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ORIGINAL ARTICLE

Integrated scenario modelling of energy, greenhouse gas emissions and forestry

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Abstract Preventing dangerous climate change requires actions on several sectors. Mitigation strategies have focused primarily on energy, because fossil fuels are the main source of global anthropogenic greenhouse gas emissions. Another important sector recently gaining more attention is the forest sector. Deforestation is responsible for approximately one fifth of the global emissions, while growing forests sequester and store significant amounts of carbon. Because energy and forest sectors and climate change are highly interlinked, their interactions need to be analysed in an integrated framework in order to better understand the consequences of different actions and policies, and find the most effective means to reduce emissions. This paper presents a model, which integrates energy use, forests and greenhouse gas emissions and describes the most important linkages between them. The model is applied for the case of Finland, where integrated analyses are of particular importance due to the abundant forest resources, major forest carbon sink and strong linkage with the energy sector. However, the results and their implications are discussed in a broader perspective. The results demonstrate how full integration of all net emissions into climate policy could increase the economic efficiency of climate change mitigation. Our numerical scenarios showed that enhancing forest carbon sinks would be a more cost-efficient mitigation strategy than using forests for bioenergy production, which would imply a lower sink. However, as forest carbon stock projections involve large uncertainties, their full integration to emission targets can introduce new and notable risks for mitigation strategies.

Keywords Climate change mitigation · Energy systems · Forests · Carbon sink · Scenario analysis

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1 Introduction

The energy sector has a central role in climate policies, since it is responsible for more than 60% of the global greenhouse gas (GHG) emissions (IEA 2015). A majority of these emission arise from the combustion of fossil fuels, which currently satisfy roughly 80% of total global primary energy demand, despite the ongoing efforts to shift towards more sustainable energy systems (IEA 2015).

Forests are closely interlinked with both climate change and the energy sector (see Fig. 1). As a part of the global carbon cycle, they capture, store and release carbon through natural processes. If a forest absorbs more carbon than it releases, it acts as a carbon sink and contributes to climate change mitigation. Deforestation—the permanent clearing and combustion of forest biomass—on the other hand is a significant component in global GHG emissions. Large differences in forest carbon sink and emission occur between regions: in some regions, forests are a net carbon sink whereas in others, they form a significant source of emissions due to deforestation (Pan et al. 2011). In the European Union (EU), forests comprise a net sink, corresponding about 10% of total emissions in recent years (Eurostat 2016).

Forests are also a source of bioenergy and wood material, which can be used for substituting fossil fuels and replacing more energy- and emission-intensive materials. These can contribute to emission reductions, especially if bioenergy is considered carbon neutral and wood is used for long-lived products, which act as a carbon stock. The carbon neutrality of sustainably grown biomass is often justified by the rationale that carbon released during the biomass combustion is sequestered back into forests during the regrowth (Schlamadinger et al. 1995). However, a significant time delay exists before the carbon released during biomass combustion is sequestered back to the re-growing biomass, causing temporary increase in CO_2 concentration in the atmosphere (see e.g. Pingoud et al. 2016), and the same argument also holds with short-lived wood products. Thus, trade-offs exist between increasing the forest carbon sink and using forests for energy or material substitution.

An ambitious global agreement was adopted in Paris in 2015 to restrict the increase in average global temperature below 2 °C and striving towards 1.5 °C above pre-industrial levels (UNFCCC 2016a). Forestry and other land-use have indisputable climatic importance, and meeting the ambitious emission targets requires the mobilization of all relevant sectors. A majority of countries have included land-use and forestry in their mitigation contributions to the Paris Agreement (UNFCCC 2016b).

As a part of the global mitigation action, the European Union (EU) is committed to cut its greenhouse gas emissions substantially in order to tackle dangerous climate change.

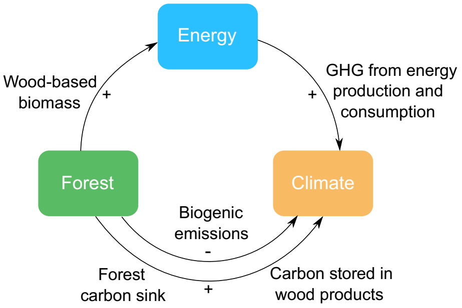

Fig. 1 The main linkages between climate, energy and forests. The *plus and minus signs* refer to positive (+) and negative (−) influences. *Biogenic emissions* refer here to the emissions related to the natural carbon cycle as well as those resulting for example from the production, harvesting, combustion and processing of wood-based materials

The long-term target is to reduce emissions by 85–90% by 2050 compared with 1990 levels, which is in accordance with the objective to restrict the global warming below 2 °C (European Commission 2011).

Land-use and forestry have gained increasing attention also in the EU climate policy. The European Commission has proposed a separate target and accounting rules for land-use, land-use change and forestry (LULUCF) as a part of its 2030 targets (European Commission 2016). While the extent of land-use accounting in 2030 policy will still be limited—e.g. due to the restricted amount of accountable carbon sinks from forestry—a more comprehensive consideration for land-use and forestry carbon stocks can be expected to emerge towards 2050.

Another major development within the EU is the aim to shift towards a bioeconomy, which refers to a sustainable production and conversion of renewable biological resources, and promotes the enhanced use of bio-based products and bioenergy (European Commission 2012; Scarlat et al. 2015). In addition, several countries within the EU have their own bioeconomy strategies (Dieckhoff et al. 2015).

Both the enhanced role of forest in climate policy and the bioeconomy strategies reinforce the interactions between energy, forestry and greenhouse gas emissions. Thus, better understanding of the linkages and cross-sectoral impacts of different actions and policies is important in establishing coherent climate, energy, forestry and bioeconomy strategies, and finding the synergies and trade-offs between them. Interactions between the sectors are of particular relevance for countries with large forest resources, and may become even more important if the integration of forests into climate policies will be further strengthened in the future.

We present here a quantitative scenario model that integrates energy, forestry and greenhouse gas emissions into a single framework. Such a model allows to study the interactions and the impacts of various policies between the sectors, and to optimize the system as a whole, instead of optimizing actions separately in each sector.

A number of large-scale models exist that focus on a single sector, such as Global Forest Model (G4M) and European Forest Information Scenario Model (EFISCEN) on forestry (Böttcher et al. 2012) or Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) on energy (Riahi et al. 2007). Of the global integrated assessment models (IAMs), only few cover land-use, energy and greenhouse gas emissions, for example Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al. 2014), Global Change Assessment Model (GCAM) (Brenkert et al. 2003; Joint Global Change Research Institute 2016) and Integrated Global System Modelling (IGSM) (Sokolov et al. 2005). However, according to the authors' knowledge, none of the existing models contain a detailed physical representation of the energy system, forest growth and greenhouse gas emissions to allow a full and integrated analysis of climate policies and emission targets with a single model.

