46 |

2.4. Conversion technologies

As the OFR model jointly considers the bioenergy and forest industrial sectors it contains a high number of technologies representing conversion technologies, specific processes, factories, and the transport of biomass sources. Since the OFR model’s planning horizon is up to 2100, existing and developing conversion technologies were considered. A start year was used to specify when developing conversion technologies would become commercially available, and technological developments were defined in terms of changes in fuel efficiency and production costs (e.g. capacity, investment costs, variable and fixed operational & management (O&M) costs). Although technological learning and subsequent cost reductions over time are dependent on demand-driven market dynamics, technological learning was exogenously defined as independent from market developments.

For biofuel production, 1$^{st}$ and 2$^{nd}$ generation conversion technologies were considered, including two general types of 2$^{nd}$ generation biofuel conversion technologies: a Fischer-Tropsch diesel (FT) process and a lignocellulosic bioethanol (LE) process (see Table 3). For a detailed description of the techno-economic parameters and price of by-products, we refer to Lorne et al. (2010), Millet (2010), and Nguyen The et al. (2010). The importance of considering by-products of biofuel production in techno-economic models has been recognized in several analyses (Babcock, 2008; Tyner and Taheripour, 2008), and was taken into account in the proposed OFR model. The prices of the different by-products were set in line with current prices and assumed to be fixed over the planning horizon. By-products taken into account in the model were: glycerin, brewer’s spent grain, press cake, propane, naphtha, carbon dioxide, wine products, and electricity.

As forest industries are both large producers and consumers of bioenergy, they were considered in the OFR model on a highly detailed level. In all, four general types of industries were included in the model: sawmills, pulp & paper factories, board & panel factories, refined woody products factories. For the production of pulp, the production share of chemical, mechanical, and half chemical-mechanical pulp was set according to current levels, and assumed to be fixed over the planning horizon. Data concerning the production costs, efficiency, and conversion rates of the different industries were gathered from an extensive literature review (Commission, 2001; Djemaa, 2009; Ekbom et al., 2005; Ekbom et al., 2003; Skogsindustrierna, 2010; Skogsstyrelsen, 2010). See Table 4 for an overview.
Table 3. Techno-economic overview of the 1st and 2nd generation biofuel conversion technologies employed.

| Technology                         | Capacity (ton input/year) | Fuel efficiency (ton input/ton output) | Fixed O&M cost (ton input) | Variable O&M cost (ton output) | Investment cost (ton input) |
|-----------------------------------|---------------------------|----------------------------------------|--------------------------|--------------------------------|----------------------------|
| Hydrotreated vegetable oils       | 500,000                   | 40.00%                                 | 58                       | 750                            | 115                        |
| Transesterification of vegetable oils | 123,584               | 97.09%                                 | 33                       | 575                            | 56.6                       |
| Advanced transesterification of vegetable oils | 119,800               | 100.00%                                | 62                       | 598                            | 132.5                      |
| Bio-ethanol from sugar crops      | 460,000                   | 34.00%                                 | 101                      | 516                            | 239                        |
| Bio-ethanol from starch crops     | 460,000                   | 34.35%                                 | 202                      | 605                            | 659                        |
| HVO production from vegetable oils | 736,555                  | 21.42%                                 | 436                      | 452                            | 1,128                      |
| Ethanol from lignocellulose       | 170,000                   | 86.30%                                 | 112                      | 741                            | 256                        |
| Fischer-Tropsch from lignocellulose | 912,000              | 15.22%                                 | 1,195                    | 605                            | 3,319                      |

2.5. Demand of bioenergy and woody products

As the OFR model jointly considers the contribution of forestry and agricultural biomass sources to the bioenergy and forest industrial sectors, end-use demand can be divided into two categories: bioenergy and woody products. Demand for bioenergy was defined in terms of demand of heating, electricity, and biofuels, while demand of woody products was defined in terms of board and panels, sawn wood, paper, export timber, export pulpwood, and export pulp. End-use demand of the different commodities evolves individually over the planning horizon. To differentiate further between the types of end-use demands and to pinpoint differences in market shares of specific products, some of the demands were further separated into sub-demands. Heating demand was divided into three demands corresponding to demand for process, district, and direct heating. Demand for electricity was divided into one industrial electricity demand and one overall electricity network demand. The industrial electricity demand corresponds to electricity produced and consumed by industries, while the electricity network demand corresponds to electricity produced by district heating plants and sold to the network. Demand for biofuels was divided into one demand for bioethanol and one

Table 4. Techno-economic overview of the forest industries.

| Technology               | Fuel efficiency (ton input/ton output) | Fixed O&M cost (ton input) | Variable O&M cost (ton output) | Investment cost (ton input) | Lifetime (years) |
|--------------------------|----------------------------------------|---------------------------|--------------------------------|------------------------------|-----------------|
| Sawmill                  | 100%                                    | 10                        | 10                             | 300                          | 30              |
| Chipping                 | 100%                                    | 0.71                      | 2.38                           | 3.01                         | 12              |
| Mechanical pulping       | 95%                                     | 15                        | 10                             | 500                          | 30              |
| Half chemical-mechanical pulp | 90%                                      | 35                        | 28                             | 1,007                        | 30              |
| Chemical pulping         | 50%                                     | 15                        | 10                             | 1,560                        | 30              |
| Briquettes & Pellets     | 99%                                     | 3.58                      | 34.76                          | 122.41                       | 30              |
demand for biodiesel. Note that end-use demand of bioenergy is defined in terms of demand for the Swedish market, while end-use demand for woody products is expressed both in terms of domestic and export markets. Demand for timber, pulpwood, and pulp is expressed in terms of export, while demand for board and panels, sawn wood, and paper is expressed in terms of production for domestic and export markets.

