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Immediate and long-run impacts of a forest carbon policy—A market-level assessment with heterogeneous forest owners

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ABSTRACT

Sequestering carbon in forests and wood products is an inexpensive way to reduce the atmospheric carbon concentration. However, its full potential is not utilized in present climate policies. Optimizing sequestration, while continuing to harvest wood for materials and energy, could reduce the economic burden of mitigation efforts. Optimal sequestration can be incentivized by subsidizing carbon storage according to its social value. We analyze the dynamic market-level impacts of implementing a forest carbon policy by using the Finnish Forest and Energy Policy model (FinFEP). We find that sizeable and immediate increases in carbon sinks can be obtained, even with low carbon prices. High carbon payments strongly increase the carbon sink in the short run, but this impact diminishes over time. Low payments have a milder but longer-lasting impact. Forest owners' valuations of forest amenities also affect the magnitude and dynamics of harvest and carbon sequestration results. Thus, a realistic description of forest owner behavior is needed to assess the impacts of forest carbon policies. Moreover, we show that a market-level model is necessary for assessing the regional carbon sequestration impacts and costs. Relying on stand-level models with fixed timber prices may yield overly optimistic results.

Introduction

The potential of forest carbon sinks in mitigating climate change is well-understood in scientific literature since the 1990's (Houghton et al., 1990). Under the United Nations Framework Convention on Climate Change (UNFCCC), it is mandatory to report carbon stocks and fluxes in Land Use, Land-Use Change and Forestry (LULUCF) sector. However, the use of climate policy instruments that regulate the development of forest carbon sinks has been sporadic. The Paris agreement (UNFCCC, 2017) seeks to limit global warming to 1.5–2° centigrade above the pre-industrial level. To reduce the economic burden of mitigating climate change, a cost effective climate policy should be an objective. Such a policy would incentivize mitigation measures in the order of cost—starting from the cheapest and then moving on to more expensive measures. Carbon sequestration in forests could have a role in these endeavors, as considerable reductions in net emissions might be obtained at relatively low cost (e.g. Vass and Elofsson, 2016). In this study we analyze the market-level impacts of a policy that fully internalizes the carbon externality of forestry.

In the literature, two approaches have been suggested to provide forest owners an incentive to take carbon sequestration benefits into account at a socially optimal level. A flow-based forest carbon policy subsidizes carbon capture by growing biomass and taxes the release of this carbon (van Kooten et al., 1995). An alternative way to design a forest carbon policy is to pay forest owners a 'carbon rent', which is based on the carbon stock on a forest stand (Sohngen and Mendelsohn, 2003; Uusivuori and Laturi, 2007). Lintunen et al. (2016) show that these two schemes provide identical incentives for forest owners. In our study, a forest carbon policy is implemented as a carbon rent – scheme. In addition, we augment the policy with a subsidy for forest carbon that is stored in the harvested wood products (HWP). The resulting policy gives socially optimal incentives both for the forest owners and the wood processing industry, in a case where the life-time of HWP is exogenously given (Lintunen and Uusivuori, 2016).

Implementation of forest carbon policy immediately increases the monetary value of the standing stock and bare land, thus changing the relative value of harvested and standing timber. This makes it optimal to lengthen rotations (Hartman, 1976; van Kooten et al., 1995; Lintunen et al., 2016). In addition, the policy delays and lowers the intensity of thinnings but increases their number (e.g. Pohjola and Valsta, 2007; Pihlainen et al., 2014).

The impacts of carbon pricing on forests have often been studied

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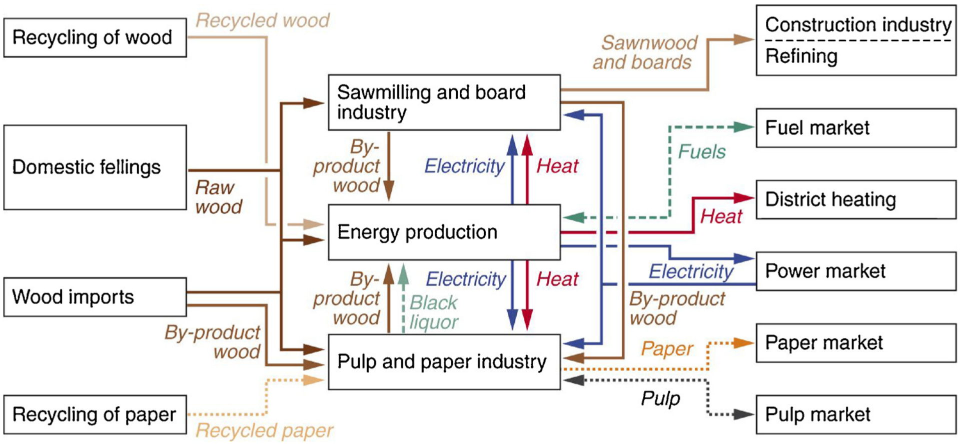

Fig. 1. Material flows between forest and energy sector modules in the FinFEP-model.

using stand-level models (see e.g. van Kooten et al., 1995; Pihlainen et al., 2014; Pohjola and Valsta, 2007). Stand-level analyses can provide detailed information on the impacts of a forest carbon policy on the forest management, such as rotation length and timing and intensity of thinning operations. However, the stand-level analysis has two important shortcomings. First, the endogenous reaction of timber prices to a forest carbon policy shock cannot be analyzed in a stand-level model, as timber markets are not included in this type of models. This can be a serious defect since timber prices might react strongly to the increased value of standing stock due to the forest carbon policy. Second, in stand-level analysis, timber harvest impacts can only be evaluated in a new steady state even if short, medium and long term impacts are likely to differ considerably.

Previously, Sjølie et al. (2013, 2014) and Lecocq et al. (2011) have included carbon pricing in their timber market models. Sjølie et al. (2014) compared the forest sector's climate change mitigation potential in Norway under the Kyoto Protocol (KP) to unlimited carbon sequestration policy with no caps on forest carbon credits. Their results suggested that carbon offsets were higher in the short run under Kyoto Protocol policy than under unlimited policy but KP policy failed to utilize carbon sequestration potential in the long run. Sjølie et al. (2013) evaluated the importance of market adjustment on the potential and costs of mitigating climate change through carbon sequestration and utilization of bioenergy. With full market adjustment the carbon offsets were substantially larger than in the case of limited adjustment with constant harvest levels, implying that in both policy implementation and modelling efforts the full potential should be involved. In both studies carbon prices varied from 0 €/t CO_2 to 100 €/t CO_2. Lecocq et al. (2011) explored three policies to mitigate climate change in the French forest sector; namely stock and substitution policies and combination of these. Their results suggested that payment for carbon sequestration in forest stock was the only of these policies that improved the net carbon balance under the period 2010–2020. However, the political acceptance of this policy was found to be questionable as the consumer surplus was decreased.

Our study contributes to the literature on the market-level impacts of forest carbon payments. We utilize the FinFEP (Finnish Forest and Energy Policy) partial equilibrium model (Lintunen et al., 2015) to analyze the detailed impacts of an unexpected implementation of carbon payments on forest carbon flows, timber markets, forest industries and energy production. Our analysis captures the endogenous timber price adjustment and provides an adjustment path, thus exhibiting impacts in the short, medium, and long run. The results reflect the economic optimization behavior of forest owners as they respond to the new policy regime after its implementation. In addition, we demonstrate how the age-structure of forests affects the dynamic impacts of the policy. We expand upon the earlier analyses by taking into account the variation in the forest owner characteristics by including owners with amenity values. In addition, we assess the value of market-level modeling compared to the stand-level approaches by contrasting the carbon sequestration results of the full model with a model run that uses exogenously fixed timber prices. To our knowledge, this kind of comparison has not been presented in the earlier literature.

The model, the data and the studied scenarios are reviewed in Section 2. Results are presented in Section 3. In Section 4, the importance of endogenous timber price adjustment is demonstrated. In Section 5 we discuss our findings and contrast them with earlier literature. Section 6 concludes.

