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Is forest carbon sequestration at the expense of bioenergy and forest products cost-efficient in EU climate policy to 2050?

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ABSTRACT

Forest management affects the quantity of CO_2 emissions in the atmosphere through carbon sequestration in standing biomass, carbon storage in forest products and production of bioenergy. The main question studied in this paper is whether forest carbon sequestration is worth increasing at the expense of bioenergy and forest products to achieve the EU emissions reduction target for 2050 in a cost-efficient manner. A dynamic cost minimisation model is used to find the optimal combination of carbon abatement strategies to meet annual emissions targets between 2010 and 2050. The results indicate that forest carbon sequestration is a low-cost abatement method. With sequestration, the net present costs of meeting EU carbon targets can be reduced by 23%.

Introduction

Forests are important from a climate perspective because they allow carbon to be sequestered in standing biomass or stored in forest products. Alternatively, forests can produce bioenergy to replace

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fossil fuels. Several studies show that sequestration accounts for 10–50% of emissions reductions globally in a cost-efficient climate policy (Bosetti et al., 2009; Murray et al., 2009; Sohngen, 2009). It is therefore important to recognise the abatement potential of forests in climate policy. Despite the high potential and relatively low cost of sequestration, it has only partially been included in international climate agreements such as the Kyoto Protocol.

The EU climate policy framework does not recognise emissions reductions in the forest sector, apart from bioenergy. The main reasons put forward are lack of appropriate and harmonised data due to measuring and monitoring problems and non-harmonisation of reporting methods across EU countries (European Commission, 2012a). However, forest carbon sequestration can be a more effective method for reducing emissions than bioenergy (e.g. Johnson, 2009; Hudiburg et al., 2011; Holtsmark, 2012; Lundgren and Marklund, 2012; Schulze et al., 2012), as bioenergy is not carbon neutral in the short term, although it may be in the long term (European Union, 2003; Petersen and Solberg, 2005; Bright and Strømman, 2009; Sjølie et al., 2010). There are two explanations for the lack of carbon neutrality: (i) There is a long time-lag between biomass combustion, when emissions are emitted to the atmosphere, and forest regrowth, when emissions are sequestered; and (ii) a certain amount of carbon is emitted to the atmosphere from harvesting, transporting and processing biomass. As long as forest carbon sequestration is not accounted for in EU climate policy, there is a risk that European forests will become a carbon emissions source rather than a sink in the future (Böttcher et al., 2012; Kallio et al., 2013).

In a long-term perspective, the European Commission (2011) has proposed a roadmap for moving to a competitive, low-carbon economy by 2050. This roadmap proposes reductions in greenhouse gases in the range of 80–95% by 2050 compared with the level in 1990. It focuses on achieving this range cost-efficiently, implying that the inclusion of low-cost abatement options such as forest carbon sequestration needs to be evaluated.

The main purpose of this study is to assess whether it is worth increasing the amount of forest carbon sequestration at the expense of bioenergy and forest products to cost-efficiently achieve the EU carbon emissions reduction target for 2050. The topic of interest is thus the additional sequestration achieved when forest harvesting rate is reduced compared with the current level. Standing biomass, forest products and bioenergy are closely connected in physical terms, but their impacts on carbon release and uptake differ. Deployment of one of these abatement methods means an equivalent change in one or both of the other two. Moreover, policies need to consider the relative costs of sequestration and fossil fuel reductions. Therefore, abatement in the fossil fuel sector is also part of the model. For the assessment, a dynamic programming model is used in which abatement costs are minimised subject to the achievement of an 80% reduction in CO_2 emissions by 2050 compared with the level in 1990. The benefit of using a dynamic model is that the non-linear natural growth of forests can be accommodated.

Our modelling approach derives from previous work in the field of cost-efficient abatement strategies to reduce greenhouse gas emissions in land use sectors and our empirical application relates to choices between abatement methods in the forest sector. When modelling cost-efficient abatement strategies, many studies take a static perspective (e.g. Dixon et al., 2008; Eliasch, 2008; Gren et al., 2012), while Van der Werf and Peterson (2009) highlight the importance of covering several decades to accommodate the dynamic effects because forest biomass follows a non-linear growth path at stand level. Dynamic optimisation models covering different geographical areas and levels of aggregation are presented by Adams et al. (1996, 1999), Alig et al. (1997), Van Kooten (1999), Gielen et al. (2002), Sohngen and Mendelsohn (2003), Van't Veld and Plantinga (2004), Lee et al. (2005), Sathaye et al. (2005), Rokityanskiy et al. (2007), Tavoni et al. (2007), Schneider et al. (2008), Latta et al. (2013) and Eriksson (2015). These models incorporate forest carbon sequestration by means of a non-linear forest biomass growth function, which varies between models with regard to functional form and accompanying parameter values. We follow Van Kooten (1999) by using an exponential function for biomass volume that reflects natural growth. At any point in time, the level of sequestration in forests then depends on forest biomass growth and endogenously determined harvests, i.e. harvests quantified within the model. Most of the models presented in the studies cited above have endogenously determined harvests, although Gielen et al. (2002) and Sathaye et al. (2005) do not provide any details on how harvests are modelled. Our specification of abatement costs follows Adams et al. (1996, 1999) and Alig et al. (1997), who calculate abatement costs as changes in consumer and producer surplus in the agriculture and forestry markets. Abatement in the fossil fuel sector is included in the model by Eriksson (2015) and in those by Sohngen and Mendelsohn (2003), Van't Veld and Plantinga (2004) and Tavoni et al. (2007), with the latter three indirectly linking a land use sector model to some integrated assessment model. We follow Eriksson (2015) by joint modelling of fossil fuel reductions and forest management.

