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Impacts of global climate change mitigation scenarios on forests and harvesting in Sweden

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Abstract

Under climate change, the importance of biomass resources is likely to increase and new approaches are needed to analyze future material and energy use of biomass globally and locally. Using Sweden as an example, we present an approach that combines global and national land-use and forest models to analyze impacts of climate change mitigation ambitions on forest management and harvesting in a specific country. National forest impact analyses in Sweden have traditionally focused on supply potential with little reference to international market developments. In this study, we use the global greenhouse gas concentration scenarios from the Intergovernmental Panel for Climate Change to estimate global biomass demand, and assess potential implications on harvesting and biodiversity in Sweden. The results show that the short-term demand for wood is close to the full harvesting potential in Sweden in all scenarios. Under high bioenergy demand, harvest levels are projected to stay high over a longer time and particularly impact the harvest levels of pulpwood. The area of old forest in the managed landscape may decrease. The study highlights the importance of global scenarios when discussing national level analysis, and pinpoints trade-offs that policy making in Sweden may need to tackle in the near future.

Keywords: Forest impact analysis, forest product demand, scenario analysis, Swedish NFI, wood supply potential

Introduction

Forests have an important role in climate change mitigation, both as a carbon sink and for production of renewable materials and energy (IPCC 2014b). Bioenergy is an important energy source for replacing fossil fuels, and biomass from forests is seen as the main potential feedstock for bioenergy in the future in many projections (GEA 2012; IEA 2015). However, assessments of the potential for bioenergy should include analysis of consequences on biodiversity and other uses of forests and biomass in order to provide comprehensive and useful policy support (Berndes et al. 2003). The demand for wood products and bioenergy is increasingly global through international trade and various emission trading schemes, while the supply – forest biomass – is produced locally. The local level is where resources are limited, and where the trade-offs of increased biomass demand and increased timber harvests are faced at first, e.g., negative effects on other ecosystem services, decline of biodiversity, and land-use conflicts. Thus, a multi-level perspective that considers the global demand on a local scale is complex but critical if we want to address questions concerning the role and state of forests and forestry in the future.

An appropriate basis for global modeling is the new matrix framework structure, set up by the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which allows for a direct and interlinked global analysis of climate change impacts and mitigation options. The new matrix framework is constructed through a combination of two sets of independent scenarios: the four Representative Concentration Pathways (RCPs) corresponding to different levels of radiative forcing on one axis, and Shared Socio-economic Pathways (SSPs) that express the development of socioeconomic drivers on the other axis (IPCC 2014a; IPCC2014b; IPCC 2013; van Vuuren et al. 2014; van Vuuren et al. 2011). A recent publication by Fricko et al. (2016) explores the set of energy sources used under combinations of RCPs and SSPs, highlighting the increased pressure on agricultural production and land use under more stringent climate policies, and an increased global demand for forest biomass. In their study, the demand for industrial roundwood doubles by 2100 under a scenario of stringent climate mitigation (RCP2.6) combined with midway socio-economic development (SSP2), with half of this biomass being harvested in the northern hemisphere.

Other than the global study of Fricko et al. (2016), to our knowledge there are no prior studies that investigate how the SSPs and RCPs affect demand for specifically forest biomass. However, there are studies based on other climate change scenarios, and Latta et al. (2013) and Toppinen and Kuuluvainen (2010) give overviews of forest sector models that can be used to project wood demand changes under different scenarios. Raunikar et al. (2010) used the Global Forest Products Model (GFPM) to study the possible global implications of climate mitigation scenarios of the previous IPCC (fourth) assessment report on wood and forests. Their analysis projects up to a six-fold increase in the demand for energy wood already by 2060. The same scenarios were investigated also by Nepal et al. (2012), who estimated up to 16-fold increase of wood energy production in the United States alone by 2060, given the assumptions of rapid economic growth described in the A1B scenario. The results varied between regions, and emphasized the dependence of the scenario outcome on the current growing stock that is very different in different parts of the country. Kallio et al. (2016) examine the effects of EU bioenergy policies on Finnish forests. Modeling the EU forest biomass demand’s impact on Finland with the EU-wide Finnish forest sector model, SF-GTM, and further elaborating the results with the national MELA model, they found that the harvests in Finland would increase between 19% and 28% from 2010 to 2025. In their analysis, much of the increased bioenergy demand is assumed to be satisfied through increased stump harvests, which are not widely used for commercial purposes outside Scandinavia (Melin 2014).

In this study, we use the RCP-SSP scenario framework described in Fricko et al. (2016) to translate global climate change mitigation scenarios into policy relevant forest scenarios for an individual country. In Sweden, the forest sector provides 2.2% of the GDP (SFA 2014). Timber production is historically very important, and Sweden is one of the leading countries in the world in the production of sawnwood (4 % of the global production), pulp for paper (6 %) as well as paper and paperboard (3 %) even though the Swedish forest constitutes only 0.7 % of the world's forest area (FAOSTAT 2015). Forests cover 69% of the Swedish land area, and are thus an important feature in the Swedish landscape. Despite the relatively large forest area and a growing standing stock, conflicts exist both on local and national level over use of the forest resource, e.g., between production forestry, nature conservation, the usufruct rights of the indigenous Sami people, hunting, tourism and recreation. With an increased future demand for forest products and bioenergy, there will be a need for sound trade-offs among timber production and the provisioning of other ecosystem services and biodiversity (see, e.g., Beland Lindahl et al. in press; Sandström and Sténs 2015; Söderberg and Eckerberg 2013).

Few studies so far have explicitly covered the future of Swedish forests and forestry under different scenarios of global development such as various climate change mitigation ambitions and different paths of socioeconomic development. The national forest impact assessments have focused only on the supply side and the harvesting potential (e.g., Claesson et al. 2015). To complement the national forest impact assessment with analysis of potential demand, the Swedish Forest Agency used scenarios with high global demand (increased consumption of forest products in growing economies and increasing roundwood consumption due to mitigation efforts) and low global demand (forest products are substituted by other products and there is no increase in roundwood consumption due to mitigation efforts) based on existing studies, which indicates a positive development for the Swedish forest sector and a need for development of value added products (Duvemo et al. 2015). The European Forest Sector Outlook Study II (EFSOS II) included Sweden among other European countries and addressed the future development of forests and the forest sector until 2030 on European level based on the global development described in the IPCC scenario B2 (IPCC 2000) and four policy scenarios (UN 2011). The IPCC scenario B2 represents local solutions to sustainability problems in a world with increasing human population, intermediate levels of economic development, and technological change of moderate speed and diversity (IPCC 2000). The policy scenarios are formulated to result from four different policy changes made based on the B2 assumptions: Maximising biomass carbon, promoting wood energy, priority to biodiversity and fostering innovation and competitiveness (UN 2011). The results show an increasing demand for forest products and energy wood, and that the increasing pressure on forests potentially threatens biodiversity. Moreover, the EUwood project (Mantau et al. 2010) compared three potential wood supply scenarios (high, medium and low wood mobilization) for Europe with the future demand for wood raw material from the industry and for energy based on the IPCC scenarios A1 and B2. Results show that demand will exceed supply in 2030 under all scenarios. Based on the results from the EUwood project, Jonsson (2013) focused on implications for the Swedish forest sector. Results show that if the EU policy on renewable energy sources was fully implemented, there would be an increasing demand on wood from Sweden for both material and energy uses. This could favor the sawmill industry, while the demand for pulp and paper (above all newsprint) is declining due to the developments in electronic information and communication technology. The pulp and paper industry may also have to compete with the bioenergy sector for raw material. In a study on effects of global trends and market developments on the Swedish forest sector based on qualitative scenarios and existing studies, Jonsson (2011) draws similar conclusions; under all scenarios the Swedish solid wood-product industry would be well off, provided that the expected growth in demand for factory-made, energy-efficient construction components takes place and the industry adapts to this, but the future of the pulp and paper industry is more uncertain. Recently, Bostedt et al. (2015) and FOREST EUROPE (2015) showed that the reported fellings in Sweden are close to the potential, which would mean that substantial increase in demand may be difficult to satisfy through increased harvests. To sum up, existing studies are focused on wood production and show that the Swedish forest sector may have to prepare for restructuring but that the future development seems to be positive overall. Consequences for biodiversity and ecosystem services have not been explicitly included in these studies but some of them highlight that there may be negative impacts from biomass production which have to be assessed in future studies. This issue has also been pointed out by Verkerk et al. (2014) in a European level study and by Berndes et al. (2003) in a review of global studies.

