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Cost-efficient climate policies for interdependent carbon pools

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ABSTRACT

The purpose of this paper is to investigate cost-effective climate policy instruments for bioenergy and timber, adapted to the impacts on interdependent forest carbon pools, and applied in the EU climate policy to 2050. We develop a discrete time dynamic model including forest carbon pools in biomass, soil, and products, as well as fossil fuel consumption. The analytical results show that the optimal taxes on forest products depend on the growth in the respective carbon pool. The application to the EU 2050 climate policy for emission trading shows that total costs for target achievement can be reduced by 33 percent if all carbon pools are included, and the carbon tax on fossil fuel can be reduced by 50 percent. Optimal taxes on forest products differ among countries and over time depending on the potential for increased carbon sequestration over the planning period.

1. Introduction

Terrestrial carbon pools[1] have received attention for their climate change mitigation potential and the comparatively low associated costs. Increased carbon pools in natural ecosystems could thus be an alternative and complement to other measures, such as reduced fossil fuel use and increases in renewable energy (Bosetti et al., 2009; Murray et al., 2009; Sohngen, 2009). It can be costly to ignore forest carbon flows and stocks when developing strategies against climate change. In Europe, the sequestration of carbon in forest biomass and soils corresponds to 8–10 percent of the total emissions (Kuikman et al., 2011; Lal, 2005), and sequestration tends to increase over time (Kauppi et al., 1992; Liski et al., 2002). Consideration of the risk for future carbon losses and the potential for targeted increases in carbon sequestration could thus be of importance for economic and environmental reasons.

Within the European Union (EU), crediting of increases in natural carbon pools against the CO_2 burden allocation is not allowed in spite of the substantial cost savings it could entail (Gren et al., 2012; Michetti and Rosa, 2012; Münnich-Vass and Elofsson, 2016). Arguments against the introduction of policies to enhance carbon sinks in the EU include the complexity and mutual interdependence of forest carbon pools, and the difficulties of designing appropriate incentive structures (Kuikman et al., 2011). Forest carbon consists of two main natural pools; above-ground carbon in the biomass and below-ground carbon in the soil (Lal, 2005). Forest harvesting decisions affect the stock of carbon in growing biomass, but also indirectly influence the stock of soil carbon (Jandl et al., 2007; Kuikman et al., 2011; Lal, 2005). Neglect of this dependency will lead to false conclusions about the impact of forest management on total forest carbon sequestration. The dependency between forest carbon pools further aggravates policy design for

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[1] We use the IPCC (2003) definitions as presented by FAO (2014) where carbon pool refers to carbon reservoirs with the capacity to accumulate or release carbon, carbon stock to the amount of carbon in the pools at a specific point of time, sequestration as the process of increasing the carbon content in the pools, and carbon sink as a process for removing carbon content from the atmosphere.

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carbon sink enhancement. Even if only a single carbon pool is considered, there are challenges concerning monitoring of carbon stock changes and verification of the additionality and permanence of such changes (cf., Bento et al., 2015; Engel et al., 2015; Mason and Plantinga, 2013). Much of the literature on policy instruments for carbon sequestration deals with instruments directed towards individual forest owners which require measurement and monitoring of changes in each forest owner's carbon pool (Guthrie and Kumareswaran, 2009; Latta et al., 2011; Lecocq et al., 2011; Updegraff et al., 2010; van Kooten et al., 1995). Policies targeting forest products could then have an advantage because of the comparatively lower costs to measure and monitor these products (Hoel and Sletten, 2016). Additionality can still be a concern, but the issue would be reduced to evaluation of the aggregate additionality, rather than the additionality of sequestration achieved by each forest owner.

The purpose of this paper is to analyze the design of policies on forest products to enhance carbon sequestration in interdependent carbon pools as a complement to reductions in emissions from fossil fuels. The analysis is applied to carbon sequestration in forest biomass and soils, and carbon storage in forest products, in the EU climate policy from 2010 to 2050. Within the EU, inclusion of a single carbon pool can be seen as a feasible alternative if, for example, there is disagreement about the advantages of including several carbon pools. We therefore compare separate and complete inclusion of biomass, soil, and forest product pools in the policy decision, in order to assess whether separate inclusion is a step in the right direction, or even counterproductive. In addition, we investigate the cost-efficient economic incentives for achieving increased carbon sequestration. This is done with an aim to evaluate the potential for common policy instruments at the EU level to promote carbon sinks.

For these purposes, we construct a discrete dynamic model for cost-efficient attainment of future targets on carbon emission as suggested by the EU 2050 climate policy (EUCOM, 2012) by means of reduced combustion of fossil fuels and forest products and enhanced carbon sequestration. The interlinked carbon pools are managed by taxes targeting timber and bioenergy, which differ with respect to the displacement of fossil fuel. It is shown analytically that the cost efficient carbon taxes on timber and bioenergy can either increase or decrease when both biomass and soil pools are considered, instead of only one of these pools. The direction of impact depends on the effect of harvesting on the growth rate in the respective pool. It is also shown that the tax on timber decreases for a delayed combustion of wood products because of the larger discounting of future costs of carbon emissions. The empirical results show that inclusion of carbon sequestration reduces overall costs for reaching EU 2050 climate targets by 33 percent, and the optimal carbon tax on fossil fuel by up to 50 percent. If only a single carbon pool is included, the choice of pool to include matters, not only for the cost savings achieved, but also for the net impact on carbon emissions. The optimal tax on fossil fuels is increasing over time for all countries but the carbon tax on wood products can either increase or decrease depending on the forest growth rate and the time path of reduction targets.

Our study belongs to two main strands of the literature; economics of carbon regulation by forest management and design of policy instruments for carbon sink enhancement. Several earlier economic studies on forest management include more than one forest carbon pool in the analysis, such as Lubowski et al. (2006), Newell and Stavins (2000), Sohngen and Mendelsohn (2003), van Kooten et al. (1999), and Wise and Cacho (2005). However, we have not found any study which compares a second-best policy, including only a single carbon pool, with the first best policy, where several interlinked pools are included. A number of studies analyze policy instruments applied to a single (biomass) carbon pool. Using a national forest sector model, Caurla et al. (2013) and Lecocq et al. (2011) compare the impact of alternative combinations of climate policy instruments on the forest sector and resources. van Kooten et al. (1995) show that a combination of carbon taxes and subsidies can be used to achieve socially optimal forest rotation, and Latta et al. (2011) investigate the consequences of a tax/subsidy scheme, voluntary or mandatory, in a forest sector model.

With respect to the literature on policies for carbon sink enhancement, Mason and Plantinga (2013) conclude that a uniform carbon subsidy scheme implies higher costs for achieving sequestration than a contract design system. Bento et al. (2015) analyze the role of the additionality problem and monitoring costs for the design of carbon offset contracts. Using a real options model with uncertain future timber prices, Guthrie and Kumareswaran (2009) compare subsidies paid in proportion to the actual amount of carbon sequestered to credits that are allocated according to the long-run potential to sequester carbon, showing that the former generates more sequestration. Using a globally aggregated model, Hoel and Sletten (2016) analyze optimal taxes on energy consumption, differentiated between fossil fuel energy and bioenergy to account for the impact on forest sequestration. Compared to those, our study contributes through analysis and empirical calculation of cost-efficient, nationally differentiated taxes on timber, bioenergy and fossil fuels for reaching politically determined targets on carbon dioxide emissions, while accounting for the role of carbon pool interdependence.

The paper is organized as follows; first, the numerical model is described, followed by the derivation of the cost-efficient policy instruments. Then, data are described and results are presented. The paper ends with a discussion and conclusions.

2. Numerical model

Consider the EU, with $i = 1, \ldots, 27$ different countries. Together, the countries have agreed on a CO_2 emissions reduction path until 2050, which they wish to implement at least cost. The emission reductions can be achieved by either reduced consumption of fossil fuels within the EU Emission Trading Scheme, or by implementing changes in forest management. The potential to use forests for different purposes is, ultimately, determined by the existing forest biomass and its development over time. The development of the growing stock of trees[2] on an average hectare of land is defined by:

$$V_{t+1}^i = V_t^i + G_t^i\left(V_t^i\right) - H_{t+1}^i \tag{1}$$

$$V_0^i = \overline{V_0^i},$$

where variables are measured in cubic meters: H_{t+1}^i is the harvest in country i, which is assumed to take place in the beginning of the year,[3] V_t^i is the growing stock measured directly after the harvest, and $G_t^i(V_t^i)$ is the annual growth. Total stem wood volume in a country is $A^i V_t^i$, where A^i is the area of forest land, measured in hectares. It is assumed that $G_t^i(V_t^i)$is positive, differentiable and

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[2] The growing stock is typically defined as the volume of all living trees in a certain area of forest with a minimum diameter at breast height, and includes the stem from ground level or stump height up to a given top diameter, and may also include branches above a certain diameter. Here, the growing stock is assumed equal the merchantable tree volume.

[3] The choice of timing of the harvest (in the beginning rather than in the end of each time period) is made because this, later, facilitates the interpretation equations (15) and (16).

increasing up to a given, intermediate volume level, thereafter it successively declines towards zero as the forest approaches carrying capacity.

The use of a representative hectare of forest land is a simplification compared to large scale age class forestry models such as Sohngen and Sedjo (2006), which has global coverage, and Moiseyev et al. (2011), which includes the European countries. This simplification is motivated by our aim to describe the optimal time dynamics of carbon sequestration both analytically and numerically in relation to reductions in CO_2 emissions from fossil fuel. The use of a representative hectare is reasonable if the distribution of forest across different age classes is relatively even: it works less well if, for example, there is a (disproportionally) large area of forest near economic maturity, which typically implies high growth. When such a forest is harvested, and replaced by young forest, the average growth could fall more than is accounted for by equation (1). The approach is therefore more reasonable on a higher level of aggregation, such as the national level, as storm felling and fires could lead to considerable local variations in the age-class distribution, while having little impact on the aggregate national level.