The new integrated model uses the TIMES modelling framework (TIMES, The Integrated MARKAL-EFOM System, where MARKAL stands for Market Allocation and EFOM for Energy Flow Optimization Model). The specific application for numerical analyses is TIMES-VTT, a global energy system model (see e.g. Koljonen and Lehtilä 2015) which includes a detailed representation of the energy system and the associated GHG emissions. In earlier implementations of TIMES-VTT, wood supply was external and any changes on wood-use did not affect net GHG emissions. By supplementing TIMES-VTT with a novel forest module, which includes a physical representation of forest growth and carbon sequestration as forests are subjected to management activities, wood-use by the forest industry and for energy has a direct link to the forest resources and affects the forest carbon stock.

The forest module is first presented in a general form that could be applied in global, regional and national modelling contexts. Here, the integrated model is calibrated and applied to the case of Finland, which serves as a good example of a country with highly interlinked energy and forest sectors. Roughly 80% of GHG emissions in Finland arise from the energy sector while the large forest resources act as a notable carbon sink, varying from 30 to 60% of the gross emissions between 1990 and 2015 (Statistics Finland 2015). Finland is committed to the EU's climate policies while also having its own national climate, energy and bioeconomy strategies (Energy and Climate Strategy 2013; Bioeconomy Strategy 2014), in which forests have an important role both as a source of renewable energy and raw material.

Scenario analysis is used for studying the cross-sectoral interactions of energy, climate and forests, as well as the potential implications of enhanced bioeconomy and full inclusion of net forest carbon sinks into emission reductions targets. Broader applications of the integrated modelling approach include analyses of competition between tropical bioenergy plantations and deforestation (Persson 2012) or using afforestation and reforestation for mitigation (Zomer et al. 2008).

The structure of the paper is the following. Section 2 describes the developed forest module, the validation of the module and its integration into the TIMES-VTT integrated assessment model. Section 3 presents three scenarios that demonstrate different uses of the integrated model, analysing the intersectoral interactions and connecting points between climate change, forests and the bioeconomy. Last, Section 4 provides the conclusions from the results and discussion on further research.

2 The model

2.1 Model overview

TIMES is a bottom-up, techno-economic partial-equilibrium model framework (Loulou and Labriet 2008). It can be used to create long-term scenarios for analysing energy and environmental issues, e.g. studying the impacts of different policies such as energy taxes or emission targets. Analyses can be conducted on global, regional and national scales.

TIMES-VTT, a particular application of TIMES, covers the global energy system from primary sources to end-use energy services, including various transformation processes such as refining and power generation. The model contains detailed description of the currently available and future technologies, including data for example on their inputs, outputs and unit costs. The total costs of the energy system are minimized using linear programming, while number of constraints need to be satisfied and the demand for energy services have to be fulfilled. TIMES assumes price-elastic demand, competitive markets and perfect foresight. Policies can be modelled through user-defined elements like taxes, subsidies and emission limits.

For analysing climatic issues, TIMES-VTT includes a climate module, which calculates the changes in the atmospheric GHG concentrations, radiative forcing and global mean temperature. The model contains all greenhouse gases listed in the Kyoto Protocol—including also non-energy emissions such as waste and agricultural emissions—and their associated processes. In addition, the model includes technologies for reducing emissions as well as their costs.

In earlier versions of TIMES-VTT, bioenergy involved zero emissions and wood consumed for industrial uses, and energy had no connection to forest resources. Thus, the sinks and emissions from land-use, land-use change and forestry (LULUCF) sector were ignored.

The newly developed forest module describes the growth and carbon stocks of managed forests, enabling to examine the dynamics of forest carbon sequestration under different wood-use scenarios. The level of carbon stock depends on the total stem volume of forests, which is affected by forest growth and management activities. Two types of management activities are allowed in the forest module: thinnings and final fellings, which have direct effect on total stem volume. In addition, thinnings affect the growth rate, while final fellings affect the age distribution of forests, and thus, management activities have also more prolonged effects on forests. Emissions and sinks from other land-use categories than forests are excluded from the analyses.

In the following subsection, the general forest model is introduced in a non-linear form. This is then linearized, allowing its integration into TIMES, which is based on linear optimization. Understanding the mathematical formulation is not, however, necessary for grasping the main insights from the rest of the paper. The forest module is implemented with General Algebraic Modelling System (GAMS) and it can be used either as a stand-alone model or as a part of TIMES.

2.2 The forest module

The forest module is a dynamic age-class model where forest management is based on even-aged stand management. In even-aged management, a forest stand goes through a repetitive cycle, which includes regeneration, growing, thinnings and final felling. After being clear-cut in final felling, the rotation starts from the beginning.

The total forest area of age class τ_k $(k \in 1, 2, ..., K)$ at time t_j $(j \in 1, 2, ..., J)$ is denoted as $A(t_j, \tau_k)$. The modelling horizon is divided into $(T - t_1)/b$ periods, where b (years) is the length of the period and assumed to stay constant. The age classes are assumed to have the same interval b, which means that a forest stand spends b years in age class τ_k before shifting to the age class τ_{k+1}. Total forest area in each age class is affected by final fellings. Within each period, the annually felled area is assumed to be constant and is denoted as $H(t_j, \tau_k)$. For simplicity, final fellings are assumed to be carried out at the beginning of each period. Thus, the final felled area within age class τ_k at the time t_j is $b \cdot H(t_j, \tau_k)$, and the total area after final fellings—except for the first and last age classes—is

$$A(t_j, \tau_k) = A(t_{j-1}, \tau_{k-1}) - b \cdot H(t_j, \tau_k), \quad \text{if} \quad 1 < k < K. \tag{1}$$

New forest is assumed to be planted immediately after final fellings. Thus, the forest area of the first age class depends on the final felled area and the change in the total forest area, which is denoted here as z:

$$A(t_j, \tau_1) = b \cdot \sum_k H(t_j, \tau_k) + z. \tag{2}$$

If the total forest area stays constant, area of the new planted forest equals the final felled area ($z = 0$). If the total area is reduced, for example due to clearing of the land for cultivation, $z < 0$. If the total area is increased, for example due to reforestation, $z > 0$. The area of the last age class, τ_K, is reduced only through final fellings:

$$A(t_j, \tau_K) = A(t_{j-1}, \tau_{K-1}) + A(t_{j-1}, \tau_K) - b \cdot H(t_j, \tau_K). \tag{3}$$

