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Optimal forestry under climate policy

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Academic Dissertation

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ABSTRACT

Climate change mitigation aims to reduce greenhouse gases in the atmosphere. Forest mitigates climate change by accumulating atmospheric carbon to biomass. This biomass can be used to various products which also act as a carbon sink. Carbon sequestration is the opposite of carbon emission, but not fully. Forest carbon storages are uncertain and temporal but the role of forests as temporary carbon storages still has value. However, climate policy must take this into account both in the implementation of policies and in the valuation of carbon sinks.

The thesis consists of four articles and a summary chapter. Articles represent different perspectives of the forest sector and the use of forests and wood products to mitigate climate change. They cover the use of forests from the growth of trees to the use of wood products.

In the first article we analyze with an age-class model how forest owners will change their forest management if there is a subsidy based on the forest carbon storage. The results show that enhancing investments for forest growth increases and that forest rotation will be longer. We also investigate how subsidies for silvicultural investment will affect carbon sequestration of the forest. The second article analyses wood consumption and HWP carbon stock in Finland until 2050. The main HWP carbon pool consists of products made of sawn wood. The HWP carbon pool in Finland seems to increase until 2050 even in the case of decreasing consumption of sawn wood. The third article deals with optimal forest management where the growth of the forest is described by a size-class model. The results show a feature on size-classified matrix models that significantly reduces the comparability of forest management results of these models. The optimal thinning intensity and rotation length of forest are highly dependent of the specification of the model. The fourth article analyzes the existing climate policy for forestry in the EU. Because the policy only applies to one period, we can use a simple two-period model to describe the impact of the policy. The results show that constraints on current climate policy design reduce the potential of using forests to mitigate climate change.

The framework in the summary of the articles complements the conclusions in the articles and builds a view towards a more comprehensive conclusion for governance of forest sector to mitigate climate change.

Keywords: forest economy, rotation, carbon, matrix model, age-class model, reference level

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Thanks to my family and friends for their encouragement. In particular, I want to thank Suvi and Iisa for the joy they brought during the process.

LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. These papers **I–IV** are reprinted with kind permission of the publishers.

I. Uusivuori, J.& Laturi, J. 2007. Carbon rentals and silvicultural subsidies for private forests as climate policy instruments. Canadian Journal of Forest Research 37(12): 2541–2551. https://doi.org/10.1139/X07-071

II. Laturi, J., Mikkola, J. & Uusivuori, J. 2008. Carbon reservoirs in wood products-in-use in Finland: current sinks and scenarios until 2050. Silva Fennica 42(2): 307–324. https://doi.org/10.14214/sf.259

III. Laturi, J., Lintunen, J., Niinistö, S. 2012. Specification of a Size-Classified Matrix Model: The Effects on Growth Predictions and Economically Optimal Harvesting Regimes. Forest Science 58(6): 592–605. http://dx.doi.org/10.5849/forsci.11-011

IV. Laturi, J., Lintunen, J. & Uusivuori, J. 2016. Modeling the Economics of the Reference Levels for Forest Management Emissions in the EU. Climate Change Economics 7(03), 1650006. https://doi.org/10.1142/S2010007816500068

The contribution of Jani Laturi to the studies included in this thesis was as follows:

Summary: Jani Laturi (JL) wrote the summary

Study **I**: JL was responsible for the numerical analysis of the study. JL also participated in the planning and writing of the analytical part of the study.

Study **II**: JL participated in the planning of the study. JL assumed main responsibility for the analysis and writing of sections 1, 3 and 4.2-6 of the article.

Study **III**: The authors jointly planned the study. JL participated in numerical analysis, introduction, results and discussion sections of the study.

Study **IV**: The authors jointly planned the study. JL was primarily responsible for the sections 1, 3 and 4 of the article.

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1 INTRODUCTION

There is an excess of carbon dioxide CO_2 in the atmosphere today compared to pre-industrial time. The reasons for this excess are the emissions from human activities such as the use of fossil fuels and deforestation. Although carbon dioxide is a natural part of life cycle on Earth, atmospheric CO_2 influences the climate around the globe. Both theoretical results and empirical evidence indicate that higher atmospheric concentrations of CO_2 increase the radiative forcing and energy balance of climate system (IPCC 2013; Feldman et al. 2015). The warming of Earth's surface since the mid-20th century has also been observed. The dominant cause for the warming is the increased CO_2 and other greenhouse gas levels in the atmosphere (IPCC 2013).

The reason to be concerned of the increasing warming is its negative effect on the wellbeing of humans. For the policymakers, Intergovernmental Panel on Climate Change (IPCC 2018) lists 25 potential negative impacts and associated risks of stronger climate change than 1.5 Celsius. Two thirds of the effects mentioned in this list have direct effects on humans or human activity or have an effect on ecosystem services to humans. Even that climate change seems to have a relative straight effect on human welfare, the estimated costs of emission of one ton of carbon dioxide CO_2 into the atmosphere has a wide range of $2-$1000 (e.g. Tol 2005; NASEM 2017; Ricke et al. 2018). One tree in a typical boreal forest on wood production can store carbon equivalent over a ton of carbon dioxide. Clearly, given that a standing tree may have an external value equivalent to hundreds of dollars, optimal forest management changes if this externality is taken into account.

Forest management for wood production, especially in boreal forests, consists mainly of waiting. Periods of inactivity in optimal forestry are typically over 10 years (e.g. Tahvonen et al. 2013; Äijälä et al. 2019). In the Finnish forest management guidelines, the average annual administrative cost per hectare is estimated to be 11 €/ ha^{-1} $year^{-1}$ in the cases where forest rotation is 70 years, with forest management activities on six calendar years during the rotation (Äijälä et al. 2019). This feature is not present only in even-aged forestry; long periods of inactivity are also associated with uneven-aged forestry (e.g. Kuuluvainen et al. 2012). The high fixed cost of harvesting is one of the main reasons for long cycles in harvesting. It can be said that small annual costs and few higher costs and revenues characterize the ownership of boreal forest. In addition, forest management optimization is mainly capital management. However, besides timber production, forests provide other ecosystem services too. The preference of forest owners defines how these other ecosystem services will affect the forest management (e.g. Favada et al. 2009).