In this study, we use the land use model GLOBIOM-EU (Frank et al. 2016), a variant of the Global Biosphere Management Model (Havlík et al. 2014; 2011), linked with Global Forest Model (G4M), and the national forest modeling software Heureka RegWise (Wikström et al. 2011) to analyze the impacts of changes in the global wood demand on the Swedish forests. The Swedish wood demand is projected until 2100 using GLOBIOM-EU, after which Heureka RegWise is used to further analyze the implication of the projected harvest levels in terms of regional forest development, and how such scenarios would affect the environmental values in the Swedish forests. Through this linkage of two independent systems, we examine the effects of world-wide policies on a detailed national level, taking advantage of the individual strengths of the two systems: the global competition between countries and land-use based activities as presented in GLOBIOM-EU, and the detailed and nationally adjusted forest growth and yield modeling of Heureka RegWise. With this approach, this study aims to broaden the perspective of previous national level forest impact assessments to include a global outlook. More specifically, the study aims to address the following questions:

- How will scenarios on global climate change mitigation policies reflect on the future harvest levels in Sweden?
- Is this demand possible to fulfill under the current forest regulations and policies in Sweden?
- How do the different climate change mitigation scenarios affect ecological aspects such as the amount of old forest and broadleaved forest?

Material and methods

In this chapter, we first introduce briefly the two models used in the study, the national forest analysis tool Heureka RegWise and the global land use model GLOBIOM-EU. Then, we describe the scenarios used in the analysis and explain how the national wood supply scenario was combined with the global scenarios for wood demand.

Heureka RegWise

The Heureka system (Wikström et al. 2011) is an advanced forest decision support system for analysis and planning of the forest landscape developed at the Swedish University of Agricultural Sciences and is extensively used in Sweden by both researchers and forestry professionals. Heureka provides various models and tools for forest planning on different levels that support the entire planning process. Heureka RegWise is the application for long-term analysis on regional or national level and is based on a simulation approach. The core of Heureka RegWise is the projection of the development of individual trees over time based on empirical growth models, mainly derived from data from the Swedish National Forest Inventory (NFI). The growth models are applicable to all Swedish tree species as well as mixed species stands and are used to provide reliable growth predictions for up to 100 years (Fahlvik et al. 2014). To project the development of individual trees, in addition to growth models there are models for natural mortality (Fridman and Ståhl 2001) and in-growth (Wikberg 2004). The user can define many settings for forest management activities such as final felling, regeneration, thinning, fertilization, continuous cover forestry and nature conservation. Logistic regression functions are used to calculate the probability of thinning and final felling based on information on what type of stands thinning and final felling have been carried out on permanent NFI plots (Holm and Lundström 2000).

Heureka RegWise can be used to develop scenarios for large geographical areas to answer questions of "what if"-character. For example, the effects of various forest management strategies, e.g., intensive forestry or continuous-cover forestry, on the output of timber production and a number of other ecosystem services can be analyzed. Analyses with Heureka RegWise are based primarily on data from the Swedish National Forest Inventory (NFI) combined with data from digital maps.

GLOBIOM-EU

GLOBIOM-EU (Frank et al. 2016) is a version of the GLOBIOM partial-equilibrium model (Havlík et al. 2014; 2011) with refined representation of EU28 Member States. Outside of EU, GLOBIOM and GLOBIOM-EU are identical in model structure and data sets as being used. The most important features of the modeling approach are presented in Table 1.

INSERT TABLE 1 AROUND HERE

In its core, the GLOBIOM-EU is a global partial-equilibrium economic model representing land-use based activities within the forest, agricultural, and bioenergy sectors. These sectors are jointly considered within the model in a bottom-up approach based on detailed spatial information on the biophysical conditions and technical costs associated with land use. A global market equilibrium is determined through mathematical optimization where land use, utilization of resources and processing activities are allocated to maximize the sum of producer and consumer surplus subject to resource, technological, demand, trade, and policy constraints (McCarl et al. 1980). Through the use of recursive dynamic optimization, the model is run with 10 year time steps where production and international trade adjust to meet the demand for final products at the level of 57 aggregated world regions (28 EU member countries, 29 regions outside Europe). Each EU Member State, including Sweden, is thus covered based on the highest available model resolution in terms of geographical and processing of commodities. Trade is also modelled following the spatial equilibrium approach, meaning that trade flows are balanced out between the geographical regions based on cost competitiveness and bilateral trade flows.

On the supply side, the GLOBIOM-EU model is based on a bottom-up approach with a detailed disaggregated representation of land based activities. Outside of Europe, land based activities are modeled at the level of simulation units (SimUs) - clusters of 5 arcminute pixels, with the same characteristics in terms on slope, soil class, and altitude, and belonging to the same country and 0.5° × 0.5° pixel. For EU, a more detailed SimU architecture is being used (except for Croatia, Cyprus, and Malta) and were the basic simulation unit is on the level of 1 × 1 km pixel, aggregated based on six altitude classes, seven slope classes, and soil (texture, depth, coarse fragmentation), and belonging to the same NUTS2 region (Nomenclature of Territorial Units for Statistics developed for the European Union).

For the representation of the forest GLOBIOM-EU receives data from the G4M model (Gusti 2010; Kindermann et al. 2008), which provides detailed geographic explicit information concerning key forest management parameters (e.g., forest increment, harvesting costs, forest carbon stocks, harvesting potentials by wood assortment). For the agricultural sector representation, yields under different management systems are estimated by the biophysical crop model called the Environmental Policy Integrated Climate model (EPIC) (Williams 1995) which can then be used to calculate the impact of climate change on the agricultural sector (Havlík et al. 2015; Leclère et al. 2014).

Scenarios

Harvest potential in Sweden: Supply potential scenario

The present and future state of the Swedish forest have been regularly assessed in analyses of harvesting potential since the 1980's and more recently in the more comprehensive forest impact assessment (in Swedish: *Skogliga konsekvensanalyser, SKA*). The most recent forest impact assessment, SKA15, was carried out using Heureka RegWise and the results were presented in November 2015 (Claesson et al. 2015). In all, six scenarios covering the next 100 years until 2110 were analyzed in SKA15. These scenarios were: Current forestry, Increased harvesting, Decreased harvesting, Double set aside areas, Without climate effect, and With climate effect RCP8.5. In the first four scenarios, a climate change effect corresponding to RCP4.5 is modelled. This impact is manifested as an increase in growth rate of trees due to temperature rise, but does not include negative effects such as drought or pests. The process of development and analysis of scenarios involved stakeholders from the forest sector, governmental agencies as well as non-governmental organizations.