The area of each age class is converted to a stem volume of unthinned forest, $V_{\text{unthin}}(t_j, \tau_k)$, by multiplying it by the average stem volume per unit area at the given age, $\rho(\tau_k)$:

$$V_{\text{unthin}}(t_j, \tau_k) = A(t_j, \tau_k) \cdot \rho(\tau_k). \tag{4}$$

This is further converted to a stem volume of managed forest by taking into account the influence of thinnings. A term thinning deficit, $d(t_j, \tau_k)$, is used here for describing the percentual decrease in the stem volume of the managed forest compared with unthinned forest. Thinning deficit at a given time depends on the thinnings performed at that time and in the previous periods. Because of the accelerated growth after thinnings in respond to additional space and resources available, the thinning deficit decreases over time. However, the stem volume of managed forest should not exceed the volume that would be achieved if no thinnings were carried out. Therefore, the thinning deficit should approach zero at infinity. Both of these characteristics apply with an exponentially decreasing thinning deficit, which is thus used in the model. Thinning deficit of the age class τ_k at the time t_j is expressed as

$$d(t_j, \tau_k) = d(t_{j-1}, \tau_{k-1}) \cdot e^{-bx} + p(t_j, \tau_k), \quad p(t_j, \tau_k) \epsilon [0, 1], \tag{5}$$

where x is a constant, $p(t_j, \tau_k)$ is the percentage of the total stem volume that is thinned from the age class τ_k at the time t_j, and the term e^{-bx} describes the rate by which the thinning deficit is reduced within one period. The stem volume of managed forest, $V_{\text{man}}(t_j, \tau_k)$, can be expressed as

$$V_{\text{man}}(t_j, \tau_k) = V_{\text{unthin}}(t_j, \tau_k) \cdot [1 - d(t_j, \tau_k)] = A(t_j, \tau_k) \cdot \rho(\tau_k) \cdot [1 - d(t_j, \tau_k)]. \tag{6}$$

As the Eq. 6 is non-linear, it needs to be linearized to enable the integration of the forest module into TIMES. The linearization is carried out by restricting the choice of thinning percentage to given discrete options instead of enabling the model to choose it freely between 0 and 1. The thinning percentage of certain forest stand is determined by the thinning intensity class, i, which is determined by the model at the time of initiation of the stand and is assumed to stay unchanged until the stand is final felled. Thus, a given forest stand is thinned similarly at every period during each rotation of the stand. If the minimum and maximum thinning percentages are respectively set to zero and P (where $P < 1$), and the options have uniform intervals, the percentage of thinned stem volume in a certain forest stand can be expressed as

$$p(i) = (i - 1) \cdot \frac{P}{I}, \quad i = 1, 2, ..., I,$$

Now, the thinning deficit is time independent and can be stated in terms of age and thinning intensity:

$$\begin{cases} d(\tau_Y, i) = p(i) \\ d(\tau_{Y+1}, i) = d(\tau_Y, i) \cdot e^{-bx} + p(i) = p(i) \cdot e^{-bx} + p(i) \\ d(\tau_{Y+2}, i) = d(\tau_{Y+1}, i) \cdot e^{-bx} + p(i) = p(i)e^{-2bx} + p(i) \cdot e^{-bx} + p(i) \\ \vdots \\ d(\tau_K, i) = p(i)e^{-(K-Y)x} + p(i)e^{-(K-Y-1)x} + \cdots + p(i) \cdot e^{-bx} + p(i), \end{cases}$$

where τ_Y is the age class for which the first tinning is carried out. By using the formula for a geometric sum, the thinning deficit can be stated in the following form:

$$d(\tau_k, i) = \begin{cases} 0, & \text{if} \quad k < Y \\ p(i) \cdot \frac{1-e^{(k-Y+1)bx}}{1-e^{-bx}}, & \text{if} \quad k \geq Y. \end{cases}$$

The area according to the time, age and thinning intensity class is

$$A(t_j, \tau_k, i) = \begin{cases} b \cdot H(t_j, \tau_1, i) + z, & \text{if} \quad k = 1 \\ A(t_{j-1}, \tau_{k-1}, i) - b \cdot H(t_j, \tau_k, i), & \text{if} \quad 2 \leq k \leq K - 1 \\ A(t_{j-1}, \tau_{K-1}, i) + A(t_{j-1}, \tau_K, i) - b \cdot H(t_j, \tau_K, i), & \text{if} \quad k = K, \end{cases}$$

The total area in age class τ_k can be derived by summing over the intensity classes:

$$A(t_j, \tau_k) = \sum_i A(t_j, \tau_k, i).$$

Now, the linearized form of the Eq. 6 is

$$V_{\text{man}}(t_j, \tau_k) = \sum_i V_{\text{man}}(t_j, \tau_k, i) = \sum_i A(t_j, \tau_k, i) \cdot \rho(\tau_k) \cdot [1 - d(\tau_k, i)].$$

The total stem volume is converted to forest biomass by multiplying it by a biomass expansion factor (BEF). This is further converted to the forest carbon stock by multiplying the total biomass by the carbon content of biomass (c):

$$C_{\text{stock}}(t_j) = \sum_k V_{\text{man}}(t_j, \tau_k) \cdot \text{BEF} \cdot c. \tag{7}$$

The quantity of the forest carbon sink or source is calculated as the change in the carbon stock between successive time steps:

$$C_{\text{sink}}(t_j) = \frac{C_{\text{stock}}(t_j) - C_{\text{stock}}(t_{j-1})}{b} \cdot \frac{44}{12}, \tag{8}$$

where the last term is the fraction of carbon dioxide and carbon molar masses. The Eqs. 7 and 8 represent only the carbon stored in living trees. The model omits, for example, carbon stored in soil, dead trees, stumps and other harvest residues left on the forest site after final felling.

2.3 Parameter values

In this paper, the forest module is applied on Finland due to the availability of sufficiently detailed forest data. This section provides the parametrization of the model for this purpose. Given sufficient data on forest area per age class, forest volume as a function of age, thinnings (if applied) etc., the forest module could be expanded to the full global scope of the TIMES-VTT model. Although recent research has produced global maps of forest cover (Hansen et al. 2013) and tree density (Crowther et al. 2015), such data is still insufficient for calibrating the forest module presented here.