The climate benefits related to CO_2 of wood accumulate from storage of carbon. By adding this kind of passive benefit to maximizing of rarely operated actions as in wood production, will bring out very long-lasting effects. The forest is basically carbon storage and there is a win-win situation related to the increase of the volume of trees and decreasing atmospheric carbon. In that sense, if expected harvesting leads to the increase on silviculture and growth of trees today, future harvesting of those trees could mitigate climate change. However, we have scarce resources and thus benefits from this win-win situation are limited, the limiting factor being the opportunity cost of capital. Due to capital intensity and amenity preferences on forestry it is not clear when to move from win-win to win-lose situation and that is when the forest owner's benefits really begin to decline. For the policy makers it seems to be easier to make decisions on win-win situation than on the win-lose situation (Morrison-Saunders and Pope 2013).

From the point of view of climate policy, it is efficient to take advantage of the feature of forests acting as a carbon sink. However, forests are a heterogeneous renewable resource competing with other land uses. Heterogeneity is not a feature limited to forest habitats but extends to forest owners, users and end products. Thus, determining of the effective climate policy for this positive externality is complex.

This thesis examines optimal forestry under climate policy from multiple angles, which can be condensed in three research questions. *First, how to trade-off forest carbon sinks in forest against economic benefits from harvesting?* I focus separately on carbon sink of the standing wood stock in forest (article I) and extend the analysis on the use of harvested timber in the sink of wood products (article II). Second, *how a carbon subsidy on forest sinks as an economic incentive and the national reference levels for carbon sequestration as nation-wide constraints affect forest management and promote climate change mitigation*? Carbon subsidies are the topic of article I and the role of forest reference level is examined in article IV. Third, what role *do the model description of forest, silviculture and age structure play when defining climate policy for forestry?* This topic runs through articles I, III and IV and is the main theme in article III.

In article **I,** we used an age-class model with endogenous growth to analyze how forest owners will change their forest management if there is a subsidy based on the forest carbon storage. The results show that enhancing investments for forest growth increases and that forest rotation will be longer. Due to the actions, carbon sinks grow. With the low enough carbon subsidies, the optimal rotations of forests move towards maximum sustained yield (MSY) rotation. Thus, timber production increases and the possibilities to produce carbon storage on the harvested wood products (HWP) increases. However, with high enough carbon subsidies the effect is opposite: the optimal rotations of forests move so far over the MSY rotation that supply of timber and possibilities to produce HWP's will decrease.

Article **II** analyses wood consumption and HWP carbon stock. The main HWP carbon pool consists of products made of sawn wood. In Finland the current wood products stock, e.g. wooden houses, is still increasing. Thus, the HWP carbon pool in Finland seems to increase until 2050 even in the case of decreasing scenario of wood consumption. Because consumers make consumption and disposal decisions of HWP's the political governance could be targeted at them. Such a carbon subsidy policy results in both similar and different effects for HWP pool as compared to forest carbon storage. In forests, carbon subsidy increases silvicultural investments and thus carbon stock increases. On the case of HWP carbon subsidy increases used amount of wood on products. However, the lifetime of products, i.e. carbon pools, may shorten which is an opposite effect to the one in the forest case where carbon subsidy tends to lengthen the rotation.

At least since the van Kooten et al. (1995) article it has been clear that subsidy to forest carbon could create a way to mitigate climate change in forestry. However, as the results of article **I** imply, policy for existing forests may create a significant short-term market shock for round wood. Policy implications have been analyzed further, e.g. Pohjola et al. (2018), with a partial equilibrium model. Although endogenous prices, i.e. market prices, and investments on production capacity moderate the market outcomes, the short run shock can last for decades.

For many industrialized countries, forests have been a major carbon sink for decades (e.g. Gold 2003; Bellassen et al. 2011). Accepting these sinks in national carbon accounting appears to be a way to gain carbon credits. To avoid windfall profits, policy benefits from forest management have been limited by introducing reference levels (RL) for carbon sequestration (United Nations 1998; UNFCCC 2008 and 2011a). In order to determine the correct RL for the carbon sinks, forest growth and current management must be assessed.

Article **III** deals with optimal forest management. The forest owner is not expected to receive any benefits other than income from wood production. Growth of the forest is described by a size-class model. Size-class models are typically utilized in the case of uneven-aged forestry, but they can be used for describing even-aged forestry as well, as in article **III**. The results show a feature that significantly reduces the comparability of forest management results with size-classified matrix models. The economic optimization takes place in a context where the optimal thinning intensity and rotation length are highly dependent of the specification of the model. Sensitivity analysis can reduce uncertainty, but it cannot be removed.

In article **IV** we analyzed the existing climate policy for forestry in EU. The policy is based on reference levels (RL) for carbon emissions on managed forest land. These estimates are business as usual predictions and are estimated separately for each EU country. Greenhouse gas emissions and sinks resulting from forest management are compared against the reference levels during the second commitment period (2013–2020) of the Kyoto Protocol. Because the RL-policy only applies to one period, we can use a simple two-period model to describe the impact of the policy. The results show that constraints on climate policy design reduce the potential of using forests to mitigate climate change.

Articles **I-IV**, which are independent, represent different perspectives of the forest sector and the use of forests and wood products to mitigate climate change. They cover the use of forests from the growth of trees to the use of wood products. The following framework complements the conclusions in the articles and builds a view towards a more comprehensive conclusion for governance of forest sector to mitigate climate change.

2 FRAMEWORK FOR THE FOREST AND ENVIRONMENTAL ECONOMICS

2.1 Optimization of land use on forestry as renewable resource

Food and Agriculture Organization of the United Nations (FAO) defines a forest as a land area over 0.5 hectares where trees are expected to reach a height of at least 5 meters and where the canopy cover will be over 10 % (MacDicken 2014). In addition, urban or agricultural lands are not counted as a forest. The FAO definition mentions all the necessary elements to determine the optimal forest management and the value of forest land. It separates the land and tree cover into own categories. First, there must be a concrete place where trees are expected to grow. Also, to keep a particular piece of land forested, the value of forestry must be greater than other potential forms of land use, i.e. forestry is practiced up to the point where it produces the greatest plausible benefit to the landowner. Secondly, it must be possible to assume that trees will reach sufficient length and density. In other words, there must be some description of how the forest grows. 170 years ago, Martin Faustmann (1849) solved how to determine the value of a forest land V_F

$$V_F(t) = \frac{p_W f(t)e^{-rt} - k}{1 - e^{-rt}}, \quad (1)$$

Where timber price is p_W, regeneration cost of bareland is k, rotation length is t and market interest rate is $r \geq 0$. The growth of forest is a function $f(t)$ of time with $f'(t) > 0$, and $f''(t) < 0, t > \hat{t}$ where $\hat{t}$ is the inflection point after the convex part of the growth function related to young forests. The fundamental idea of Faustmann formula is the alternative return for both the above-mentioned elements, i.e. trees and land. The value of the forest land can be determined as a series of incomes that are repeated to infinity. Net profits from one rotation $p_W f(t)e^{-rt} - k$ are converted to land value by dividing them by periodical discounted rate $1 - e^{-rt}$. Pressler (1869) solved how to maximize the value of the forest land using the Faustmann formula. The land value is maximized with rotation T^0, when value growth of forest equals the alternative return of the sum of values of standing timber and bareland.