INSERT FIGURE 1 AROUND HERE

For this study, we analyze the future development of the Swedish forests based on the *SKA15 Current forestry* scenario, using the results for the whole of Sweden as well as for the four regions Norra Norrland, Södra Norrland Svealand and Götaland (Figure 1). This scenario is based on present forest management practice as observed in the NFI data and other sources such as inventory data from the Forest Agency and information about conservation areas from digital maps. The harvest level is the highest potential harvest level under the condition of sustainable yield; that is, future harvest levels can increase over time but are not allowed to decrease. Thus, in the following, this scenario is referred to as *Supply potential*. In this scenario the area of forest set aside for nature conservation (including both formally and voluntarily protected areas) is the same as today throughout the next 100 years, 16.3% of the forest area. These areas are simulated to be left unmanaged for free development. The areas set aside are distributed over the four regions and the types of areas set aside, are shown in Table 2. Reserves are formally protected and their locations are known. The total set aside areas on voluntary basis is known, and information on the location of the main part of these areas was acquired from the forest industry and from forest owners' associations. Based on this information, additional areas with similar qualities were selected and added to the category to make up for the total known area of voluntary set aside areas. Small areas are also set aside in connection to final felling according to the Swedish Forestry Act (e.g., wet areas, rocky outcrops and buffer zones). Information on such areas from the NFI, was used to select areas to be set aside in connection to final fellings in the simulation.

INSERT TABLE 2 AROUND HERE

Global scenario descriptions

The demand analysis of this study is based on the new IPCC scenario framework, and particularly assesses the impact of climate change mitigation across the RCP scenarios. The RCPs were presented in the latest Assessment Report (AR5) of the Intergovernmental Panel for Climate Change (IPCC 2014a; IPCC 2014b; IPCC 2013). The RCPs provide quantitative information concerning the radiative forcing, ranging between 2.6 and 8.5 W/m^2 in the year 2100 (van Vuuren et al. 2011). Climate models estimate that these levels of radiative forcing lead to an increase in the global temperature from below 1 °C in RCP2.6 to about 7 °C for RCP8.5 above pre-industrial levels (Rogelj et al. 2012).

Alongside with the RCPs, a set of different scenarios for possible socio-economic development has been developed (O'Neill et al. 2014). These Shared Socioeconomic Pathways (SSPs) depict different development of the societies in terms of challenges for climate change mitigation and adaptation. While the RCPs depict climate change development under different mitigation policies, the SSPs focus on socio-economic development of the societies. A full scenario analysis requires the use of a combination of both. For this study, we analyze the differences between the RCP scenarios using the socio-economic development described by the SSP2, the "Middle of the Way" pathway, with moderate challenges for climate change mitigation and adaptation (Fricko et al. 2016). In this study, we use the population growth, economic development and land use patterns (most importantly, the development of short rotation plantation driven by carbon price and bioenergy demand) for SSP2 as in Fricko et al. (2016). However, a full quantification of the SSP scenarios is still underway, and especially drivers for the forestry sector have not yet been fully developed. The development of other drivers is hence estimated by GLOBIOM-EU.

The RCP scenarios reflect both the expected outcome (change in climate) and the policies and stabilization efforts taken to reach the outcome in terms of corresponding levels of radioactive forcing. Most importantly for the modeling setup applied, the RCP scenarios differ in the amount of bioenergy used to replace fossil fuels. In this study, we focus on three of the RCP scenarios: RCP2.6, RCP4.5, and RCP8.5 (van Vuuren et al. 2011). This choice is taken so that the widest range of future bioenergy demand can be assessed. Overall, the scenarios on the global level show a clear change in the mix of energy carriers, with RCP8.5 having the lowest demand for bioenergy and the RCP2.6 scenario having the strongest bioenergy demand. In these scenarios, the projected total global energy demand from solid biomass increases from 32 EJ in 2000 to 60 EJ in RCP8.5 by 2100 (87% increase to 2000), to 123 EJ in RCP4.5 (3-fold increase to 2000), and and to 209 EJ in RCP2.6 (5.6-fold increase to 2000) (Fricko et al. 2016). The increasing demand for bioenergy is used to substitute more carbon-intensive fossil fuels in the production of electricity, heat, and biofuel production, and also to provide negative emissions through the use of carbon capture and storage (CCS) technologies. The overall use of CCS is particularly prominent and plays an important role in the RCP2.6 scenario for reaching the respective level of radioactive forcing. In the current study, the total bioenergy demand is taken as an exogenous input for each RCP, after which the GLOBIOM-EU model estimates the shares of the various feedstocks as being used. To determine the demand for various energy feedstocks in this study we rely on the output from the Model for Energy Supply Strategy Alternatives and their General

Environmental Impact (MESSAGE) (McCollum et al. 2014). In this paper, the scenarios are named *Low demand* (based on RCP8.5), *Intermediate demand* (RCP4.5) and *High demand* (RCP2.6), referring to the total demand for wood biomass in the RCP scenarios.

Combining Swedish and global scenarios

The GLOBIOM-EU model framework was linked with the Heureka RegWise system for this project as shown in Figure 2. The estimated initial forest area was calibrated in both systems to the area of productive forest area as of the latest national forest inventory (Swedish NFI 2015). This was necessary, because in the Swedish NFI, the productive forest area is defined as the area of forest with a mean annual increment potential of at least 1 m^3a^{-1}, in contrast to the area used by GLOBIOM-EU and its forest-development model G4M, which uses the land cover-based estimates of FAO FRA (2010). Based on this calibrated forest area, GLOBIOM-EU was used to estimate wood demand for Sweden under different biomass demand scenarios.

INSERT FIGURE 2 AROUND HERE

First, the global wood demand for Sweden was estimated by GLOBIOM-EU for *Low*, *Intermediate* and *High* demand. The results are shown as harvest level estimates and compared with the harvest level projections of the scenario *Supply potential*. An overview of the scenarios is given in Table 3 and Table 4.

INSERT TABLE 3 AROUND HERE

INSERT TABLE 4 AROUND HERE

Second, the GLOBIOM-EU projected wood demands in Sweden were used as target harvest levels in Heureka RegWise, all other assumptions for forest management being the same as in

Supply potential. The results show the consequences of global wood demand for the Swedish forests, and are analyzed in terms of effects on wood production variables and biodiversity indicators.

The wood production variables reflect the main assortments in Swedish forestry: sawlogs and pulpwood (see Table 5 for definitions). The volumes produced of these assortments are estimated by Heureka RegWise based on tree diameter and the prevailing price list. Log quality is not taken into account, which will lead to some overestimation of the amount of sawlogs over pulpwood since in reality a certain share of sawlogs will be classed as pulpwood due to inferior quality; however, the estimates based only on tree diameter are still valid as an indicator of the general development of different types of assortments.

The environmental consequences are analyzed based on established set of indicators for environmental quality. Sweden has set up 16 environmental quality objectives to assess the state and development of the environment (Ministry of the Environment 2013). One of the objectives, *Sustainable Forests*, focuses directly on the state of the forests, and two indicators for this objective, the area of old forest and the area of old forest rich in broadleaves, are used in this study to analyze the effects of global demand on biodiversity in the Swedish forests. The results can be compared with observed development, as statistics of historical development are available for these environmental indicators both on national and regional level.