In our empirical application, we study the choice between bioenergy consumption, carbon sequestration in forest biomass and carbon storage in forest products. This choice has previously been addressed by Gielen et al. (2002), Schneider and McCarl (2003), Hedenus and Azar (2009) and Eriksson (2015), with diverging conclusions. Hedenus and Azar (2009) report that bioenergy is a more cost-efficient abatement strategy than forest carbon sequestration, while the other studies report the opposite. In particular, we examine whether the abatement cost can be reduced by recognising additional sequestration as an abatement method in EU climate policy. This is done by examining the sequestration potential in forests and forest products and the cost of reducing bioenergy production in favour of sequestration. None of the above mentioned studies focuses specifically on Europe. We therefore add to the literature by modelling the cost-efficient choice between reductions in bioenergy and fossil fuels and increases in sequestration in Europe, using a unique forest biomass volume function for each country.

Our calculations examine whether the abatement cost can be reduced by recognising additional sequestration as an abatement method in EU climate policy. This is done by examining the sequestration potential in forests and forest products and the cost of reducing bioenergy production in favour of sequestration.

The paper is organised as follows. Section "Method" describes the model and Section "Empirical functions and data" presents the empirical functions and associated input data. The results are presented and analysed in Section "Results of cost-efficient solutions", followed by a discussion and conclusions in Section "Discussion and conclusions".

Method

Cost-efficient solutions to reach CO_2 emissions targets are calculated here based on a non-linear, discrete-time dynamic programming model. It is assumed that the ultimate objective of the EU policy maker is to achieve yearly emissions targets by 2050 at minimum cost. Four abatement strategies are available: (1) Carbon sequestration in standing biomass; (2) incremental carbon storage in forest products; (3) reduction in bioenergy; and (4) reduction in fossil fuel consumption. Sequestration is achieved through reduced harvests. The model covers 27 EU member states and has five endogenous decision variables: the level of forest products, bioenergy, coal, oil and gas.

The model

The amount of forest carbon sequestration is determined by the standing biomass volume, V_t^i, in country i, with $i = 1, \ldots, z$, at time t, with $t = 1, \ldots, T$ years. The biomass volume is calculated based on a natural growth function, where the age of the forest determines the volume. Similar to Van Kooten (1999) and Bjornstad and Skonhoft (2002), volume, V_t^i is expressed as a function of forest age y_t^i, i.e. $V_t^i = f_t^i(y_t^i)$. It is assumed that the forest volume, i.e. the amount of biomass, is low when the forest is young, increases at an increasing rate at mid-age and then levels off, or even decreases, at old age. If V_t^i is differentiated with respect to y_t^i, this gives the annual incremental volume, i.e. the forest growth: $G^i(y_t^i) = \partial V_t^i / \partial y_t^i$. Taking the inverse of the volume function, $y_t^i = f_t^{-1}(V_t^i)$, and inserting that in the growth function gives the forest growth function, $G^i(V_t^i)$, which is used in the following equations. The forest growth function is assumed to be continuous and twice differentiable in V_t^i. Using an aggregated forest growth function, we indirectly assume that the forest in a specific country can be represented by an average forest stand. This is a simplification compared to more disaggregated forest growth models, but can be a reasonable assumption in our case, given the high level of aggregation. It would not be appropriate to use this assumption at small spatial scale where there can be larger variations.

Given our formulation of the forest growth function, increased forest volume of the average forest stand then corresponds to increased average forest age, i.e. to prolongation of the average rotation period. The empirical formulation can be found in Eq. (15).

The standing biomass volume in period $t+1$, V^i_{t+1}, is determined by the volume in the foregoing period, V^i_t, forest growth, $G^i(V^i_t)$ and harvest, H^i_t, where the latter is assumed to take place at the end of the year:

$$V^i_{t+1} = V^i_t + G^i(V^i_t) - H^i_t \tag{1}$$

$$V^i_0 = \bar{V}^i$$

where $\bar{V}^i$ is the total standing biomass volume in each country in the first year of the policy period. All variables in Eq. (1) and in Eqs. (2)–(7) are measured in tonnes CO_2 per country. The harvest is used for the production of either bioenergy, B^i_t, or forest products, F^i_t:

$$H^i_t = B^i_t + F^i_t \tag{2}$$

Forest products include all products made of wood except bioenergy, e.g. timber, pulp and paper. It is assumed that forest products and bioenergy are perfect substitutes in production. This assumption is a simplification, since forest products can more easily be used as bioenergy than bioenergy substrate can be used as forest products. This is the case since all forest products can be incinerated, but at least some of the bioenergy substrate, such as harvesting residues, cannot be used for forest products. Our assumption is motivated by the fact that the share of harvest used for bioenergy varies considerably between countries (Eurostat, 2014). This could indicate either that the extraction of harvest residues varies between countries, or that harvest residues are not the only part of the trees used as bioenergy. In either case, it seems inappropriate in our case to assume that a fixed proportion of the harvest is used for each of the two product categories, as done in e.g. Carlsson (2012) and Hedenus and Azar (2009). In Section “Sensitivity analysis”, a sensitivity analysis is made with regard to the above assumption.[2] Further, we assume that without CO_2 emissions targets, the production of bioenergy and forest products would remain constant over time at a Business-As-Usual (BAU) level.

Forest carbon sequestration, S^i_t, is calculated as the incremental increase in carbon in forest biomass:

$$S^i_t = V^i_{t+1} - V^i_t \tag{3}$$

The carbon content of wood is released to the atmosphere when combusting bioenergy. We assume that this occurs during the same period as the wood is harvested. There is also a release of carbon emissions when harvesting, transporting and processing bioenergy. This is captured in the parameter φ, which expresses these emissions as a percentage of the carbon content in the biomass and, hence, that these emissions are proportional to the biomass volume. When substituting fossil fuels for bioenergy, the carbon content in the replaced fossil fuels is never released. This carbon emissions offset is denoted as γ and expresses the number of tonnes of fossil fuel carbon replaced by one tonne of carbon in bioenergy. Thus, net emissions to the atmosphere from using bioenergy, L^i_t, are expressed as follows:

$$L^i_t = (1 + \varphi - \gamma)B^i_t \tag{4}$$

It is assumed that there is no effect on the demand for fossil fuels when bioenergy production decreases. This is based on the fact that the amount of bioenergy produced in European forests is small, approximately 1%[3] of the amount of energy from fossil fuels.