Forest carbon sequestration occurs in growing trees and in forest soil. Net annual carbon sequestration in trees, W^i_t, is assumed to be defined by:

$$W^i_{t+1} = \eta\beta^i A^i\left(V^i_{t+1} - V^i_t\right), \tag{2}$$

where β^i is the ratio of total wood volume to stem volume and η is a parameter for conversion of tree volume to ton CO_2-equivalents removed from the atmosphere.

The development of the soil carbon stock on a representative hectare of land, P^i_t, is mainly determined by the wood volume, which adds to the soil carbon stock as litter falls to the ground, by forest harvest, and natural carbon release. Following Liski et al. (2002) we assume that litter from the growing stock adds to the soil carbon stock, and that the decomposed litter added is a constant share, κ^i, of the total wood volume in a given year. Harvesting can cause a release of soil carbon on the harvested area due to disturbances in the soil structure, shifts in abundance of woody and herbaceous vegetation, and altered soil, water and temperature conditions which increase decomposition (Jandl et al., 2007; Kuikman et al., 2011). It is here assumed that the release of soil carbon depends on the area of final felling and carbon content in the soil. The harvested share of the forest land area is then described by $\gamma^i H^i_{t+1}/(V^i_t + G^i_t(V^i_t))$, where γ^i is a constant converting the share of volume harvested, $H^i_{t+1}/(V^i_t + G^i_t(V^i_t))$, into the share of harvested area.[4] We have $\gamma^i < 1$ since forest is harvested at an old age when the growing stock per hectare is relatively large. The carbon release from a representative hectare of forest land due to final felling is then assumed to equal the harvested share of the area times a constant fraction, ν^i, of the carbon soil pool, P^i_t. This gives release[5] in period *t+1* as a share, $0 \le \nu^i\gamma^i H^i_{t+1}/(V^i_t + G^i_t(V^i_t)) \le 1$, of P^i_t. In addition, soil carbon is assumed to be continuously released due to natural processes. We follow Liski et al. (2002) by assuming that the carbon pool P^i_t decays at constant rate, ϑ^i, in each time period.[6] The development of the soil carbon stock[7] on an average hectare of forest land, P^i_t, is then defined by:

$$P^i_{t+1} = P^i_t - \nu P^i_t \gamma \frac{H^i_{t+1}}{\left(V^i_t + G^i_t\left(V^i_t\right)\right)} + \kappa^i\eta\beta^i V^i_t - \vartheta^i P^i_t, \tag{3}$$

The second term on the r.h.s. expresses soil carbon losses due to final felling in the beginning of time $t+1$.[8] The third term shows the added carbon from litter, and the fourth the natural decay of soil carbon, accounting for the release of carbon to the atmosphere. Total annual carbon sequestration in forest soil, M^i_t, can then be expressed as the incremental change in the soil carbon stock:

$$M^i_{t+1} = A^i_{t+1}\left(P^i_{t+1} - P^i_t\right). \tag{4}$$

Total carbon sequestration in trees and soils, S^i_t, is then:

$$S^i_t = W^i_t + M^i_t. \tag{5}$$

The harvested forest volume is used for two different purposes, bioenergy and timber:

$$A^i H^i_t = B^i_t + T^i_t, \tag{6}$$

where B^i_t and T^i_t are the total volumes of bioenergy and timber, respectively. Bioenergy and timber both affect CO_2 emissions. Following Hoel and Sletten (2016) we assume that the CO_2 content of bioenergy, ηB^i_t, is released to the atmosphere in the same time period as it is harvested. The released CO_2 is, however, partly offset by displacement of fossil fuels. Displacement depends on the relative efficiency of bioenergy and replaced fossil systems (Schlamadinger and Marland, 1996). The parameter τ, with $\tau \in (0,1)$, expresses net CO_2 emissions per unit of CO_2 in bioenergy after taking fossil fuel displacement into account, implying that net CO_2 emissions from bioenergy are equal to $\tau\eta B^i_t$.

When used as timber, carbon is stored in wood products, which are assumed to have a life span of k_i years (cf. Eggers, 2002), after which they are combusted for energy purposes, and the CO_2 content is released. Like bioenergy, timber that is combusted is assumed to replace fossil fuels, hence the emissions are partially offset, implying that the net release of CO_2 after k_i years is $\tau\eta T^i_{t-k_i}$. The contribution of bioenergy and timber to CO_2 emissions in a given yearL^i_t, can then be summarized as:

$$L^i_t = \tau\eta\left(T^i_{t-k_i} + B^i_t\right), \tag{7}$$

where the first term is the release of carbon from wood products combusted at the end of their lifetime, and the second is the net contribution of bioenergy to CO_2 emissions, given the displacement of fossil fuels. The above formulation implies that we abstract from carbon emissions that arise during harvesting, transporting and processing of bioenergy and timber. This simplification is justified by the fact that these emissions only correspond to about 2 per cent

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[4] Recall that H^i_{t+1} occurs in the beginning of period t+1, whereas $(V^i_t + G^i_t(V^i_t))$ is the volume measured in the end of period *t*.

[5] We make a simplification by assuming that all of the loss occurs within a single time period albeit a net decline in soil carbon might continue over 10–15 years (Covington, 1981; Federer, 1984). This simplification is only motivated by convenience of modelling.

[6] Detailed soil carbon models such as that in Liski et al. (2002) divide soil carbon into several, interdependent sub-pools, while assuming a constant rate of decay for each of these sub-pools.

[7] Measured at the end of the time period.

[8] We include the possibility for such losses here, but given the mixed empirical evidence on such losses, as the losses typically depend on harvesting technology (Jandl et al., 2007), we also investigate a case with zero carbon losses from final felling in the sensitivity analysis.

of the total carbon emissions from wood products (Petersen Raymer, 2006). The net reduction of CO_2 in the atmosphereR_t^i, due to forest carbon sequestration and the different uses of forest products, can then be summarized as:

$$R_t^i = S_t^i - L_t^i. \tag{8}$$

The combustion of fossil fuels in each country contributes to CO_2 emissions. Emissions of CO_2 from fossil fuels are determined by the quantities of fossil fuels consumed, X_t^{ij}, with $j = 1, \ldots, 6$, different types of fuel,[9] and emission coefficients for each fuel type, α^j. Total emissions in all countries from fossil fuels and forest managementE_t, are then:

$$E_t = \sum_i \left(\sum_j \alpha^j X_t^{ij} - \tilde{R}_t^i \right). \tag{9}$$

There are costs associated with reduced fossil fuel consumption and a changed supply of forest products. The cost for reducing the consumption of a certain type of fossil fuel is defined by $C_t^{Xij}(X_{BAU}^{ij} - X_t^{ij})$, where X_{BAU}^{ij} is the business-as-usual (BAU) consumption of the fossil fuel in question. It is assumed that the cost function is twice differentiable, decreasing and convex, and that the consumption cannot fall below a given minimum level$\underline{X}_t^{ij}$, i.e.,$\underline{X}_t^{ij} \le X_t^{ij} \le X_{BAU}^{ij}$.

The use of timber and bioenergy can, in principle, be either reduced or increased in order to abate carbon emissions. The cost of changing bioenergy production is defined as $C_t^{Bi}(B_{BAU}^i - B_t^i)$, where B_{BAU}^i is the BAU production of forest bioenergy. It is assumed that B_t^i is subject to lower and upper bounds, such that $\underline{B}^i \le B_t^i \le \overline{B}^i$. In a corresponding manner, changes in the production of timber give rise to a cost, $C_t^{Ti}(T_{BAU}^i - T_t^i)$, where T_{BAU}^i is the BAU production level, and lower and upper bound apply, i.e. $\underline{T}^i \le T_t^i \le \overline{T}^i$. The cost functions for bioenergy and timber are assumed to be continuous, convex, and decreasing (increasing) in B_t^i and T_t^i below (above) the BAU level.

Costs are assumed to be separable in bioenergy, timber and fossil fuels. Studies applied at the regional scale often assume that a fixed share of the forest harvest is used for bioenergy, see, e.g., Carlsson (2012) and Trømborg and Sjølie (2011). In contrast, the global model in Eriksson (2015) assumes bioenergy and timber are separable in production. Notably, there is large variation in the share of forest harvest used for bioenergy in different European countries, see Table A1 in the Appendix; which implies that fixed shares is not an appropriate assumption at this scale[10]. The assumption about cost separability in fossil fuels and forest products is motivated by the comparatively small role of bioenergy and timber combustion for total energy consumption.[11] A more elaborate analysis of the substitution in production and consumption, and hence cost interdependence, between bioenergy and fossil fuels would require detailed analysis of supply and demand in different industries, which is beyond the scope of this paper, given its focus on sequestration time dynamics and carbon pool interdependencies. Instead, the substitution is accounted for in a simplified manner through the use of a displacement factor, see equation (7).

It is assumed that EU policy makers want to meet a sequence of annual emissions targetsE_t^{MAX}, which are based on EU's roadmap for moving to a low-carbon economy by 2050 (EUCOM, 2012). The sequence of emission targets can be met by reductions of the consumption of fossil fuels and changes in forest management which affect bioenergy and timber production as well as carbon sequestration in growing forests and soils. The emission targets are expressed as:

$$E_t \le E_t^{MAX}. \tag{10}$$

for the targets years t = 1, …,40. It is assumed that policy makers wants to meet (10) at a minimum cost. The decision problem is then to:

$$\underset{X_t^{ij}, B_t^i, T_t^i}{Min}\ TC = \sum_t \sum_i \rho_t \left[C_t^{Bi}\left(B_{BAU}^i - B_t^i\right) + C_t^{Ti}\left(T_{BAU}^i - T_t^i\right) + \sum_j C_t^{Xij}\left(X_{BAU}^{ij} - X_t^{ij}\right) \right] \tag{11}$$

s.t. (1)–(10), and the upper and lower bounds on the decision variables. The dynamic discrete time Lagrangian for this problem, and the associated necessary conditions for an interior solution, are presented in the Appendix. In the following section, we present the cost-efficient policy instruments which are derived from the necessary conditions.