The indicators relevant for this study are listed in Table 5. Harvest levels considered in this study cover all harvests in productive forests (i.e., forests with an annual growth of 1 m^3ha^{-1} or more). These forests include also official or voluntary reserves, which are not primarily managed for timber production, but where some harvests may still be done to promote ecological aspects, e.g., to preserve the age or tree species structure. For the assessment of the environmental indicators, we show the development of the indicators both in all productive forests, including areas set aside for nature conservation ("All productive forest"), and in areas which do not have any restrictions for harvesting ("Managed productive forest").

INSERT TABLE 5 AROUND HERE

Results

The *Supply potential* scenario shows an initial potential harvest level of 90.8 million m^3 over bark (o.b.) in 2010 and increases to ca 120 million m^3o.b. by year 2090 (Figure 3). In all three demand scenarios the demand for wood is lower than the level of the *Supply potential* scenario throughout the projection period. However, in the period from 2020 to 2040 all demand scenarios display similar levels of high demand which are close to the potential supply, i.e., the harvest level in the *Supply potential* scenario. From 2040, the demand scenarios show different trajectories for the demand for wood; in *High demand* the demand is the highest and the level rather close to the harvest level in *Supply potential* while the demand is lower in the *Intermediate demand* and especially in the *Low demand* scenarios.

INSERT FIGURE 3 AROUND HERE

Using the harvest levels from the different demand scenarios as target harvest levels in Heureka RegWise provides an output of sawlogs and pulpwood as shown in Figure 4. The output of sawlogs is almost the same for all demand scenarios, and slightly lower than in the original *Supply potential* scenario. In the scenarios with high wood demand, the final fellings are made earlier, leading to an output of harvesting lower-diameter trees and more pulpwood compared to scenarios with lower demand or the *Supply potential* scenario. The ratio of pulpwood to sawlogs is increasing somewhat over time in both the *Supply potential* scenario and in the demand scenarios.

INSERT FIGURE 4 AROUND HERE

The effects on the environment from the demand for wood in the demand scenarios, as assessed with the environmental quality objective indicators, are shown in Figures 5-7.

The area of old forest on all productive forest land (i.e., managed productive forest as well as areas set aside for conservation) increases over time after an initial decrease but compared with the original *Supply potential* scenario, the *Low* and *Intermediate demand* scenarios result in a larger area of old forest over time, ca 370 000 ha more in 2100, due to lower harvest levels (Figure 5).

When only managed productive forests (i.e., the productive forest outside protected areas) is considered, the area of old forest decreases initially with as much as 500 000 to 600 000 ha by 2060 in both the *Supply potential* scenario and the demand scenarios (Figure 5). After 2060 the area of old forest start to slightly increase again in the *Low* and *Intermediate demand* scenarios to ca 700 000 ha, and in the *High demand* scenario there is a slow increase up to 500 000 ha. However, in the *Supply potential* scenario the area of old forest stay on the level of around 350 000 ha.

INSERT FIGURE 5 AROUND HERE

As for the geographical distribution, the area of old forest is the same in northern Sweden (N and S Norrland) for the *Intermediate demand* and *Supply potential* scenarios; however, in Svealand and especially Götaland the area of old forest is considerably larger in the *Intermediate demand* scenario (Figure 6). For clarity, the figures only show development in the *Intermediate demand* and *Supply potential* scenarios; the *Low demand* scenario is almost identical to the *Intermediate demand* scenario and *High demand* is closer to the *Supply potential* scenario.

INSERT FIGURE 6 AROUND HERE

The area of old forest rich in broadleaves increases initially in all scenarios, decreases after 2030 and then increases again around 2080. The pattern is similar in the *Supply potential* scenario and the demand scenarios, with the largest changes in *Supply potential* and the smallest in *Intermediate* and *Low demand* (Figure 7). Moreover, this pattern is visible when the total productive forest area is considered as well as when only the managed productive forest area is considered.

INSERT FIGURE 7 AROUND HERE

Discussion

Swedish forests are an important natural resource that is managed for providing a sustainable yield of timber as well as for supplying a range of other ecosystem services and the preservation of biodiversity. Many processes can be expected to affect the way the Swedish forests are managed in the future. The Swedish forest impact assessments have addressed some different national forest management scenarios but been focused mainly on the supply and harvesting potential. In this study, we incorporate information on future global scenarios in the national-scale forestry analysis to estimate wood demand, and hence offer a new viewpoint for the future strategy development. The approach presented in this paper combines models and scenarios at different levels, and could be used to analyze other countries or areas as well.

The three demand scenarios analyzed in this study show essentially three levels of wood biomass demand, high (*RCP2.6*), medium (*RCP4.5*) and low (*RCP8.5*). High global climate change mitigation ambitions in the *High demand* scenario lead to a demand for biomass from Sweden which is close to the harvesting potential, shown in *Supply potential*. However, in the next 25 years, the demand is so high in all demand scenarios that nearly the full harvesting potential in Sweden has to be used in order to fulfill the demand, regardless of scenario. This finding is in line with the results from the studies by Jonsson (2013; 2011) and Duvemo et al. (2015), and also agrees with the analyses of the current harvest potential in FOREST EUROPE (2015) and Bostedt et al. (2015). Thus, the harvest level will fulfill the condition of sustainable yield – albeit barely - but the harvesting potential is exploited to the maximum extent. This result may either not realize, or it may have severe consequences for the Swedish forests. First, it is not likely that all the potential supply will be harvested in reality. The share of non-industrial private forest owners is relatively large in Sweden: ca 50% of the productive forest, and 50% of privately owned forest estates are 20 ha or smaller (SFA 2014). Consequently, many forest owners are not directly dependent on the forest for income and prioritize other objectives than timber production (Eggers et al. 2014). Because of this, it is likely that all harvest potential may not be easily accessible in reality. Second, if the national Swedish forest policy would be directed towards other goals such as increasing the area of productive forest to be set aside for nature conservation, it may prove difficult to provide biomass on a level that would satisfy the global demand. A scenario where the total area set aside is doubled was developed in the SKA15 project, resulting in a harvest level well below even the *Low demand* scenario until 2090 (Claesson et al. 2015). A doubled conservation area is not currently realistic in the Swedish forest policy context but this scenario was set up to analyze the consequences of ambitious conservation objectives.It is assumed that policies that may be realized, even ambitious ones, will fall somewhere in between this scenario and the *Supply potential* scenario. Third, woody biomass is not the only component in the task to achieve the ambitious targets for climate mitigation set in the *High demand* scenario. For instance, the scenario assumes that other types of energy sources and carbon capture and storage (CCS) techniques are to be developed. If these endeavors are not successful, the pressure on forests to produce renewable energy may be even larger (Berndes et al. 2003).

Yet another uncertainty is the effect of climate change on Swedish forests. In the Heureka RegWise simulations the climate effect is included as increasing forest growth rates; ca 21% higher by 2100 compared to simulations without climate effects (Claesson et al. 2015). The Heureka RegWise estimate is based on the climate change effect in the RCP4.5 scenario and would be lower if the RCP2.6 had been used. Thus, with the *High demand* scenario (RCP2.6) it would have been likely to assume lower harvest potential than the present estimate in the *Supply potential* scenario, further stressing the uncertainty to fulfill the condition of sustainable yield for that combination of scenarios. The estimated increase in forest growth for the supply scenarios could also be overestimated since the Heureka RegWise model did not include possible negative effects by increased wind damage, droughts and pests related to climate change (Claesson et al. 2015).