$$p_W f'(T^0) = r\big(V_F(T^0) + pf(T^0)\big). \quad (2)$$

The Faustmann formula eq.1 and its maximizing condition eq.2 represent the case of land use on the identical renewable resource with the same growth function. It is also assumed that the surrounding world, such as prices and costs, does not change. Thus, the optimal use of natural resources remains unchanged indefinitely. In other words, if it is optimal to do the harvest at this period, in the future, when the renewable resources are in the same state, it is best to redo the harvest. However, Faustmann condition eq.2 can be used to maximize one rotation problem too with alternative land use and value for bareland $V_F(T^0)$. If the alternative land use does not meet the definition of forest, then we are no longer dealing with a forest management problem, but with a problem of deforestation.

2.2 Supply of carbon services of forestry

As the forest is a complex system with multiple ecosystem services there is a need for diverse valuation methods to augment the Faustmann formula. Richard Hartman's much referred article, "The harvesting decision when a standing forest has value", was published in 1976. As the title suggests, both values, timber harvesting and standing value of forest, are noted in the same formula. Value of timber production in this so-called Hartman formula is equivalent to that of the Faustmann formula. The value of standing forest is a function of the age of forest $F(s)$. Net present value of standing forest over one rotation is $\int_0^t F(s)e^{-rs}ds$. The net present value of timber production and standing forest can be calculated from the infinite series of rotations as in Faustmann formula. The value $V_H(t)$ of a forest stand by Hartman formula is:

$$V_H(t) = \frac{p_W f(t)e^{-rt} - k + \int_0^t F(s)e^{-rs}ds}{1 - e^{-rt}}. \quad (3)$$

By reordering, for the first order condition for maximization of $V_H(t)$, we get

$$p_W f'(t) + F(t) = \mathrm{r}\big(V_H(t) + pf(t)\big). \quad (4)$$

If the value of standing timber increases with the rotation age of the stand $F'(s) > 0$, then optimal rotation length will be longer than the Faustmann rotation.

Van Kooten et al. (1995) extended the Hartman model by including the value of carbon changes in the standing forest and the benefit of carbon stored in the long-lived wood products. They valued carbon sequestration as a biomass change over the rotation, i.e., their model is consistent with a situation where the government purchases forest carbon sinks (subsidy) and sells emission allowances (tax) in connection with logging. However, their formulation of the problem based on forest biomass change is equivalent with the formulation based on rental payment for standing timber $rf(s)$ as,

$$V_K(t) = \frac{\left[(p_W + \alpha\beta p_C)f(t)e^{-rt} - k + \alpha p_C \int_0^t rf(s)e^{-rs}ds\right]}{(1 - e^{-rt})}, \quad (5)$$

where α and p_C are carbon content of timber and constant carbon emission price respectively. So called pickling factory β is the share of harvested timber which is used for long- lasting wood products (HWP). At the harvesting moment, the forest owner is granted a type of subsidy, given by $\alpha\beta p_C$ to produce HWP. Lintunen et. al (2016) analyzed the market outcomes of the systems based on either the rental payment or a payment for biomass change. They found that those outcomes are equal under perfect capital markets and rational expectations over carbon price. Those assumptions are assumed to be present in the analysis of van Kooten et al. (1995) study.

The van Kooten's formula assumes constant pickling factor β. If β is defined so that it depicts the lifetime carbon storage of the HWPs, then, according to the formula, forest owner receives the full benefit from carbon capture of the HWP's. This raises the question whether those benefits should go to the forest owner or to someone else (see e.g. Sedjo & Sohngen 2012). Production of HWP's requires logging, which causes immediately reduction in the carbon stock in the forest. In the longer term, these products turn into waste. Economic analysis provides a way to look at the balance between these stocks over time (e.g. Price & Willis 2011). In article **II** the lifetimes of HWP's in Finland are analyzed with statistics. However, HWP owners as well as forest owners can influence their respective carbon storages. In that case, the decision of the owner of the HWP can be illustrated by a variation of the van Kooten model and the model used in article **I**. By allowing endogenous investments for carbon storage, as in article **I**, and by determining its lifetime, as in van Kooten et al. model, all necessary elements are present to optimize HWP use with a subsidy for carbon storage.

2.3 The value and lifetime of harvested wood products

Next, I will present a model that complements the climate policy by linking the description of harvested wood products (HWP) carbon storage and the use of wood products. Traditionally, HWP sinks have been described through the amount of wood consumption, as in article II, omitting the preferences as to why these products are consumed. The average decay rates for timber and wood panels in Finland are calculated in article II. Such an average decomposition rate ignores why products are manufactured and consumed. Here I base the analysis on the benefits of the use of wood products. With this analysis it is possible to look deeply into the lifetime and the amount of wood in products. Consumer preferences and needs determine the purchase of new products and maintenance of the old ones. As consumers can affect the material usage in products and their lifetime, they also determine the carbon sequestration on HWP's. Previous analysis has ignored the relevance of consumers and their possibility to govern the HWP pools.

Assume that a HWP owner maximizes the benefits W_{HWP} of using wood products over an infinite time horizon by selecting both the optimal size of a product, e.g. a wooden house, and its optimal lifetime. The optimal lifetime defines the age of the product at which it will be replaced by a new product. We assume a concave utility function for the use of the wood product $B(T,Q)$, with $\partial B(T,Q)/\partial T > 0$, $\partial^2 B(T,Q)/\partial T^2 < 0$, $\partial B(T,Q)/\partial Q > 0$, $\partial^2 B(T,Q)/\partial Q^2 < 0$, $\partial^2 B(T,Q)/\partial T \partial Q = 0$ where the utility depends on the lifetime of the product T and the used amount of wood Q. The longer the wood product is used, the more it produces benefits but decreasingly in time. The more wood is used for the product, the more it produces benefits, but this slows down unit by unit. The combined production and maintenance costs of the wooden product are denoted by $C(T,Q)$, with $\partial C(T,Q)/\partial T > 0$, $\partial^2 C(T,Q)/\partial T^2 > 0$, $\partial C(T,Q)/\partial Q > 0$, $\partial^2 C(T,Q)/\partial Q^2 > 0$, $\partial^2 C(T,Q)/\partial T \partial Q = 0$. These costs depend on the amount of wood used, Q (production costs) and on the lifetime T (maintenance costs). The longer the lifetime is sought, the more expensive the methods must be used. Thus, the second derivative $\partial^2 C(T,Q)/\partial T^2$ is positive. Because of this, at some point, the marginal cost of increase of lifetime rises faster than interest rates. The decay rate for the wood in HWP's is φ.