[2] Notably, our empirical results show that bioenergy in particular is reduced in favour of forest carbon sequestration. Hence, in the empirical model the assumption of perfect substitutability seems unproblematic, as it is reasonable to reduce bioenergy, e.g. through a reduction in the extraction of harvest residues, without an accompanying reduction in forest products.

[3] The calculation of the share of bioenergy to fossil fuels is based on data for 2010 on fossil fuel consumption (Eurostat, 2013b) and bioenergy production (Eurostat, 2013a), using a factor 0.18 to convert m^3 biomass to tonnes oil equivalent (toe) (Forest Sweden, 2012).

Net carbon removal by forest products is determined by the carbon content of wood, emissions related to harvesting, transporting and processing biomass and the rate of decay of these products. It is assumed that the amount of CO_2 emissions released when harvesting, transporting and processing forest products is the same as for bioenergy, φ. We also assume that forest products decay and hence release carbon over time. Following e.g. Hedenus and Azar (2010), the rate of decay, θ, is assumed to be constant. Hence, net CO_2 removal by forest products, M_t^i, is calculated as:

$$M_t^i = (1-\varphi)F_t^i - \theta\left[\sum_{\tau=0}^{t-1}(1-\theta)^{t-1-\tau}F_\tau^i\right] \tag{5}$$

where the first term is the incremental storage of carbon in forest products, and the second is the release of carbon from the stock built up in foregoing periods τ. With this formulation, we do not take into account potential carbon substitution effects of forest products. In this regard, we follow earlier studies in the field. In our case, this decision is motivated by the large uncertainty regarding the type of products replaced and the associated amount of carbon replaced, see e.g. Sathre and O'Connor (2010).

Emissions from fossil fuel combustion are determined by the quantities consumed, X_t^{ij}, by the fossil fuel type, j, with $j = 1, \ldots, w$. Fossil fuels are measured in tonnes CO_2 emissions. Total net emissions to the atmosphere, E_t, are then calculated as:

$$E_t = \sum_i \left[\sum_j X_t^{ij} + L_t^i - M_t^i - S_t^i\right] \tag{6}$$

Annual net emissions must be lower than or equal to the emissions target, E_t^{MAX}, which is determined by the EU climate policy up to 2050:

$$E_t \le E_t^{MAX} \tag{7}$$

The cost of reducing bioenergy and forest products is denoted $C_t^{iB}(\hat{B}^i - B_t^i)$ and $C_t^{iF}(\widehat{F^i} - F_t^i)$, respectively, where $\hat{B}^i$ and $\hat{F}^i$ are the Business-As-Usual (BAU) levels. Reductions in these products will only happen if it is cost advantageous to reduce emissions by means of forest carbon sequestration. Furthermore, we assume that the costs of reducing these products are separable. This is motivated by lack of knowledge about cost dependences in production of bioenergy and forest products in European countries, as mentioned above.[4] The abatement cost related to fossil fuel reductions is denoted $C_t^{iX}(\hat{X}^{ij} - X_t^{ij})$, where $\hat{X}^{ij}$ is the BAU level, which is assumed constant over the period considered. The cost functions are assumed to be continuous, decreasing and convex in their arguments.

The decision problem of the policy maker under the EU 2050 scenario is then formulated as the minimisation of total abatement costs in present value terms:

$$\min_{B_t^i, F_t^i, X_t^{ij}} TC = \sum_t \sum_i \rho^t C_t^{iB}(\hat{B}^i - B_t^i) + C_t^{iF}(\hat{F}^i - F_t^i) + \sum_j C_t^{iX}(\hat{X}^{ij} - X_t^i) \tag{8}$$

subject to (1)–(7) and

$$0 \le B_t^i \le \hat{B}^i, \quad \forall i, t$$

$$0 \le F_t^i \le \hat{F}^i, \quad \forall i, t$$

$$0 \le X_t^{ij} \le \hat{X}^{ij}, \quad \forall i, j, t$$

[4] As mentioned, we perform a simple sensitivity analysis on the impact on results of assuming that bioenergy is a by-product of forest product production.

where $\rho = 1/(1+\delta)$ is the discount factor and δ is the discount rate. To solve the decision problem defined by (1)–(7), the discrete time Lagrangian is established:

$$L = \sum_t \sum_i \rho^t \left[C_t^{iB}(\hat{B}^i - B_t^i) + C_t^{iF}(\hat{F}^i - F_t^i) + \sum_j C_t^{iX}(\hat{X}^{ij} - X_t^i) - \rho\mu_{t+1}^i (V_t^i + G^i(V_t^i) - H_t^i - V_{t+1}^i) \right. \\ \left. - \lambda_t \left(-\sum_j X_t^{ij} - L_t^i + M_t^i + S_t^i + E_t^{MAX} \right) \right] \tag{9}$$

The cost-efficient allocation of emissions reductions can be determined from the solution to (8). Assuming an interior solution, we derive the necessary first-order conditions for cost minimisation that give the optimal allocations of B_t^i, F_t^i, X_t^{ij} and V_t^i, see Appendix B. From the first-order conditions, the marginal cost of a unit reduction in bioenergy and forest products can be derived. For period t, this can be expressed as follows:

$$\frac{\partial C_t^{iB}(\hat{B}^i - B_t^i)}{\partial B_t^i} = -\lambda_t(1 + \varphi - \gamma) - \rho\mu_{t+1}^i \tag{10}$$

$$\frac{\partial C_t^{iF}(\hat{F}^i - F_t^i)}{\partial F_t^i} = \lambda_t(1 - \varphi) - \sum_{\tau=t+1}^{T} \rho^{\tau-t}\lambda_t\theta(1-\theta)^{\tau-1-t} - \rho\mu_{t+1}^i \tag{11}$$