All demand scenarios result in rather similar amounts of sawlogs over time, on levels that are quite close also in the *Supply potential* scenario. The difference between the scenarios is in the amount of pulpwood produced. This reflects the high demand for wood for energy purposes: pulpwood quality roundwood is less valuable as feedstock for material purposes, and thus the main source of roundwood for energy. Pulpwood is also mainly acquired from thinnings, while a major part of sawlogs are harvested in final fellings. On the high levels of wood demand predicted in all demand scenarios, final harvests are likely to be made as early as possible, which leads to a larger proportion of pulpwood from final fellings, as well as an overall trend of decreasing age and dimensions of harvested forests. It should be noted that the current analysis does not account for collection of harvest residues or stump harvests. Currently, the volume of this residual biomass is only a fraction of the total harvests in Sweden, but could be increased considerably if the technically feasible potentials (almost 20 mill. m^3 altogether) were harvested (Routa et al. 2013). Another possible bioenergy feedstock could be the small trees cut in thinnings which are too small to be used as pulpwood and thus largely left in the forest. If these additional energy feedstocks were harvested more actively, the pressure to increase pulpwood harvests would likely be smaller than shown in our results. A number of studies have also shown a large potential to increase forests production in the boreal landscape (e.g., Larsson et al. 2008; Nilsson et al. 2011). Including new types of feedstocks as well as silvicultural measures to further increase forest growth to the model framework would be an interesting topic for future studies.

Sustainable yield means that harvest levels are sustainable in the long term, but this is not a sufficient condition for sustainable forest management; ecological and social functions of the forests should also be preserved and supported (Hahn and Knoke 2010). In this study, the area of old forest and old forest rich in broadleaves are used as indicators for sustainable forest management, and the results show that the area of old forest will continue to increase over time in all demand scenarios in line with the recent historical trend. On a general national level this indicates that the harvesting is sustainable even under the *High demand* scenario. However, most of this increase takes place in areas set aside for conservation purposes. In managed productive forests outside conservation areas, much of the old forest is harvested in the near future to satisfy the high demand and then slowly increases over time again when the demand as well as the area of final felling decreases. In the case of the *High demand* scenario, with a continuous high demand, the area of old forest levels off. Whether the forest management is sustainable or not from an ecological point of view depends to a large extent on how the old forest is distributed over the landscape and on which types of forests. Thus, since most of the old forest is found in areas that are set aside, the distribution of these areas is important. However, only the locations of formally protected areas are known. Locations and distribution in the landscape of voluntarily set aside areas as well as areas set aside in connection to final felling, which make up 78% of the area set aside in productive forest, are likely to be more or less evenly distributed over estates and in connection to final felling. This is however not known for certain and it is not possible to evaluate the ecological functionality of the areas set aside without further studies on the spatial distribution in the landscape and how this changes over time (see, e.g., Mönkkönen et al. 2014; Shifley et al. 2006).

The results on regional level show that most of the remaining old forest in the managed productive forest is harvested in northern Sweden (N and S Norrland) in all scenarios due to the high demand. To satisfy the demand, practically the full potential is harvested which also leads to relatively early final fellings and no old forest left in the managed forest except for areas set aside. In southern Sweden (Svealand and Götaland), the area of old forest is increasing more over time in the scenarios *Intermediate* and *Low demand* compared with the *Supply potential* scenario, meaning that the pressure for harvesting in these scenarios is lower than the potential harvest level.

In comparison to the area of old forest, the area of mature forest with a large share of broadleaved trees is not constrained to the same extent by harvesting. This is an important distinction between the two types of ecological indicators: broadleaved trees will be present also in the managed productive forest since current forest management practices favors broadleaves and the lowest allowable final felling age is high enough for development of this forest type to take place.

The demand projections for woody biomass were calculated using a global model GLOBIOM-EU, which is adapted to the EU but still provides a fairly coarse spatial definition of Sweden compared to the national model Heureka RegWise. To capture the regional differences in the results and allow for best possible estimates of the environmental impacts, we only used the demand for the total harvest volume from GLOBIOM-EU, letting the timber assortments and spatial distribution of the harvests be defined by Heureka RegWise. This approach allowed us to include a global outlook dimension into a national forest analysis without an extensive programming work that would be needed to fully integrate the models. However, as there is no feedback loop from the national model back to the global model, we cannot analyze the effects that the available timber assortments have on the forest product prices. While our estimates provide good grounds for analyzing the ecosystems services impacts of the global scenarios, further work would be needed to analyze the development of the forest-based industrial sector development in Sweden.

In future studies, feedback from the national system (here, Heureka RegWise) should be provided to the global model (here, GLOBIOM-EU), to analyze direct and indirect effects of the national forest management strategies on trade and harvest levels in other countries (cf. Nepal et al. 2016). Such an analysis could provide insight to what would be the consequences, e.g., on trade if wood supply from a specific country would decrease or increase. Additionally, it could be used to investigate where the woody biomass would be produced if the supply from one country would decrease and what the effects of this would be in both economic and ecological terms. As discussed by Kallio et al. (2006), decreased supply of raw material through e.g. increased protection may lead to increased imports and potentially a reduction or restructuring of the forest sector, as well as indirect economic and ecological effects in the places where the biomass is produced instead. Another pertinent topic for future studies is to include carbon storage as an issue in the analysis to see how different demand scenarios and forest policies affect the carbon storage both in the forest and in forest products (see, e.g., Lundmark et al. 2014).

Conclusions

In this study, we show that ambitious policies for global climate change mitigation are likely to result in high harvest levels in Sweden With current forest management practices, the supply of wood from Sweden is seen to be just sufficient to fulfill a high global demand; this would however require mobilization of the full harvesting potential. Consequently, there are intricate trade-offs to be dealt with concerning future forest management and land use. Our study shows also that harvesting to fulfill a high demand could affect negatively the Swedish environmental quality objective *Sustainable forests*, with especially preserving old forests becoming almost fully reliant on protection areas.

The key strength of this analysis is that it combines the detailed knowledge and models on the national level with an overview of the possible global developments in biomass demand. This approach produced results that neither model alone could have provided, showcasing a global outlook that is valuable for discussions on national forest strategies for the future. However, this study is focused on timber production and ecological aspects and based on biophysical and economic modeling that could be developed further and refined. Moreover, it highlights the need for further model development in order to explicitly include different ecosystem services and social aspects in future studies. In a world where global agreements are increasingly affecting individual countries, it is essential that the impacts of international policies are analyzed thoroughly on the national level, using best possible knowledge on both the global development as well as national circumstances.

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Tables

Table 1. The data sources used in the GLOBIOM model framework.