3. Cost-efficient policy instruments

For fossil fuels, the cost efficient tax is defined by:

$$-\partial C_t^{ij}\left(X_{BAU}^{ij} - X_t^{ij}\right) \Big/ \partial X_t^{ij} = \lambda_t \alpha^j, \tag{12}$$

i.e., each fuel is taxed in proportion to the carbon emissions per unit of fuel. Thus, we get the well-known result that all fuels can be taxed in proportion to the carbon emissions, using a tax per ton of carbon equal to λ_t, i.e. the shadow cost of the emission constraint. The shadow cost increases over time due to increased target stringency, and depends jointly on the costs for fossil fuel reductions and changed forest management at different points in time.

Taxes on timber and bioenergy will affect the decisions by forest product suppliers. Assuming that there are well-functioning market for forest products in all countries, the forest supply sectors' decision problem will be to minimize the sum of the costs for

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[9] Hard coal, lignite, natural gas, light fuel and heating oil, heavy fuel oil and jet fuel.

[10] One possible reason for variations in forest use is differences in the use of forest residues for energy purposes. Data on the use of forest residues would be necessary to empirically assess the degree of cost separability between timber and bioenergy, but such data are not available for the EU countries.

[11] Using data for 2010 on fossil fuel consumption and bioenergy production, see Appendix, and a factor 0.18 for conversion of biomass in m3 to toe, the bioenergy produced in European forests corresponds to about 1 per cent of the total energy from fossil fuels.

producing below or above the BAU levels, i.e., the levels that would be privately optimal in the absence of taxes, plus costs for taxation:

$$\underset{B_t^i, T_t^i}{MinTC} = \sum_t \sum_i \rho_t \left[C_t^{Bi}\left(B_{BAU}^i - B_t^i\right) + C_t^{Ti}\left(T_{BAU}^i - T_t^i\right) + \Psi_t^{Bi} B_t^i + \Psi_t^{Ti} T_t^i \right], \tag{13}$$

where Ψ_t^{Bi} and Ψ_t^{Ti} are the unit taxes on bioenergy and timber, respectively. Assuming an interior solution, the first order conditions for the problem in (13) require that:

$$-\frac{\partial C_t^{Ti}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i} = \Psi_t^{Ti} \tag{14}$$

and

$$-\frac{\partial C_t^{Bi}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i} = \Psi_t^{Bi}, \tag{15}$$

i.e., the marginal cost for adjusting timber and bioenergy supply equals the tax on the respective products. Comparing the expressions in (14) and (15) with the first-order conditions for the policy makers' decision problem in (11), see Appendix, we find that the efficient level of adjustment of timber supply will be induced by setting the tax on timber such that the indirect effects on sequestration in trees and soils are taken into account:

$$\begin{aligned}\Psi_t^{Ti} &= -\frac{\partial C_t^{Ti}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i} \\ &= -\mu_t^{Vi}\frac{1}{A_t^i} - \mu_t^{Pi}\nu\gamma\frac{P_t^i}{\left(V_{t-1}^i + G_{t-1}^i\left(V_{t-1}^i\right)\right)A_t^i} + \rho^{k_i - 1}\lambda_{t+k_i}\tau\eta.\end{aligned} \tag{16}$$

Thus, the optimal tax on timber is set such that the marginal cost, i.e. the foregone current return due to a change in timber production, equals the marginal benefit to society of that change. The marginal benefit equals the value of the associated impact on growing stock and soil carbon stock, and the discounted value of the impact on the emission target k_i periods later. The two first terms on the r.h.s. reflect the country-specific impact of changed timber production on the costs of future sequestration, due to the impact on tree and soil carbon stocks. It should be noted that the marginal user cost of the growing stock and soil carbon, μ_t^{Vi} and μ_t^{Pi}, can be positive or negative, depending on whether forest growth is positively or negatively affected by the changed forest volume, and harvests increase or decrease. Thus, taxes may differ across countries in both sign and magnitude.

The corresponding efficient tax on bioenergy is defined by:

$$\begin{aligned}\Psi_t^{Bi} &= -\frac{\partial C_t^{Bi}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i} \\ &= -\mu_t^{Vi}\frac{1}{A_t^i} - \mu_t^{Pi}\nu\gamma\frac{P_t^i}{\left(V_{t-1}^i + G_{t-1}^i\left(V_{t-1}^i\right)\right)A_t^i} + \lambda_t\tau\eta,\end{aligned} \tag{17}$$

where the interpretation of the two first terms on the r.h.s. is similar to that in equation (16). The last term expresses the marginal value of the impact on emission constraint in current year. Comparing equations (16) and (17), it can be seen that the efficient taxes on bioenergy and timber differ only due to the timing of the release of the carbon content. The difference is then determined by the development of the discounted shadow cost over time.

To further understand how the efficient taxes on bioenergy and timber are determined, we can look closer at the determinants of the marginal user costs. Using the necessary condition for the growing stock we have that:

$$\begin{aligned}\mu_t^{Vi} &= \rho\mu_{t+1}^{Vi}\left(1 + \partial G_t^i / \partial V_t^i\right) \\ &\quad + \rho\mu_{t+1}^{Pi}\left(\nu P_t^i \gamma \frac{H_{t+1}^i\left(1 + \partial G_t^i / \partial V_t^i\right)}{\left(V_t^i + G_t^i\left(V_t^i\right)\right)^2} + \kappa\beta^i\right) \\ &\quad + \left(\rho\lambda_{t+1} - \lambda_t\right)\eta\beta^i A^i\end{aligned} \tag{18}$$

Equation (18) shows, first, that the marginal user cost of the growing stock, μ_t^{Vi}, depends on the future value of the stock, given forest growth. If an increase in stock volume leads to increased forest growth, μ_t^{Vi} is larger. There is then an additional value of leaving the wood in the forest because of the higher future sequestration that will be achieved. Second, there is a value of the positive impact of increased forest volume on the soil carbon stock. This impact is high if litter production, κ_i, and soil carbon stocks are large, as increased forest volume reduces the area subject to final felling, *ceteris paribus*. The last term expresses the impact of a change in forest volume on the emission targets at time t and t+1. As the marginal user cost of forest volume, μ_t^{Vi}, is determined by the increase in the discounted shadow cost λ_t, we can conclude that rapidly increasing target stringency in combination with a low discount rate will imply a higher marginal user cost. In such a case, it is cost-efficient to allocate harvests over time such that high sequestration can be obtained in the latter part of the policy period, thereby reducing the need for costly fossil fuel reductions.

Turning to the marginal user cost of soil carbon stock, it can be written as:

$$\mu_t^{Pi} = \rho\mu_{t+1}^{Pi}\left(\left(1 - \vartheta^i\right) - \nu\gamma\frac{H_{t+1}^i}{\left(V_t^i + G_t^i\left(V_t^i\right)\right)}\right) + \left(\rho\lambda_{t+1} - \lambda_t\right)A^i \tag{19}$$

The marginal user cost of soil carbon, μ_t^{Pi}, reflects the future value of the soil carbon stock for meeting annual climate targets. It is affected by stock development, captured in the first term on the r.h.s of equation (19). A high decay rate ϑ^i reduces the marginal user cost as a soil carbon stock increase in the current time period will, to a larger extent, be lost to the atmosphere in the following time period. Similarly, a high share of harvested volume, i.e. a high $H_t^i/(V_t^i + G_t^i(V_t^i))$, implies that an increase in the carbon soil stock will to larger extent be lost in the following time periods due to final felling. Both a high decay rate and a high harvest share will therefore increase user costs of soil carbon in the current time period. The last term in (19) carries a similar interpretation as in equation (18).

Common to all countries is the increase in the carbon tax over time from increased target stringency as expressed by λ_t. Depending on the marginal user costs of the growing stock and soil carbon pool, the taxes on timber and bioenergy products can increase or decrease over time. The tax is relatively high when the marginal user costs are high, i.e. when the accumulation of carbon in trees and soil is large, which occurs for a relatively high marginal growth in tree volume and a low rate of decay of soil carbon.

4. Data

Data and method for calculation of fossil fuels reduction costs within the EU Emissions Trading System follow Gren et al. (2009), where the costs are calculated as the decrease in consumer surplus when fossil fuel consumption is reduced. Emission coefficients for each type of fossil fuel have been obtained from the same source. Cost functions for decreases and increases in bioenergy and timber are calculated as changes in producer surplus, i.e., the cost to producers in terms of profits foregone (in the case of a reduction) and costs above the market price payment (in the case of an increase). Inverted, linear supply functions for forest products were calculated based on estimates of price elasticities, price data and input use data. These supply functions were used to calculate quadratic cost functions. Consumer side welfare effects are not included for forest products because for bioenergy, demand is highly politically determined, and because trade in forest products is not easily incorporated in a partial model. For both fossil fuels and forest product it is assumed that BAU prices and quantities are constant over the studied time period. This is a simplification, as technological development or changes in demand could alter these prices and quantities. The simplification is motivated by the use of a partial equilibrium model and the focus on the role of different carbon pools for climate policy. Cost functions for fossil fuels and forest products and data used for the calculations can be found in the Appendix.

Aggregate forest growth functions on national level, suitable for our purpose, are not available. Some earlier studies, such as Kallio et al. (2004), use aggregate biomass and forest growth functions, but assume a constant forest growth rate. Other studies, such as Schulp et al. (2008), assume a constant forest growth until a given forest age is reached, and growth shifts to zero. None of these approaches are suitable when the focus is on the dynamics of sequestration over a longer time period, as the successive decline in growth, and hence sequestration, is not accounted for. Following Amacher et al. (2009, chapter 4), we have therefore estimated concave forest growth functions, using data from Eurostat forestry statistics which report growing stock and increment for commercial forests for each EU country and four years; 1990, 2000, 2005, and 2010. This gives a panel data set with 28 countries and 4 years. A quadratic function, describing the relationship between growing stock per hectare, and the associated gross increment, is estimated for commercial forests. We take into account differences in growth rates across regions with different climate, using dummy variables for the (colder) boreal and (drier) Mediterranean regions, where growth can be expected to be lower than in central Europe.