The module covers the forest land available for wood production, about 18,500 ha or 91% of the total forest land in Finland, excluding for example low-productivity forest land and conservation areas (Natural Resources Institute Finland 2012). The forest land is divided into two regions: Northern and Southern Finland. All forests within the regions are approximated as one forest stand with the same averaged growth and yield. The modelling horizon is 2010−2100 and a 10-year time step is used ($t_1, t_2, ..., t_J = 2010, 2020, ..., 2100$). The total forest area is divided into 17 age classes with 10-year intervals so that the first class includes all 0–10-year-old forests (average age of 5 years) and the last all over 160-year-old forests ($\tau_1, \tau_2, ..., \tau_K$ = 5, 15,..., over 160). The initial age class distribution within regions is based on the 11th National Forest Inventory (NFI11) which was carried out in 2009−2013 (Natural Resources Institute Finland 2012).

The total forest area is assumed to stay constant ($z = 0$). This is based on the facts that in Finland forest legislation obligates the owner to plant a new forest after final felling (Ministry of Agriculture and Forestry 1996) and the total forest area has stayed relatively constant since the cessions of territory in 1944 (Finnish Forest Research Institute 2013).

Thinning is allowed for forests older than 20 years and the minimum age for final felling is 50 years. These correspond to the current forest management practices in Finland where the first commercial thinning is usually carried out in forests older than 15−20 years and regeneration maturity is reached at the age of 40−60 years depending on the location (Äijälä et al. 2014). Eleven thinning intensity classes ($I = 11$) are set with a 20% upper limit for the thinning percentage ($P = 0.2$). The upper limit is set to keep thinnings at a reasonable level and to prevent the thinning deficit from increasing unrealistically high. The total harvests in 2010 are fixed according to the realized harvests.

The average stem volume of unmanaged forest is represented in the form of a yield curve, which is estimated from the NFI11 data. The curve is assumed to be s-shaped, start from the origin and saturate as the forest ages (see e.g. Nabuurs et al. 2013). At first, yield curves are estimated separately for 14 regions corresponding the provincial forestry centres in Finland for which the inventory data is collected. Yield curves for Southern and Northern Finland are obtained by taking area-weighted-average of the region-specific curves and are presented in Fig. 2. The yield curves are assumed to stay unchanged during the whole modelling horizon, excluding, e.g. the effects of climate change on future forest growth (see e.g. Matala et al. 2005).

The initial thinning deficit for each age class is adjusted so that the total stem volume by age class corresponds to the stem volumes of NFI11. The area within each age class at the beginning of the first period is divided into thinning intensity classes so that the total thinning deficit of each age class equals the initial thinning deficit.

The exponent x (see Eq. 5) is obtained by fitting exponential reduction to the thinning deficit estimates of the Motti model (Matala et al. 2005). The exponent is estimated separately for three main species (see Fig. 3), after which a volume-weighted-average is taken, yielding to a national-level estimate $x = 0.033$. The total volumes of the tree species are derived from the NFI11 data.

A constant value 0.72 Mgm^{-3} is used for the biomass expansion factor. It is obtained as area-weighted-average from the species specific BEFs estimated by Lehtonen et al. (2004). The assumed carbon content of biomass is 50%.

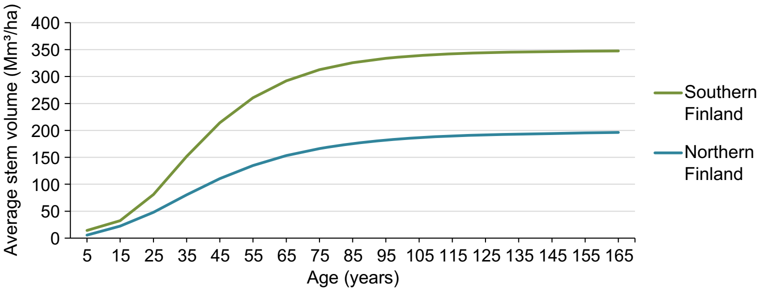

Fig. 2 The stem volume yield curve used in the forest module. It represents the average stem volume per unit area in unmanaged forests

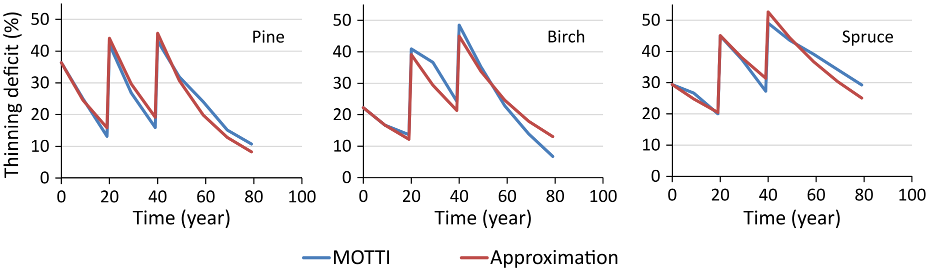

Fig. 3 Thinning deficit in pine, birch and spruce stands in the Motti model (Matala et al. 2005) and the fitted approximation with exponentially decreasing thinning deficit. The time series starts from the first thinning and the following thinnings are carried out 20 and 40 years after the first thinning

2.4 Validation of the forest module

The linear, stand-alone forest module is validated by comparing its forest carbon sink estimates with the actual sink during the recent years and with the projections of MELA (Metsälaskelma), a more detailed forestry model (Siitonen et al. 2001). The comparison is carried out with two timber demand scenarios where total harvested volume is fixed on 60 and 86 Mm^3year^{-1} in 2020–2040. These correspond the current and maximum sustainable harvest levels in MELA scenarios, respectively (Natural Resources Institute Finland 2015a).

In 1997–2014, the average annual harvests were 60 Mm^3year^{-1} and forest carbon sink 32 Mt CO_2eq (Natural Resources Institute Finland 2015b; Statistics Finland 2015). The annual harvests varied between 57 and 65 Mm^3 and carbon sink between 22 and 42 Mt CO_2eq, apart from 2009 when harvests were 48 Mm^3 and the carbon sink was 51 Mt CO_2eq because global recession reduced the demand for forest products.