For an interior solution to (10) and (11), the marginal cost of reducing bioenergy or forest products must equal the sum of the marginal user cost and the impacts on the emissions targets in the same and future periods, multiplied by the respective shadow cost. The marginal cost of reducing bioenergy and forest products is thus determined by two factors. The first is the shadow cost for the emissions target, λ_t, multiplied by the respective impacts on emissions. In (10), the impact on the emissions target, $(1+\varphi-\gamma)$, is the net emissions avoided per unit reduction in bioenergy in the same year. In (11), $(1-\varphi)$ is the reduction in carbon added to the forest product stock and $\theta(1-\theta)^{\tau-1-t}$ is the avoided release of carbon in a future period τ when less wood is used for forest products at time t. Second, both (10) and (11) include the marginal user cost of forest biomass, μ_{t+1}^i, which reflects the value of the impact on the carbon stock in standing forest in period $t+1$ of harvesting an additional unit in period t. The marginal user cost can be either positive or negative depending on the impact harvesting has on standing biomass growth and hence on sequestration. When the average forest stand is young, with comparatively low growth, there is a cost associated with harvesting an additional unit today because the average age and stand volume fall in the next period, implying lower growth. In this case the marginal user cost is positive. In contrast, when the average stand is old, with comparatively low growth, there is a benefit associated with harvesting an additional unit today because the average forest age falls in the next period, which implies higher growth. In this case the marginal user cost is negative.

The marginal cost of an additional unit of fossil fuel reduction in period t is defined as:

$$\frac{\partial C_t^{iX}(\hat{X}^{ij} - X_t^{ij})}{\partial X_t^{ij}} = -\lambda_t \tag{12}$$

i.e. the marginal cost equals the Lagrange multiplier of the emissions target.

Conditions (10)–(12) show that the marginal cost, i.e. the cost of reducing bioenergy, forest products or fossil fuels by one unit, differs between these abatement methods. To achieve cost efficiency, the ratio of the different marginal costs on the left-hand side of (10)–(12) at time t must equal their relative impacts on the targets, as shown on the right-hand side of the same equations. In Eq. (13), this ratio is shown for reductions in bioenergy and forest products:

$$\frac{\frac{\partial C_t^{iB}(\hat{B}^i - B_t^i)}{\partial B_t^i}}{\frac{\partial C_t^{iF}(\hat{F}^i - F_t^i)}{\partial F_t^i}} = \frac{-\lambda_t(1+\varphi-\gamma) - \rho\mu_{t+1}^i}{\lambda_t(1-\varphi) - \sum_T^{\tau=t+1}\rho^{\tau-t}\lambda_t\theta(1-\theta)^{\tau-1-t} - \rho\mu_{t+1}^i} \tag{13}$$

The right-hand side shows how one unit of bioenergy should be traded against one unit of forest products in period t. The expression in (13) is >1 when the impact on the emissions target of reducing bioenergy is greater than that of increasing forest products. This will be the case if fossil fuel displacement is small and the discount rate is high or future annual targets are less stringent. The two latter factors imply that the present cost of future release of carbon from forest products is smaller. When there are yearly emissions targets, as in this model, there is no possibility to trade between periods.

Everything else being equal, a larger impact on emissions implies higher use of an abatement measure. Taking a static view of the problem, sequestration in forests should not be increased much at the expense of forest products because that carries a relatively high cost, and the impacts on emissions in the same year are similar when the rate of decay is low. However, due to the dynamics in forest carbon sequestration, it can potentially be worth increasing sequestration at the expense of forest products, provided that this increases future forest growth, even if the latter carries a cost.

Empirical functions and data

The empirical model is built in GAMS using the CONOPT3 solver for all calculations (Brooke et al., 1998). The model is divided into yearly periods and the results are shown for the policy period 2010–2050. However, the model is run until 2080 with the same annual reduction target as in 2050 to have reasonable terminal conditions. All costs are discounted with a 3% annual discount rate. This rate falls between the rates applied in Stern (2008) and Nordhaus (2007), who both discuss the ethics concerning the discount rate that should be applied in studying the economics of climate change when several generations are affected by the emissions and the associated costs.

Abatement in the forest sector

Forest management is modelled at an aggregate, national level. Standing biomass is calculated in each country based on a representative stand of one hectare that has a constant mix of tree species and is of average age. The volume of this stand is multiplied by the forest area to obtain the total biomass volume of a country in cubic metres. This volume is converted to CO_2 emissions using conversion factors obtained from IPCC (2006); see Appendix C. The calculation of standing biomass volume in Eq. (1) is based on the so-called Chapman–Richard (C–R) function (Van Kooten, 1999; Bjornstad and Skonhoft, 2002; Asante et al., 2011), which measures cumulative standing biomass volume, Z_t^i, in cubic metres per hectare as a function of forest age, y_t^i, as follows:

$$Z_t^i(y_t^i) = k^i(y_t^i)^{m^i} e^{-n^i y_t^i} \tag{14}$$

$$Z_0^i(y_0^i) = \bar{Z}(\bar{y}^i)$$

where k^i, m^i and n^i are positive country-specific parameters that are determined by e.g. tree species, soil fertility, temperature and forest management. Here we assume that this function can be applied to the representative stand in each country. The parameters have been calibrated using data on average age and volume in each country, as well as maximum volumes in unmanaged forests obtained for representative countries for different bio-climate zones: Boreal, Temperate Oceanic, Temperate Continental and Mediterranean[5] (Christensen et al., 2005). Estimates from unmanaged forests, instead