Model, data and scenarios

Model

We analyze the effects of a forest carbon policy using the FinFEP (Finnish Forest and Energy Policy) partial equilibrium model covering the forest and energy sectors in Finland. In the model, the supply of wood is based on the detailed forest inventory data and a description of landowner behavior. The demand for wood is based on a detailed technological description of the wood using industries and is driven by exogenous demand functions for final goods made of wood. As wood is utilized by forest industries and the energy sectors, both sectors are integrated in the model. The model consists of five modules: energy processing, pulp and paper processing, wood-product processing, final good demand and timber supply. The modules are linked to each other through the material flows between processes, see Fig. 1. The processing modules have been previously used for separate policy analyses. Kangas et al. (2009) examined the wood fuel use decision of a single co-combusting power plant when emission trading is combined either with a feed-in-tariff or a production subsidy. Lintunen and Kangas (2010) introduced an energy market setup and examined the market outcomes under the same policy setup. The impacts of production, input and investment subsidies in promoting the biofuel production in the pulp and paper sector were analyzed in Kangas et al. (2011), and in the case of pellet production in Finnish sawmills in Mäkelä et al. (2011). In both studies the relative effectiveness of these instruments were compared. In the FinFEP model, forest and energy sector firms maximize the NPV of profit streams and the representative forest owners maximize Hartmanian (Hartman, 1976) type of objective functions. Here, we outline the elements of the model that are essential for understanding how the studied policies are implemented in the model. Lintunen et al. (2015) provide a more comprehensive description.

Timber supply in the FinFEP-model is based on stand-level management decisions of individual forest owners. The forest owners apply even-aged timber management and choose the intensity and timing of thinning and clear-cutting operations. The objective function consists of profits from forest management net of subsidies and taxes, and in situ amenity values. We account for the heterogeneity of forest owners by dividing them into three types. Each forest-owner type has a different weight for the amenity values in the Hartman (1976) type of objective function. A baseline is provided by "Faustmannian" forest owners who maximize NPV of timber profit flows, without consideration of the amenity values of forests. The two other types assign positive value to amenities.

The forest management decisions are made under uncertainty. The future development of timber prices is determined by exogenous, autoregressive random processes. We solve the optimization problem using dynamic programming and ordinary value function iteration (e.g., Judd 1998, 412–415). The value function is denoted as $V(s_t)$, where the state vector, s_t, describes stand properties (time since regeneration, number of trees, average tree volume and volume distribution width) and the current timber prices. The Bellman equation of the forest owner's optimization problem is

$$V(s_t) = \max_{x_t} R_f(s_t, x_t) + \beta E_t V(s_{t+1}),$$

where the control vector, x_t, denotes management possibilities (thinning intensity and binary clear-cutting decision). The discount factor is $\beta = (1 + r)^{-1}$, with discount rate r. The next period state is given by the equation $s_{t+1} = g(s_t, x_t)$. Since we approximate the development of timber prices by a Markov random process, the expectations are based on the information available at the current period. The conditional expectation operator is denoted by E_t. Details regarding the states and controls as well as the state dynamics are discussed in Lintunen et al. (2015). The payoff function, R_f, is forest-owner-type-specific (the type is denoted by the index f) and is defined as

$$R_f(s_t, x_t) := \pi(s_t, x_t) + \sigma(s_t, x_t) + w_f \alpha(s_t, x_t),$$

where functions π, σ, and α denote the timber profits, carbon payments and amenity values, respectively. The–owner-type-specific parameter $w_f \geq 0$ denotes the weight of the amenity values in the objective function. For "Faustmannian" forest owners $w_f = 0$.

The solution of the optimization problem results in a policy function $x_f(s_t)$ that describes the optimal thinning intensity and clear-cut decisions for each state of the stand and timber prices. These optimal type-specific stand-level management decisions $x_f(s_t)$ are aggregated to provide the timber supply functions in the equilibrium model as described in Lintunen et al. (2015).

In this paper, we implement a forest carbon policy by using a carbon rent scheme. Under this policy, the forest owners receive periodical rental payments based on the amount of stored carbon in their forest stands. Thus, it is different from the usual flow based policies, where carbon storage increments are subsided and reductions taxed (e.g. van Kooten et al., 1995). Yet, the two approaches provide equal incentives for the forest owner (Lintunen et al., 2016). With a time-invariant carbon price, the annual carbon rent payment is simply

$$\sigma(s_t, x_t) = r p_c S(s_t, x_t),$$

where r is the interest rate, p_c the carbon price and $S(s_t, x_t)$ the carbon stock of a given forest stand. The management profits, $\pi(s_t, x_t)$, are typically an increasing function of management intensity, whereas both the carbon rent, $\sigma(s_t, x_t)$, and amenity values, $\alpha(s_t, x_t)$, are decreasing functions with respect to thinning and clear-cutting. Therefore, the effect of carbon rent on forest management is analogous to that of amenity values.

In FinFEP, the demand for final goods is represented by exogenous demand functions. This demand is satisfied by the supply of final goods by representative firms. The representative firms maximize the stream of periodic profits by optimizing the input use given the size of the production capacity. The capacity investments are forward looking as they are based on current and future conditions. However, the foresight is not perfect but the decisions are made with restricted planning horizon. The optimized input use generates the derived demand for timber and intermediate goods such as energy. In a competitive equilibrium the markets of all the goods clear and all goods have positive prices.

The input uses of the representative firms are directly affected by two components of the climate policy modeled in this paper. These components are an exogenous carbon price and a subsidy for storing carbon in wood products (HWP).[1] The emission price is applied to carbon emissions from fossil fuels and it has straightforward implications on fuel use decisions. The HWP carbon subsidy is paid all at once to wood processing firms that produce long-lasting wood products. The size of the subsidy, σ^{HWP}, is based on the size and the duration of the storage:

$$\sigma^{HWP} = \frac{r}{r + \delta_{HWP}} p_c \rho_{HWP},$$

where ρ_{HWP} denotes the amount of carbon stored into a HWP fraction and δ_{HWP} is the geometric decay rate of the HWP fraction (Lintunen and Uusivuori, 2016). The formulation utilizes the fact that the carbon price is time-invariant in our scenarios.

The policy studied in this paper follows the changes in carbon stocks (see e.g. Lintunen and Uusivuori, 2016). As a result, the harvested forest biomass carbon is treated as an emission and, to avoid double counting, the wood fuels are treated as emission free in the energy sector. Analogously, storing carbon in products is seen as a carbon sequestration activity, which is correspondingly subsidized.

Data

The FinFEP-model contains a detailed description of forest resources available for wood production in Finland. Only the poorest sites, where forestry is not commercially viable, are omitted. The data describing stand development in the model, i.e. growth predictions for different harvesting regimes, are based on simulations conducted using the MOTTI forest simulator (e.g. Hynynen et al., 2002). MOTTI contains an up-to-date representation of the tree growth dynamics in Finnish growing conditions. MOTTI is based on deterministic growth models developed utilizing data from on extensive measurements at permanent and temporary inventory plots and field experiments of the Natural Resources Institute Finland Luke.

Data on the current state of the forest resource were obtained from the 10th National Forest Inventory (NFI10) (e.g. Tomppo, 2006). It was treated in a disaggregated level in order to achieve the desired resolution. We used five year age-classes in 18 regions of Finland, for three tree species and five site classes. To smooth out sampling noise, a joint method of simulation and regression analysis was used for determining the stand parameters describing the stand properties. The carbon in forest biomass is calculated using biomass expansion factors on growing stock volumes. The uncollected harvest residues and natural mortality contribute to the dead organic matter carbon polls of the forests. The litter production of living trees is assumed to be constant over the simulations. Production of wood products stores carbon into HWP carbon pools. These HWP pools decay at exogenous product specific rates.

A substantial share of the forest area in Finland consists of stands, that are "too old" on the standards of profit-maximizing commercial forestry, i.e. their age is far beyond the rotation which maximizes the net present value of wood production with positive interest rates. This suggests that forest owners also value non-timber amenities, and that these valuations affect forest management. In FinFEP, forest owners' amenity values are used to explain current forest management and the existence of old forests. The intensity of amenity values needed to

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[1] We follow the IPCC terminology and denote the carbon stock in wood products as a harvested wood product (HWP) carbon pool.