	Europe	Globally
Land cover	Corine land cover maps	GLC2000 (Global Land Cover)
Forest		
Initial forest growing stock	Gallaun et al. (2010)	Kindermann et al. (2008)
Forest NPP	Cramer et al. (1999)	Cramer et al. (1999)
Biomass map	Kindermann et al. (2008)	Kindermann et al. (2008)
Forest species	Fir, spruce, pine, birch, beech, oak and larch	Evergreen, deciduous, needle-leaved, broadleaved
Wood harvesting commodities	pulpwood, sawlogs, traditional firewood/fuelwood, harvesting residues, other wood products)	pulpwood, sawlogs, traditional firewood/fuelwood, harvesting residues, other wood products)
Wood processing residues	bark, black liquor, sawdust, and sawchips	bark, black liquor, sawdust, and sawchips
Semi-finished woody products	sawnwood, mechanical pulp, chemical pulp, plywood, particleboard	sawnwood, mechanical pulp, chemical pulp, plywood, particleboard
Production of commodities as of 2010	FAOSTAT statistics	FAOSTAT statistics
Harvesting costs	Kindermann et al. (2006)	Kindermann et al. (2006)
Agriculture		
Management systems	3 alternative tillage systems and 2 alternative irrigation and fertilization systems	4 different management systems
Coverage of crops	barley, corn, corn silage, cotton, fallow, flax, oats, other green fodder, peas, potato, rapeseed, rice, rye, soybeans, sugar beet, sunflower, soft- and durum wheat	barley, dry beans, cassava, peas, corn, cotton, groundnuts, millet, potato, rapeseed, rice, soybeans, sorghum, sugar cane, sunflower, sweet potatoes, wheat, palm oil
Production of commodities as of 2010	EUROSTAT statistics	FAOSTAT statistics
Livestock		
Production systems	8 aggregate systems for ruminants	8 aggregate systems for ruminants
Species aggregates	cattle and buffaloes (bovines), sheep and goats (small ruminants), pigs, and poultry	cattle and buffaloes (bovines), sheep and goats (small ruminants), pigs, and poultry
Total animal products	beef, lamb, pig, and poultry meat, bovine and small ruminant milk and eggs	beef, lamb, pig, and poultry meat, bovine and small ruminant milk and eggs
Parametrization of	Herrero et al. 2013	Herrero et al. 2013

production systems		
Trade		
Historical trade flows	Gaulier et al. 2008	Gaulier et al. 2008
Trade calibration approach	Jansson et al. 2009	Jansson et al. 2009
Traded forest products	pulpwood, saw logs, sawnwood, mechanical pulp, chemical pulp, plywood, particleboard	pulpwood, saw logs, sawnwood, mechanical pulp, chemical pulp, plywood, particleboard
Traded agriculture products	barley, corn, corn silage, cotton, fallow, flax, oats, other green fodder, peas, potato, rapeseed, rice, rye, soybeans, sugar beet, sunflower, soft- and durum wheat	barley, dry beans, cassava, peas, corn, cotton, groundnuts, millet, potato, rapeseed, rice, soybeans, sorghum, sugar cane, sunflower, sweet potatoes, wheat, palm oil
Traded livestock products	beef, lamb, pig, and poultry meat, bovine and small ruminant milk and eggs	beef, lamb, pig, and poultry meat, bovine and small ruminant milk and eggs

Table 2. Type and areas of set asides distributed over four regions in Sweden

	Total area of productive forest	Formal reserves	Areas set aside on voluntary basis	Areas set aside in connection to final fellings
N Norrland	6 953	486 (7%)	543 (7.8%)	449 (6.5%)
S Norrland	5 768	105 (1.8%)	319 (5.5.%)	538 (9.3%)
Svealand	5 364	131 (2.4%)	276 (5.1%)	329 (6.1%)
Götaland	5 014	100 (2.0%)	197 (3.9%)	302 (6.0%)
Total for Sweden	23 099	822 (3.6%)	1 335 (5.8%)	1 619 (7.0%)

Table 3. Scenarios used in the study

	Scenario	Basis for the scenario
Supply scenario as in Claesson et al. (2015)	*Supply potential*	SKA15 Current forestry. Forest harvests in Sweden are the highest possible under sustainable yield over time.
Demand scenarios based on Fricko et al. 2016	*Low demand*	RCP8.5: low policy efforts to mitigate climate change, low bioenergy demand.
	Intermediate demand	RCP4.5: intermediate policy efforts to mitigate climate change, intermediate bioenergy demand
	High demand	RCP2.6: ambitious policy efforts to mitigate climate change, high bioenergy demand

Table 4. Outcome of the scenarios for Sweden in terms of demand of woody biomass feedstock for bioenergy production (including solid and liquid woody biomass feedstocks for energy production), production of semi-finished woody products commodities, and net trade of woody products (wood harvesting commodities and semi-finished woody products). The scenarios are here presented as the relative change to 2010.

Variable/Indicator	Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Bioenergy demand	**RCP2.6**	1.00	1.23	1.47	1.61	1.63	1.59	1.86	2.00	2.05	2.07
	RCP4.5	1.00	1.25	1.44	1.57	1.62	1.59	1.57	1.58	1.54	1.53
	RCP8.5	1.00	1.25	1.43	1.57	1.60	1.56	1.53	1.56	1.52	1.52
Production of semi-finished woody products	**RCP2.6**	1.00	1.08	1.16	1.22	1.27	1.27	1.34	1.41	1.47	1.48
	RCP4.5	1.00	1.09	1.16	1.21	1.26	1.27	1.28	1.29	1.32	1.34
	RCP8.5	1.00	1.09	1.17	1.22	1.26	1.27	1.27	1.28	1.29	1.30
Net trade of woody products	**RCP2.6**	1.00	1.32	1.68	1.85	1.91	1.91	1.79	1.90	1.87	1.86
	RCP4.5	1.00	1.33	1.70	1.74	1.86	1.88	1.91	1.91	1.93	1.93
	RCP8.5	1.00	1.33	1.69	1.83	1.90	2.02	2.04	2.05	2.05	2.06

Table 5. List of the wood production variables and environmental indicators used in this study.

Variable/Indicator	**Definition**
Sawlogs	Length of logs >=310 cm and <=550 cm. Diameter at the top >=12 cm.
Pulpwood	Length of logs >=300 cm and <=500 cm. Diameter at the top >=5 cm.
Area of old forest	Forest age >140 years in northern Sweden (Norrland, Dalarna, Värmland och Örebro counties), and >120 years in the rest of the country
Area of old forest, rich in broadleaved trees	Forest in which >=25% of the basal area consists of broadleaved trees and the forest age is >80 years in northern Sweden (Norrland, Dalarna, Värmland and Örebro counties), and >60 years in the rest of the country.

Figure captions

Figure 1. Map of Sweden with the four regions delineated.

Figure 2. Schematic description of the model interlinkage.

Figure 3. Total harvest of wood projected for Sweden for 2010-2100 in the supply scenario (*Supply potential*) and in the demand scenarios (*High, Intermediate* and *Low demand*), as well as the historical harvest development for 1956-2009 (SFA 2014).

Figure 4. Volume of pulpwood and sawlogs harvested in the different scenarios.

Figure 5. The development of old forest area in the supply and demand scenarios on all productive forest land and on the share of productive forest land managed for biomass production and the historical development on all productive forest land (Swedish NFI 2015).

Figure 6. The development of old forest area on all productive forest land in the four regions of Sweden in the *Supply potential* and the *Intermediate demand* scenarios, and the historical development on all productive forest land in the regions (Swedish NFI 2015).

Figure 7. Development of the area of old forest rich in broadleaves in the different supply and demand scenarios and the historical development for managed productive forest (Swedish NFI 2015).