[5] Countries in the Boreal zone are Sweden and Finland; in the Temperate Oceanic zone Belgium, Czech Republic, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, United Kingdom; in the Temperate Continental zone Austria, Bulgaria,

of data from managed forests, are used to avoid having an empirical growth function that is biased because of thinning and other management measures typically applied in managed forests. For the calibration, we use the average standing biomass volume per hectare, the associated average forest age in 2010 in each country (UNECE, 2013) and the maximum standing biomass volumes in the relevant bio-climate zone. This procedure implies that the maximum volume is reached at different ages in different countries. The annual increment per hectare in 2010 (Eurostat, 2011) is used to evaluate the fitted C–R functions, and this comparison shows that reasonable estimates of annual growth are obtained. The growth in standing biomass volumes is also comparable to results reported by Nabuurs and Lioubimov (2000), who found the maximum net annual increment for spruce to be approximately 7 m^3/ha per year at an age of 95. Our estimates for Finland and Sweden, which both have large proportions of spruce, are 6.4 and 7.6 at ages of 119 and 100, respectively. Appendix D, Table D1, shows the data used for age, volume, increment and area for each country. The calibrated parameters can be found in Table D2 in Appendix D.

The sequestration in forests under BAU harvests can be compared against results reported in other studies. Karjalainen et al. (2003) estimate that the amount of CO_2 stored in trees in European forests will increase from 60 to 78 Mg C/ha in 2010–2050 based on continuation of 1990 harvest levels. In terms of sequestration, this is an approximate increase of 10.4 billion tonnes CO_2 removed from the atmosphere during that period.[6] Our BAU estimate for sequestration in standing biomass for the same policy period is 66.7 billion tonnes CO_2. The difference in sequestration between the two studies seems to depend on the inclusion of unmanaged forest in this study and differences in BAU harvest levels.

The 27 different C-R functions obtained reflect that forests generally grow faster in temperate than boreal regions (e.g. Holtsmark, 2012; McKechnie et al., 2011). Due to the large influence of age and volume on the shape of the growth functions, a sensitivity analysis is carried out in the results section.

The growth, $G^i(Z_t^i)$, in standing biomass volume is calculated by taking the derivative of the volume function with respect to age:

$$G^i(Z_t^i) = \frac{\partial Z_t^i(y)}{\partial y_t^i} = m^i \frac{Z_t^i(y_t^i)}{y_t^i} - n^i Z_t^i(y_t^i) \qquad (15)$$

This equation expresses the growth of biomass when age increases by one unit, i.e. during one year. By inserting the initial average biomass volume and age into Eq. (15), we obtain the initial forest growth for the average forest stand. Together with the endogenously determined harvest for the initial year, the biomass volume for the subsequent year is determined. Once these variables are known, the average age can be calculated from Eq. (14). For all subsequent years, the average biomass volume needed for the right-hand side of (15) is obtained from Eq. (14) for the foregoing year. The average age of the forest varies over time due to forest growth and harvests. The forest is rejuvenated when the harvest level is higher than the growth level in any year and *vice versa*.

Bioenergy in the form of fuel wood, pellets and wood chips is often used for space heating and power generation in Europe, thus replacing fossil fuels. Following e.g. Van Kooten (1999), Kirchbaum (2002) and Holtsmark (2012), we assume that bioenergy will replace coal in combined heat and power (CHP) plants because coal has the highest carbon content, implying that such replacement reduces emissions the most. The calculation of net emissions from bioenergy is based on the substitution for fossil fuels, as well as emissions stemming from harvesting, transporting, processing and burning bioenergy (Petersen, 2006), as explained in Appendix C. Emissions from harvesting, transporting and processing biomass also affect forest products. In addition, it is assumed that forest products decay at a constant rate of 2% per year, which is the rate reported in the literature for a combination of wood products in temperate forest regions (Winjum et al., 1998; Hedenus and Azar, 2010).

Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and in the Mediterranean zone: Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain.

[6] The conversion from Mg C/ha to tonnes CO_2 is based on the IPCC (2006) conversion rate, where 1 tonne C is equivalent to 3.67 tonnes CO_2 and the area estimate is the same as in our study, 157.8 million hectares for EU27.

Cost functions for reducing bioenergy and forest products

The cost of reducing bioenergy and forest products for the benefit of increased forest carbon sequestration is defined as reductions in producer and consumer surpluses, following the approach in Adams et al. (1996, 1999) and Alig et al. (1997). Reductions in producer surplus stem from foregone producer profits, while reductions in consumer surplus are, correspondingly, the foregone consumption value of the same products. The producer surplus is calculated as the area above the linear inverse supply function bounded by the observed market price of the product, while the consumer surplus is calculated as the area below the linear inverse demand curve bounded by the same market price. The maximum reduction possible is 100%. The derivation of the cost of reducing bioenergy and forest products is similar; see Appendix A.

Restrictions are imposed on bioenergy and forest products whereby they must be positive and lower than or equal to the BAU level. Data for prices of forest products and bioenergy for each country can be found in Appendix D, Table D3. Supply and demand elasticity values for forest products and bioenergy can also be found in Table D3. These elasticity values are not available for each country and hence estimates for some representative countries are used for other countries within the same bio-climate zone. Data on harvests of bioenergy and forest product volumes can be found in Appendix D, Table D4.

Cost functions for reducing fossil fuels

The costs of fossil fuel reductions are calculated as the costs of the foregone consumption of fossil fuel products, which is defined as decreases in the consumer surplus of these products. Costs for reductions in the consumer surplus for three main classes of fossil fuel products (oil, coal and natural gas) are calculated as losses in consumer surplus in a corresponding manner as for bioenergy; see Appendix A.

It is assumed that the EU is a price taker on the world market for fossil fuels and that the supply function is perfectly elastic. Restrictions are imposed in terms of an upper quantity bound, which is constant over time and equal to the BAU level of consumption, and a lower bound, which is equal to zero. All numbers for quantities, prices and demand elasticities used in the model can be found in Appendix E, Table E1 and the emissions coefficients for fossil fuels in Appendix C, Table C1.