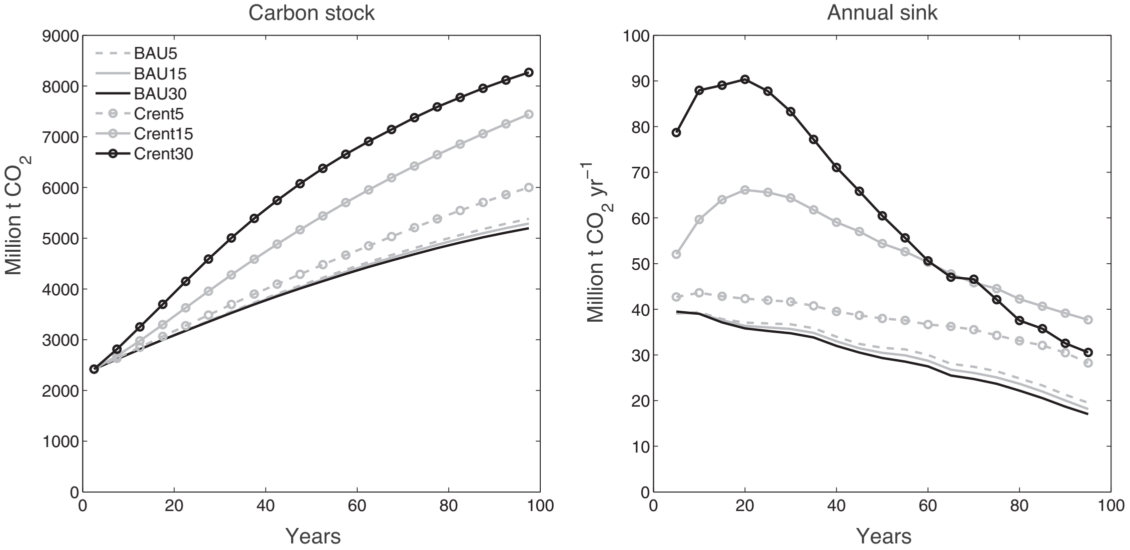

Fig. 2. Carbon storage (left) and annual sink (right) in living trees in three BAU scenarios and three forest carbon policy scenarios with carbon prices of 5, 15 and 30 €/t CO_2.

explain the extent of current old forests was determined for each representative site category. The model has been calibrated regionally by dividing forest owners into three categories according to the intensity of their amenity valuation, namely Faustmannian forest owners (F) and forest owners with low (Lo) and high (Hi) amenity values. As a result of the calibration, the model reproduces the regional thinning levels, clear cut areas and harvest volumes for the calibration year 2010.

The plant-level data of forest industries are from public sources. The data includes capacity levels for all pulp and paper mills in Finland, the number of which is currently about 30. Capacity levels for the 30 or so saw and board mills with a capacity over 20 000 m^3 are also present in the data. In addition, data for aggregate sawmills in different regions are included. The technology parameters are process-specific. The process parameters and production capacities were based on engineering-level data on individual plants presented in various environmental reports of the companies. The demand for forest products is assumed to be sensitive to price changes. The price elasticity of demand is assumed to be -5 for paper products that are mainly exported, while an elasticity of -3 is applied to sawnwood and plywood products. Due to these elasticities, industries can, to some extent, shift cost increases into the prices of their products. The wood imports are assumed to be inelastic with price elasticity of 0.5.

For the production of electricity and heat, the efficiency coefficients for converting fossil and wood-based fuels to electricity and heat were obtained from the websites and the environmental reports of companies. Power plants have one or more boilers, which are able to utilize one or more fuel types, based on their technical properties. The transformation of energy into heat and power is linear. However, non-linear transportation and co-firing costs enable interior solutions in fuel use optimization. In the case of co-firing boilers, a cost parameter captures the costs of deviating from the optimal fuel mix, e.g. in the case of peat and wood.

Model parameters, for which reliable data sources were not available, were calibrated using the initial values based on expert assessment.[2] In the calibration process the equilibrium solution was made to match the observed data for the year 2010. The result of the calibration is not unique as all of the model variables have no direct statistical counterparts that could have been used as a calibration reference. The final assessment of the parameters was based on expert opinion.

Scenarios

We perform two types of scenarios: business as usual (BAU) and carbon rent (CRENT) scenarios. In the BAU scenarios the CO_2 pricing is only applied to the emissions trading sector which in our model covers heat and power production. The CRENT scenarios expand upon the BAU scenarios by including a forest carbon policy which implements carbon rentals for forest and wood product carbon stocks. Both scenarios are calculated with three carbon price, i.e. 5, 15 and 30 €/t CO_2. The main results are presented for all the carbon prices while the more disaggregated results are shown for the median carbon price of 15 €/t CO_2. The absolute values for the BAU scenario with the carbon price of 15 €/t CO_2 are presented in the Table S1. Carbon rents are based on the constant carbon prices and a 2.5% interest rate. It is assumed that carbon rent policies are implemented unilaterally. Thus, the analysis omits the impacts of carbon sequestration policies implemented multilaterally on world market prices and demand for forest products or import prices of timber.

In all scenarios, the energy sector faces the corresponding carbon payment per ton of CO_2 e.g. via emission trading system. In addition, wood-based biomass in energy production is subsidized according to current renewable energy policy in Finland. A new nuclear power plant, which is under construction, is assumed to enter in the electricity markets in 2020. Development of the demand for the end products is divided into two groups based on their expected prospects. We assume increasing demand for sawnwood and paper boards, and a decreasing demand for news and magazine papers for the first 50 years, and a stable demand thereafter. These changes are implemented by changing demand functions annually by 1%. All exogenous prices such as fossil fuels are assumed to be constant over time. Impacts of climate change on forest growth and mortality are not taken into account in this study, due to the lack of reliable estimates for these parameters.

The examined time period is 100 years, which enables us to capture impacts that occur over the long adjustment period of forests. The model is solved for 5-year time steps.

Results

Impacts on the forest carbon

In the BAU scenarios, the total growing stock volume in Finland is projected to increase substantially during the next hundred years

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[2] These parameters include the shape parameters of the investment cost function and the process unit costs, which include exogenous cost components.

(Fig. 2). The dominant driver for this is the current age structure. A large share of the total forest area in Finland is covered by young, fast growing forests. The median age is about 50 years. These young forests have been under intensive management and they are denser and more productive than the forests of the same age were some decades ago (e.g. Mielikäinen, 2012). This age structure implies high annual volume growth for several decades ahead. In the BAU scenarios with the current policies, the growing stock volume doubles in 100 years irrespective of the used carbon price level.

The implementation of a forest carbon policy changes forest management practices immediately. The policy provides an incentive to use longer rotations, i.e. postpone clear-cuts and thinning operations. The transition towards longer rotations decreases clear-cuts which increases annual volume growth in the short and medium run. As a result, both carbon sink (i.e. net carbon stock change) and forest carbon stock increase (Fig. 2): the higher the carbon rent, the greater the forest carbon stock in every time period throughout the model runs. However, in the long run, the net volume growth declines to nearly the same level as without a forest carbon policy. This decline is caused by the increasing natural mortality and slower volume growth of ageing forest stands. Carbon rents based on the carbon prices of 5, 15 and 30 €/t CO_2 lead to 11, 41 and 59% higher carbon stock levels in living trees within 100 years, compared to the corresponding BAU scenarios (Fig. 2 (left)).

The annual forest carbon sink starts to increase immediately after a forest carbon policy is imposed (Fig. 2 (right)). The strongest increase is observed during the first decades after implementing the policy. A carbon rent based on the carbon price of 5 €/t CO_2 provides quite steady annual increase in the carbon sink: the difference with respect to the BAU level increases from 4 $MtCO_2yr^{-1}$ to 9 $MtCO_2yr^{-1}$ over the century. With a carbon price of 15 €/tCO_2, the increase in annual carbon sink is considerably larger. Initially, the difference to the corresponding BAU is 13 $MtCO_2yr^{-1}$, which then rapidly grows to almost 30 $MtCO_2yr^{-1}$ before gradually decreasing to 20 $MtCO_2yr^{-1}$. The carbon price of 30 €/tCO_2 more than doubles the annual carbon sink during the first 50 years, compared to the BAU. The absolute increase is in the range of 35–55 $MtCO_2yr^{-1}$. Interestingly in the carbon rent scenarios, the carbon price of 30 €/tCO_2 leads to a weaker long-run carbon sink than the carbon price of 15 €/tCO_2. This is because in the scenario with higher price, forests grow old faster, and thus end up having a lesser annual growth rate than in the scenario with a lower carbon price. These increases in the carbon sink are notable compared to the average annual greenhouse gas emissions of about 65 $MtCO_2eq.yr^{-1}$ during the current decade in Finland excluding land use, land-use change and forest (LULUCF) sectors (Statistics Finland, 2016).