2.6. Sensitivity analysis

To evaluate the sensitivity of the optimal forest harvesting level computed by the OFR model as well as the development of the Swedish bioenergy system in line with key parameters, a number of scenarios were developed. With these scenarios, a sensitivity analysis of the modeled results could be performed based on changes to the main economical, technical, and resource-based assumptions. The scenarios constructed represent a selection of relevant variations in parameters in which future levels are uncertain. The scenarios were created based on variations of the development of four key aspects: demand for bioenergy, demand for woody products, agricultural biomass source potential, and the cost of agricultural biomass sources. A total of 10 scenarios were created from the different assumptions, each deviating from the reference REF scenario (see Table 5).

Table 5. Overview of the scenarios created for performing a sensitivity analysis.

| Scenarios | Demand for bioenergy | Demand for woody products | Potential of agricultural biomass sources | Cost of agricultural biomass sources |
|-----------|----------------------|---------------------------|------------------------------------------|-------------------------------------|
|           | BE1 | BE2 | BE3 | WP1 | WP2 | WP3 | MED | HI | LO | NO | MED | HI | LO |
| REF       | X   | X   | X   | X   |     |     |     |     |     | X  | X   |     | X   |
| DB_H      | X   | X   | X   | X   |     |     |     |     | X   | X  | X   |     | X   |
| DB_L      |     | X   | X   | X   |     |     |     |     |     | X  | X   |     | X   |
| DW_H      | X   | X   |     | X   |     |     |     | X   |     | X  | X   |     | X   |
| DW_L      |     | X   |     | X   |     |     |     |     | X   | X  | X   |     | X   |
| Pot_H     | X   |     |     |     | X   |     |     |     |     |     | X   |     |     |
| Pot_L     |     | X   |     |     |     | X   |     |     |     |     |     | X   |     |
| Pot_N     |     |     |     | X   |     |     |     |     |     |     |     |     | X   |
| Pri_H     | X   |     |     |     |     |     |     |     | X   |     |     |     | X   |
| Pri_L     |     | X   |     |     |     |     |     |     |     |     |     |     | X   |

2.6.1. Demand scenarios

To explore the bandwidth within which end-use demands for bioenergy may evolve, three bioenergy demand cases and three woody product demand cases were developed (see Figures 4 and 5). The bioenergy demand cases were developed based on the 2010 long-term energy projection made by the Swedish Energy Agency (SEA) (Energimyndigheten, 2011). The SEA long-term forecast projects the development of end-use energy demand up to 2030 according to projections of techno-economic drivers. Three projections of the Swedish energy system have been developed by SEA, reflecting a bandwidth within which the energy system may evolve. The three projections developed by SEA specify how the energy system may evolve up to 2030, and have been used to formulate three demand scenarios for the bioenergy sector up to 2100. Note that as main explorative scope of the study is on the forest strategies, only a simplified set of demand scenarios were created. After 2030, each individual demand continues to grow in a linear fashion according to the average growth rate between 2020 and 2030. The demand cases were defined as follows:

- **BE1**: Case based on the SEA “business as usual” projection.
- **BE2**: Case based on the SEA “high economic growth” projection.
- **BE3**: Case based on the SEA “high fuel prices” projection.

The demand cases for woody products were developed based on historical data on the development of demand for woody products (Energimyndigheten, 2010; Skogsstyrelsens, 2010). Three cases were developed to reflect a bandwidth within which the end-use demands of woody products may evolve due to changes in both domestic and external growth. The demand cases were defined as follows:
• **WP1:** Case assumes moderate growth in demand of woody products.
• **WP2:** Case assumes rapid growth in demand of woody products.
• **WP3:** Case assumes limited growth in demand of woody products.

2.6.2. Supply and cost scenarios

To explore the impact of assumptions and parameters concerning the potential and cost of biomass sources, six cases were developed under different assumptions. Along with a reference case, three cases were developed concerning the amount of freed-up agricultural land, and two cases concerning the cost of acquiring agricultural crops for energy purposes. Note that as the potential of forest biomass sources is endogenously computed, the cases only impact the price and cost of agricultural biomass sources. The cases were defined as follows:

• **MED:** Reference case created in accordance with assumptions described in Section 2.3 concerning the potential and cost of agricultural biomass sources.

• **HI potential:** Case assumes a rapid development of agricultural production coupled with technological developments thus lowering the amount of land required for food and feed production. In all, 30% more agricultural land is freed up for growing energy crops than in MED.

• **LO potential:** Case assumes increased domestic and global demand for agricultural crops that drives up the amount of land required for food and feed production. 30% less agricultural land is freed up for growing energy crops than in MED.

• **NO potential:** Case assumes that due to a combination of general unwillingness to grow energy crops and increased domestic and global demand for agricultural crops, no further agricultural land is freed up for growing energy crops after 2010.

• **HI cost:** Case assumes high increments in farm expenses, processing, and distribution costs that drive up the cost of growing agricultural crops. Cost of acquiring agricultural biomass sources for energy purposes is 30% higher than in MED.
LO cost: Case assumes that technological developments and subsidies help to bring down the cost of growing agricultural crops, such that the cost of acquiring agricultural biomass sources for energy purposes is 30% lower than in MED.