The functions $B(T,Q)$ and $C(T,Q)$ are assumed to be separable between the initial amount of the wood and the lifetime of the product. This allows a separable solution Q^* for the optimal use of wood , for each lifetime.

In eq. 6, the possibility for the carbon rental for the HWP owners are added to the maximizing problem of the HWP user. The value of the total carbon storage benefits $\int_0^T p_C r\alpha Q e^{-(r+\varphi)s} ds$ over the cycle T of the wood product, is the discounted cumulative rental value of the amount of carbon on the remaining wood.

$$W_{HWP} = \left[B(T,Q) - c(T,Q) + \int_0^T p_C r\alpha Q e^{-(r+\varphi)s} ds\right](1 - e^{-rT})^{-1}. \tag{6}$$

First we solve the optimal amount of wood in HWP for each lifetime of T. The optimal amount of wood will be conditional on the applied lifetime of the wood products. Taking the derivative of W_{HWP} with respect to Q, and assuming the existence of an interior solution, leads to a following first order condition

$$\frac{\partial W_{HWP}}{\partial Q} = \left[\frac{\partial B(T,Q)}{\partial Q} - \frac{\partial C(T,Q)}{\partial Q} + \int_0^T p_C r\alpha e^{-(r+\varphi)s} ds\right](1 - e^{-rT})^{-1} = 0. \tag{7}$$

The condition in eq. 7 will hold when the numerator equals zero. Reordering the numerator and substituting the optimal uses of wood Q^* for the HWP with lifetime T , will yield eq.8.

$$\frac{\partial C(T,Q^*)}{\partial Q^*} = \frac{\partial B(T,Q^*)}{\partial Q^*} + \int_0^T p_C r\alpha e^{-(r+\varphi)s} ds \tag{8}$$

This condition states that the marginal production costs on the left hand side (LHS) equal the total marginal benefits of each unit of wood used during the lifetime T on the right hand side (RHS). The total marginal benefits consist of the increase $\partial B(T,Q^*)/\partial Q$ and the carbon storage benefits $\int_0^T p_C r\alpha e^{-(\mathrm{r}+\varphi)s} ds$. It can be readily seen that an increase in the price of carbon increases the amount of wood material used.

The optimal lifetime of the wooden product can be derived from the first order condition of eq. 6 with respect to T. This yield

$$\frac{\partial B(T,Q^*)}{\partial T} - \frac{\partial C(T,Q^*)}{\partial T} + rp_C\alpha Q^* e^{-(\mathrm{r}+\varphi)T} = re^{-rT}\frac{B(T,Q^*)-c(T,Q^*)+\int_0^T p_C r\alpha Q^* e^{-(\mathrm{r}+\varphi)s} ds}{(1-e^{-rT})}. \quad (9)$$

The interpretation of this maximizing condition is similar to the Hartmann formula. The optimal time for giving up the wood product, and replacing it with a new one, is when the marginal benefit of having the product, the LHS of eq. 9, equals the marginal cost, of increasing the lifetime of the product, the RHS of eq. 9. The LHS consists of marginal benefits minus marginal costs of the use of the product plus the rental value of the remaining carbon storage in HWP. The marginal cost of increasing the lifetime of HWP is the market interest rate times the net present value of the upcoming rotations, W_{HWP}. In the case of $\varphi = 0$ there is no decay process during the lifetime of HWP. In fact $\varphi = 0$ implies that the lifetime of a HWP is infinite. In that case the expression for the discounted value of carbon storages in wood products, $\int_0^T p_C r\alpha Q^* e^{-\mathrm{r}s} ds\,(1 - e^{-rT})^{-1}$ can be replaced by that of the value of the emissions of the same amount of carbon, $p_C\alpha Q^*$. With the infinite lifetime of HWP carbon, the payment terms will be absent in eq. 9 and, and the carbon rental has no influence on the lifetime of the wood products.

Typically, there are factors such as fungi and insect pests which result in $\varphi > 0$. The influence of carbon price can be formally derived by comparative statics of this model. If we assume that interior solutions exist and write the optimal cycle of HWP use as a function of exogenous parameters $T^\circ = T^\circ(Pc, r, \varphi)$. Next, to demonstrate the impact of possible carbon policies, the comparative static result with respect to carbon price is illustrated. To investigate the properties of $T^\circ(Pc, r, \varphi)$, we totally differentiate the equilibrium conditions eq. 8 and eq. 9 with respect to exogenous parameter p_C. Reordering the terms yields

$$\frac{\partial^2 W_{HWP}}{\partial T^2}\frac{dT}{dPc}+\frac{\partial^2 W_{HWP}}{\partial T\partial Q}\frac{dQ}{dPc}=-\frac{\partial^2 W_{HWP}}{\partial T\partial Pc} \tag{10}$$

$$\frac{\partial^2 W_{HWP}}{\partial Q\partial T}\frac{dT}{dPc}+\frac{\partial^2 W_{HWP}}{\partial Q^2}\frac{dQ}{dPc}=-\frac{\partial^2 W_{HWP}}{\partial Q\partial Pc} \tag{11}$$