The size and dynamics of carbon policy impacts on carbon sink depend on the forest owners' preferences for amenity values (Fig. 3 for 15€/tCO_2). Forest owners with low amenity values contribute the most to the increase in the annual carbon sink both in absolute terms and per hectare. They provide quite steady annual increase in carbon sink over time compared to the BAU scenario. The carbon sink in the forests of the Faustmannian forest owners increases strongly during the early phase due to the carbon policy but declines then rapidly after 30 years. In both the BAU and CRENT scenarios, the forests turn into a carbon source in the later periods, as the drain exceeds growth. The source is slightly stronger in the CRENT scenario than in BAU. The reasons for the differences in the dynamic impacts as well as for the cyclicality that is visible in Fig. 3 are explained in Section 3.3.

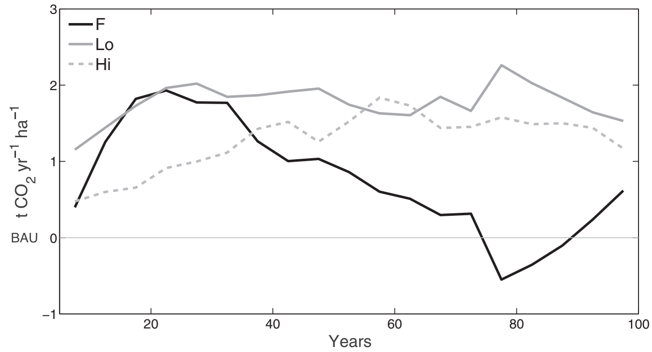

Fig. 3. Impact of forest carbon policy on the average annual carbon sink compared to BAU scenario per hectare across regions and site types and tree species for different types of forest owners: Faustmannian forest owner (F), forest owner with low amenity values (Lo) and forest owner with high amenity values (Hi). The carbon price is 15 €/t CO_2.

Impacts on the atmospheric carbon

Besides the forest biomass carbon stock, forest carbon policy also affects other carbon stocks and emissions. These components are shown in Fig. 4, along with their net impact on atmospheric carbon accumulation. The impact of a carbon rent policy on soil carbon stocks is negative, because the decrease in fellings reduces the amount of harvest residues. Especially in the short run, the amount of carbon in the forest soil decreases compared to the BAU. The carbon rent policy also decreases the carbon stock in harvested wood products, even though HWP carbon storage is subsidized. However, the reduction is small, because only a small amount of unrealized harvests would have been used for long-lived wood products. Similarly, the carbon rent policy increases fossil fuel emissions, as the supply of energy wood is reduced.

The effect of a forest carbon policy on forest biomass stock dominates over the effects on soil and product stocks and fossil emissions. Therefore, a net result of such a policy is a decrease of atmospheric carbon concentration. The dynamics of the net impact resembles that of the biomass carbon sink (Fig. 4).

Impacts on the timber markets

The unexpected implementation of a forest carbon policy gives forest owners incentives to postpone harvests. This causes an immediate shock in the timber market (see Fig. 5). The policy increases the value of growing stock and forest owners are willing to harvest only with higher timber price. With high carbon prices (15 and 30 euro/tCO_2), the short-run price increase is 35–100% but the impact deteriorates rapidly and after 30 years the price increase is only 20–35% in the case of logs. Both the demand and supply sides contribute to the lowering equilibrium prices. First, the demand is lowered as the reduced profits cause a gradual reduction of production capacity. Second, the supply recovers as forest stands age towards their new equilibrium rotations and, as a result, the annual per hectare yield increases. For low carbon price of 5 €/t CO_2, the impact is moderate for the whole simulation period.

Felling effects are a mirror image of price results, with the effects remaining somewhat more moderate (Fig. 5). In the model run with low carbon price (5 €/t CO_2), the carbon rent causes a relatively steady and moderate (5%) reduction in the annual fellings. With a carbon price of 15 €/t CO_2 harvests decrease for the first 20 years after the implementation of the carbon rent policy. The maximum reduction in harvests is roughly 25% compared to the BAU. After that period, the first forest stands begin to reach their new optimal rotation age and harvests start to approach the BAU level. After 70 years, the harvests are less than 10% below their level without the carbon rent. With a high carbon price (30 €/t CO_2) the market shock is dramatic. During the first decade, harvests are roughly halved compared to the corresponding BAU scenario. After that harvests gradually recover within the next 60 years. It takes over 70 years after the policy's implementation for the harvests to stabilize, after which they remain 15% below the BAU harvest level until the end of the simulation.

The effects of carbon rent on forest management vary between the forest-owner preference categories (Fig. 6). Forest owners who maximize the net present value of harvest profits use rotations shorter than

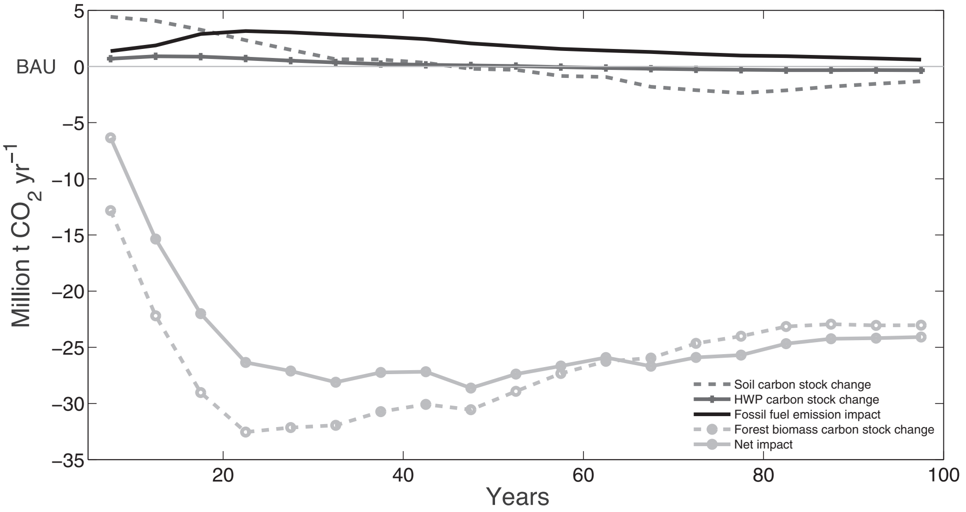

Fig. 4. Impact of forest carbon policy on the atmospheric carbon stock compared to BAU scenario with the carbon price of 15 €/t CO_2.

the ones providing the maximum sustainable yield (MSY). The harvests carried out by this group of owners rise above the baseline level (see “F” in Fig. 6) 50 years after implementing the carbon rent policy, with carbon price of 15 €/t CO_2. The increase in the long-run timber supply is in-line with theory. This follows as forest carbon policy induces longer rotations that are closer to the MSY rotation. The sudden implementation of a forest carbon policy strongly decreases the area of clear-cut forests. As a result, the regenerated areas are small for several decades. This age-structure shock of small age-classes is likely to contribute to the decline in harvests of the Faustmannian forest owners from 70 years onwards (Fig. 6). This kind of cyclicality has been observed with age-class models (see e.g. Uusivuori and Laturi, 2007). The market equilibrium cannot fully smooth out these fluctuations. The total cumulative harvested volumes by this type of forest owners during the first 100 years are only 3% less when a forest carbon policy is implemented than when it is not. However, the timing of these harvests differs substantially.

Forest owners who value amenities practice long rotations even without carbon sequestration incentives. Thus in the BAU scenario, their rotations are close to or even above the MSY (maximum sustainable yield) rotation. Thus, paying carbon rent could even decrease the long run timber supply, if these rotations are lengthened beyond the MSY. Carbon policy does not affect storage in forests that are not commercially harvested e.g. due to the amenity values. Thus the harvest reduction is smaller in high amenity forests than in low amenity ones.

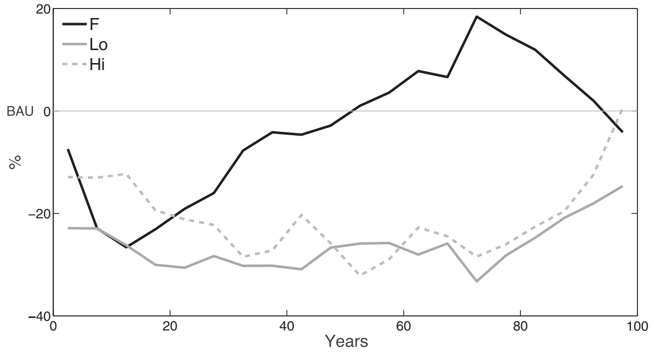

Fig. 6. Impact of forest carbon policy on felling volumes compared to BAU scenario for different types of forest owners: Faustmannian forest owner (F), forest owner with low amenity values (Lo) and forest owner with high amenity values (Hi). The carbon price is 15 €/t CO_2.