3. Results

3.1. National forest harvesting level

Overall, the reference REF forest harvesting level endogenously computed by the OFR model was found to be relatively similar to that of the predefined BAU harvest trajectory (see Table 6). In other words, for the REF scenario, the OFR model selected a linear combination of the harvest projections that resembled the BAU harvest trajectory. The harvesting level for the REF scenario was at most 14% higher than the BAU harvesting level, which is minor in comparison to the possible span of harvesting levels given by the exogenously defined harvest trajectories (see Table 2). Given that the REF scenario assumes a fairly stable increase in demand of bioenergy and woody products, it is understandable that the OFR model endogenously selects a harvest level that provides a relatively stable supply of woody biomass over time (e.g. trajectory 5, 6, and BAU in Table 2) instead of a scenario with a high harvest level during a specific time period but with low harvest levels during other time periods (e.g. trajectory 2 and 7 in Table 2). In comparison to the BAU harvest trajectory, the harvesting level for the REF scenario resulted in a higher level of harvest from 2010 until 2029. High harvest levels during earlier periods thereafter forced the REF harvest level to descend below that of the BAU from 2030 until 2059, after which it remained relatively similar to that of the BAU harvest trajectory. Thus, the OFR model selected for the REF scenario a harvesting level that in comparison to the BAU harvest trajectory would supply a higher level of biomass resources for the bioenergy sector from 2010 until 2029 to support the growth of the bioenergy sector. After 2030, the supply of biomass from freed up agricultural land has in the REF scenario augmented to such a level that the use of forestry biomass resources for energy purposes could be decreased without creating supply shortages. Inter-regional variations in the REF harvesting level were also observed. While the REF and BAU harvesting levels were the same for the North (1) and Mid (2) regions of Sweden, a noticeable difference was observed the Central (3) and South (4) regions of Sweden.
Table 6. The REF forest harvesting level endogenously computed by the OFR model in comparison to predefined BAU harvest trajectory. Harvest of forestry biomass is expressed in terms of harvest volume year\(^{-1}\) in million m\(^3\) standing volume. Harvest is expressed per region and the national harvest level is the sum over the 4 regions of Sweden.

| Geographical level | Trajectory | Periods       |
|--------------------|------------|---------------|
|                    | 2000-      | 2010-         |
|                    | 2010-      | 2020-         |
|                    | 2020-      | 2030-         |
|                    | 2030-      | 2040-         |
|                    | 2040-      | 2050-         |
|                    | 2050-      | 2060-         |
|                    | 2060-      | 2070-         |
|                    | 2070-      | 2080-         |
|                    | 2080-      | 2090-         |
| Region 1 - North   | REF        | 6.18          |
|                    |            | 6.18          |
|                    |            | 17.08         |
|                    |            | 17.08         |
|                    |            | 16.77         |
|                    |            | 16.77         |
|                    |            | 16.30         |
|                    |            | 16.30         |
|                    |            | 17.72         |
|                    |            | 17.22         |
|                    |            | 17.04         |
|                    |            | 21.61         |
|                    |            | 18.95         |
|                    |            | 19.38         |
| North BAU          | 6.18       | 6.18          |
|                    | 17.08      | 17.08         |
|                    | 16.77      | 16.77         |
|                    | 16.30      | 16.30         |
|                    | 17.72      | 17.22         |
|                    | 17.04      | 17.04         |
|                    | 21.61      | 21.61         |
|                    | 18.95      | 18.95         |
|                    | 19.38      | 19.38         |
| Region 2 - Mid     | REF        | 18.27         |
|                    |            | 18.27         |
|                    |            | 18.17         |
|                    |            | 19.93         |
|                    |            | 19.35         |
|                    |            | 19.99         |
|                    |            | 21.00         |
|                    |            | 22.26         |
|                    |            | 23.33         |
|                    |            | 23.70         |
| Mid BAU            | 18.27      | 18.27         |
|                    | 18.17      | 19.93         |
|                    | 19.35      | 19.99         |
|                    | 21.00      | 22.26         |
|                    | 23.33      | 23.70         |
| Region 3 - Central | REF        | 30.20         |
|                    |            | 30.87         |
|                    |            | 27.77         |
|                    |            | 21.45         |
|                    |            | 20.88         |
|                    |            | 22.81         |
|                    |            | 24.17         |
|                    |            | 26.01         |
|                    |            | 27.15         |
|                    |            | 28.16         |
| Central BAU        | 30.20      | 30.20         |
|                    | 30.87      | 27.77         |
|                    | 27.77      | 21.45         |
|                    | 20.88      | 22.81         |
|                    | 24.17      | 26.01         |
|                    | 27.15      | 28.16         |
| Region 4 - South   | REF        | 19.34         |
|                    |            | 20.04         |
|                    |            | 23.47         |
|                    |            | 17.67         |
|                    |            | 17.30         |
|                    |            | 18.14         |
|                    |            | 18.90         |
|                    |            | 20.80         |
|                    |            | 21.11         |
|                    |            | 21.56         |
| South BAU          | 19.34      | 19.34         |
|                    | 19.34      | 18.16         |
|                    | 19.56      | 19.15         |
|                    | 19.73      | 19.73         |
|                    | 20.97      | 20.97         |
|                    | 21.40      | 21.40         |
| National REF       | 73.98      | 75.35         |
|                    | 86.48      | 75.82         |
|                    | 73.83      | 75.82         |
|                    | 81.12      | 81.12         |
|                    | 90.67      | 90.67         |
|                    | 90.54      | 90.54         |
|                    | 92.82      | 92.82         |
| National BAU       | 73.98      | 73.98         |
|                    | 75.80      | 80.10         |
|                    | 77.52      | 80.72         |
|                    | 82.57      | 90.57         |
|                    | 91.20      | 91.20         |
|                    | 94.21      | 94.21         |

The REF forest harvesting level showed a surprisingly robust reaction to changes in key variables represented by the sensitivity scenarios. Sensitivity analysis based on the scenarios developed showed that the REF forest harvesting level was stable in the face of the considered changes in demand of bioenergy, demand of woody products, supply of agricultural biomass sources, and cost of agricultural biomass sources. The harvesting level was indeed found to be same for scenarios: REF, DB\_H, DB\_L, Pri\_H, Pri\_L, Pot\_H, Pot\_L, and Pot\_N. The harvest level was found to be slightly influenced by the demand for woody products (see Table 7). However, the harvesting levels for scenarios DW\_L and DW\_H were more similar to the REF harvesting level than the BAU harvesting trajectory. It was noted that, as the demand for woody products increases from a moderate to a high level, the forest harvest level increased during the peak period 2020–2029. On the other hand, as the demand for woody products decreased from a moderate to a low level, the forest harvest level decreased during the peak period 2020–2029.