Emissions targets

The total emissions in our model in a BAU scenario, where the consumption of fossil fuels, bioenergy and forest products remains constant at the initial 2010 level, are calculated to be approximately 4.1 billion tonnes CO_2 per year in Europe if fossil fuel consumption, bioenergy use and the production of forest products remain at the BAU levels. This amount is lower than the 4.7 billion tonnes CO_2 in 2010 reported in official statistics (Eurostat, 2012). The difference between the official estimates and our calculated total emissions is most likely due to so-called process emissions that occur when processing certain raw materials and emissions from bioenergy combustion and forest product decay.

The calculation of the required emissions reduction target for the year 2050 is based on an 80% reduction in emissions from the 1990 level (Eurostat, 2012). Targets for intermediate years are calculated assuming a stepwise reduction by the same percentage each year from 2010 to 2050 to reach the target level in 2050. The required annual reduction is then approximately 3.5%. When doing the calculations, we only account for the impact on the emission targets of the *additional* carbon sequestration and the *additional* carbon impacts of bioenergy and forest products, compared with the levels achieved under BAU production of bioenergy and forest products.

Results of cost-efficient solutions

Two scenarios for cost-efficiently achieving the EU 2050 emissions reduction target are examined: with and without additional sequestration. The scenario with sequestration includes four abatement

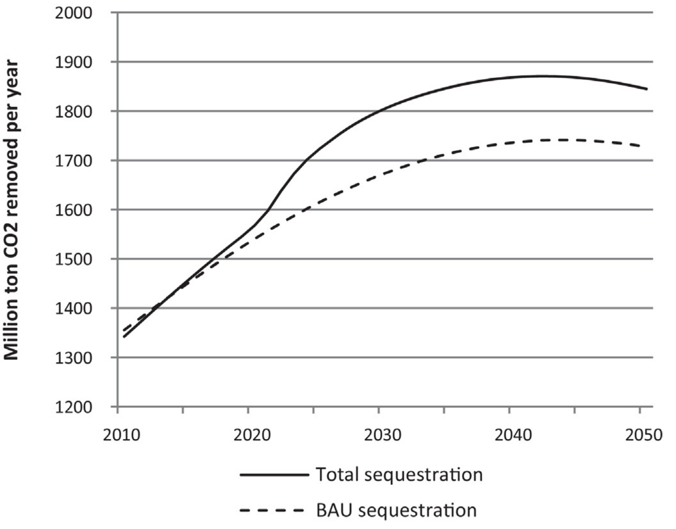

Fig. 1. Development of cost-efficient total and Business-As-Usual (BAU) sequestration in forests and forest products over the policy period to 2050.

options: carbon sequestration in forests, incremental carbon storage in forest products, reductions in bioenergy and reductions in fossil fuel consumption. The scenario without sequestration only includes reductions in fossil fuels.

The development of sequestration in forests and storage in forest products is shown in Fig. 1 as total cost-efficient and BAU sequestration. The difference between the two curves is the additional sequestration. In both cases sequestration increases over time, but the amount differs between −13 and 134 million tonnes of CO_2 per year, which corresponds to at most 7% of the emissions reduction required in a specific year. The total amount of additional sequestration is 3.7 billion tonnes CO_2 over the policy period and constitutes approximately 4.7% of the total emissions reduction required by 2050.

Comparatively few studies on carbon sequestration until 2050 take into account the mutual exclusivity between different forest uses. The best available study to compare with is the review by Ovando and Caparros (2009), which based on a number of previous studies calculates that forests in the EU-25 can sequester 6–10% of a 60% emissions reduction target by 2050. These values are larger than those estimated here, which can be due to the lack of cost considerations in the reviewed studies and the studies allowing for increased forest area. The lack of previous analysis of the competition between different land-based carbon mitigation options, an issue highlighted by Ovando and Caparros (2009), implies that our estimates of the economic sequestration potential can broaden the literature on this subject and contribute to European climate policy making.

As Fig. 1 shows, it is optimal to manage forest so that total sequestration reaches a maximum in 2042. The additional sequestration largely occurs at the expense of bioenergy, which is completely phased out in 2028 (see Fig. 2). Beyond the policy period considered, further increases in sequestration are possible in some countries, although at a higher cost. The maximum volume is never reached in any of the countries during the policy period. However, the average age increases in all countries by up to 19 years compared with the BAU scenario.

The change in fossil fuel consumption in the scenario with sequestration is shown in Fig. 2. Oil is reduced the most in absolute terms, followed by natural gas and coal. When coal, which has the highest carbon content, is phased out in 2023, more expensive abatement methods must be used. Gas, oil and bioenergy therefore experience a steeper fall when there are no more coal abatement opportunities.

The total discounted abatement cost, summed over all EU countries, of achieving the emissions target every year is shown in Fig. 3. In both scenarios, the cost first increases slowly and then more

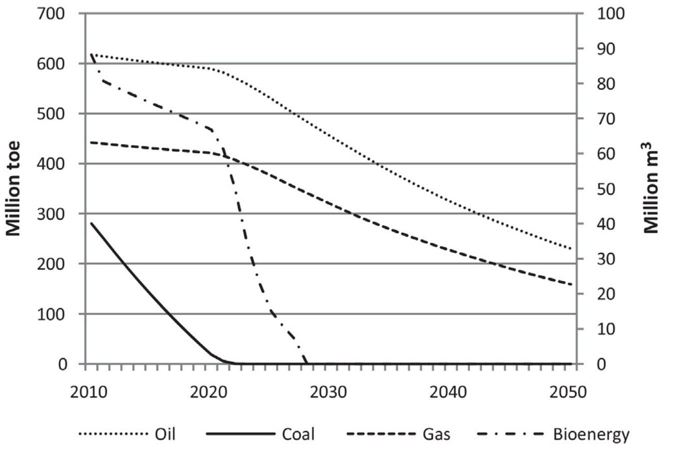

Fig. 2. Change in consumption of fossil fuels (million toe) and bioenergy (million m^3) over the policy period to 2050.