Second derivatives are as follows

$$\frac{\partial^2 W_{HWP}}{\partial T^2}=\frac{\partial^2 B(T,Q)}{\partial T^2}-\frac{\partial^2 C(T,Q)}{\partial T^2}-(\mathrm{r}+\varphi)rp_C\alpha Qe^{-(\mathrm{r}+\varphi)T}<0, \tag{12}$$
$$\frac{\partial^2 W_{HWP}}{\partial T\partial Q}=rp_C\alpha e^{-(\mathrm{r}+\varphi)T}>0, \tag{13}$$
$$\frac{\partial^2 W_{HWP}}{\partial Q^2}=\left[\frac{\partial^2 B(T,Q)}{\partial Q^2}-\frac{\partial^2 C(T,Q)}{\partial Q^2}\right](1-e^{-rT})^{-1}<0, \tag{14}$$
$$\frac{\partial^2 W_{HWP}}{\partial Q\partial Pc}=\left[\int_0^T r\alpha e^{-(\mathrm{r}+\varphi)s}ds\right](1-e^{-rT})^{-1}>0, \tag{15}$$
$$\frac{\partial^2 W_{HWP}}{\partial T\partial Pc}=\mathrm{r}\alpha Q\left(e^{-(\mathrm{r}+\varphi)T}-r\frac{\left[\int_0^T e^{-(\mathrm{r}+\varphi)s}ds\right]}{(1-e^{-rT})^{-2}}\right)=?. \tag{16}$$

We assume that $\frac{\partial^2 W_{HWP}}{\partial T^2}, \partial^2 W_{HWP}/\partial Q^2 > (\partial^2 W_{HWP}/\partial T\partial Q)^2$. Then the determinant of the Hessian matrix of the above maximizing problem eq. 12 is positive and valid.

$$\Delta=\begin{vmatrix}\frac{\partial^2 W_{HWP}}{\partial T^2} & \frac{\partial^2 W_{HWP}}{\partial T\partial Q}\\ \frac{\partial^2 W_{HWP}}{\partial Q\partial T} & \frac{\partial^2 W_{HWP}}{\partial Q^2}\end{vmatrix}=\frac{\partial^2 W_{HWP}}{\partial T^2}\frac{\partial^2 W_{HWP}}{\partial Q^2}-\left(\frac{\partial^2 W_{HWP}}{\partial T\partial Q}\right)^2. \tag{17}$$

Cramer's rule states that

$$\frac{dT}{dPc}=\frac{\begin{vmatrix}-\frac{\partial^2 W_{HWP}}{\partial T\partial Pc} & \frac{\partial^2 W_{HWP}}{\partial T\partial Q}\\ -\frac{\partial^2 W_{HWP}}{\partial Q\partial Pc} & \frac{\partial^2 W_{HWP}}{\partial Q^2}\end{vmatrix}}{\Delta}=\frac{-\frac{\partial^2 W_{HWP}}{\partial T\partial Pc}\frac{\partial^2 W_{HWP}}{\partial Q^2}+\frac{\partial^2 W_{HWP}}{\partial T\partial Q}\frac{\partial^2 W_{HWP}}{\partial Q\partial Pc}}{\Delta}=? \tag{18}$$

The sign of eq. 18 is ambiguous, so the increase on carbon price could shorten or lengthen the lifetime of harvested wood products with infinite consumption cycles. However, the surprising finding here is that the increase on the price of carbon could shorten the lifetime of HWP in use.

Above, an infinite structure of the model has been used. However, consumption of HWP could also be a single event. In that case, consuming the product will be beneficial as long as it is in use. There is no effect on consumption related to the future consumption and needs. By removing the life-cycle part from eq. 6 the benefit $\widehat{W}_{HWP}$ for the consumption of HWP product would be as follows

$$\widehat{W}_{HWP} = B(\hat{T},Q) - c(\hat{T},Q) + \int_0^{\hat{T}} p_C r\alpha Q e^{-(\mathrm{r}+\varphi)s} ds. \quad (19)$$

In the single rotation case, the rule for the optimal consumption level of wood material for HWP's is the same as the rule given in eq. 8 for the case of infinite time horizon. Given the optimal consumption level, the optimal lifetime of the wooden product $\widehat{T}$ can be derived from the first order condition of eq. 19 as

$$\frac{\partial B(\hat{T},Q)}{\partial \hat{T}} - \frac{\partial C(\hat{T},Q)}{\partial \hat{T}} + rp_C \alpha Q e^{-(\mathrm{r}+\varphi)\hat{T}} = 0. \quad (20)$$

We assume that there exists an interior solution and write the optimal lifetime of single event HWP as a function of exogenous parameters $\hat{T}^{\circ} = \hat{T}^{\circ}(Pc, r, \varphi)$. To investigate the properties of $\hat{T}^{\circ}(Pc, r, \varphi)$, we totally differentiate the equilibrium conditions, eq. 20 and eq. 8, with respect to the exogenous parameter p_C and obtain the second derivatives, with the signs given in eq.12-15. However, the sign of the derivative $\hat{\partial}^2 w_{HWP}/\partial\hat{T}\partial Pc$ is positive in eq. 21, while it was ambiguous in eq. 16 for the case of the infinite cycles of HWP's.

$$\frac{\hat{\partial}^2 w_{HWP}}{\partial \hat{T} \partial Pc} = \mathrm{r}\alpha Q e^{-(\mathrm{r}+\varphi)\hat{T}} > 0, \quad (21)$$

We assume as for eq. 12 that the determinant $\hat{\Delta}$ of the Hessian matrix is positive. Then the Cramer's rule states that

$$\frac{dT}{dPc} = \frac{\begin{bmatrix} -\frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{T} \partial Pc} & \frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{T} \partial \hat{Q}} \\ -\frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{Q} \partial Pc} & \frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{Q}^2} \end{bmatrix}}{\hat{\Delta}} = \frac{-\frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{T} \partial Pc}\frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{Q}^2} + \frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{T} \partial \hat{Q}}\frac{\partial^2 \widehat{W}_{HWP}}{\partial \hat{Q} \partial Pc}}{\hat{\Delta}} > 0 \quad (22)$$

The sign of eq. 22 is positive. This implies that the lifetime of HWP increases when the carbon price increases in the case of a one-rotation HWP.

In summary, the carbon subsidy tends to increase the amount of wood material used and correspondingly, it increases the amount of carbon over time. In the case where the consumption of wood products is based on infinite time horizon, it is profitable to renew wood products earlier than in the one-rotation case to account for the impact of future cycles. Carbon subsidy tends to increase the lifetime of a HWP when one-rotation model is applied, while in the infinite-time model the impact of carbon subsidy is ambiguous. An exceptional case is a wood product that does not decay over time. For such a product, carbon subsidy has no impact on its lifetime.