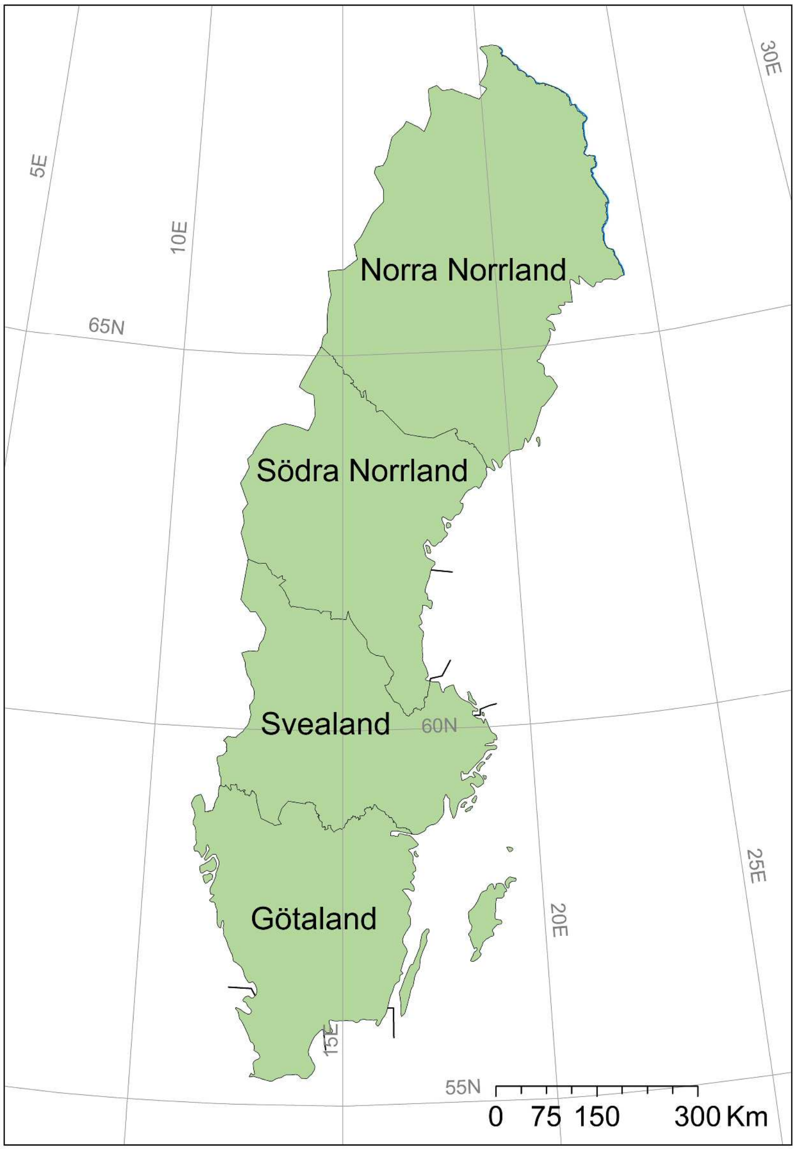

Figure 1. Map of Sweden with the four regions delineated.

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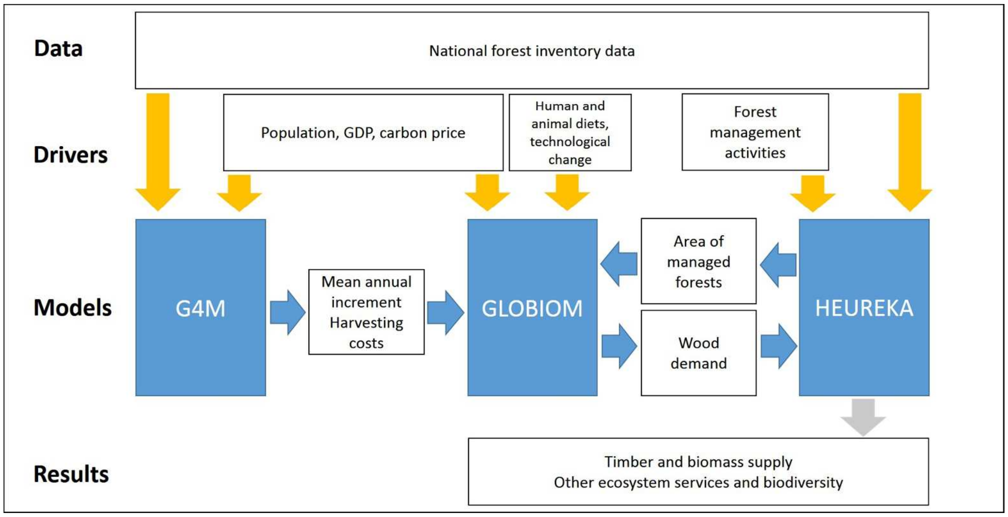

Figure 2. Schematic description of the model interlinkage.

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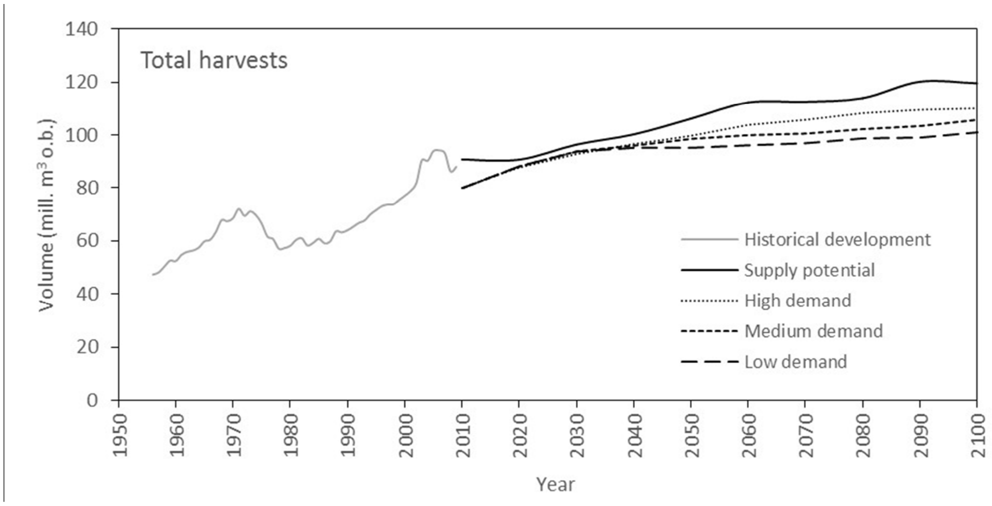

Figure 3. Total harvest of wood projected for Sweden for 2010-2100 in the supply scenario (Supply potential) and in the demand scenarios (High, Intermediate and Low demand), as well as the historical harvest development for 1956-2009 (SFA 2014).

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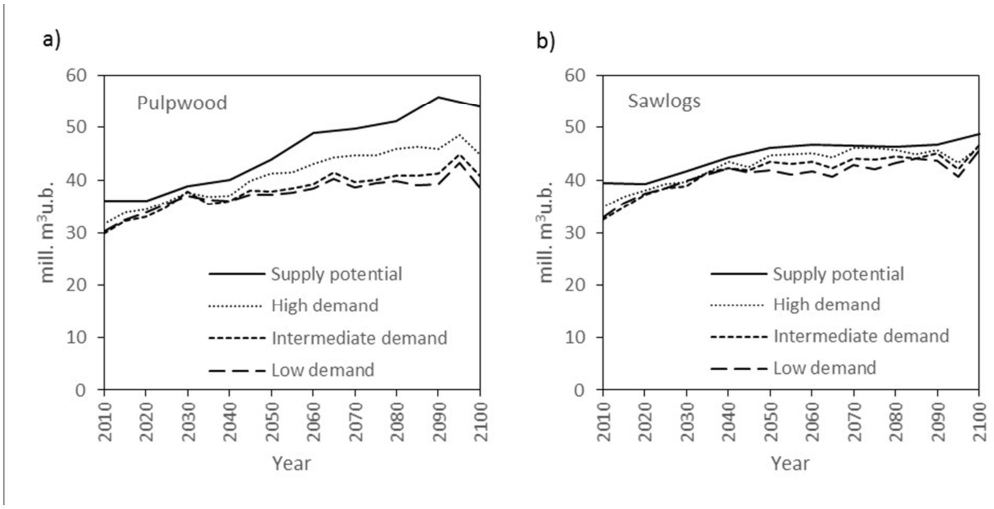

Figure 4. Volume of pulpwood and sawlogs harvested in the different scenarios.