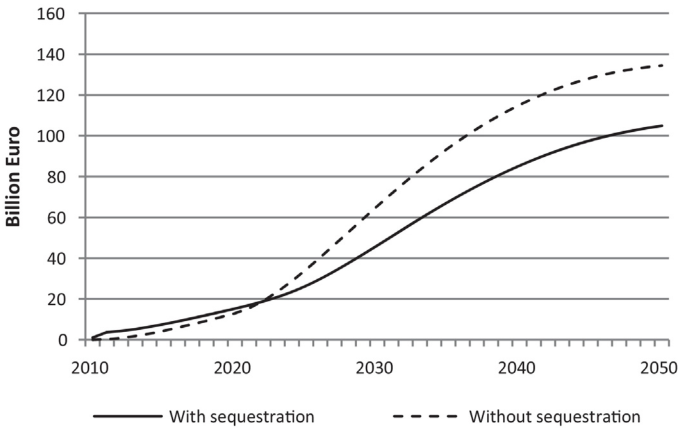

Fig. 3. Annual discounted abatement cost with and without sequestration for all European countries over the policy period to 2050.

rapidly after 2024, as the emissions target becomes successively more stringent. Towards the end of the period, the discounted cost increases at a decreasing rate. In the scenario with sequestration, the cost is slightly higher in the beginning, but then becomes lower after 2024 compared with the scenario without sequestration.

The explanation for the higher cost in the beginning in the scenario with sequestration is that bioenergy and forest products are reduced not only to sequester carbon in the same year, but also to increase future sequestration because for several countries, a higher biomass volume implies more rapid growth.

The annual costs in the scenario without sequestration can be compared against estimates in Capros et al. (2012), who calculated the average annual cost in 2011–2050 to be 2659–3090 billion EUR for an 80% reduction in GHG emissions in Europe by 2050. These costs are in line with our total abatement cost to 2050 rather than the annual costs. The main reason for this major discrepancy is that those authors assume an inelastic energy demand, which is met by costly energy efficiency improvements, expensive renewable energy sources such as solar and wind power, and expensive low-carbon technologies. We assume quite differently that all substitution possibilities are implicitly captured by the fossil fuel

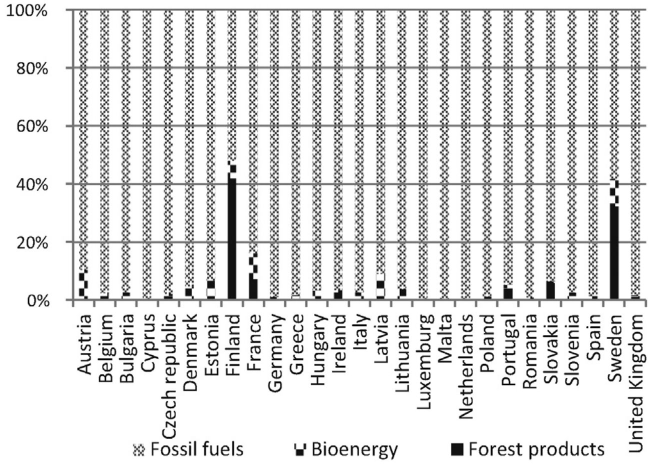

Fig. 4. Cost shares per EU country for reductions in fossil fuels, bioenergy and forest products.

demand curve. A sensitivity analysis on the effect of varying the fossil fuel demand elasticity is made in Section "Sensitivity analysis".

The results from Den Elzen et al. (2005) can be compared to our scenario with sequestration. Those authors calculate the abatement cost in Europe to be approximately 1–2% of GDP in 2050 for three different emissions reduction targets in the range of 60–95% for the EU plus countries (OECD-Europe and Eastern Europe) compared with a baseline level in 2050. With regard to abatement in the forest sector, they include sequestration by forest management, afforestation, reforestation and emissions from deforestation. They assume that the credits earned via forest management actions remain at the current level beyond the Kyoto Protocol period for Annex 1 countries, i.e. countries with commitments under the Kyoto Protocol. Their estimated cost is lower than ours, which can be explained by their inclusion of global carbon trading and CDM credits,[7] and inclusion of afforestation and reforestation.

The share of the total cost related to reductions in fossil fuels, bioenergy and forest products in all countries is shown in Fig. 4. The difference between countries can be explained by taking two extreme cases, Germany and Sweden. The cost share related to reductions in bioenergy and forest products is higher in Sweden than in Germany. This is explained by reductions in Swedish bioenergy and forest products having a considerable impact on sequestration, because the Swedish forest is relatively young and therefore far from its maximum growth at the start of the policy period. Hence, forest growth can continue to increase throughout the period. This is not the case in Germany, which at the start has an older forest and reaches its growth peak in just a few years. Thus, there is no reason to reduce bioenergy and forest products in Germany because it would only lead to slower forest growth in the future.

Fig. 5 shows how additional sequestration develops in the countries with the highest level of sequestration during the entire policy period.

Curves for the other countries can be found in Appendix F, Figs. F1 and F2. The development varies between countries and can be explained by two main factors: (1) The difference in shape of the biomass growth function and in the initial forest age. Countries with a low initial forest age have a higher potential to increase sequestration than countries with a high initial age, and (2) the differences in cost of reducing bioenergy in particular and in some cases also forest products, in favour of sequestration. Forest products are reduced in favour of sequestration in some countries, because it leads to increased

[7] CDM credits stem from Clean Development Mechanism projects. These are emissions reduction projects carried out in so-called Annex 1 countries to the Kyoto Protocol, which have no binding emissions reduction targets according to this protocol.