The forest carbon sink and stock at different harvest levels in MELA and the forest module are presented in Fig. 4. The carbon stock in 2010 is at the same level in both models since the starting point is fixed according to the actual stand volume that year according to NFI11. In both models, carbon stock increases when the harvested volume is 60 Mm^3year^{-1} and slightly decreases when the harvested volume is 86 Mm^3year^{-1}. However, the carbon stock is higher in the MELA model in both scenarios. This is due to a larger annual carbon sink

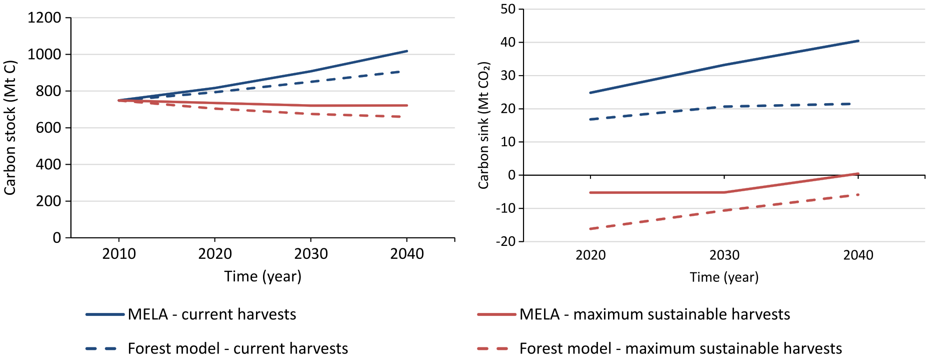

Fig. 4 Carbon sink and stock in MELA and TIMES forest module when total harvested volume is 60 Mm^3year^{-1} (current harvest) and 86 Mm^3year^{-1} (maximum sustainable harvests)

which varies between 25–40 and -5–0 Mt CO_2 when harvests are 60 and 86 Mm^3year^{-1}, respectively. The corresponding figures in the forest module are 17–22 and -16–6 Mt CO_2.

The carbon sink projection of the forest module at the current harvest level is slightly lower than the average sink in recent years and in both scenarios lower than the estimates of the MELA model. The difference with the actual sink in recent years is partly explained by the fact that the forest module covers only the forest land available for wood production, whereas all forest land is accounted in the statistics. The differences with MELA might be explained by different assumptions about forest growth and the more detailed representation of forest dynamics in the MELA model. Variation may occur for example in the growth of old forests, which is especially difficult to predict due to limited data availability. This is especially true in the case of managed forests, which are often final felled before reaching the age of 100 years. In addition, higher natural mortality among older forests—due to increased vulnerability to natural disturbances—is difficult to predict. Due to uncertainties, the assumed growth of old forests is very conservative in the forest module, assuming the saturation of growth before the age of 100 years.

Altogether, the carbon sink projections of the forest module seem to be of the right magnitude but rather conservative. However, high uncertainties are involved in predicting the forest growth and carbon sequestration (Monni et al. 2007b; Kangas 1997) and the carbon sink has varied considerably between years, even at relatively constant harvest levels. In addition, the future impact of climate change on forest growth and natural disturbances is still unclear. Due to these high uncertainties, future carbon sink projections can in any case be only seen as indicative estimates. Yet, the carbon sink estimates of the forest module are sufficiently accurate for the purpose of the model, which is to study the interactions between climate, energy and forest sectors, rather than to predict the exact amount of the future carbon sink.

3 Scenarios

3.1 Scenario assumptions

Three scenarios are presented in order to demonstrate the potential applications of the integrated TIMES-VTT and forest module system, and to study the interactions between energy, climate and forest sectors. The emission limits for Finland and EU are based on the Energy and Climate Roadmap 2050 of Finland (Parliamentary Committee on Energy and Climate Issues 2014) and the European Commission Low Carbon Roadmap 2050 (European Commission 2011), respectively. They both state target to reduce emissions by at least 80% by 2050. The accounting rules of forest carbon sink in the emission reductions of Finland are varied between the scenarios. In other regions, emission limits apply only to other sectors than LULUCF and are kept unchanged in all scenarios. The emission target for the European Union corresponds to the European Commission Low Carbon Roadmap 2050 and for the rest of the world to the 2 °C global warming pathway. The targets are set as overall targets, and the model will optimize in which sectors the emission reductions are carried out.

In addition to analysing the forest carbon sink, we portray a simple example on how a growing emphasis towards bioeconomy could affect the considered sectors. Bioeconomy is a very broad concept, and the products that might be made from biogenic materials are numerous (Scarlat et al. 2015). However, our demonstration considers a simple substitution of concrete with wood. While substituting concrete—the production of which is very energy- and emission-intensive—could provide major emission reduction benefits, the interaction with the forest carbon sink and bioenergy use makes the overall impact of this substitution non-trivial to assess (Gustavsson et al. 2006). Thus, this case provides a good case for demonstrating integrated analysis.

The scenarios are defined as follows:

Reference The 2050 emission target for Finland is -80% compared with 1990 level. The 2050 target level is 14.3 Mt CO_2eq and a linear target pathway is assumed between 2010 and 2050, after which emissions stay at 2050 level or below. Sinks and emissions from the LULUCF sector are not taken into account in emission reductions, and thus, the reductions have to be achieved within other sectors. A small negative price (-0.1 $/Mt CO_2eq) is set for forest carbon sink.[1]

Forest sink The emission target is set to equal to the resulting net emissions in the *Reference* scenario. Net emissions refer here to the total emissions including changes in forest carbon stock but excluding other emissions and sinks from LULUCF. Forest carbon sink can be fully utilised in achieving the target.

Bioeconomy The same emission limit, accounting rules and price for the forest carbon sink are applied as in the *Reference* scenario. In addition, a separate assumption is made for concrete substitution: 30% of the total concrete consumption is replaced with wood, which corresponds about half of the concrete used for housebuilding. One kilogramme of wood is assumed to substitute for 3.6 kg of concrete (Pingoud et al. 2000).

3.2 Results

3.2.1 GHG emissions and forest carbon sink

The total emissions are highly influenced by the emission targets, but variation between scenarios exist due to different target settings. The *Reference* and *Bioeconomy* scenarios have the same emission limit for total emissions excluding LULUCF (see dashed line, *total without forest sink*, in Fig. 5). These emissions are significantly higher in the *Forest sink* scenario especially in the mid-century when emissions are more than double compared with those in the other scenarios. The *Reference* and *Forest sink* scenarios have the same emission limit for net emissions which include also forest carbon sinks and emissions but exclude the rest of LULUCF. These emissions are higher in the *Bioeconomy* scenario (see solid line, *total with forest sink*, in Fig. 5). However, when the additional sink in wood constructions is also taken into account, emissions are only slightly higher in the *Bioeconomy* scenario until 2050, and lower in the latter half of the century as the net emissions increase slightly in the other scenarios (see dotted line, *total with forest sink and sink in wood buildings*, in Fig. 5). Increased net emissions result from the decrease in the forest carbon sink and the fact that no additional emission reductions are required in other sectors after 2050.