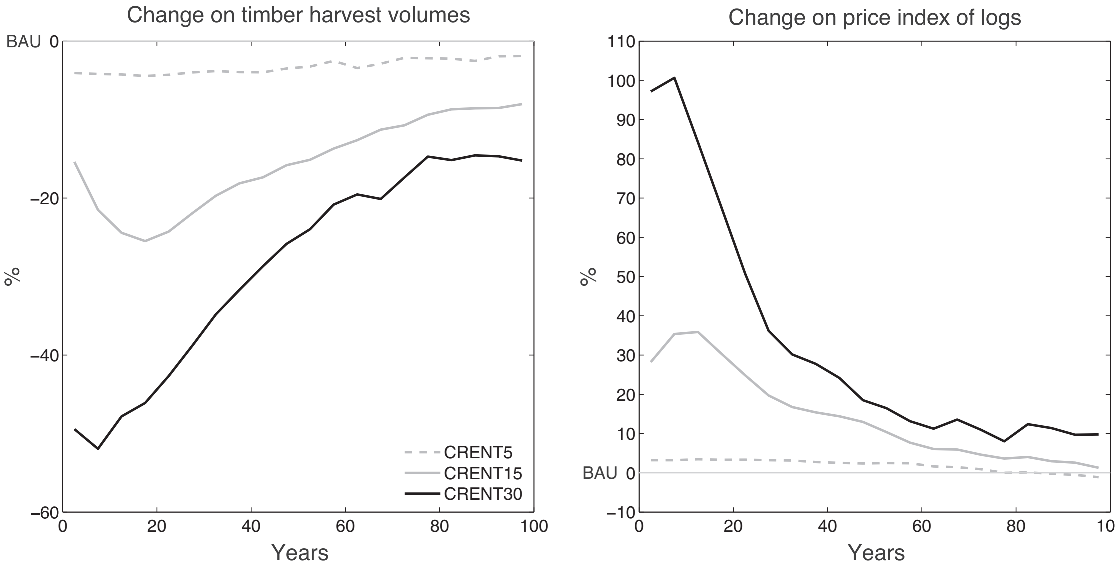

Fig. 5. Impact of forest carbon policy on timber harvest volumes compared to BAU scenario with carbon prices of 5, 15 and 30 €/t CO_2.

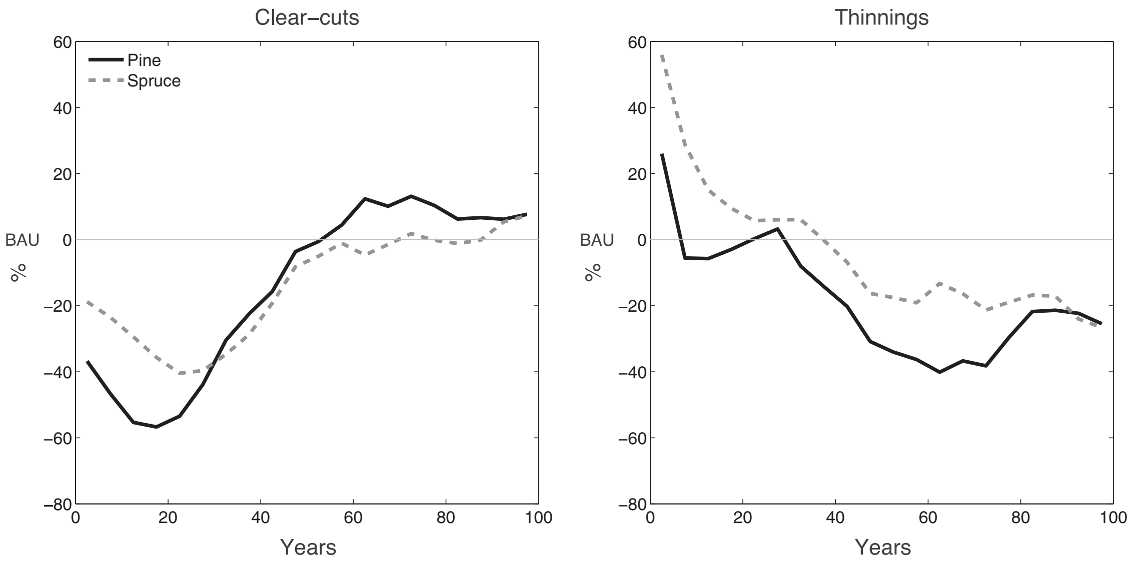

Fig. 7. Impact of forest carbon policy on clear-cuts (left) and thinning (right) volumes for Norway spruce and Scots pine with the carbon price of 15 €/t CO_2.

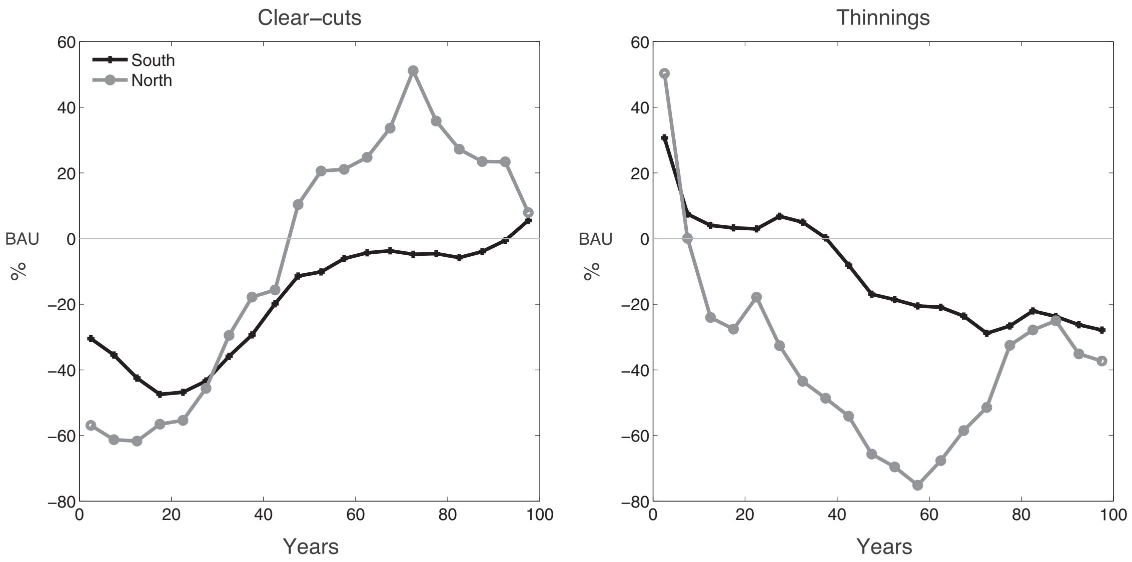

Fig. 8. Impact of forest carbon policy on clear-cuts (left) and thinning (right) volumes compared to BAU scenario for Southern and Northern Finland with the carbon price of 15 €/t CO_2.

Next, we decompose the harvests into clear-cuts and thinnings, and analyze how the carbon rents impact them with carbon price of 15 €/t CO_2. We examine both Scots pine and Norway spruce species as well as regional effects (Figs. 7 and 8). During the first 30 years, clearcuts (Fig. 7 left panel) decrease considerably, as forest owners shift to longer rotations. This is in line with the stand level models (e.g. van Kooten et al., 1995; Pohjola and Valsta, 2007). At the same time thinning operations are substituted for clear-cuts. Thus, in the short run the volumes harvested in thinning operations increase. Substitution occurs especially in forests with high standing timber volume, while clear-cuts more often target forests with lower timber volume. The substitution is large especially for Norway spruce stands and in northern forests.