2.4 Optimal policy for externalities in forestry

Climate change and the global economy are strongly interconnected. The correct price of a negative externality, such as carbon emissions, is the net present value of damages caused by the emissions over time (e.g. Pigou 1920). Ample amount of research has been carried out to estimate this correct price for carbon emissions, referred to as social cost of carbon (SCC) (e.g. Parry et al. 2007). The estimates for the present value of future damages include climate and socio-economic uncertainties and are sensitive to the used interest rate (e.g. Tol 2005; NASEM. 2017; Ricke et al. 2019). According to the estimates, the social cost of emissions of one ton of CO_2 to atmosphere could be even $1000. High prices of SCC compared to wood prices necessarily lead to the question: are the current forestry and forest policies optimal? For example, in Finland the roadside price of pulpwood is about 30€/m^3. One cubic meter of wood contains about 0.2 tons of carbon corresponding to about 0.7 tons of carbon dioxide, implying that the carbon storage value of timber could be even 20 times the value of pulpwood.

In his 1960 article Coase argued that the Pigouvian-style tax can be replaced by a market mechanism where the parties trade with rights to externalities (Coase 1960). According to Coase, with some limitations, Pareto-optimal allocation can be achieved without government intervention. It is prerequisite that there is no transactions cost and that the rights for externalities are fully defined. In the case of forests, carbon storage is a positive external effect that is generated by trees and soil. In forests where the ownership of these two, i.e. soil and standing timber, is defined, it is possible to determine the ownership of the related externalities. Using satellite imagery and remote sensing monitoring, carbon stocks can be accurately verified at a low cost. Similarly, trading with nonphysical product is easy in principle. However, Coase concludes that in order to carry out a market event, it is necessary to define and approve an agreement and ensure compliance with the terms of the agreement. These measures are often very expensive, in any case expensive enough to prevent many transactions from occurring in a world where the pricing system operates free of cost. Therefore, it is unrealistic to assume that a pure market mechanism would be able to solve these forest-related carbon storage issues.

In addition, although it is clear to whom the trees and forests would belong, the ownership of the carbon stocks externality is not properly defined. The fact that governments control the rights for the externality with the national accounting system and could use them in their climate policy, creates a situation where the forest owners have no full rights to externalities related to their forests. This can lead to a situation where the market mechanism creates real additional sinks sold on the market. However, the state can reuse these same sinks in its own climate targets.

The Clean Development Mechanism (CDM) in the Kyoto Protocol enables carbon sequestration additions of forest offset programs in developing countries to be exploited in emission trading schemes (e.g. IPCC 2006). In the CDM projects, the ownership of additional offsets has been transferred to forest owners and thus incentives for carbon sinks are created. Nevertheless, the usability of carbon sequestration benefits still depends on the acceptability by the host country and third-party verifier (Dormady & Englander 2016). In article **IV** we analyzed the current climate policy for forestry in developed countries. In the study forest carbon sinks are utilized, as the social planner maximizes society's wealth under current climate policy. In that case forest owners manage their forest as they have full rights for their forest carbon externality. As stated in the study, if governments have the privilege of benefiting from carbon sequestration of forestry for their climate targets, it would be efficient to transfer those positive externality benefits with a Pigouvian-type subsidy to forest and HWP owners.

The use of forests and the benefits of their carbon sinks can only be a partial solution in mitigating climate change. In Europe, forests' negative emissions have been about one tenth of the greenhouse gas emissions in recent decades (EEA 2018, UNFCCC 2011b). According to article **IV,** the potential impact of setting of an individual forest policy compared to current level of global GHG emissions remains low. So, it can well be interpreted that marginal benefits are flat or even constant in the perspective of a climate policy targeted to forestry. However, there are uncertainties about the costs of carbon sequestration in forestry. In such a case, referring to the results of Weitzman (1974) article, a regulator should use price mechanism instead of quantity control. With existing forests, the risk of subsidizing non-additional carbon sinks is high (e.g. Pohjola et al. 2018). Those so-called windfall benefits can be limited by reference levels (RL) beyond which gains are earned. Article **IV** analyzes the current European Union forest climate policy, where reference levels are used to prevent windfall profits. In addition, gains from the policy are restricted with caps. Therefore, it is within limits set by the regulation that carbon sinks can be utilized. Hence, the RL policy with caps is a quantity control mechanism in the presence of uncertainty about costs, a case where price mechanism should be preferred.

2.5 Carbon value of forest-based sinks

The fundamental difference between the values of carbon emission and biological sequestration stems from the fact that the first one changes solid or liquid material into gas while the other one changes gas into solid matter, such as wood. The carbon dioxide emission into the atmosphere is a one-way event. There is no way to catch up the same molecules back to the original matter. Instead, in carbon capture, molecules are specifically taken out of the atmosphere and captured into a tangible matter. The length of time that carbon molecules stay in the tangible matter such as wood or soil can be measured. Thus, the period of time that carbon is out of atmosphere can be valued.

Here we assume that carbon sequestration is a perfectly reverse process of emission. In addition, it is assumed that carbon dioxide emission represents a change in ownership, including the responsibility for the harm and benefits caused by climate change to the society, i.e., at the time of emission the onus is released, while at sequestration, the ownership and responsibility to the society are obtained. Then the correct Pigouvian-style tax $\tau_C(t)$ for carbon emission is the value that is required to take responsibility for the future benefits $B(t,s)$ and disadvantages $D(t,s)$ associated with the emission at moment t as

$$\tau_C(t) = \int_t^\infty [D(t,s) - B(t,s)]e^{-rs}ds. \tag{23}$$

As the carbon emission is an irreversible event within a temporally complex system, the value is calculated by its effects, ad infinitum. By being able to determine the value of irreversible CO_2 emissions, the correct value of temporary sequestration could be calculated. Let y denote the moment when the stored carbon, e.g. in wood, is released into the atmosphere

$$W^Y(t) = \int_t^y [D(t,s) - B(t,s)]e^{-rs}ds = \tau_C(t) - \int_y^\infty [D(t,s) - B(t,s)]e^{-rs}ds. \tag{24}$$

The value of temporal carbon storage $W^{Y}(t)$ is the worth of avoided effects of carbon while it was out of the atmosphere between t and y. If climate change has reached a level at which carbon emissions are harmful, $D(t,s) > B(t\,,s)$, for the society in all periods $t < s < y$ before releasing, then storing carbon has a positive value $W^{Y}(t) > 0$.