In all scenarios, managed forests act as a carbon sink rather than a source, with the exception of the year 2030 in the *Bioeconomy* scenario. In the *Reference* and *Forest sink* scenarios, sink increases towards the mid-century, after which it declines. This is due to the decelerated growth of forests as their average age increases. The sink is substantially

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[1] A small negative price is set because otherwise there would be no incentive to care about the forest carbon sink and do rational harvesting decisions, like thin during the stage of fast growth and final fell close or after the saturation of growth. The price is kept small so that it does not affect other decisions made by the model, such as the total harvested volume.

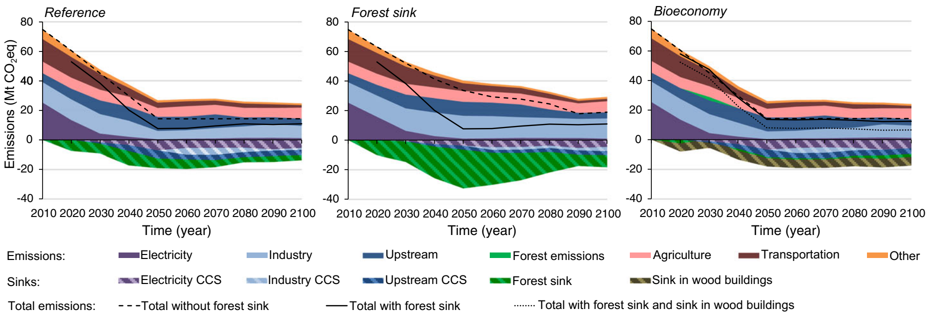


Fig. 5 Greenhouse gas emissions and sinks by sector. Negative emissions result from the use of carbon capture and storage (CCS) as well as sinks in forest and wood buildings. *Total without forest sink* include emissions from all sectors except LULUCF. Total with forest sink adds forest carbon sink to total emissions, but excludes other emissions and sinks from LULUCF. In the *Bioeconomy* scenario, total emissions with forest sink include also additional sink in wood buildings. The category *other* includes commercial and residential emissions and all F-gases

higher in the *Forest sink* scenario compared with that in the other scenarios, sequestering as much as 77% of the emissions in 2050. This is due to the fact that forest carbon sink can be fully utilised in achieving the emission target, which incentivizes sink enhancement for offsetting emissions in other sectors when cost-effective. In the *Reference* and *Bioeconomy* scenarios forests sequester 46 and 4% of the emissions in 2050, respectively. In the *Bioeconomy* scenario, the sink is small throughout the modelling horizon because additional wood is needed for substituting concrete in housebuilding. However, the sum of forest carbon sink and additional sink in wood buildings is almost equal with forest carbon sink in the *Reference* scenario and exceeds it from 2060 onwards. Thus, these results indicate that net climatic effect of the wood substitution is negative in the short term but positive in the long term.

In other sectors, no major differences occur between the *Reference* and *Bioeconomy* scenarios. In the *Forest sink* scenario, instead, emissions are higher especially in electricity and industry sectors. In the *Reference* and *Bioeconomy* scenarios, the net emissions in these sectors decline steeply until 2050 and 2060, respectively. In the *Forest sink* scenario, the decrease is not as fast and the industrial emissions even slightly increase until 2040 before starting to decline. Lower emissions in the *Reference* and *Bioeconomy* scenarios result from the use of less emission-intensive energy sources and more intensive use of carbon capture and storage (CCS). For example, coal consumption is close to zero from 2050 onwards and the use of biofuels is substantially increased in 2010–2060. From 2050 onwards, electricity production is based mainly on emission-free sources—that is renewables and nuclear power. Net emissions in electricity sector are negative from 2040 onwards in all the scenarios, which is possible due to the combined use of bioenergy and CCS. This is based on the assumption that equivalent amount of carbon is sequestered back into living biomass during the regrowth of the plants than was carbon released during biomass combustion, while released carbon is captured and stored in the underground geological formations. As a result, more carbon is sequestered than was initially released into the atmosphere, leading to negative net emissions.

In conclusion, the main trade-offs between different scenarios occur in emissions on electricity, industry and forest sectors. If forest carbon sink is counted in full in emission reductions, higher emissions in the electricity and industry sectors are possible without compromising the net emissions. In the *Forest sink* scenario, substantial emission reductions are achieved by enhancing forest carbon sink, whereas in the other scenarios, CCS has a more important role. In all the scenarios, negative emissions—including forest carbon sink, sink in wood buildings and CCS—decrease after 2050 since no additional emission reductions are required, and thus, the need for carbon sinking is relaxed. The additional bioeconomy target slightly increases net emissions until 2050, but reduces them in the longer term.

3.2.2 Harvested wood

Total harvested volume increases until 2030 from the 2010 level (60 Mm^3year^{-1}) in all the scenarios (see Fig. 6). The harvested volume is highest in the *Bioeconomy* and lowest in the *Forest sink* scenario. In the latter, harvested volume is 66 Mm^3year^{-1} in 2030, after which it decreases until 2050 and stabilises to approximately 55 Mm^3year^{-1}. In the *Reference* and *Bioeconomy* scenarios, harvests stabilise close to 2030 level and remain almost constant until the end of the century, being approximately 71 and 78 Mm^3year^{-1}, respectively.

Higher harvest levels in the *Bioeconomy* scenario result from the substitution of concrete in housebuilding. Compared to the *Reference* scenario, additional harvests of about 5 Mm^3year^{-1} are needed for fulfilling the increased wood demand. In the *Forest sink* scenario, significantly lower harvest rates are obtained due to the economic incentive to increase the forest carbon sink when it is more cost-effective than alternative means to reduce emissions. This creates a competing use of forest resources besides the raw material extraction.

3.2.3 Primary energy supply

Total primary energy supply is relatively equal across the scenarios. The total supply peaks in 2030 after which it decreases towards 2100 (see Fig. 7). The main structural changes in 2010–2100 are the significant reduction in coal and oil supply and increase in the biomass and nuclear power supply. The latter two are the main primary energy sources from 2030 onwards. Their combined share of the total primary energy supply increases from 39% in

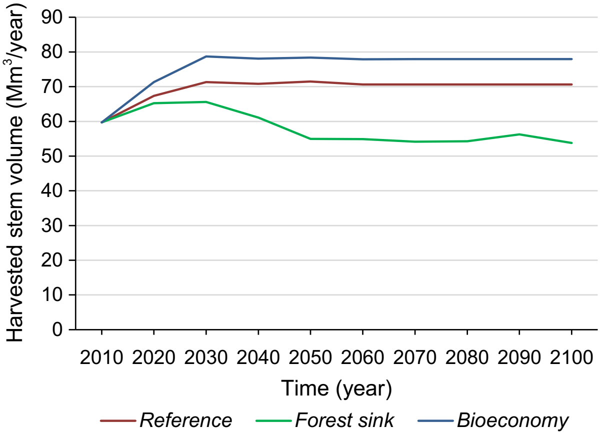


Fig. 6 Total stem volume of harvested wood which is obtained from thinnings and final fellings