In the later periods of model run, the impacts on clear-cuts and thinnings are opposite to those observed in earlier periods. The clear-cut area increases from 20 to 35% as a result of the carbon rent (15 €/t CO_2) over a hundred years. The average clear-cut volumes per hectare first decreases, but starts to gradually increase. It takes about 40 years before the average clear-cut volumes per hectare catch up with the volumes in the BAU scenario. After that the total clear-cut volumes reach the BAU levels and even exceed them in Northern Finland. On the other hand, the long-run cumulative thinning volumes are smaller than in the BAU scenarios, especially in the north. In the long run, thinnings of stands are postponed or avoided when the forest carbon policy is implemented. Thinning volumes permanently decrease below the BAU levels 10 and 40 years after the implementation of the policy in northern and southern Finland, respectively. This leads to 30% and 55% decreases in total thinning volumes and area, respectively, in the latter half of the model horizon. This suggests that, with carbon rents, the forest owners are less interested in harvesting cheaper timber assortments, such as pulp wood, as the policy subsidizes total biomass.

Growth conditions also affect the way how carbon payments change forest management (e.g. Pihlainen et al., 2014). In both regions the clear-cut volumes decline dramatically during the first periods. The decrease is over 50% in Northern Finland (Fig. 8). At the outset, the decrease in total harvests at a carbon price of 15 €/tCO_2 is smaller in the Southern Finland (between 10 and 20%), than in the Northern Finland (even 50%).

In Northern Finland clear-cut volumes recover faster than in the Southern Finland and, after 45 years, these volumes rise over their BAU levels. In the poor growth conditions of the North, monetary profits of thinnings are small, because the harvest yield is small and the share of valuable sawlogs is low. In addition, thinnings have smaller positive impact on the relative growth rate than in Southern Finland. As carbon rent increases the value of standing timber, it is relatively more profitable to restrain from thinning at sites with poor growth conditions, than at sites with better growth conditions.

Impacts on the forest industry

The implementation of a forest carbon policy causes considerable increases in roundwood prices in the short and medium term. These price increases imply higher production costs for forest industries. When the carbon price is 15 €/tCO$_2$, some paper and sawnwood producers are still able to utilize their full capacity in the first period by cutting their profits, while others have to reduce their production. Later on, the adjustments are done by reducing investments. When the carbon price is 30 €/tCO$_2$, most plants find it unprofitable to utilize their full capacity during the first 15 years. At the industry level, adjustment takes place by reducing investments and producing below capacity levels.

In the early periods, the sawnwood industry suffers the most from the forest carbon policy. This is due to the fact that the cost share of wood is higher in the production of sawnwood than in the pulp mills. Also, the possibility to adjust by importing logs is more limited than possibility to increase pulpwood imports. The HWP carbon subsidy improves the profitability of wood processing firms producing long-lasting wood products. The impact of the subsidy is however limited, because it is paid only for wood ending up to primary products. Also, sawnwood industry benefits slightly from the higher prices of the by-products. In the short run, the implementation of a carbon rent reduces the production of the sawnwood and plywood industries by 0, 10 or over 30% compared to the BAU, for carbon price of 5, 15 or 30 €/t CO$_2$, respectively (Fig. 9). In the long run, production of sawnwood almost recovers to the BAU level. This follows from the longer rotations that increase supply of logs.

The maximum decrease of paper and paperboard production, compared to the BAU scenarios, is 2, 10 or 20% with carbon prices of 5, 15 or 30 €/t CO$_2$ (Fig. 9). The impacts on paper production are the largest 15–25 years after the implementation of carbon rent policy. This is due to the fact that during the first periods, firms adjust to increased costs by cutting their profits. Imports of chemical pulp and timber are increased to soften the increase of raw material costs, especially right after the policy is implemented. However, wood imports only compensate for a small part of the loss in domestic harvests. Carbon rent decreases the long-run supply of pulpwood by decreasing thinnings. Thus, production of paper and paperboard adjust to this lower supply of pulpwood and production stabilizes below BAU levels.

Impacts on the production of electricity and heat

Forest carbon policy reduces the supply of wood-based fuels, which affects the fuel-mix and the total use of fuels in the energy sector. The supply of forest residues and pulpwood is decreased because of the lower level of harvests, while the supply of by-products is reduced due to the lower level of production in sawmills. The higher prices make wood-based fuels less competitive against fossil fuels. Impacts on the supply side are largest in the short run, while the demand side impacts strengthen in the long term. The demand side adjustments include gradual depreciation of old capital stock and accumulation of new capital through investments, both of which take time. The total impact, measured in terms of deviation from the BAU scenario, is the largest 15–25 years after the carbon rent policy is established.

Carbon rents considerably reduce investments in CHP (combined heat and power) plants using wood, especially in the first decades of the policy. Also the investments in wood-using heat plants and recovery boilers decline. Lower investments in wood-based plants are only partly compensated by increased investments in CHP pulverized fuel plants using peat or coal or plants using natural gas. Even high carbon rents do not make investments in condensing coal power plants profitable.

Carbon rents change the fuel mix of power and heat production. The effect is largest 20 years after implementing the carbon rents (Fig. 10). The use of residues and black liquor is clearly at a lower level and the use of pulpwood is close to zero with carbon price of 15€/tCO$_2$. The decrease in the use of by-products is more modest. To compensate for the drop in wood fuel use, fossil fuel use is increased. The largest increase is observed in the use of natural gas. In BAU, the combined cycle gas turbine is the marginal power plant type and, therefore, their utilization is reduced notably when new nuclear power plant enters in the market in the early phase of the simulation period. Carbon rents make these plants profitable again to some extent, which explains the increase in natural gas use. In the co-firing power plants, wood is partly replaced by peat and to a lesser extent coal. However, moving from the technically optimal mix of wood and coal/peat involves costs and, thus, restricts the amount of substitution. Most of the increase in peat use

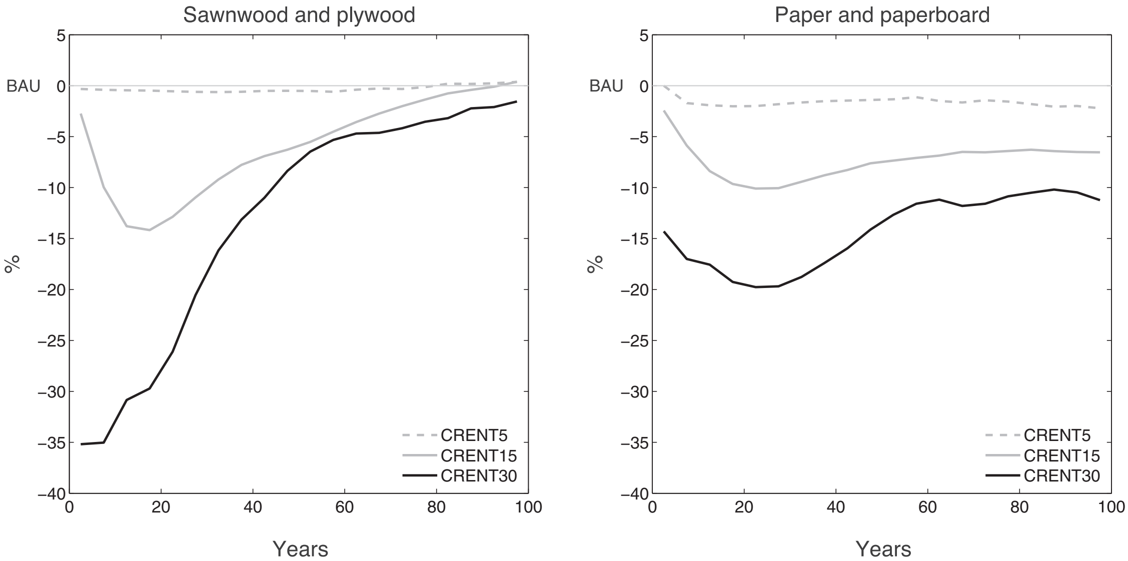

Fig. 9. Impact of forest carbon policy on production levels of the sawnwood and plywood industry (left) and paper and paperboard industry (right) compared to BAU scenario with carbon prices of 5, 15 and 30 €/t CO$_2$.