Table 7. Harvest level endogenously computed by the OFR model for the REF, DW\_H, DW\_L scenarios. BAU is the predefined business as usual forest harvest trajectory. Harvest of forestry biomass is expressed in terms of harvest volume year\(^{-1}\) in million forest m\(^3\). Harvest is expressed on a national level as the sum over the 4 regions of Sweden.

| Trajectory | Periods       |
|------------|---------------|
|            | 2000-         |
|            | 2010-         |
|            | 2020-         |
|            | 2030-         |
|            | 2040-         |
|            | 2050-         |
|            | 2060-         |
|            | 2070-         |
|            | 2080-         |
|            | 2090-         |
| ORF - REF  | 73.98         |
| ORF - DW\_H| 73.98        |
| ORF - DW\_L| 73.98        |
| BAU        | 73.98         |

3.2. Use of forestry biomass sources

Although the harvest of forestry biomass sources was found to be relatively stable over time, there were significant changes in the biomass source used for bioenergy production over time. As the amount of freed-up agricultural land for growing energy crops increased over time, it was observed that the district heating sector switched from being highly reliant on forestry biomass sources to a high reliance of the less expensive agricultural biomass sources. While bioenergy production by sawmills and pulp and paper industries continued to be based on woody by-products from their own
production, in the scenario the district heating sector started to rely on a high share of agricultural biomass sources from 2020 (see Figure 6). The underlying reason for this is that from 2020, the amount of freed-up agricultural land has become high enough to fulfill biofuel demand as well as to substitute portions of the pulpwod acquired by district heating plants. While the amount of forestry residues available for energy production also increases over time due to a higher forest harvest level, there were not enough forestry residues available to alone fulfill demand by district heating plants. As the use of pulpwod decreased, the use of agricultural biomass sources increased. Thus, large amounts of woody crops were estimated to be grown on freed-up agricultural land after 2020 to support the increasing demand for biomass sources within the energy sector.

Figure 6. Overview of biomass sources used by the district heating sector for heat and electricity production in the REF scenario. Use of biomass sources is expressed in terms of millions of tons of dry biomass per year.

In terms of the use of pulpwod for bioenergy production, it was observed that, in the REF scenario pulpwod will continue to be used for bioenergy purposes until 2055. On the other hand, timber was not used for bioenergy purposes in any scenario. Pulpwod is currently used to a small extent for bioenergy purposes in Sweden, and in the REF scenario the use for bioenergy purposes was found to increase from its current level until 2030. We observed that significantly higher levels of pulpwod were used for bioenergy purposes in 2030 than is currently the case. After a peak in 2030, the use for bioenergy purposes was observed to decrease until none was used for energy purposes by 2055. However, the use for energy purposes was found to vary significantly between the different scenarios. See Figure 7 for an overview of results. In a number of scenarios (REF, DB_H, DB_L, DW_H, DW_L, Pri_L, Pot_H), the use of pulpwod for energy purposes increased from its current level to peak in 2030 or 2040, thereafter gradually decreasing until no pulpwod was used for energy purposes. However, in scenarios Pri_H and Pot_N the use of pulpwod for energy purposes was observed to continue increasing over time, resulting in very high levels being used for energy purposes from 2050 up to 2100. In conclusion, if agricultural land continues to be freed up for growing energy crops and the cost of growing energy crops is not high, the pulpwod quantity used for bioenergy purposes will decrease. However, if agricultural land is not freed up for growing energy crops, farmers prove unwilling to grow energy crops, or the cost of energy crops is high, then the use of pulpwod for energy purposes may continue to increase in the medium and long term.

On the other hand, there was continued, high use of forestry residues for bioenergy purposes throughout the planning horizon, mainly due to its low harvesting cost. In all but the Pri_L scenario,
all available forestry residues were harvested and used for bioenergy purposes during all time periods. Thus, the harvest of forestry residues for energy purposes will only decrease if the cost of agricultural biomass sources remains low. Furthermore, even after pulpwood has been substituted by agricultural biomass sources for bioenergy production, there will still be a high demand for forestry residues for bioenergy production. This shows the importance of forestry residues in the Swedish bioenergy sector, and the likelihood that high demand for forestry residues will continue in the future.

![Figure 7. Overview of the use of pulpwood for bioenergy purposes (heat, electricity, biofuels) for the different scenarios. Use of pulpwood is expressed in terms of millions of tons of dry biomass per year.](image)

3.3. Domestic bioenergy production

The results show that for end-use demands to be fulfilled, imports of timber have to increase from current levels (See Figure 8). Note that as the import price of timber was set to be higher than national timber production costs, import was only selected as a last resource to meet end-use demand. Imports thereby show the limit of the considered timber potentials and the estimated harvest levels. No agricultural biomass sources were imported during the planning horizon, while on the other hand, woody biomass in the form of timber was imported at significant levels from 2030. As no import of pulpwood or woody chips was noted, import was only required to fulfill end-use demand of sawn wood. That is, the considered harvest trajectories were unable to supply the quantity of timber required for the increasing demand of sawn wood products. Up until 2025, only a small amount of timber was imported. However, from 2030, large amounts of timber were imported to fulfill end-use demand. Import level were found the same for scenarios REF, DB_H, DB_L, Pri_H, Pri_L, Pot_H, Pot_L, and Pot_N, as import was only required to fulfill demand of sawn wood. On the other hand, as the DW_H and DP_L scenarios assume different demand of sawn wood product, import levels increased and decreased, respectively, for the DP_H and DW_L scenarios in comparison to the REF scenario.
Figure 8. Overview of the import of timber for the different scenarios. Import of timber was the same for scenarios: REF, DB_H, DB_L, Pri_H, Pri_L, Pot_H, Pot_L, and Pot_N. Import is expressed in terms of millions of tons of dry biomass per year.