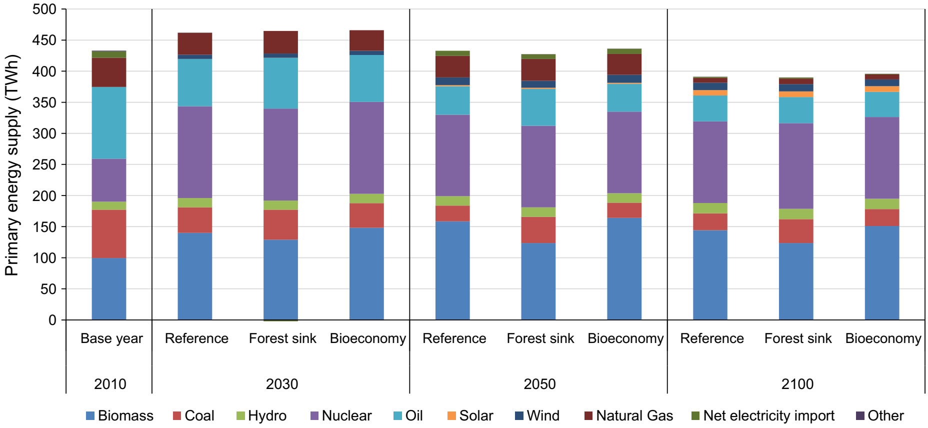


Fig. 7 Primary energy supply by source in 2010, 2030, 2050 and 2100. The supply in the base year 2010 is equal in all the scenarios

2010 to approximately 60% by 2030. The amount of nuclear power is mainly determined by the user-defined assumption about the nuclear power capacity.

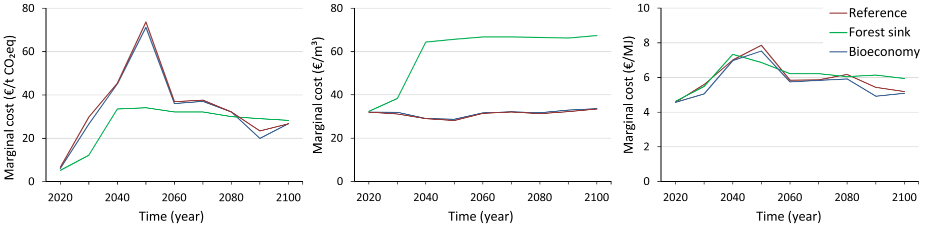
The source-specific primary energy supply differs between the scenarios, especially the biomass and coal supply. In the *Forest sink* scenario, the share of biomass is approximately 30% after 2030, whereas in the *Reference* and *Bioeconomy* scenarios it is 36 and 38%, respectively. The corresponding shares of coal are 10% in the *Forest sink* and 7% in the other scenarios. Biomass supply is lower in the *Forest sink* scenario because it is, at least to some extent, more cost-effective to reduce emissions by increasing forest carbon sink than substituting fossil fuels with biomass. At the same time, coal supply is higher because part of the emissions from coal burning can be offset by forest carbon sink. Also, oil supply is somewhat higher in the *Forest sink* scenario, especially around the mid-century. However, biomass is still the most important primary energy source with nuclear power, indicating that emission target can be achieved cost-effectively by utilising forests both as a source of bioenergy and as a carbon sink.

Between the *Reference* and *Bioeconomy* scenarios, both total and source-specific primary energy supply are almost equal. The small difference in the biomass supply arises from the wood substitution in the *Bioeconomy* scenario, since increased harvest rates increase also the amount of harvest residues available for bioenergy production.

3.2.4 Marginal costs

The marginal cost of emission reductions increases steeply towards 2050 as the emission target becomes tighter. In the *Reference* and *Bioeconomy* scenarios, marginal costs are at the highest 74 and 72 €/t CO_2eq, respectively (Fig. 8). After 2050, marginal costs decrease and reach the level 27 €/t CO_2eq by the end of the century. In the *Forest sink* scenario, the increase is more moderate and marginal cost stay relatively stable after 2040, varying between 28 and 34 €/t CO_2eq.

The difference is highest in 2050, as the marginal cost of emission reductions in the *Forest sink* scenario is less than half compared with that in the other scenarios. The lower marginal cost towards 2050 indicates that emissions could be reduced more cost-effectively if forest sink was fully utilised in the emission reductions. This suggests that the forest sink



(a) *Emission reduction* (b) *Wood raw material* (c) *Solid biomass*

Fig. 8 Marginal costs of emission reductions (**a**), wood raw material (**b**) and solid biomass for energy (**c**)

could replace more expensive means to reduce emissions, like CCS, and offset emissions from cheap but high-emitting energy sources, like coal.

The marginal cost of timber is almost equal and relatively constant in the *Reference* and *Bioeconomy* scenarios, staying between 28 and 34 €/m^3 throughout the century. In the *Forest sink* scenario, however, the marginal cost for timber is more than twice as high between 2040 and 2100. This is due to the increased competition for forest resources, as forest land is used as a carbon sink to meet the emission targets.

The marginal cost of solid biomass does not differ significantly between the scenarios. Biomass consists mainly of forest residues and by-products of forest industry and the supply of solid biomass is mainly dependent of the timber demand of the forest industry. While the *Forest sink* scenario involved a smaller amount of harvested wood, forest residues' carbon stock changes were not accounted for, leading to that the marginal cost effect from the sink did not extend to bioenergy use.

4 Conclusions

In this paper, we introduced a new model integrating energy, forestry and greenhouse gas emissions, and presented three scenarios demonstrating potential applications of the model. The scenarios included differing assumptions on the inclusion of forest carbon stocks in emission targets and the use of wood as raw material, reflecting the current and possible future climate policies and the development of the bioeconomy. The model is generic, and given an appropriate input data, it could be applied to analyse a wide range of global, regional and national settings involving interactions between these three fields, such as competition between bioenergy production and deforestation (see e.g. Persson 2012) or forest management under uniform carbon pricing across the economy (Ekholm 2016).

Scenario results illustrate the interactions between the sectors and diverse impacts of policies on optimal energy production and emission reduction strategies. Different policies involve trade-offs between costs, energy sources, associated risks and net emission reductions. This highlights the importance of analysing all relevant sectors in an integrated framework, taking into account the sectoral dependencies and disclosing trade-offs involved in different policy options.