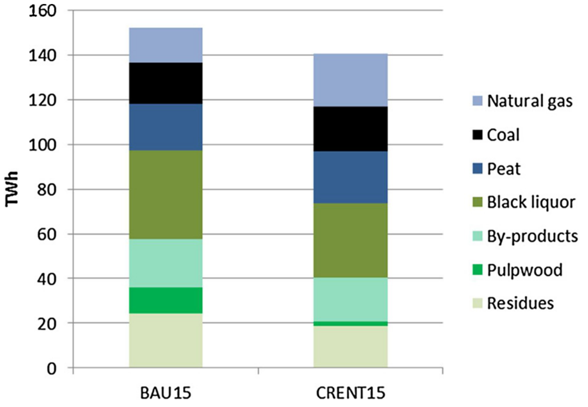

Fig. 10. The use of various wood-based and fossil fuels in the production of electricity and heat in BAU and forest carbon policy scenarios 20 years after implementing the carbon policy with the carbon price of 15 €/tCO$_2$.

takes place in co-firing boilers while the use of coal is increased most in the existing CHP pulverized fuel plants, instead of replacing wood by coal in the co-firing boilers.

Carbon rents reduce the total use of fuels, as the use of electricity and heat decreases as a result of lower production levels in forest industries. The share of wood-based fuels in combustion plants reduces from 64% in the BAU scenario to 52% with carbon price of 15 €/tCO$_2$ and from 69% to 44% with carbon price of 30 €/tCO$_2$. The joint share of fossil fuels and peat increases correspondingly.

The importance of endogenous timber prices

Since the implementation of a forest carbon policy causes a negative supply shock, it is likely to lead into a positive timber price shock. This price shock affects the management decisions by the forest owner. In the FinFEP model, the supply and demand of timber are balanced and timber prices are endogenously determined in a competitive equilibrium. Thus, it accounts for the effects of the price shock on forest owner behavior. In stand-level models with carbon sequestration policy (e.g. van Kooten et al., 1995; Uusivuori and Laturi, 2007; Pihlainen et al., 2014), timber prices are exogenous and constant. Here, we evaluate the importance of the endogenous price adjustments when studying the effectiveness of a forest carbon policy. This evaluation is performed by comparing the results of the full FinFEP-model with results obtained by solving only the supply side of the FinFEP using fixed timber prices. These fixed prices are derived from the BAU simulation, that is, without the carbon rents.

In Fig. 11, we compare the impact of forest carbon policy (based on a carbon price of 15 €/t CO$_2$) on the carbon sink with endogenous and fixed timber prices. The short-run increase in the carbon sink caused by the carbon rent is substantially higher, when the timber prices are fixed than when they are endogenous. This follows from the fact that the endogenous equilibrium prices jump up when the sudden policy implementation cuts down the supply. Thus, when timber prices rise, timber harvests are maintained at a higher level than what they would with fixed, and thus lower, prices as in many stand-level models. In a market-level model, the economy as a whole adjusts to carbon subsidies, which changes equilibrium timber prices and production. Therefore, the effects of a forest carbon policy are more moderate than in the case of fixed timber prices.

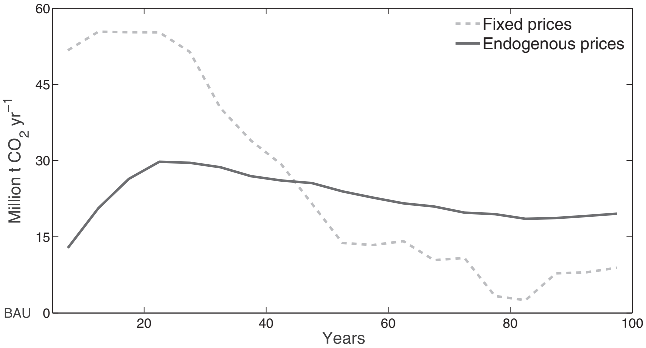

Fig. 11. Impact of forest carbon policy on forest carbon sink compared to BAU scenario in the cases of fixed and endogenous timber prices with a carbon price of 15 €/t CO$_2$.

The market mechanism with endogenous prices smooths the variation in harvest levels between periods. Thus, the short-run shock induced by the implementation of a forest carbon policy is smaller. In the fixed price case, forests remain uncut until new steady-state rotations are reached. At that point, harvests increase substantially and the carbon sink decreases rapidly. Our findings suggest that the estimates of the carbon sequestration potential and their costs may be overly optimistic if they are based on stand-level models. Especially, estimates of costs are too low when short run carbon sequestration is preferred over long run, for example, through discounting of carbon flows.

Discussion

Our results confirm the key finding of previous forest carbon policy studies. Even a relatively low carbon price can induce substantial carbon sequestration in forests (e.g., Sjølie et al., 2013, Pihlainen et al., 2014). A forest carbon policy, such as carbon rent, immediately increases the opportunity cost of harvesting, which incentivizes the forest owners to adjust their forest management plan for the current and future rotations. As a result, the timber supply goes down immediately and equilibrium harvests decrease. This increases the forest carbon sink. In addition, a forest carbon policy induces longer equilibrium rotations (e.g., van Kooten et al., 1995). The new equilibrium rotations are approached gradually and at the same time the sequestration weakens (Lintunen & Uusivuori 2016). In line with the theory we observe a large initial effect, which gradually weakens as a new steady-state is approached. The higher the carbon price the larger the initial effect. Similar dynamics has been observed also by Alig et al. (2010).

Interestingly, Sjølie et al. (2013, 2014) report results with Norwegian forest sector model (NorFor) that are contrary to ours. In their results, the initial carbon sequestration is relatively weak, and both the harvest and the carbon sink impacts gradually strengthen over time, even in the case of high carbon price. Unfortunately, we cannot pinpoint the exact cause for the differing results. However, there are several modeling differences between FinFEP and NorFor that are likely to contribute to the deviating results. For example, NorFor allows for fertilization and tree species change which can strengthen the long term impacts relative to the near term impacts. In addition, there are differences how the forest management decisions and forest owner preferences are modeled, both of which can affect the results.

Since the forest owners in the FinFEP model are categorized into the three groups based on their preferences, we were able to examine the effect of preferences on the equilibrium carbon sequestration. Our results (Fig. 6) are best understood in relation to the maximum sustainable yield (MSY) forest management. Without a carbon policy the forest owners who maximize the net present value of harvest profits (i.e, the "Faustmannian" forest owners) manage their forest so that the annual yield is below the MSY level. The carbon policy changes the management towards larger biomass levels and longer rotations, which increases the annual yields from these stands in the long run. This result was observed also in Lintunen and Uusivuori (2016). In the steady-state analysis, the same observation is made in e.g., Pohjola and Valsta (2007) and Pihlainen et al. (2014). Instead, if the forest owner has "Hartmanian" preferences and gains amenity services from the forest, the no-policy forest management is already closer to the MSY management. As the carbon policy incentivizes even greater densities and longer rotations, the management can go beyond the MSY level, which may reduce the annual yields. As a result, the forest owner preferences influence the carbon policy impacts on carbon sequestration and harvests.

Similarly to the heterogeneity of the forest owners, the heterogeneity of site productivities influences the policy impacts. This is in line with previous findings (Pohjola and Valsta, 2007; Niinimäki et al., 2013; Backéus et al., 2005). However, our results indicate that there may be interaction between the two attributes. Equivalently to Backéus et al. (2005), we found that the largest relative policy impact on carbon sequestration is in low productivity forests of "Faustmannian" forest owners. However, for the forest owners with high amenity valuation we observed an opposite result that the highest relative increases in carbon storage were obtained in the better growth conditions of Southern Finland than in poorer conditions of Northern Finland. Thus, our results suggest that a good assessment of forest owner preferences, site productivities, and their interactions is needed before policy impact assessments can be reliably made.

In the simulations, the longer rotations naturally imply a higher average age of forests. In the case of carbon price of 30 €/t CO_2, the average age is about 100 years at the end of the simulation. The change in age-structure is substantial, when compared to the current average age of 55 years and the average age of 70 years at the end of simulation without carbon rents. At the same time, the average density triples from its current level of 100 m^3/ha to about 300 m^3/ha. This corresponds to the current typical densities of 200–330 m^3/ha in central European countries (Metla, 2014). An important concern is how reliable the growth and mortality functions are in the situations where the average standing stocks are far away from the current forests. In addition, these old and volume rich forests may face up new kind of risks, e.g. due the changing climate, fires, pest and diseases, which needs more experiments and analysis. According to our results, carbon policy could lead to situation where over 150 years old forest contains even quarter of the total standing stock. In the current situation only 3% of the total standing stock is in forests of that age.

We did not consider how climate change affects forest growth and mortality. Kallio et al. (2013) have simulated these growth impacts over the next decades in the case of Finnish forests. Lobianco et al. (2016) suggest that climate change affects forest management directly through the changing growth conditions, and indirectly through the changes on global demand for forest products. Further research regarding the impacts of forest carbon policy needs to take into account the effects of climate change on forest growth and mortality as well as demand for forest products.