We test for random effects with a Breusch and Pagan Lagrange multiplier test, which shows that this hypothesis cannot be rejected. However, existence of contemporaneous correlation may exist among countries (Pesaran, 2004). Cross-sectional dependence can occur in countries which are subjected to the same type of regulations, such as the EU directives. If our independent variables do not reflect these cross-sectional dependencies the estimated standard errors will be affected. A Pesaran test gave a value of $p = .60$ which indicates non-existence of cross-section dependence. A test was also made for heteroscedasticity which showed no correlation in the errors. The quadratic functions where therefore estimated with ordinary least square estimator. Data and results of estimations can be found in the Appendix.

The estimated growth functions imply that forest growth in different countries varies depending on climatic region and initial growing stock. The maximum forest growth occurs when average growing stock per hectare is 266 m^3. Countries in the dataset with a growing stock equal to $266 \pm 30\,m^3$ have an average age of 55 years,[12] and other studies suggest that the age of maximum sequestration should occur close to this age (Newell and Stavins, 2000; Schulp et al., 2008). Already in the initial time period, eight of the countries have a growing stock larger than 266 m^3. Hence, for several countries increased average forest age could lead to reduced sequestration over time. Corresponding data are not available for non-commercial forests which might, in the future, be used as commercial ones. We therefore apply the estimated growth function to all forest land in each country. The ratio of total forest volume and volume of the growing stock is calculated using the average biomass expansion factors for conifers and broadleaves IPCC (2003) to obtain the above-ground tree volume. Thereby, we get β^i equal to 1.125 and 1.175 for boreal and temperate countries, respectively. Based on data in Trømborg and Sjølie (2011), the CO_2 content per cubic meter of wood is assumed to be 0.8 tons.[13]

To obtain parameter values for the soil carbon equation, we make use of estimates of soil carbon stock and sequestration reported in Liski et al. (2002). Their soil carbon stock estimates apply to the tree-originating carbon in the organic soil plus the topmost 20 cm mineral soil layer. National estimates for 1990 are available for 14 countries of those included in this study. We adjust these estimates for the average stock change 1990–2010 in the region, to which the country belongs; North, Northwest, Central or South Europe. For the 13 remaining countries in our study, we use the average stock for the corresponding region. Further, we use annual sequestration estimates in Liski et al. (2002) for 1990, assuming they apply also in 2010, while for countries not included in their study, we use the average for the region, to which the country belongs. We assume that 50 percent of the soil carbon is lost on forest land subject to final felling, as suggested in early studies on the subject (Covington, 1981; Federer, 1984; Yanai et al., 2003). Later studies have shown that the magnitude of soil carbon loss can sometimes be much smaller, even zero (Covington, 1981; Federer, 1984; Johnson and Curtis, 2001; Yanai et al., 2003), and that the harvesting method and the extent of site preparation are important for the magnitude of the losses (Jandl et al., 2007). Therefore, a case with zero soil carbon losses due to final felling is investigated in the sensitivity analysis. Building on Swedish data for 2010 (Swedish Forest Agency, 2013), γ is calculated to be 0.6, which we assume to apply for all countries. Decay rates are calculated from the functions for decomposition rates for slow and fast humus presented in Liski et al. (2002), where decomposition is modeled as functions of annual mean temperature. We use the average of the decomposition rates for fast and slow humus. The rate of

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[12] Calculated from data in the Appendix and Vilén et al. (2012). Note that with our growth functions this volume is reached earlier in central Europe, and later in the boreal and Mediterranean regions.

[13] Trømborg and Sjølie (2011) report CO_2 content to be 0.7–0.92 depending on tree species.

Table 1
Scenarios.

Scenario	Abatement alternatives included in optimization				
	Fossil fuels	Bioenergy	Timber	Biomass sequestration	Soil sequestration
ALL	X	X	X	X	X
FOSSIL	X				
FPRO	X	X	X		
BIO	X	X	X	X	
SOIL	X	X	X		X

litter fall, κ^i, is used to calibrate the functions such that the above-mentioned sequestration is achieved in the initial year. Calibrated values then range from 0.0011 to 0.0334 which can be compared with Liski et al. (2002), where, e.g., the rate of litter to growing stock is reported to be 0.0043 for coniferous forests and 0.0087 for deciduous trees. The variation in obtained litter coefficients seems reasonable given that the impact of tree growth on soil carbon accumulation differs between tree species (Jandl et al., 2007).

Production of bioenergy requires fossil fuel in the refinement process, and this process is typically less energy efficient than for refining fossil fuels. The carbon displacement is therefore typically less than one. Schlamadinger and Marland (1996) judge that 0.6 is a reasonable estimate of the displacement for bioenergy given current technology, and Sathre and O'Connor (2010) argue based on several studies that the bioenergy displacement factor can range from less than 0.5 up to 1.0, depending on the type of fossil fuel replaced and their relative combustion efficiencies. Cannell (2003) estimates that biomass used to generate electricity displaces coal by a factor 1.0, oil by a factor 0.88 and natural gas by a factor 0.56. We here assume that displacement equal 0.75, implying that $\tau = 0.25$. The average lifetime of timber products, i.e. k_i, is obtained from Eggers (2002). The BAU consumption and production levels are assumed equal to the levels in 2010. It is assumed that fossil fuel consumption and bioenergy and timber production can, at most, be reduced by 95, 55 and 20 percent, respectively, compared to BAU. Also, it assumed that bioenergy and timber production can at the most be increased by 75 percent, which is reasonable compared to short and long term increases in renewables discussed by the EU Commission (EUCOM, 2012, 2013).

The EU emissions target is interpreted as a successive reduction of CO_2-emissions by 80 percent until 2050. This target is assumed to be tightened by the same percentage each year from 2010 to 2050, taking into account that 2010 emissions are eleven percent below those in the reference year 1990 (EUCOM, 2012). In principle, a successive reduction of emissions is mainly motivated when capital investments are necessary to achieve carbon reductions, such as is relevant for fossil fuel reductions. However, we do not explicitly model capital vintages for the fossil fuel sector. Instead, we use the successive tightening of targets as a simple way of achieving a similar overall carbon reduction path. This makes it possible to investigate the role that carbon sequestration can play for reducing abatement costs along that path. A discount rate of 3 percent is applied, as suggested by Boardman et al. (2011) to be an appropriate level for public undertakings.

5. Results

We calculate results for five different policy scenarios, shown in Table 1. The first scenario, ALL, includes all abatement alternatives and their effects on carbon release and uptake. The ALL scenario provides a benchmark, and corresponds to a cost-effective policy. The second scenario, FOSSIL, is one where emission targets have to be achieved by only reductions in fossil fuel consumption. Forest harvests are held constant over time, and equal to BAU levels, implying that carbon pools in trees, soil and forest products change. The third scenario, FPRO, adds the possibility of changing the use of forest products and accounts for their direct impact on emissions to the decision problem (as defined by equation (7)), but the consequential impact on sequestration is ignored. In the fourth scenario, BIO, impacts on sequestration and carbon pools in trees are further added (as defined by equation (2)). The fifth scenario, SOIL, is similar to the third, but instead of sequestration and pools in trees, soil sequestration and soil carbon pools are included. The scenarios thus permit comparison of costs and emission impacts under different assumptions about the number of carbon pools that are taken into account in the policy decision. Thereby, it becomes possible to investigate whether a simplified policy, where only a single carbon pool is included, is an improvement compared to not including sequestration at all.

When carrying out the optimization, only sequestration in addition to that with BAU harvests is considered to contribute to the climate targets. For tractability, the model is aggregated into 5-year time periods. The model is run for 20 years beyond 2050, requiring that emissions then remain constant and equal to those in 2050, in order to avoid end-of-period effects.

5.1. The minimum cost

The discounted minimum cost of meeting the EU Roadmap targets is shown in Fig. 1 for each scenario. As seen, inclusion of more abatement options reduces the cost of meeting the targets. The cost in the FOSSIL scenario corresponds to approximately 0.4 percent of aggregate GDP, which is within the range of costs

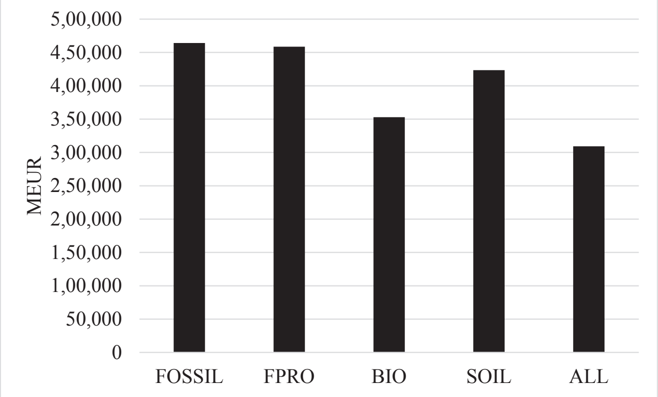

Fig. 1. Minimum discounted cost in Million EUR of meeting emission target in different scenarios.

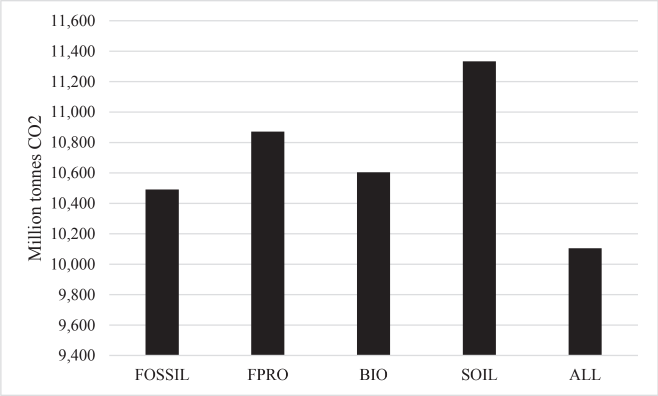

Fig. 2. Aggregate reductions during 2010–2050 in CO_2 equivalents under different scenarios on inclusions of carbon sequestration and pools for reaching EU Roadmap targets.

estimated in Capros et al. (2014) .[14] The total cost in the ALL scenario is 33 percent lower than in the FOSSIL scenario. This can be compared to Michetti and Rosa (2012) and Gren et al. (2012), where cost savings from carbon sequestration are estimated to be 30 percent and 65 percent, respectively. Comparing approaches, our analysis is applied to the more demanding 2050 target, compared to the 2020 target analyzed in Michetti and Rosa (2012) and Gren et al. (2012). This could imply a tendency towards smaller cost savings if the potential for increased sequestration is limited. Moreover, the two mentioned studies allow for afforestation, and Gren et al. (2012) include the non-trading sector,[15] which works in the same direction. On the other hand, our inclusion of soil sequestration should increase the cost savings compared to these studies.