4. Discussion

By integrating forest harvest trajectories into the energy system model, we show how decisions within the bioenergy and forest industrial sectors can be explicitly considered within a joint framework. The presented OFR modeling approach as such allows the study of how decision-making in one sector influences the other sector, and how the link and flow of commodities between the two sectors may be influenced by specific policies. As the bioenergy and forest industrial sectors are becoming more and more reliant of each other through an increasing use of forestry commodities for energy purposes and the use of forests as abatement for climate change, integrated assessment tools that may jointly consider decision in both sectors are in need.

The operation of the presented model was demonstrated by evaluating the optimal long-term harvest level of Swedish forests for the development of the bioenergy and forest industrial sectors. As the emphasis of this paper was on methodology, results should be viewed within the limits of data applied for this study. However, the problem is a good example of cross-sectorial problems and dynamics that can be assessed and evaluated with the integrated approach. Furthermore, the integration of highly detailed cost-supply curves for forestry residues and regional definition of harvest trajectories illustrated the capability of the model to consider data on a highly detailed level as well as regional differentiations. Cost-supply curves of all primary energy resources can readily be integrated into the model, as well as regional specifications both in terms of supply or demand of resources.

A short-term increase in the Swedish national forest harvest level was found to be beneficial for the joint development of the bioenergy and forest industrial sectors. It has been suggested that the forest harvest level should be increased to match the level of forestry increment to create additional supply of biomass sources for bioenergy production (Börjesson et al., 1997; Ericsson and Nilsson, 2006; Wiesenthal et al., 2006). However, results in this paper suggest that the bioenergy sector only requires a short-term increment in the national forest harvest level and that in the long term, the harvest level endogenously computed by the OFR model was similar to that of a continuation of the current trend of harvesting almost 65% of the annual increment (Skogsstyrelsen, 2010). There is currently a steadily increasing pressure on forestry biomass sources in Sweden due to increasing
demand. If supply of agricultural and forestry biomass sources is not mobilized fast enough to match demand, shortages may be experienced in the supply of pulpwod, and the price of forestry and agricultural biomass sources may rise even though harvesting costs continue to fall. As some forest industries have already expressed concerns about the price of forestry biomass, further increases may induce difficulties for some forest industries and hamper the development of the bioenergy sector. However, as logging and transportation techniques for forest biomass are well developed, and as the logistic chain from harvesting sites to plants is very mature, Sweden is in a good position for increasing its national forest harvest level. Furthermore, the results suggest that as the amount of freed-up agricultural land starts to accumulate, the availability of biomass sources for bioenergy production increases significantly, and expensive forestry biomass sources such as pulpwod may no longer be economically beneficial sources of bioenergy production. Thus, while the bioenergy sector would benefit from an increased collection rate of forestry residues, it may not benefit from a long-term increased harvest level of more expensive forestry biomass such as timber and pulpwod.

However, it is interesting to note that from a cross-sectorial point of view, the model showed that it was optimal to select a forest harvest level that will results in high harvests of biomass sources in early periods but that requires import of timber in later periods. The real future needs of sawn wood imports could however be questioned. The reason is that the harvest levels of the trajectories that are presented here are in general lower than current and expected future levels. For instance, the projection in Claesson et al. (2008) that best resemble the BAU trajectory is close to 20 million m$^3$ standing volume above the harvest level of BAU. One likely reason for this underestimate is an underestimation of growth due to old data (from the 1980’s) of stand establishment (Sallnäs, 1990). Another reason for timber imports some 30 years from now is that there is in the trajectories a shift to more volume from thinning and less from final harvests, leading to more pulpwod and less sawn wood. This trend is also found in the projections in Claesson et al. (2008), however as this shift will have a large impact on the forest sector, it is uncertain if it will occur.

It is important to consider that the forest harvest level endogenously computed by the OFR model is a theoretical measure, and achieving an increased harvest level is dependent on a number of factors. In real-life conditions, forest owners decide on the timing of forest harvesting operations. As approximately 50% of all forests in Sweden are privately owned (Skogsstyrelsen, 2010), and as the current national forest harvest level does not exceed the annual forest increment, political instruments may have to be put into place to induce an increase in harvest levels. It has previously been observed that a high price of timber and pulpwod may drive up the national harvest level, thus economic incentives may stimulate forest owners to perform harvesting operations. Other instruments such as regulatory changes may also induce higher harvest levels. The implementation of such incentives would help to safeguard the supply of biomass sources at a price that supports the development of the bioenergy and forest industrial sectors. Increased forest production may also result from forest management actions not accounted for in the forest model. One is fertilization, which in its more intensive forms could increase production by one third (Larsson et al., 2009). Another is more intensive stand establishment (Pohjola and Valsta, 2007).