The atmospheric lifetime of carbon is not infinite (Archer 2005). The CO_2 emission increases the amount of CO_2 molecules in the atmosphere but this increase decreases from one period to another. This kind of decreasing effect can be considered as a negative interest rate. There is also feedback between ocean temperature and atmospheric carbon. When the CO_2 emissions increase ocean temperatures, the ability of oceans to act as a carbon sink will be reduced (Archer 2005). However, for the present purposes we assume that the atmospheric lifetime of carbon is infinite, e.g. the absorption into seas is ignored. We also assume that there exist no indirect marginal effects over time between ocean temperature and its ability to act as a carbon sink. Because of these restrictions, the emission moment is ignored from the benefit and disadvantage functions, $D(t,s) = \widehat{D}(s)$ and $B(t,s) = \hat{B}(s)$. Then the term $\int_{y}^{\infty}[D(t,s) - B(t,s)]e^{-rs}ds$ in eq. 24equals the carbon tax $\tau_C(t+y)$, and the eq. 24 can be written as

$$W^{Y}(t) = \tau_C(t) - \tau_C(t+y)e^{-r(y-t)}. \tag{25}$$

By assuming an infinite atmospheric lifetime of carbon and by limiting the indirect effects of carbon emissions over time, we see from eq. 25 that the value of temporal carbon storage $W^{Y}(t)$ equals the discounted difference of correct tax τ_C for carbon emissions between the initial t and releasing moments $t+y$.

If the carbon tax is constant, i.e. $\tau_C(t) = \tau_C(t+y)$ in eq. 25, the correct social value for temporal carbon storage $W^{Y}(t) = \tau_C(t)\left(1 - e^{-r(y-t)}\right)$ equals the rental payment of the carbon sequestration between periods y and t. This is a similar payment for carbon sequestration as in article **I**.

One aspect that separates emissions and biological sinks is uncertainty. Emissions are irreversible, but the value of sinks is time dependent. In the case of forests, e.g. forest fires are a threat that can cause carbon dioxide to be released before scheduled by forest management. The value of an uncertain carbon sink depends on the expected releasing time $Z(\theta)$ of that sink. Typically risks such as fires affect negatively the expected storing time of carbon $Z(\theta) < (t+y)$. By changing the scheduled time y to uncertain time $Z(\theta)$ in the eq. 24, it can be written as

$$EW^{Z(\theta)}(t) = \tau_C(t) - \int_{Z(\theta)}^{\infty}[D(t,s) - B(t,s)]e^{-rs}ds. \tag{26}$$

The value of an uncertain carbon sink is less than that of a certain sink $EW^{Z(\theta)}(t) < W^{Y}(t)$, because $Z(\theta) < (t + y)$.

Within carbon sink trading, uncertainty is also related to the responsibility to provide agreed sinks and the benefits caused by the reversed emissions. A temporary carbon sink may be released by the other party earlier than agreed in the contract, and the desired carbon sequestration benefits may be lost. Also, there may be a doubt related to the counterparty's ability to control the storage. However, these uncertainties can be avoided or reduced by paying offsets afterwards, using collaterals, or by using a carbon-rental based policy. Carbon rental payments are paid only based on actual climate benefits. Therefore, when the climate benefits are decreased, as in the case of logging or harvesting of a forest, the payments can be decreased as well, and there would be no need to recover the payments already made, as in the subsidy-tax based policy.

3 SUMMARIES OF THE ARTICLES

Article I Uusivuori and Laturi: Carbon rentals and silvicultural subsidies for private forests as climate policy instruments

This article applies an endogenous growth model with a description of an age-class structure to study the impacts of climate policies on privately owned and managed forests. The model describes the behavior of a utility-maximizing private nonindustrial landowner who optimizes consumption flow, harvest timing and the temporal allocation of silvicultural investments. Two policy options, one in which the landowner is granted periodic carbon rental payments and one in which the government subsidizes the costs of silvicultural investments that enhance tree growth, are studied. The rules for when the policy measures have both intended and unintended effects are derived. Using numerical examples, we demonstrate that the effectiveness of both policy options depends on the age-class structure of forests when future carbon benefits are discounted. In the case of discounting, carbon rental payments are more effective for forests with old age-class structures, while silvicultural subsidies are more effective for forests with young age-class structures. Carbon rentals generally lengthen the rotations used and increase the use of silvicultural investments. This will lead to higher timber volume and carbon stock of forest in both the long and short run.

In the case of subsidies to the silvicultural costs, the amount of investments to enhance tree growth increases. This increased growth will lead to higher timber volume and carbon stock in each age-class. However, our numerical example demonstrates the effect that the increase on the subsidy to silvicultural costs tends to shorten the rotation. In those cases where subsidy is large enough to shorten rotation, the long-run net effects of the subsidy-based policy on total timber volumes become negative.

Article II Laturi, Mikkola and Uusivuori: Carbon reservoirs in wood products-in-use in Finland: current sinks and scenarios until 2050.

This paper addresses the question of how much carbon will be sequestered in wood products during the upcoming decades in Finland. Using sawnwood and other wood material consumption data since the 1950s and inventory data of carbon reservoirs of wood products in the Finnish construction and civil engineering sector, we first derive estimates for the carbon reservoirs in wood products-in-use in that sector. We then extend the estimate to include all wood products-in-use. We find that the carbon pool of wood products in the Finnish construction and civil engineering sector grew by about 12% since an inventory for 2000, and that the overall estimate for carbon reservoirs of Finnish wood products in 2004 was 26.6 million tons of carbon. In building the scenarios until 2050, econometric time series models accounting for the relationship between wood material consumption and the development of GDP were used. The results indicate that the range of carbon reservoirs of wood products in Finland will be 39.6–64.2 million tons of carbon in the year 2050. The impacts of different forms of the decay function on the time-path of a carbon sink and its value in wood products were also studied. When a logistic decay pattern is used, the discounted value of the predicted carbon sink of wood products in Finland is between €850 and €1380 million at the price level of €15/CO_2 ton as opposed to 440–900 million euros, if a geometric decay pattern is used.

Article III Laturi, Lintunen and Niinistö: Specification of a size-classified matrix model: the effects on growth predictions and economically optimal harvesting regimes

This paper addresses the effect of specification of a size-class model on the solution for economically optimal forest management. We first focused on the choice of the conversion method to convert the growth data of individual trees into size-class structure; i.e., we tested two alternative estimators (proportion and increment). Next we studied the effects of specification of size classes with different numbers of diameter classes and partitioning within. Growth description was based on the MOTTI stand-level simulator built on data from extensive field measurements in managed forests in Finland. Optimal forest management with the size-classified matrix model included thinning and clear-cutting and was studied for even-aged forest stands. We found that the proportion estimator better captured growth dynamics of small-diameter trees, whereas for larger-diameter trees the difference between estimators was less evident. The effect of the number and partitioning of size classes depended on the estimator method. With the proportion estimator, the number of size classes did not have systematic effects on timber yield nor land expectation value. With the increment estimator, yield and land expectation value systematically decreased when the number of size classes was increased. The results show that specification of a size-class model has clear effects on growth predictions as well as on optimized economic indicators. Therefore, it is important to check the robustness of results and policy recommendations with different numbers of size classes, different partitioning, and alternative conversion methods and their combinations.