5.2. Emission reductions achieved

In the ALL scenario, the optimization problem captures all carbon effects from the measures being undertaken. In other scenarios, only some of the effects are taken into account. If we wish to evaluate second-best policy scenarios, all impacts on carbon emissions must be added to identify the total impact on carbon emissions. In Fig. 2, we therefore compare the total emission reductions in the different scenarios. In the FOSSIL scenario, a considerable amount of sequestration occurs as a consequence of BAU forest management. The total reduction in the figure is then the sum of reductions due to reduced fossil fuel consumption, and BAU sequestration.

In all other scenarios, bioenergy and timber are both reduced in the cost-efficient solutions. In the FPRO scenario, bioenergy and timber are reduced in order to avoid emissions from combustion, but the associated impact on sequestration is not taken into account. However, the reduction of forest products implies that sequestration is increased. As a consequence, the total emission reduction is larger than in the FOSSIL scenario. In the BIO scenario, the policy maker accounts for the effects of both reduced forest products and increased sequestration. Therefore, fossil fuel reductions are smaller compared to the FPRO scenario. This saves costs, but also implies that the total emission reductions are smaller than under FPRO. The total emission reduction is the highest in the SOIL scenario because increased growing stocks are required to increase soil sequestration. The scenario is more expensive than the BIO scenario, because sequestration in trees is cheaper than soil sequestration as carbon sequestered in soils is partially lost through decay and at the time of harvesting. The ALL scenario exactly achieves the emission targets, implying the lowest cost as well as the lowest emission reductions.

Compared to the FOSSIL scenario, the FPRO and SOIL scenarios imply a small or modest reduction in costs, but increases the total emission reductions. The SOIL scenario outperforms the FPRO scenario with respect to both emissions and costs. The BIO and ALL scenarios significantly reduce costs, but have a minor positive and a negative impact, respectively, on emission reductions achieved. Hence, the preferred policy depends on the value that policy makers attach to emission reductions in excess of the targets defined in the Roadmap.

5.3. The fossil fuel carbon tax

Carbon taxes on fossil fuels, bioenergy and timber can be applied to meet the climate targets for the EU, as shown in the model section. Fig. 3 displays the cost-efficient CO_2-tax on fossil fuels in the FOSSIL and ALL scenarios. The CO_2-tax increases over time when the emission target becomes more stringent, and is higher in the FOSSIL scenario than in the ALL scenario. In the ALL scenario, carbon taxes increase from €20 per tCO_2 in 2010 to €55 in 2050. The 2010 tax level can be compared with the actual carbon price, which ranged between €8 and €29 per tCO_2 between 2008 and 2010 (Chen et al., 2013). Our estimated carbon tax levels can also be compared with permit prices 2020, calculated by Böhringer et al. (2009) from three different CGE-models. They estimate that the permit price for the EU ETS will be €50–75/tCO_2 in the absence of additional efforts to promote renewables. Our comparable estimate in the FOSSIL scenario, €42 per tCO_2 in 2020, is below their estimated price interval, which can be explained by the fact that we do not take into account economy-wide dispersal effects. Furthermore, Capros et al. (2014) estimate that carbon prices will reach €243-€565 in 2050. Our result in the FOSSIL scenario is only €108, which is likely to be explained by their inclusion of the non-trading sector, where abatement costs are higher than in the trading sector. Michetti and Rosa (2012) estimate that the carbon price is reduced by

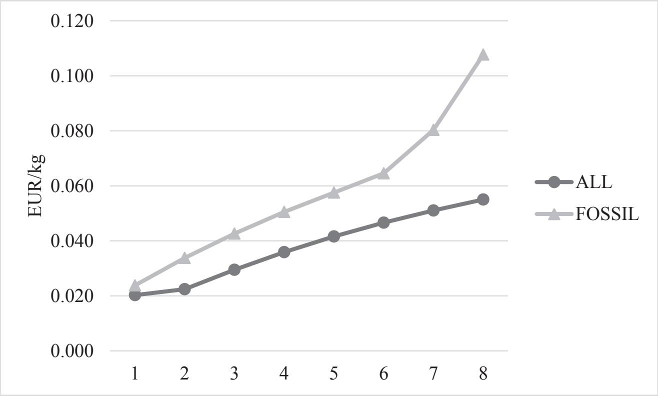

Fig. 3. Development of CO2-tax on fossil fuels in current value in FOSSIL and ALL scenarios.

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[14] Capros et al. (2014) compare three large-scale energy-economy models with regard to the least-cost strategy for meeting 2050 targets, and conclude such a strategy can reduce GDP by 0.0–0.5%. Different to this study, their calculations include also the non-trading sector, which is larger than the trading sector and abatement costs are higher, see e.g. Böhringer et al. (2009).

[15] The non-trading sector has higher abatement costs, so crediting carbon sequestration against targets for the non-trading sector implies large cost savings.

Table 2
Forest data 2010 for Germany, Finland and Spain.

	Total forest and other wooded land area	Growing stock	Forest growth, estimated	Soil C stock	Soil C sequestration
	1000 ha	m^3/ha	m^3/ha	t CO_2-eq/ha	ton CO_2-eq/ha
Germany	11076	315	7.6	220	0.183
Italy	10916	133	4.9	48	0.029
UK	2901	131	5.8	139	0.213

30 percent in 2020 when forest sequestration is included. For that time period, we obtain almost exactly the same price reduction.

5.4. *Taxes on timber*

Timber production is reduced in all countries. Seven of the 27 countries reduce timber production down to the lower bound, $\underline{T}^i$, during the whole time period.[16] The high reductions in these countries are explained by a high potential for increased forest growth and, hence, increased sequestration in forests and soils, and comparatively low costs for reducing timber production. For 18 countries, the lower bound is not binding at any point in time during the policy period considered.[17] We illustrate the results on efficient timber taxes by comparing three countries where the lower bound is not binding during the time period; Germany, Italy and the UK. These countries differ with respect to initial growing stock and forest growth, and soil carbon pools and sequestration, see Table 2. The growing stock per hectare is the largest in Germany, almost three times higher than the European average, whereas that in Italy and UK is close to the European average. Forest growth is high in Germany due to the favorable climate and large growing stock compared to Italy and the UK. The initial soil carbon stock is large in Germany, moderate in the UK and small in Italy, and due to the higher rate of litter fall soil sequestration is higher in Germany and the UK compared to Italy.

Sequestration in trees increases in Italy and the UK until the fifth and seventh time period, respectively, and then falls. In Germany sequestration in trees falls over the whole policy period. In spite of this, the efficient tax on timber increases over time for all three countries in both scenarios, except for a small decline in the last period in the UK in the ALL scenario, see Fig. 4. The simultaneous increase in the tax and decrease in sequestration is explained by relatively low costs for reducing timber production and, hence, sequestering additional carbon in the same year in order to meet that year's environmental target, compared to the disadvantage of having the future potential for sequestration reduced.

In both the UK and Germany the timber taxes are higher in the ALL scenario than in the BIO scenario during the whole policy period. This is explained by the large positive impact of increased forest volume on soil carbon sequestration due to high litter fall in these countries, an effect which is accounted for in the ALL scenario but not in the BIO scenario. The highest rate of litter fall is found in the UK, and hence also the highest difference in the tax between the two scenarios. In contrast, the timber tax in Italy is similar in both scenarios, due to the small rate of litter fall and, hence, small soil sequestration. The development of the tax over time in the three countries is more similar in the ALL scenario; the tax increases between 1.3 and 2.6 times over the whole time period. The rate of increase varies more in the BIO scenario, between 1.9 and 8.8 times. In both scenarios, the highest increase occurs in Germany and the lowest in the UK. The high increase in the German tax in the BIO scenario is a consequence of the low cost efficiency of timber reductions in early time periods, as the large growing stock implies that there is no potential for increased forest growth, while in later time periods reductions become cost-efficient in order to meet the stringent carbon targets in the shorter run.

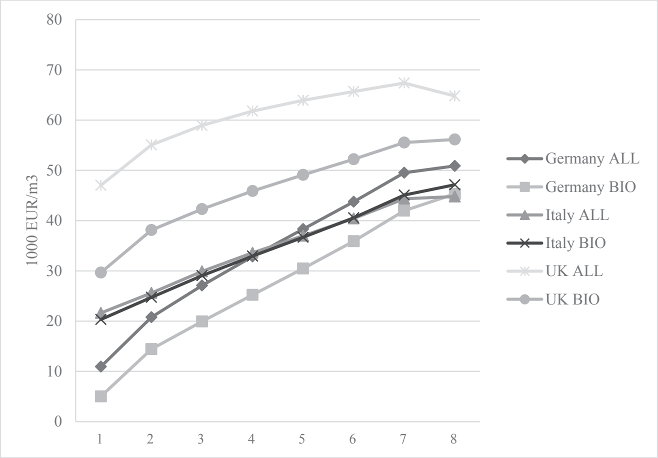

Fig. 4. Efficient tax on timber products in the ALL and BIO scenarios, in current value.