Steps may also have to be taken to ensure the large-scale development of energy crops and a provision of sustainable biomass resources. Production of energy crops has been modest in Sweden so far. In 2006, less than 3% of all agricultural land in Sweden was used to grow energy crops (Regeringskansliet, 2007). Numerous obstacles need to be overcome for a large-scale production to occur. Significant developments are required in terms of the supply infrastructure, production chain, and distribution chain. Unfortunately there is a considerable amount of uncertainty regarding the attractiveness of energy crops, with the result that farmers tend to hesitate about growing them. Farmers may not be willing to switch from annual crops to growing energy crops with a rotation period of 20 to 30 years until instruments are put into place that guarantee profitability. Until a stable and sustainable demand for energy crops is proven, farmers may be unwilling to switch to energy crops that take two harvest cycles to recoup initial investments and only generate income every three to five years.

While heat and power generation from biomass sources can reduce GHG emission, production and logistics need to be performed in a sustainable manner. Large-scale biomass production of energy crops will require new legislation and setting up industrial standards to ensure the protection of biodiversity and other environmental values. Note however that all harvest trajectories considered in the study result in roughly the same state of the forest in 2100. As such, an increase in harvest operations during a short period of time will not impact the long-term sustainability of the forest.
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on a national level. However, increased harvest operations may damage key animal habitats, and as the age structure of the forest will be affected by the increased harvest, the amount of available habitats of some species may be affected. The supply of dead tree biomass in the forest may affect the forest ecosystem. However, biodiversity issues are commonly considered when logging operations take place. Legislation and industrial standards to prevent loss of biodiversity have been developed over a long period of time and may be considered as mature. Also, as the harvest level endogenously computed by the OFR model will not exceed the annual forest increment and as Swedish legislation does not allow deforestation, the impact on environmental and biodiversity values may be minor. Furthermore, as the decrease in forest harvesting would take place after the peak year, the resulting forest volume in 2100 would be the same as if forest harvesting had followed the current trend.

5. Conclusions

This study presents the development and demonstration of an approach for incorporating decisions concerning forest management within the framework of an energy system model. This new model makes it possible to study questions concerning forest management within the framework of the bioenergy and forest industrial sectors. As both forest and agricultural biomass sources are likely to be used for energy production in the future, better co-ordination of forestry, agricultural, and energy policies would ensure that industrial and environmental values are not hampered. The linkage between the bioenergy and forest industrial sector is increasing as more and more forestry resources are not only being used for energy production but also to help mitigate climate change and increase energy security.

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References

Ajanovic, A. (2011) Biofuels versus food production: Does biofuels production increase food prices? Energy 36: 2070-2076.

Anderson, G.Q.A. and Fergusson, M.J. (2006) Energy from biomass in the UK: sources, processes and biodiversity implications, Ibis 148: 180-183.

Athanassiadis, D., Melin, Y., Nordfjell, T. and Lundström, A. (2009) Harvesting potential and procurement costs of logging residues in Sweden. In: Bioenergy 2009: Sustainable Bioenergy Business 4th International Bioenergy Conference and Exhibition. Jyväskylä, Finland.

Babcock, B.A. (2008) Distributional implications of US ethanol policy, Appl. Econ. Perspect. P. 30: 533-542.

Banse, M., Van Meijl, H., Tabeau, A. and Woltjer, G. (2008) Will EU biofuel policies affect global agricultural markets? Eur. Rev. Agric. Econ. 35: 117-141.

Baum, C., Leinweber, P., Weih, M., Lamersdorf, N. and Dimitriou, I. (2009) Effects of short rotation coppice with willows and poplar on soil ecology, Agric. Forestry. Res. 3: 183-196.

Bisaillon, M., Ekström, C., Fritz, P., Gode, J., Jöborn, I. and Larsson, G. (2008) Biokon: Konsekvenser för energi- och skogssektorn av förändrad efterfrågan på biomassa - Sammanfattande rapport. In: 08:60 : Elforsk. (in Swedish)

Blesl, M., Das, A., Fahl, U. and Remme, U. (2007) Role of energy efficiency standards in reducing CO₂ emissions in Germany: An assessment with TIMES, Energ. Policy 35: 772-785.
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Börjesson, M. and Ahlgren, E.O. (2010) Biomass gasification in cost-optimized district heating systems–A regional modelling analysis, Energ. Policy 38: 168-180.

Börjesson, P., Gustavsson, L., Christersson, L. and Linder, S. (1997) Future production and utilisation of biomass in Sweden: Potentials and CO2 mitigation, Biomass. Bioenergy. 13: 399-412.

Capros, P., et al. (2016) EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050.

Claesson, S., et al. (2008) Skogliga konsekvensanalyser 2008 - SKA-VB 08 Skogsstyrelsen (Swedish Forest Agency). (in Swedish)

Commission, E. (2001) Integrated pollution prevention and control (IPPC) reference document on best available techniques in the pulp and paper industry, Eur. Commiss., EU directive 96: 61.

Crutzen, P.J., Mosier, A.R., Smith, K.A. and Winiwarter, W. (2008) N20 release from agro-biofuel production negates global warming reduction by replacing fossil fuels, Atmos. Chem. Phys. 8: 389-395.

Djemaa, A. (2009) Modélisation Bottom-Up, un outil d’aide à la décision long terme pour les mesures politiques en matière d’énergie et d’environnement □ Le modèle TIMES appliqué aux industries grandes consommatrices d’énergie, École Nationale Supérieure des Mines de Paris. (in French)

Edwards, R., Mahieu, V., Griesemann, J.C., Larive, J.F. and Rickeard, D.J. (2004) Well-to-wheels analysis of future automotive fuels and powertrains in the European context, SAE Transactions 113: 1072-1084.

Eggers, J., et al. (2009) Is biofuel policy harming biodiversity in Europe? GCB. Bioenergy 1: 18-34.