160x80mm (150 x 150 DPI)

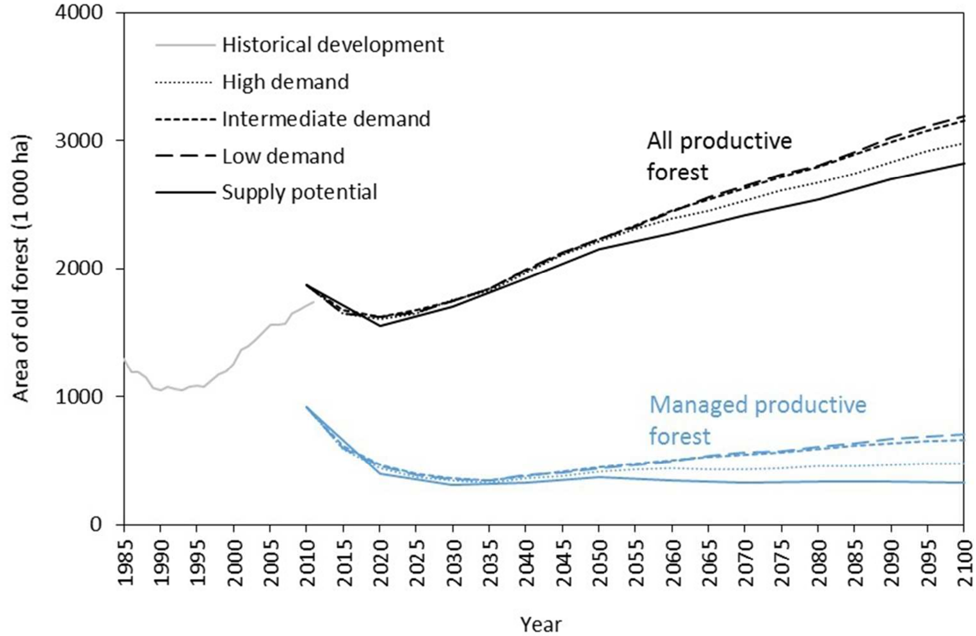

Figure 5. The development of old forest area in the supply and demand scenarios on all productive forest land and on the share of productive forest land managed for biomass production and the historical development on all productive forest land (Swedish NFI 2015).

150x100mm (150 x 150 DPI)

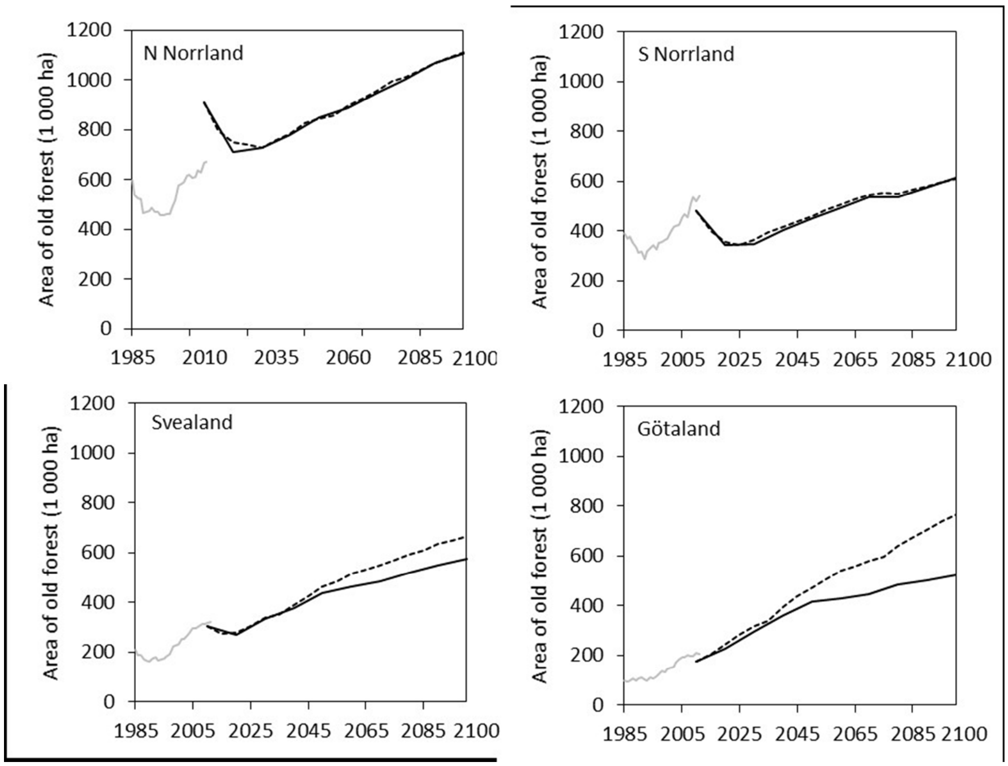

Figure 6. The development of old forest area on all productive forest land in the four regions of Sweden in the Supply potential and the Intermediate demand scenarios, and the historical development on all productive forest land in the regions (Swedish NFI 2015).

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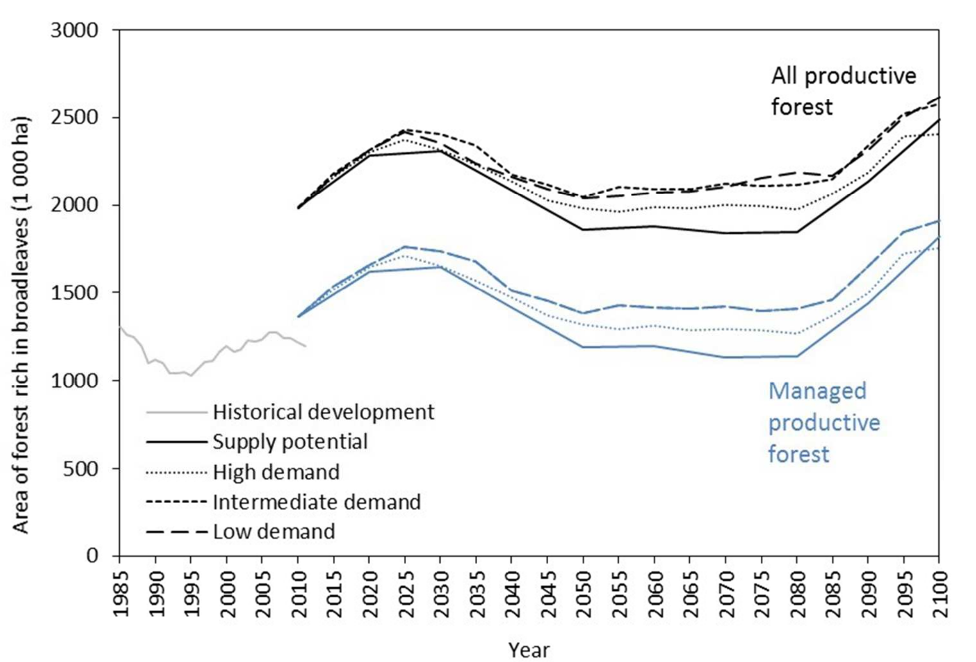

Figure 7. Development of the area of old forest rich in broadleaves in the different supply and demand scenarios and the historical development for managed productive forest (Swedish NFI 2015).

150x100mm (150 x 150 DPI)