In both scenarios, the timber tax is the highest in the UK. This is explained by a relatively high potential for increased forest growth in combination with high litter fall and soil sequestration. In the ALL scenario, Germany has the lowest timber tax over the first half of the policy period, and Italy over the latter. After half of the policy period, forest growth in Italy has become small, and the rate of litter fall is not large enough to motivate further increases in the growing stock. In Germany, forest growth falls over the whole time period, but the successive growth of forest volume implies increased amounts of litter and hence increased soil sequestration, which explains this outcome.

As seen in Fig. 4, cost-efficient timber taxes differ substantially between countries, suggesting that uniform timber taxes at the EU level would not be optimal, in particular, in the shorter run. Towards the end of the policy period, taxes tend to converge as the growing stock and soil carbon stocks saturate and become more similar across countries.

Corresponding taxes on bioenergy follow a similar increasing pattern over time as those on timber. The level of the tax is lower because of the earlier release of the carbon, as predicted in the theoretical section.

5.5. *Sensitivity analysis*

In the sensitivity analysis, we first investigate the impact of assumptions about forest growth, as changed growth is a possible

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[16] Spain, Finland, Greece, Sweden, Ireland, Portugal and Cyprus.

[17] Two countries; Estonia and Latvia, have a binding lower bound in the two or three last time periods.

Table 3
Sensitivity analysis in the ALL scenario. Figures refer to the relative level of the variable, compared to that in the reference scenario. A figure below (above) 1 thus implies a reduction (increase).

	Net present cost	Aggregate sequestration in trees	Aggregate soil carbon sequestration	Timber tax at t = 1, Germany	Timber tax at t = 1, Italy	Timber tax at t = 1, the UK
Changed forest growth by 10%	0.91	1.08	1.07	0.72	1.03	0.81
No soil carbon losses from harvesting	1.60	1.01	0.63	1.22	1.34	1.04

consequence of climate change. Increased growth is a likely consequence of higher temperatures in north and east Europe, whereas decreased growth due to drier climate can be expected in the Mediterranean area (Lindner et al., 2010). Here, we assume that forest growth increases by 10 percent in all countries, and for all time periods, except in the Mediterranean countries where, instead, it decreases by the same rate.

Second, we analyze the role of assumptions made about soil carbon sequestration, given differing conclusions in the literature regarding the magnitude of soil carbon losses at the time of harvesting. Here, we therefore recalibrate the soil carbon stock function, assuming that losses from harvesting are zero. The recalibration implies that the litter coefficient, which is the calibrated parameter, is reduced to be compatible with the same sequestration given the smaller soil carbon losses. Results from the sensitivity analysis, calculated for the ALL scenario, are shown in Table 3.

With changed forest growth, aggregate sequestration increases and, hence, costs fall. The relative impact on tree and soil sequestration is similar. Larger forest growth on the aggregate level implies that there is less need for policy efforts towards fossil fuels and sequestration in order to meet targets. Hence timber taxes fall in most countries, such as is the case for Germany and the UK. However, for a few countries (Italy and France) taxes increase because the additional growth increases the value of leaving the wood in the forest as this implies that significantly more sequestration can be achieved in the country during the policy period at a given cost. It can be noted that the impact on timber taxes in a given country is not proportional to the size of the assumed change in forest growth, but is determined by the country's forest growth function and costs of timber reductions.

When the soil stock function is calibrated for zero losses from final felling, the net present cost increases and soil sequestration falls, while sequestration in trees is almost unaffected. Timber taxes are increased in all countries, because further efforts are made to increase biomass sequestration to compensate for the lower soil sequestration in this scenario. Fossil fuel taxes are increased even further, in the first period by about 60 per cent.

6. Discussion and conclusions

The aim of this paper is to evaluate policy instruments applied to forest products as a means to achieve carbon sequestration in a cost-efficient manner. We also compare the economic and environmental consequences of separate inclusion of one carbon pool in the EU's climate policy to that of including three interdependent pools. The theoretical analysis shows that biomass, soil, and forest product pools could be included in a policy by means of differentiated taxes on bioenergy and timber. The optimal taxes account for the impact of direct emissions from bioenergy and timber, displacement of fossil fuels, and the consequences for current and future sequestration in trees and in soils. A numerical model is developed, which includes cost functions for fossil fuels and forest products, and functions which describe the development of forest biomass and soil carbon stocks.

Our analysis suggests that the cost-efficient taxes on forest products could be relatively high in countries with large potential for increased sequestration over the policy period. Given the wide variation in tree and soil carbon stocks and forest growth, the efficient level and time path of subsidies and taxes varies substantially across countries. Therefore, a system with uniform EU-wide taxes on forest products is not a cost-efficient policy over the next decades. Instead, a coordinated approach with differentiated tax levels could work better. Uniform EU-wide policy instruments for forest products might be justified on cost-efficiency grounds closer to the target year 2050, provided that national policies to increase sequestration are introduced within the near future.

The model is used to analyze separate and combined inclusion of different carbon pools compared to a policy where fossil fuel reductions are the only means to meet the EU Roadmap targets. Different to most earlier studies on dynamic forest sequestration, applied at small (Updegraff et al., 2010; van Kooten et al., 1995; Wise and Cacho, 2005) and large (e.g., Latta et al., 2011; Lecocq et al., 2011; Sohngen and Sedjo, 2006; Moiseyev et al., 2011) spatial scale, we treat the carbon price as endogenous, and show empirically that inclusion of forest carbon sequestration at EU scale can lead to a considerable reduction in carbon price when climate targets are ambitious. Further, lop-sided consideration of fossil fuel displacement resulting from the use of bioenergy and timber can be detrimental as increased forest harvests over time reduces the potential for sequestration. Our results show that successively increased reductions in harvest can be a cost-efficient ways to meet carbon targets. In this regard, our results support conclusions drawn in Eriksson (2015) and Münnich-Vass and Elofsson (2016), which suggest that sequestration in forest biomass is a cheaper abatement method than bioenergy at global and EU scales, respectively. Similar conclusions are drawn by Schulze et al. (2012) when evaluating the consequences for greenhouse gases emissions from an increase of the share of forest biomass in global primary energy supply. It can be noted that the EU's policy against greenhouse gas emissions is focused on CO_2 emission trading for fossil fuel use, in combination with a target to have 20 percent renewable energy by 2020. Our results suggest that the latter can have a negative effect on overall carbon sequestration if bioenergy and used timber make up a large share of the renewable energy and the consequences for sequestration are ignored.

The results further suggest that a separate inclusion of either biomass or soil carbon pools to the EU's climate policy will lead to improvements compared to both a strictly fossil fuel based policy and a policy which combines fossil fuel reductions with efforts to increase carbon displacement by bioenergy and timber. However, the improvement will be different in nature. Inclusion of biomass sequestration will reduce costs more, while inclusion of soil sequestration lead to further emissions reductions. Thus, the choice of which single pool to include in the policy is determined by the policy makers' valuation of emission reductions in excess of the target.

The above analysis has limitations, including the partial approach, and the exclusion of land use change, the non-trading sector, uncertainty, and heterogeneity in carbon sequestration within each country. Forest growth functions are aggregated at national level, which is a simplification. If they were replaced by growth functions that were disaggregated over space and age classes this would affect the level of taxes, but not conclusions regarding the potential for uniform taxation of bioenergy and timber or the consequences of separate inclusion of a single carbon pool. Also important to the interpretation of results is the exclusion of transaction costs for alternative policy instruments for sequestration. Nevertheless our analyses and results can contribute to the ongoing debate on carbon pools in the EU, which mainly concerns the rules for reporting of carbon pools (Kuikman et al., 2011). The EU Commission has recently introduced harmonized rules for carbon accounting, implying that national reports should capture all relevant effects from land use, land management, and harvested wood products (EU, 2013). This can be a step towards policies promoting forest carbon sequestration. Our results can then serve as an input in the discussion since they point out principles for determining cost efficient policy instruments targeting forest products under different scenarios. It seems likely that additionality and permanence in carbon enhancement in these products is easier, and hence cheaper, to measure, monitor and verify compared to policies targeting carbon pools at stand level. Also, compared to a system with a combination of subsidies and taxes on carbon pools at stand level as suggested by, e.g., van Kooten et al. (1995) and Latta et al. (2011), our system implies that fewer, and in total smaller, financial transactions take place, which could facilitate implementation by reducing transaction costs. On the other hand, policies directed towards products only regulate carbon pools indirectly, which is a relative disadvantage as sequestration heterogeneity within each country is ignored.

7. Software availability

The GAMS code used for the paper is available as Supplementary Material on the journal homepage. Running of the code requires installation of the software GAMS 23.9.5 or higher and the CONOPT2 solver, available at https://www.gams.com/download/. The code developed for the study is not copy protected and can be distributed freely.

Acknowledgements

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Appendix

The Lagrangian and the necessary first order conditions.

The dynamic discrete time Lagrangian is:

$$L=\sum_t\sum_i\rho^t\begin{bmatrix}C_t^{Bi}\left(B_{BAU}^i-B_t^i\right)+C_t^{Ti}\left(T_{BAU}^i-T_t^i\right)+\sum_j C_t^{Xij}\left(X_{BAU}^{ij}-X_t^{ij}\right)+\\ \rho\mu_{t+1}^{Vi}\left(V_t^i+G_t^i\left(V_t^i\right)-\frac{\left(B_{t+1}^i+T_{t+1}^i\right)}{A^i}-V_{t+1}^i\right)+\\ \rho\mu_{t+1}^{Pi}\left(P_t^i-\nu P_t^i\gamma\frac{\left(B_{t+1}^i+T_{t+1}^i\right)}{\left(V_t^i+G_t^i\left(V_t^i\right)\right)A^i}+\kappa_i\beta^iV_t^i-\vartheta^iP_t^i-P_{t+1}^i\right)-\\ \lambda_t\left[E_t^{MAX}-E_t\right]\end{bmatrix}\tag{A1}$$

where $\rho=1/(1+r)$ is the discount factor and, r, is the discount rate, $\lambda_t>0$ is the shadow cost for the emission constraint at time t, $\mu_{t+1}^{Vi}><0$ and $\mu_{t+1}^{Pi}><0$ are the shadow costs of forest biomass and soil carbon stock.