Ekborn, T., Berglin, N. and Lögberg, S. (2005) Black liquor gasification with motor fuel production- BLGMF II. Swedish Energy Agency, Nykomb Synergetics.

Ekborn, T., Lindblom, M., Berglin, N. and Ahlvik, P. (2003) Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses-BLGMF. EU Contract No 4: 01-087.

Energimyndigheten (2015) Energy in Sweden - facts and figures 2015. In: ET 2015:19 SEA Swedish Energy Agency.

Energimyndigheten (2011) Marknaderna för biodrivmedel 2014. Tema: HVO. In: ET 2014:27 (2014): SEA Swedish Energy Agency. Energimyndigheten. Långsiktsprogno 2011. In: ER 2011:03 Swedish Energy Agency. (in Swedish)

Ericsson, K. and Nilsson, L.J. (2006) Assessment of the potential biomass supply in Europe using a resource-focused approach, Biomass. Bioenergy. 30: 1-15.

Eriksson, L.O., Sallnäs O. and Ståhl, G. (2007) Forest certification and Swedish wood supply, Forest. Policy, Econ. 9: 452-463.

Ewert, F., Rounsevell, M., Reginster, I., Metzger, M. and Leemans, R. (2005) Future scenarios of European agricultural land use: I. Estimating changes in crop productivity, Agric., Ecosyst. Environ. 107: 101-116.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O’hare, M. and Kammen, D.M. (2006) Ethanol can contribute to energy and environmental goals, Science 311: 506-508.

Fitzherbert, E.B., et al. (2008) How will oil palm expansion affect biodiversity? Trends. Ecol. Evol. 23: 538-545.

Forsell, N., et al. (2016) Study on impacts on resource efficiency of future EU demand for bioenergy (ReceBio). Final report. Project: ENV.F.1/ETU/2013/0033. In: Luxembourg: Publications Office of the European Union 43.
Gargiulo, M. (2009) *Getting started with TIMES-VEDA (version 2.7)*. Energy Technology Systems Analysis Program (ETSAP).

Hartman, J.C., Nippert, J.B., Orozco, R.A. and Springer, C.J. (2011) Potential ecological impacts of switchgrass (*Panicum virgatum L.* ) biofuel cultivation in the Central Great Plains, USA, *Biomass. Bioenerg.* 35: 3415-3421.

Havlík, P., *et al.* (2011) Global land-use implications of first and second generation biofuel targets, *Energ. Policy* 39: 5690-5702.

Havlík, P., *et al.* (2015) Climate change impacts and mitigation in the developing world: an integrated assessment of the agriculture and forestry sectors. Policy Research Working Paper; No. 7477. World Bank, Washington, DC.

Helbling, D.L., Mercer-Blackman, V., Dao, C.T.N., Erbil, N. and Oakes, E. (2008) Is inflation back? commodity prices and inflation. *World Economic Outlook.*

Hill, J., Nelson, E., Tilman, D., Polasky, S. and Tiffany, D. (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels, *PNAS* 103: 11206-11210.

Johnsson, B. (2006) Bioenergi - ny energi för jordbruket (bioenergy - new energy for agriculture), Jordbruksverket (Swedish Board of Agriculture). (in Swedish)

Kanudia, A., Labriet, M., Loulou, R., Vaillancourt, K. and Waaub, J.P. (2005) The World-MARKAL model and its application to cost-effectiveness, permit sharing, and cost-benefit analyses. In: Loulou, R., Waaub, J.P. and Zaccour, G. (eds), *Energy and Environment.* Springer, Boston, MA.

Kanudia, A. and Loulou, R. (1999) Advanced bottom-up modelling for national and regional energy planning in response to climate change, *Int. J. Environ. Pollut.* 12: 191-216.

Kraxner, F., *et al.* (2013) Global bioenergy scenarios—Future forest development, land-use implications, and trade-offs, *Biomass. Bioenerg.* 57: 86-96.

Larsson, S., Lundmark, T. and Ståhl G. (2009) Möjligeter till intensivodling av skog. Slutrapport från regeringsuppdrag Jo 2008/1885, Swedish University of Agricultural Sciences. (in Swedish)

Lauri, P., Forsell, N., Korosuo, A., Havlík, P., Obersteiner, M. and Nordin, A. (2017) Impact of the 2 °C target on global woody biomass use, *Forest. Policy. Econ.* 83: 121-130.

Lauri, P., Havlík, P., Kindermann, G., Forsell, N., Böttcher, H. and Obersteiner, M. (2013) Woody biomass energy potential in 2050, *Energ. Policy* 66: 19-31.

Loulou, R., Goldstein, G., Kanudia, A., Lehtila, A. and Remme, U. (2016) Documentation for the TIMES Model Part I. Energy Technology Systems Analysis Programme.

Lorne, D., Bouvert, F., Guerassimoff, G. and Assoumou, E. Valerbio, tâche 2-a, définition des hypothèses technico-économiques de conversion de la biomasse (2010): TUCK foundation. (in French)

Lotze-Campen, H., *et al.* (2014) Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison, *Agr. Econ.* 45: 103-116.

Millet, G., Valerbio, (2010) Tâche 1-B, Estimation de la ressource agricole disponible Scénarios d’offre. TUCK foundation. (in French)

Mitchell, D. (2008) A note on rising food prices. World Bank Policy Research Working Paper; No.WPS 4682. Washington, DC: World Bank.