In Finland land use changes are relatively low. Thus, we use fixed forest land area. Deforestation has been only about 0.05% yr^{-1} (Statistics Finland, 2016). Implementing carbon rent policy would increase profitability of forestry, but the market effect of land use change would be small because of the long rotations and already high share forest land of the total land area in Finland. By allowing land use changes, the carbon policy would lead to an increase in the forest land area. However, it will take more than 30 years until those new plantations would affect the timber supply in Finnish growth conditions.

We found that the effect of a forest carbon policy on forest biomass stock dominates over the effects on soil and product stocks and fossil fuel emissions from energy production. Therefore, the net result of a forest carbon policy was a clear decrease in atmospheric carbon concentration. However, the impacts on emissions from material substitution are not included in the model and therefore the increase in these emissions could not be taken into account in the quantitative FinFEP impact assessment. We have however evaluated the potential increase in emissions by using the mean and upper limit values for substitution factors from literature (Soimakallio et al., 2016). Increase in emissions follows as forest carbon policy reduces the harvests and thus implies e.g. replacement of some wood construction by concrete buildings, paperboard packages by plastics and paper by electronic media. With mean values for those substitution factors, the annual net impact reduced at most from 26.5 $MtCO_2yr^{-1}$to 23 $MtCO_2yr^{-1}$ and for upper limits of values to 21.5 $MtCO_2yr^{-1}$ in the case of carbon price of 15 €/t CO_2. The small impact is explained by the fact that only a fraction of the forest biomass that is removed from the forest is linked to the material substitution. Furthermore, the impact of increased emissions from material substitution diminishes over time when the harvests approach the BAU level. The dominance of the biomass effect was also observed by Lintunen and Uusivuori (2016), who used a full optimization setup, in which material substitution was taken into account.

Carbon rents strongly increase forest owners' profits. In the first decade forest owners profits are 19, 79 and 130% higher with carbon rent than in the BAU simulations with carbon prices 5, 15 and 30€/tCO_2 respectively. Forest owners' profits increase both because of the higher timber prices and carbon compensations. Incomes from carbon rents increase over time when the standing stock increases, but the timber price shock tapers off over time. As the carbon rent increases the standing stock, also the amenity value of forests increases. Forest owners with amenity values benefit from a forest carbon policy, as it increases both their amenity and monetary utility.

The total annual income from carbon rent, based on a carbon price of 15 €/tCO_2, would be 950 million euros in 5 years, and 2.1 billion euros in 50 years after implementing the policy, given that carbon rents were paid according to total carbon stock. These annual carbon rent payments levels are over 70% of forest owners profits on the BAU scenario on those years with the same price of carbon. If carbon rents were paid for additional carbon stock only, the payments would be significantly lower, namely 30 million euros, in 5 years and 550 million euros, in 50 years after implementing the policy. This means that if all carbon storage were credited, most of the payment would be paid for carbon storage that would take place even without forest carbon policy. The amount of this "wind-fall" payment would be 920 million euros in 5 years, and 1.55 billion euros in 50 years after implementing the policy. All forest owners would receive these payments irrespective of their preferences for amenities or the site quality of their forests. In the model, the payment based on the additionality is straight-forward to calculate as additional carbon storage is a difference in storages between policy and BAU scenarios carbon storage in BAU scenario. In practice, the policy based on additionality would have some obvious difficulties. For Faustmannian forest owners, the forest management recommendations could be used to approximate the amount of carbon storage in BAU scenario. For Hartmanians, the determination of the amount of carbon stored without the forest carbon policy would be more challenging.

Obviously, quantitative and possibly also qualitative results depend on the parameter values used in the model. Price elasticities of demand, both domestic and export, and imports are among the parameters whose values are most likely to affect the results. Therefore, we performed sensitivity analysis for the values of those price elasticities. With lower price elasticities of demand, the size of carbon sink is at a lower level while the fellings and production levels in forest industries remain higher than with default values. In the case of higher elasticities the impacts are opposite. With more elastic wood imports, fellings are lower than with default elasticity values while the size of carbon sink and production levels of forest industries are higher. The dynamics of the policy impact remain similar, that is, the impact of forest carbon policy continues to be strongest in the first decades. To summarize, varying the values of price elasticities affects the quantitative results to some extent. However, the key messages of the study remain the same.

In the calculations with a single-country market model, we assumed that a forest carbon policy is implemented in Finland only. This assumption strengthens the impact of carbon rents on the carbon sink compared to a multilateral implementation of the policy. Our results demonstrate that the unilateral implementation of carbon rents increases the imports of timber and pulp from countries outside the policy, thus causing carbon leakage.

International climate policy has been based on relatively short term agreements, when contrasted with the time-scales of forestry in boreal forests. For example Kyoto II was designed for 2013–2020. In a sense, the politically relevant time scale is biologically too short (Lecocq et al., 2011). It can be stated that also from the economic point of view the politically relevant time-scale is too short. Our results, and those of Sjølie et al. (2013), show that an economic adjustment path to a forest carbon policy can last for a century or more. Even the strongest early shock stage can last over 30 years in the forest and economic sectors. The decision horizon of a forest related climate policy should be a century rather than a decade.

Even if the forest sector seems to have cost-effective potential to mitigate climate change, current international climate policies do not encourage countries to implement nationwide payments for carbon sequestration (e.g. Laturi et al., 2016). Carbon sequestration benefits have been limited in order to prevent countries from escaping their commitments to reduce emissions, but at the same time this limits the possibilities to increase carbon storage (e.g. Ellison et al., 2014). Our results indicate that carbon rent is an effective climate change mitigation policy. The short-sightedness of international climate policy and its restrictions on rewarding additional carbon storage most likely discourage countries from implementing this kind of policy.

Conclusions

We evaluated the impacts of forest carbon policies, with carbon rents for forest and wood product carbon stocks, on the Finnish forest and energy sectors. Our results suggest that carbon sequestration payments, such as carbon rents, could be an effective instrument to mitigate climate change. Even with low carbon prices, sizeable and immediate increases in carbon sinks can be obtained. Furthermore, our results demonstrated the importance of including the adjustment path in the analysis, as the short-run and long-run impacts differ substantially. The higher the carbon price behind the carbon rent, the larger was the short run effect. However, in the long run, aggregate harvests and carbon sinks approached the BAU levels, with studied carbon prices. Forest owners' preferences for amenity values determine whether the BAU-rotations are shorter or longer than MSY-rotations. Thus, as the carbon rent lengthens optimal rotations, these preferences determine whether the policy increases or decreases the timber supply. Forest owners with low amenity values contributed the most to the increase in the annual carbon sink both in absolute terms and per hectare. Our results indicated that market-level models with endogenous price responses are needed for regional carbon sequestration assessments, since the stand-level models with fixed timber price may yield overly optimistic results about the cost of carbon sequestration.

Carbon rents affect the fuel-mix in the production of electricity and heat by decreasing the use of wood-based fuels and increasing the use of fossil fuels. This follows as the reduced supply of wood-based fuels increases their equilibrium prices and weakens their competitiveness against fossil fuels. Thus, there is a trade-off between carbon sequestration and energy use of biomass. The trade-off is apparent in countries like Finland, in which the policies that increase the use of renewables mainly target wood-based fuels.

In addition, forest carbon policies require a very long-term commitment to the policy in order to ensure its effectiveness. This is because the market reactions following the abandonment of a carbon rent could be strong, and might even reverse its achievements. In that case, harvests would increase substantially and the carbon, which was sequestered while the policy was in place, would be released back into the atmosphere.

In order to mitigate climate change in a cost-effective way, the carbon rents should be based on the same carbon price used for other sectors, e.g. in emission trading system. However, according to our results, the short-run timber market effects might be very strong for carbon rents based on the carbon price of 30 €/t CO_2. Thus, it might be politically more acceptable to implement the policy gradually e.g. by starting with low carbon rent and by increasing it over time. Moreover, in our calculations with single-country market model, we assumed that policies were implemented only in Finland. The assumption of unilateral implementation strengthens the impact of carbon rents on the carbon sink compared to multilateral implementation of policy. It is important to implement the incentive system internationally to prevent carbon leakage.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jfe.2018.03.001.

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