The necessary conditions for an interior solution are:

$$\rho^{-t}\frac{\partial L}{\partial X_t^{ij}}=\frac{\partial C_t^{ij}\left(X_{BAU}^{ij}-X_t^{ij}\right)}{\partial X_t^{ij}}+\lambda_t\alpha^j=0\tag{A2}$$

$$\begin{aligned}\rho^{-t}\frac{\partial L}{\partial B_t^i}=&\left[\frac{\partial C_t^{Bi}\left(B_{BAU}^i-B_t^i\right)}{\partial B_t^i}-\mu_t^{Vi}\frac{1}{A_t^i}\right.\\&\left.-\mu_t^{Pi}\nu\gamma\frac{P_{t-1}^i}{\left(V_{t-1}^i+G_{t-1}^i\left(V_{t-1}^i\right)\right)A_t^i}+\lambda_t\tau\eta\right]\\=&\,0\end{aligned}\tag{A3}$$

$$\begin{aligned}\rho^{-t}\frac{\partial L}{\partial T_t^i}=&\left[\frac{\partial C_t^{Ti}\left(T_{BAU}^i-T_t^i\right)}{\partial T_t^i}-\mu_t^{Vi}\frac{1}{A_t^i}\right.\\&\left.-\mu_t^{Pi}\nu\gamma\frac{P_{t-1}^i}{\left(V_{t-1}^i+G_{t-1}^i\left(V_{t-1}^i\right)\right)A_t^i}+\rho^{k_i-1}\lambda_{t+k_i}\tau\eta\right]\\=&\,0\end{aligned}\tag{A4}$$

$$\rho^{-t}\frac{\partial L}{\partial V_t^i}=\begin{bmatrix}\rho\mu_{t+1}^{Vi}\left(1+\partial G_t^i\big/\partial V_t^i\right)-\mu_t^{Vi}+\rho\mu_{t+1}^{Pi}\left(\nu P_t^i\gamma\dfrac{H_{t+1}^i\left(1+\partial G_t^i\big/\partial V_t^i\right)}{\left(V_t^i+G_t^i\left(V_t^i\right)\right)^2}+\kappa\beta^i\right)-\lambda_t\eta\beta^iA^i+\\ \rho\lambda_{t+1}\eta\beta^iA^i\end{bmatrix}=0 \tag{A5}$$

$$\rho^{-t}\frac{\partial L}{\partial P_t^i}=\left[\rho\mu_{t+1}^{Pi}\left(\left(1-\vartheta^i\right)-\nu\gamma\frac{H_{t+1}^i}{\left(V_t^i+G_t^i\left(V_t^i\right)\right)}\right)-\mu_t^{Pi}-\lambda_tA^i+\rho\lambda_{t+1}A^i\right]=0. \tag{A6}$$

Table A1
Forest area, growth, fellings, forest products and prices.

	Total forest and other wooded land area[a]	Growing stock[a]	Gross increment[a]	Fellings[a]	Use of domestic forest[a]		Prices[b]		Price elasticity[c]	
					Bio-energy	Oth. forest prod.	Bio-energy	Other Forest prod.	Bio-energy	Oth. forest prod
	1000 ha	m^3/ha	m^3/ha	m^3/ha	%	%	MEUR/ 1000 m^3	MEUR/ 1000 m^3		
EU 27	177003	137	5.8	3.2	21	79				
AT	3991	286	7.5	5.3	26	74	0.0227	0.0697	0.55	0.21
BE	706	238	7.9	7.2	15	85	0.0227	0.0728	0.55	0.21
BG	3927	167	5.1	2.0	47	53	0.0227	0.0742	0.55	0.21
CY	387	27	0.9	0.2	41	59	0.0227	0.0768	0.55	0.21
CZ	2657	290	9.9	7.2	12	88	0.0227	0.0708	0.55	0.21
DE	11076	315	10.1	5.1	18	82	0.0227	0.0723	0.55	0.21
DK	635	180	10.0	4.6	40	60	0.0227	0.0767	0.55	0.21
EE	2337	191	5.6	3.6	27	73	0.016	0.0473	0.55	0.21
ES	28214	32	3.1	1.1	32	68	0.0227	0.0665	0.55	0.21
FI	23116	96	4.6	2.6	10	90	0.0235	0.0503	0.55	0.21
FR	17572	148	6.2	3.7	47	53	0.0227	0.0733	0.55	0.21
GR	6539	31	1.3	0.3	68	32	0.0227	0.0768	0.55	0.21
HU	2039	174	6.4	3.3	52	48	0.0227	0.0768	0.55	0.21
IE	788	95	9.8	5.7	7	93	0.0227	0.0768	0.55	0.21
IT	10916	133	4.0	1.0	66	34	0.0227	0.0743	0.55	0.21
LT	2249	214	5.7	3.8	27	73	0.0188	0.0453	0.55	0.21
LU	88	295	7.5	3.2	6	94	0.0227	0.0768	0.55	0.21
LV	3467	183	5.8	4.0	18	82	0.016	0.0505	0.55	0.21
MT	0	0	0.0	0.0	–	–	0.0227	0.0768	0.55	0.21
NL	365	192	7.6	3.7	27	73	0.0227	0.0723	0.55	0.21
PL	9319	247	8.0	4.2	12	88	0.016	0.0487	0.55	0.21
PT	3611	52	10.5	5.3	6	94	0.0227	0.0594	0.55	0.21
RO	6733	207	6.5	2.5	20	80	0.0227	0.0768	0.55	0.21
SE	30625	106	4.7	3.5	8	92	0.0235	0.0518	0.55	0.21
SK	1938	265	7.4	5.4	5	95	0.0227	0.0687	0.55	0.21
SI	1274	327	7.8	2.5	37	63	0.0227	0.0751	0.55	0.21
UK	2901	131	8.6	4.0	14	86	0.0227	0.0746	0.55	0.21

[a] All forest data are for 2010 and have been obtained from Eurostat (2012).

[b] The price of other forest products is the weighted average price of logs and pulp in 2010 in Finnish Forest Research Institute (2011), where prices are available for Austria, Estonia, Lithuania and Sweden. Those were extrapolated to the other countries as shown in the table. No official price statistics for bioenergy are available. Here, the price of bioenergy is assumed to be 2/3 of the pulp price.

[c] Price elasticities are obtained from Geijer et al. (2011). Due to lack of elasticity estimated across the EU countries, the same elasticity is assumed for all countries.

Table A2
Soil carbon stock and sequestration.

	Soil C stock[a]	Soil C Sequestration[a]	Conversion factor[b] γ	Litter coeff[c], κ^i	Decomposition rate[a], ϑ^i	Harvest to volume ratio[d],	Harvest impact coeff, υ
	ton CO2/ ha	ton CO2/ha	% volume to % area harvested	%	%	%	%
AT	220	0.183	0.6	0.0053	4.94E-13	0.019	0.5
BE	139	0.213	0.6	0.0066	6.07E-13	0.03	0.5
BG	220	0.183	0.6	0.0065	4.94E-13	0.012	0.5
CY	48	0.029	0.6	0.0054	7.80E-13	0.007	0.5
CZ	220	0.183	0.6	0.0067	4.94E-13	0.025	0.5
DE	220	0.183	0.6	0.0043	5.43E-13	0.016	0.5
DK	180	0.084	0.6	0.0087	4.98E-13	0.026	0.5
EE	180	0.084	0.6	0.0061	4.98E-13	0.019	0.5
ES	48	0.029	0.6	0.0174	9.24E-13	0.034	0.5
FI	180	0.084	0.6	0.0179	2.46E-13	0.027	0.5
FR	220	0.183	0.6	0.0135	6.53E-13	0.025	0.5
GR	48	0.029	0.6	0.0058	9.16E-13	0.01	0.5
HU	220	0.183	0.6	0.0093	4.94E-13	0.019	0.5
IE	139	0.213	0.6	0.0334	5.80E-13	0.06	0.5
IT	48	0.029	0.6	0.0011	7.80E-13	0.008	0.5
LT	180	0.084	0.6	0.0053	4.98E-13	0.018	0.5
LU	139	0.213	0.6	0.0024	6.07E-13	0.011	0.5
LV	180	0.084	0.6	0.0080	4.98E-13	0.022	0.5
MT	48	0.029	0.6	NA	7.80E-13	NA	0.5
NL	139	0.213	0.6	0.0056	5.90E-13	0.019	0.5
PL	220	0.183	0.6	0.0057	5.43E-13	0.017	0.5
PT	48	0.029	0.6	0.0305	9.39E-13	0.102	0.5
RO	220	0.183	0.6	0.0050	4.94E-13	0.012	0.5
SE	180	0.084	0.6	0.0196	2.95E-13	0.033	0.5
SK	220	0.183	0.6	0.0060	4.94E-13	0.02	0.5
SI	220	0.183	0.6	0.0023	4.94E-13	0.008	0.5
UK	139	0.213	0.6	0.0123	5.43E-13	0.031	0.5

[a] Own calculation based on Liski et al. (2002).
[b] Own calculation based on data from Swedish Forest Agency (2013).
[c] From calibration of model.
[d] Calculated from data in Table A1.

Table A3
Coefficients of cost functions for fossil fuel consumption in the EU ETS sector. Cost functions are quadratic: $C_t^{Xij} = a - bX_t^{ij} + c(X_t^{ij})^2$. NA = zero consumption, the fuel type in the country is not included in the calculations.
Sources: Method and data for calculation of cost function is obtained from Gren et al. (2009).