Article IV Laturi, Lintunen and Uusivuori: Modeling the economics of the reference levels for forest management emissions in the EU.

This paper investigates the timber market impacts and the effectiveness of the reference level policy in promoting forest management actions in the EU countries. We also study how setting of caps for policy-based gains affects the effectiveness of the policy. We found that the policy enhances carbon sequestration, if it is implemented in such a way that it affects harvests. The market impacts and the effects on forest sinks can be substantial in countries where non-LULUCF sector emissions are high relative to the potential of forest resources to act as sinks. In smaller countries with relatively large forest resources, the effectiveness of the policy is dampened by upper limits imposed on the emission compensations. The results of our study can be used to improve the effectiveness of policies in climate change negotiations.

4 CONCLUSIONS

Forests provide a carbon sink, which plays a role in the optimal climate policy. However, forests are a renewable resource where management considers the benefits of both existing and future trees in relation to other returns. In addition, forests are a very heterogeneous resource, both biologically and in terms of the ecosystem services they provide.

This thesis considered optimal forestry under climate policy. The main research questions were a*) How to trade-off forest carbon sinks in forest against economic benefits from harvesting? b) How a carbon subsidy on forest sinks as an economic incentive and the national reference levels for carbon sequestration as nation-wide constraints affect forest management and promote climate change mitigation? c) Do the model description of forest, silviculture and age structure play when defining climate policy for forestry?*

In order to consider the externalities of the carbon stocks of both wood products and forests, carbon policy must also address two issues. Two policies are needed, one for increasing the use of wood products and the other for increasing the carbon stock of forests. The results show that if carbon sequestration in forest is subsidized, the first impacts on harvesting will take effect on existing forests near harvesting age. Because carbon subsidy tends to increase the rotation length, logging tends to decrease in the short term. This decrease in logging reduces the ability to produce HWPs. The long-term impact of carbon subsidy depends on the level of subsidy. At low levels of subsidy, both the logging and the standing stock increase in the long run for two reasons. First, carbon subsidy tends to increase the use of silvicultural investments. Second, the longer rotation cycles produce older and larger trees for harvesting. However, if the carbon subsidy is high enough, the optimal rotation occurs beyond the MSY rotation age, in which case a marginal increase in carbon subsidy tends to decrease average annual harvesting and thus the ability to produce HWPs in long term. Thus, the trade-off between the carbon stocks of wood products and forests requires a subsidy policy accounting for both.

One way to mitigate climate change is to increase forest growth by paying subsidies to silvicultural investments that enhance the growth. The results show that forest growth and harvesting will increase both in the short-term and in the long-term if the subsidy is low enough for the optimal rotation cycle not to shorten. With high enough silvicultural subsidy the optimal rotation cycle will be shortened. In that case the carbon storage in forests tends to decrease. Therefore, the trade-off between the monetary income of harvesting and carbon stock requires policies that address both.

Management of existing forests and trees is an essential part of using forests to mitigate climate change. The theories of forest economics indicate that forest owners change their forest management when policies address their forestry objectives. The reference levels, used in the EU climate policies for forests, are country-level targets for forest management emissions. For these reference levels to have a real impact on the carbon sink of forests and

HWPs, governments need to implement policies on forest management and on the use of HWPs. First, the externality related to carbon storage in forests and wood products needs to be priced correctly. This price mechanism would create an incentive for forest and HWP owners to improve and preserve those reservoirs. The price for externality could be created with different ways such as using subsidies or with market mechanism. However, the property rights for externalities should be fully defined before market mechanism could perform perfectly. Both the sellers and the buyers should be confident that there are no other parties that have the privilege to use the object of exchange. Also, other transaction costs disrupt the market mechanism.

Carbon stocks of forests and HWP's are temporary and often vulnerable to the risk of carbon being released back into the atmosphere as a result of fire. Also, the contracting of a temporary carbon sink may be rejected by the other party. In addition, there may be a doubt related to the counterparty's ability to control storage. These temporal limitations and risks should be considered when valuing these stocks. These kinds of uncertainties related to plausibility can be reduced and handled by paying offsets afterwards, using collaterals or by using carbon rental-based policy.

The effects of carbon subsidies on the use of forests and on wood products differ to some extent from each other. In both cases, the compensation increases the amount of carbon in storage during one lifetime of HWP or one rotation of forest stand. However, in terms of the length of carbon storage the results may differ. A subsidy lengthens the forest rotation, but a subsidy paid for HWP could shorten the lifecycle of storage that decays over the lifetime, because it may be profitable to renew wood products earlier than without subsidy. However, a carbon subsidy tends to increase the lifetime of HWP's whose consumption is not permanent.

In a situation of existing forests and wood products, there is a risk that a policy will be directed towards actions that would be taken even without the policy, i.e. a non-additionality issue arises. Reference levels with caps aim to prevent gains and losses from activities that are not affected by the policy. For example, the carbon stock in HWPs in Finland seems to increase without additional policy measures. However, the caps on the reference level policy prevent the implementation of effective national policy measures, because they limit the gains to such a low level that it is not worthwhile to implement a real policy measure. This is particularly the case in countries with a high forest cover in relation to the population and total emissions. The slow implementation of national policies is also affected by long time horizon in forestry and slow adaptation in forest growth. As a result, an international climate policy related to forestry would be more effective if the time horizon of the objectives were closer to that of forestry objectives.

Forests are complex systems and even with the absence of uncertainty or non-timber ecosystem benefits, , the defining of the optimal use of forests is a demanding task. For example, the effects of specifying a size-classified matrix model on the results are already significant in growth predictions and optimizing wood production, so it can be assumed that those effect also related to optimization of carbon sequestration together with timber production. Including such uncertainties and features in the policy context can have profound impacts in defining policy objectives and levels.

From the perspective of climate policy, it should be noted that forestry is about the management of a renewable resource with potentially positive externalities. The optimal management depends on the current state of the resource and its growth capacity. The optimal path for the carbon stock may be or may become cyclical, and the short- and long-term effects may be different. In the case of forestry subsidies targeting directly the carbon stock tend to work correctly.

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