In terms of policy, we propose countries to adopt emission targets that cover the total net emissions, i.e. including sources and sinks also from land-use and forestry. Integration of all sectors into climate policy enables finding the most cost-efficient measures for reducing net emissions, enhancing the economic efficiency of mitigation—a result expressed clearly in the marginal emission reduction costs of our numerical scenarios. By contrast, ignoring some sectors overlooks the climate impacts of some activities and necessitates cost-*in*efficient emission reductions in other sectors (see also Wise et al. 2009 and Vass and Elofsson 2016 for similar conclusions). The full inclusion of all emission sources and sinks has certain implications for how policy incentivizes emission reduction measures, which are discussed below.

The current formulation of most nations' emission targets imply such ignorance for the climate impact of biomass: it is assumed to have zero emissions when combusted, while the changes in forest carbon stock are not accounted in emission targets. The scenario where emission targets covered also forest sinks involved far less bioenergy use and lower mitigation costs than the scenario which omitted sinks from emission targets. Past analyses have additionally suggested e.g. that the forest sink is expected to decline in the EU towards 2030 due to increased wood harvests for energy and material use (Böttcher et al. 2012). Without more comprehensive integration of the LULUCF sector into climate policy the impact of such activities will be neglected.

Regarding concrete mitigation strategies, our scenarios suggested that enhancing forest carbon sinks would be a more cost-efficient mitigation strategy than using forests for bioenergy production, which would imply a lower sink. Including forest carbon stocks in emission targets, which implies a uniform marginal cost for emission reductions and changes in forest carbon stocks, led to lower harvest rates of managed forests in our results. This echoes with earlier theoretical research that forest sinks could provide highly cost-efficient potential for mitigation, particularly under gradually rising mitigation efforts and carbon prices (Ekholm 2016). Full accounting of forest and land carbon stocks would also provide incentives for adding forest area through afforestation and limiting deforestation, although these were not considered in our scenarios.

Wood-use could be increased without compromising forest carbon stock by using it for long-lived products, such as buildings (c.f. Pingoud et al. 2012). In the short term, such bioeconomy strategy may reduce forest carbon sink due to more intensive fellings, whereas in the longer term, the sink may even increase as forest growth is enhanced through earlier intensive management and carbon remains stored in the wood products for a long time. These temporal dynamics need to be considered as rapid actions are required to prevent hazardous climate change, and as the time-frame of the most climate strategies extends only until 2050. In addition, bioeconomy strategies could be further enhanced if material substitution is accompanied with cascade use of wood, which means that wood products and raw material are recycled and reused, and burned only at the end of the life cycle (Sathre and Gustavsson 2006). Though cascading use of wood already exists, there are still both technical and administrative barriers for the full utilisation of its potential (Vis et al. 2016). All in all, establishing efficient bioeconomy strategies requires understanding the linkages between energy and material substitution as well as their overall impact on the atmospheric carbon balance (see also Scarlat et al. 2015).

The European Commission (2016) proposal for including LULUCF in the 2030 climate policy framework is a step forward in mobilizing all sectors for climate change mitigation, though the role of forests will remain limited. The main difficulty in integrating forests into climate policy is the significant uncertainty involved in land-use carbon sink and source inventories (Monni et al. 2007a). If uncertain and less predictable mitigation efforts substitute for more certain ones, the coherence of climate policy might be diminished.

In addition, uncertainties are involved in the permanence of forest carbon stocks since stored carbon may be released into atmosphere in later periods for example due to natural disturbances or increased fellings (see e.g. Marland et al. 2001). If carbon sink does not evolve as expected, other sectors may be forced to carry out fast and expensive emission reductions, or even lead to failure in achieving the emission target. However, if these issues can be adequately addressed, the integration of forests into climate policy may be enhanced in the future. Several studies highlight the importance of more comprehensive integration of LULUCF into EU climate policy in order to more effectively mitigate climate change (see e.g. Ellison et al. 2014; Haskett et al. 2010; Böttcher et al. 2012)

However, notable uncertainties exist also with other mitigation measures. In the numerical scenarios for Finland, the forest carbon sink, when covered by the emission targets, substituted especially for the use of carbon capture and storage (CCS) in electricity and industry. Yet, large uncertainties persist whether large-scale commercial use of CCS will be feasible (see e.g. Pires et al. 2011), and thus, high risks are also involved under a mitigation strategy relying heavily on CCS. Due to the similarity of sectors across developed countries, this result might be generalized to broader set countries. By extending the forest module to other countries, the generality of these findings could also be verified with the TIMES-VTT model.

Certain caveats pertaining to the model's assumptions and the associated uncertainties should be noted. The area and growth rates of managed forests were assumed to remain constant over time. If either would be increased—e.g. due to climate change enhancing forest growth or forest area expansion through afforestation—the higher carbon sink could reduce the effort and costs needed to achieve the emission reduction targets. Further, expansion of forest conservation areas (Pouzols et al. 2014) would remove some of the modelled area from the influence of thinnings and final fellings, affecting also the carbon sink. On contrary cases—e.g. due to higher forest damages following a warmer climate or increased forest-clearing for cultivation or infrastructure—the sink could be significantly smaller than anticipated. Of these two, a higher uncertainty is perhaps associated with the growth curve, which is based on a limited set of evidence on forest growth in historical climatic conditions. As the growth curve assumption involves a rather conservative growth rate (see Section 2.4), the carbon sink is more likely to be underestimated than overestimated in the model.

In future research, the analyses could be extended to cover a broader set of policy measures, land-use categories and countries. National policies are not in isolation but in a close connection to regional or global policies which should aim to create fair and effective incentives for cost-effective mitigation. The further integration of forest sector into climate policy is not likely to concern only an individual country but be a part of larger climate policy framework—for example within the EU or on a global scale. Because of the uneven distribution of forest resources, the benefits and disadvantages of such a policy can vary between countries, which need to be considered in policy-making.

Climate change mitigation, sustainable management of natural resources and ensuring energy security are significant challenges in the twenty-first century. Resolving them is not an easy task in the face of growing population and increasing energy and raw material demand. Thus, restricting global warming to 2 °C or even below—as outlined in Paris agreement (UNFCCC 2016a)—requires substantial efforts and global co-operation. Since current ambition is not sufficient even for achieving the 2 °C target (UNFCCC 2015), it is important to mobilize emission reduction measures on all sectors of the economy. This creates increasing demand for integrated analysis, which can support in identifying optimal strategies and building comprehensive climate policy framework for efficient climate change mitigation.

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