	Hard coal & derivatives			Lignite & derivatives			Natural & derived gases		
	a	b	c	a	b	c	a	b	c
AT	540.92	0.407	7.67E-05	30.75	0.407	1.35E-03	2434.40	0.978	9.83E-05
BE	588.68	0.418	7.40E-05	31.73	0.418	1.37E-03	4160.74	0.946	5.38E-05
BG	310.65	0.283	6.45E-05	591.72	0.283	3.38E-05	346.55	0.345	8.58E-05
CY	NA	NA	NA	NA	NA	NA	NA	NA	NA
CZ	665.10	0.341	4.37E-05	2240.70	0.341	1.30E-05	1530.38	0.769	9.67E-05
DE	5264.33	0.274	3.56E-06	5128.95	0.274	3.65E-06	19623.20	1.086	1.50E-05
DK	671.32	0.246	2.25E-05	NA	NA	NA	1150.33	0.933	1.89E-04
EE	3.68	0.283	5.44E-03	312.21	0.283	6.42E-05	63.09	0.224	1.99E-04
ES	2170.72	0.278	8.92E-06	188.85	0.278	1.03E-04	7472.50	0.648	1.41E-05
FI	646.98	0.288	3.20E-05	318.31	0.288	6.51E-05	891.63	0.422	4.99E-05
FR	2227.42	0.451	2.29E-05	NA	NA	NA	7775.83	1.167	4.38E-05
GR	38.38	0.269	4.73E-04	1088.60	0.269	1.67E-05	415.61	0.382	8.77E-05
HU	102.04	0.283	1.96E-04	241.58	0.283	8.29E-05	1285.97	0.534	5.55E-05
IE	171.99	0.249	9.03E-05	54.34	0.249	2.86E-04	1071.00	0.792	1.47E-04
IT	2844.17	0.398	1.39E-05	0.40	0.398	9.94E-02	17744.78	0.919	1.19E-05
LT	19.25	0.283	1.04E-03	0.42	0.283	4.72E-02	228.82	0.328	1.17E-04
LU	22.34	0.418	1.95E-03	0.63	0.418	6.96E-02	322.16	0.865	5.80E-04
LV	5.09	0.283	3.93E-03	0.14	0.283	1.42E-01	141.93	0.276	1.34E-04
MT	NA	NA	NA	NA	NA	NA	NA	NA	NA
NL	1075.96	0.341	2.70E-05	NA	NA	NA	9892.73	1.212	3.71E-05
PL	4558.81	0.293	4.71E-06	1842.71	0.293	1.16E-05	2132.00	0.684	5.49E-05
PT	483.71	0.293	4.44E-05	NA	NA	NA	1034.28	0.720	1.25E-04
RO	226.02	0.283	8.86E-05	983.32	0.283	2.04E-05	1611.72	0.414	2.66E-05
SE	348.31	0.477	1.63E-04	57.97	0.477	9.82E-04	587.75	1.078	4.95E-04
SK	39.91	0.283	5.02E-04	175.35	0.283	1.14E-04	137.97	0.569	5.87E-04

Table A3 (*continued*)

	Hard coal & derivatives			Lignite & derivatives			Natural & derived gases		
	a	b	c	a	b	c	a	b	c
SI	336.12	0.283	5.96E-05	105.29	0.283	1.90E-04	624.05	0.517	1.07E-04
UK	5255.75	0.288	3.94E-06	NA	NA	NA	20854.64	1.219	1.78E-05
	Light fuel oil/ Heating oil			Heavy fuel oil			Jet fuel		
	a	b	c	a	b	c	a	b	c
AT	442.04	1.713	1.66E-03	219.33	0.778	6.90E-04	3172.50	9.000	6.38E-03
BE	299.68	0.937	7.32E-04	260.00	0.444	1.90E-04	5305.50	9.000	3.82E-03
BG	113.10	0.650	9.34E-04	100.36	0.388	3.74E-04	918.00	9.000	2.21E-02
CY	5.49	1.569	1.12E-01	38.90	0.608	2.37E-03	1386.00	9.000	1.46E-02
CZ	96.25	1.100	3.14E-03	61.60	0.467	8.84E-04	1575.00	9.000	1.29E-02
DE	3412.41	1.103	8.92E-05	1060.86	0.517	6.30E-05	39343.50	9.000	5.15E-04
DK	512.23	2.277	2.53E-03	192.43	1.447	2.72E-03	4135.50	9.000	4.90E-03
EE	4.71	0.725	2.79E-02	NA	NA	NA	144.00	9.000	1.41E-01
ES	3422.58	1.422	1.48E-04	2218.77	0.822	7.62E-05	25105.50	9.000	8.07E-04
FI	506.79	1.190	6.98E-04	406.39	0.810	4.04E-04	2767.50	9.000	7.32E-03
FR	2151.73	1.288	1.93E-04	1815.95	0.635	5.54E-05	31837.50	9.000	6.36E-04
GR	1148.17	1.627	5.77E-04	532.59	0.706	2.34E-04	5827.50	9.000	3.47E-03
HU	158.49	1.338	2.82E-03	69.80	0.400	5.73E-04	1224.00	9.000	1.65E-02
IE	152.29	1.259	2.60E-03	238.97	0.724	5.49E-04	3915.00	9.000	5.17E-03
IT	4883.86	2.636	3.56E-04	2586.16	0.864	7.21E-05	17914.50	9.000	1.13E-03
LT	110.95	0.700	1.10E-03	48.05	0.388	7.81E-04	238.50	9.000	8.49E-02
LU	3.93	0.873	4.85E-02	NA	NA	NA	1822.50	9.000	1.11E-02
LV	2.44	0.813	6.77E-02	7.94	0.388	4.73E-03	301.50	9.000	6.72E-02
MT	9.01	1.386	5.33E-02	NA	NA	NA	346.50	9.000	5.84E-02
NL	5459.76	2.190	2.20E-04	244.17	0.833	7.11E-04	16663.50	9.000	1.22E-03
PL	857.09	1.512	6.67E-04	443.77	0.674	2.56E-04	1930.50	9.000	1.05E-02
PT	94.14	1.207	3.87E-03	429.66	0.690	2.77E-04	4158.00	9.000	4.87E-03
RO	318.83	0.650	3.31E-04	156.74	0.388	2.39E-04	625.50	9.000	3.24E-02
SE	1126.37	1.911	8.10E-04	563.57	1.429	9.05E-04	3915.00	9.000	5.17E-03
SK	14.80	0.800	1.08E-02	16.86	0.475	3.35E-03	193.50	9.000	1.05E-01
SI	202.30	0.850	8.93E-04	49.28	0.338	5.78E-04	117.00	9.000	1.73E-01
UK	2577.09	1.513	2.22E-04	1387.03	1.103	2.19E-04	58464.00	9.000	3.46E-04

Table A4

Coefficients of cost functions for forest products. Cost functions are quadratic: Timber: $C_t^{Ti} = a - bT_t^i + c(T_t^i)^2$, Bioenergy: $C_t^{Bi} = a - bB_t^i + c(B_t^i)^2$. NA = zero production, and the product in the country is not included in the calculations.
Sources: Data on production volume, prices, and price elasticities are found in table A1.

	Timber			Bioenergy		
	a	b	c	a	b	c
AT	2595.78	0.3317	3.75E-06	113.33	0.0412	1.06E-05
BE	748.88	0.3466	2.70E-05	15.71	0.0412	4.01E-05
BG	735.28	0.3533	5.58E-06	76.06	0.0412	4.24E-05
CY	8.35	0.3657	6.49E-04	0.65	0.0412	4.00E-03
CZ	2837.55	0.3371	8.98E-06	47.3	0.0412	1.00E-05
DE	7970.52	0.3442	2.03E-06	209.52	0.0412	3.71E-06
DK	319.96	0.3651	1.76E-05	24.08	0.0412	1.04E-04
EE	692.29	0.2254	6.40E-06	33.04	0.0291	1.84E-05
ES	3339.49	0.3165	2.07E-06	204.65	0.0412	7.50E-06
FI	6476.8	0.2395	3.56E-06	128.45	0.0427	2.21E-06
FR	6012.17	0.3489	6.74E-07	629.67	0.0412	5.06E-06
GR	114.79	0.3657	1.54E-05	27.49	0.0412	2.91E-04
HU	590.59	0.3657	5.89E-06	72.1	0.0412	5.66E-05
IE	725.26	0.3655	6.90E-05	6.15	0.0412	4.61E-05
IT	656.94	0.3540	2.86E-06	148.46	0.0412	4.77E-05
LT	672.89	0.2157	7.41E-06	39.44	0.0342	1.73E-05
LU	48.4	0.3657	1.22E-03	0.35	0.0412	6.91E-04
LV	1367.32	0.2405	5.83E-06	36.31	0.0291	1.06E-05
MT	NA	NA	NA	NA	NA	NA
NL	169.65	0.3442	5.65E-05	7.51	0.0412	1.75E-04
PL	3995.99	0.2320	3.10E-06	68.32	0.0291	3.37E-06
PT	1271.28	0.2827	3.59E-05	11.83	0.0412	1.57E-05
RO	2462.35	0.3657	6.12E-06	69.37	0.0412	1.36E-05
SE	12163.56	0.2467	2.49E-06	183.27	0.0427	1.25E-06
SK	328.37	0.3273	1.75E-05	24.28	0.0412	8.16E-05
SI	1777.56	0.3576	3.94E-05	10.78	0.0412	1.80E-05
UK	1772.73	0.3553	1.27E-05	33.48	0.0412	1.78E-05

Table A5
Summary statistics.

		Mean	Min	Max	Stdev	Obs
G_i	Forest growth, m^3/ha	6.6	0.9	12.2	0.2	109
V_t^i	Forest volume, m^3/ha	211.1	47.6	459.2	7.9	109
$(V_t^i)^2$		51373.2	2265.0	210846.8	3542.5	109
SC^i	Dummy for SE, FI	0.1	0	1	0.025	109
ME^i	Dummy for PT, ES, FR, IT, GR, SI	0.2	0	1	0.040	109

Table A6
OLS estimation, dependent variable, G_t^i, forest growth in m^3/ha.

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
V_t^i	0.05881	0.00460	12.80	<.0001
$(V_t^i)^2$	−0.00011044	0.00001591	−6.94	<.0001
SC^i	−1.32664	0.93064	−1.43	0.1570
ME^i	−0.96340	0.57831	−1.67	0.0987
Prob > F = 0.000				

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envsoft.2017.12.006.

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