Mueller, S.A., Anderson, J.E. and Wallington, T.J. (2011) Impact of biofuel production and other supply and demand factors on food price increases in 2008, *Biomass. Bioenerg.* 35: 1623-1632.
Swedish Forest Harvest Level Considering Demand of Biomass

Nguyen The, N., Thivolle-Cazat, A., Berthelot, A. and VALERBIO, (2010) Valorisation énergétique de la biomasse, Livrable 1a / 1c, Synthèse sur la disponibilité de matière ex bois en France, y compris TCR. TUCK foundation. (in French)

O’Hare, M., Plevin, R.J., Martin, J.I., Jones, A.D., Kendall, A. and Hopson, E. (2009) Proper accounting for time increases crop-based biofuels’ greenhouse gas deficit versus petroleum, Environ. Res. Lett. 4: 024001.

Pohjola, J., Valsta, L. (2007) Carbon credits and management of Scots pine and Norway spruce stands in Finland, Forest. Policy. Econ. 9: 789-798.

Popp, A., et al. (2017) Land-use futures in the shared socio-economic pathways, Global Environmental Change 42: 331-345

Räisänen, T. and Nurmi, J. (2011) Impacts of changing the minimum diameter of roundwood on the accumulation of logging residue in first thinnings of Scots pine and Norway spruce, Biomass. Bioenergy. 35: 2674-2682.

REFUEL (2008) Renewable Fuels for Europe, Intelligence Energy Europe.

Regeringskansliet. Bioenergi från jordbruket - en växande resurs (Bioenergy from agriculture - a growing resource) (2007): Statens offentliga utredningar (Official Government Report). (in Swedish)

Remme, U., Blesl, M. and Fahl, U. (2008) Future European gas supply in the resource triangle of the Former Soviet Union, the Middle East and Northern Africa, Energ. Policy 36: 1622-1641.

RES2020. Monitoring and Evaluation of the RES directives implementation in EU27 and policy recommendations for 2020 (RES2020). In: EISAS/EIE/06/170/2006 (2009): Intelligence Energy Europe.

Rounsevell, M., Ewert, F., Reginster, I., Leemans, R. and Carter, T. (2005) Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland, Agric., Ecosyst. Environ. 107: 117-135.

Routa, J., Asikainen, A., Björheden, R., Laitila, J. and Röser, D. (2013) Forest energy procurement: state of the art in Finland and Sweden, WIREs Energ. Environ. 2: 602-613.

Sallnäs, O. (1990) A matrix growth model of the Swedish forest, Studia Forestaha Suecica, No. 183, Uppsala, Sweden.

Searchinger, T.D. (2010) Biofuels and the need for additional carbon, Environ. Res. Lett. 5: 024007.

Semere, T. and Slater, F. (2007) Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus ⌠ giganteus) and reed canary-grass (Phalaris arundinacea) fields, Biomass. Bioenergy. 31: 20-29.

Skogsindustrierna. Skogsindustrin - En fakta samling för 2010 års branchstatestik (2010): Skogsindustrierna. (in Swedish)

Skogstysyns. Skogstysynskårbok 2010 (Swedish Statistical Yearbook of Forestry 2010) (2010): Skogstysyns (Swedish Forest Agency). (in Swedish)

Tyner, W.E. and Taheripour, F. (2008) Policy options for integrated energy and agricultural markets, Appl. Econ. Perspect. P. 30: 387-396.

Valin, H., et al. (2015) The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts.

Valin, H., et al. (2014) The future of food demand: understanding differences in global economic models, Agr. Econ. 45: 51-67.
Wiesenthal, T., Mourelatou, A., Petersen, J.E. and Taylor, P. (2006) How much bioenergy can Europe produce without harming the environment? *EEA Report No. 7/2006*, European Environment Agency, Copenhagen.

Wright, E.L., Belt, J.A.B., Chambers, A., Delaquil, P. and Goldstein, G. (2010) A scenario analysis of investment options for the Cuban power sector using the MARKAL model, *Energy. Policy* 38: 3342-3355.
The TIMES model is defined as the following linear programming model:

Variables

\( VAR_{ACT_{k,i}} \) Variables that defines the activity levels of end-use technologies

\( X \) Expresses all the general variables defining the model

Parameters

\( DM_i \) Exogenous demands to satisfy, such as the demand of end-use energy services.

\( c \) Cost vector defining costs for aspects such as capital costs, fixed and variable operation costs, subsidies, etc.

Indexes

\( k \) commodities (energy, material, emission)

\( i \) demand categories

\( t \) time periods

Objective function

\( \min c \times X \)

Constraints

\[ C.1 \quad \sum_k VAR_{ACT_{k,i}}(t) \geq DM_i(t) \quad [\forall i, \forall t] \]

\[ C.2 \quad B \times X \geq b \]

Constraint 1 are the demand satisfaction constraints and constraint 2 expressed the general constraints of the TIMES model such as flow, trade, capacity, and technologies. For a full detailed description of the mathematical formulation of the TIMES energy model we refer to Loulou et al. (2016).

To allow for changes in forest management and forest harvest within the Times modelling framework, the following two constraints were added to the linear programming approach.

Variables

\( A_{i,r} \) Percentage contribution from the exogenously defined harvest trajectory \( i \) for region \( r \) (%)

\( H_r \) Final harvest level for region \( r \) (m\( ^3 \))

Parameters

\( B_{i,r} \) Harvest for each exogenously defined harvest trajectory \( i \) in region \( r \) (m\( ^3 \))

Indexes

\( r \) regions within Sweden (4)

\( i \) exogenously defined harvest trajectory (8)

Constraints

\[ C.3 \quad H_r = \sum_i A_{i,r} \times B_{i,r} \quad [\forall r] \]

\[ C.4 \quad \sum_i A_{i,r} = 1 \quad [\forall r] \]

Constraint 3 sets the regional specific harvest level \( (H_r) \) according to the percentage contribution from each exogenously defined harvest projection. Constraint 4 ensures that a 100% percentage contribution from each exogenously defined harvest projection is selected.