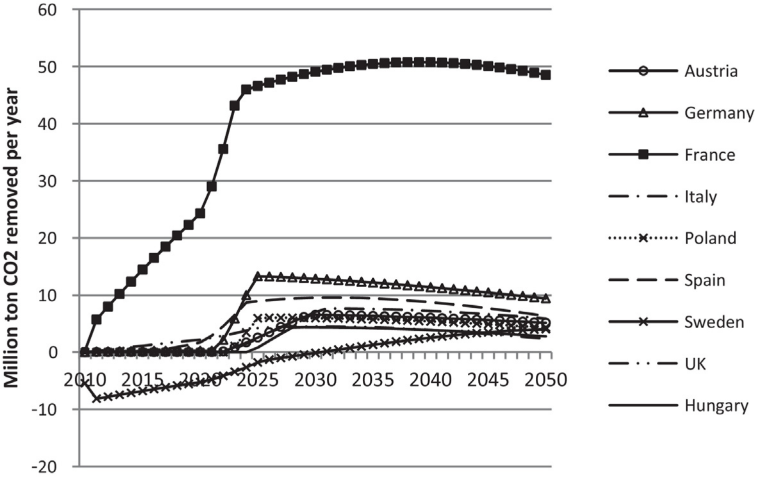

Fig. 5. Development of additional sequestration in forest and forest products over the policy period to 2050.

forest age and hence a higher level of sequestration. The kinks in some of the curves in Fig. 5 during the early 2020s are explained by the rapid phase-out of bioenergy. The explanation for the comparatively high level of additional sequestration in France is the initially high level of bioenergy production, which can be reduced at a comparatively low cost. The negative level of additional sequestration in Sweden during the first two decades is explained by a comparatively high reduction in forest products during this period. This is done in favour of higher growth and sequestration levels in the later decades.

Sensitivity analysis

The levels of forest carbon sequestration in both standing biomass and forest products are crucial for the results. The sequestration potential in each country builds on data for average forest age, standing biomass volume and forest area in 2010. Therefore, a sensitivity analysis is presented for changes in initial average age and forest area. We also analyse the effects of changing the price elasticities and product prices. The reason is that forest product elasticity data are difficult to find in the literature and those estimates that exist are based on specific data for some countries and that fossil fuel elasticity data are quite old. Similarly, the availability of price data for fossil fuels and forest products is limited, as companies are reluctant to report such data.

The effects on the total abatement cost of reducing or increasing these parameters by 50% in the sequestration scenario are shown in Table 1. The results indicate that the total cost is sensitive to changes in forest area, with a decrease in cost of 61.5% when the area is increased by 50%. The reason is that the area determines the overall availability of forest carbon sequestration opportunities in a country. Changing the age of the forest also means large changes in costs, which is explained by the fact that the age determines forest growth and hence the level of sequestration. An increase in forest age means that maximum sequestration is reached faster in most countries, which in turn implies a slower forest growth earlier in the policy period. A decrease in forest age means moving down the biomass function, which in turn results in slower growth in the beginning of the policy period in most countries. Table 1 also shows the changes in overall cost as a consequence of changing the elasticities and prices of forest products, bioenergy and fossil fuels. The results show that the abatement cost is more sensitive to changes in bioenergy supply and demand elasticities than forest product supply and demand elasticities, which is explained by bioenergy consumption being reduced from the BAU level to a larger extent.

Table 1
Percentage change in total costs of achieving the emissions targets by 2050 in the scenario with sequestration when the parameters are decreased or increased by 50%.

	50% decrease	50% increase
Forest age	17.0%	NF[b]
Forest area	NF[b]	−61.5%
Forest product supply elasticities	0.7%	−0.3%
Bioenergy supply elasticities	1.2%	−0.9%
Forest product demand elasticities[a]	0.6%	−0.4%
Bioenergy demand elasticities[a]	1.7%	−0.6%
Forest product prices	−3.3%	0.4%
Bioenergy prices	−2.3%	0.8%
Fossil fuel demand elasticities[a]	90.2%	−32.1%
Fossil fuel prices	−48.1%	45.4%

[a] For demand elasticities that are negative, a downward change in the parameter means that the initial elasticity is multiplied by 0.5 and an upward change means multiplication by 1.5.
[b] NF: not feasible.

The cost is also more sensitive to a downward shift in bioenergy and forest product prices and elasticities than an upward shift. With respect to fossil fuels, the effect on cost is especially high when reducing the elasticities. This nearly doubles the total costs, while an increase only gives a reduction in costs of about one third. Upward and downward changes in fossil fuel prices result in more or less equivalent increases and decreases in costs.

In the model, we assume that bioenergy and forest products are perfect substitutes. If we instead assume that 70% of the harvest is used for forest products in all countries, as in Hedenus and Azar (2010), the overall cost increases by 19.3%.

Sensitivity analysis is also needed on the discount rate, because it may have an effect on the amount of sequestration. Varying the discount rate to 2, 4 or 5% gives scarcely any change in the amount of sequestration. The difference in the sum of sequestration over the entire policy period falls by 0.52% when the discount rate is 2% and increases by 0.12% when the discount rate is 5%. The explanation for this result is that a higher discount rate means that the forest is managed so that the cost is lowest in the beginning of the policy period. Because it is costly to reduce harvesting rate, a higher discount rate means that the level of sequestration is increased in the first 15 years compared with the baseline rate. Following this, the level of sequestration is the same for the rest of the policy period, despite the fact that the discount rate changes.

A change in the decay rate of forest products also has an effect on the results. An increase in the decay rate from 2 to 4% per year means that the cost increases by 1.0%, while a decrease in the decay rate to 1% means a cost decrease of 5.1%.

Timber losses due to logging and processing activities have previously been estimated to range between 2 and 5% of the total volume, depending on the harvesting method used (Gerasimov and Seliverstov, 2010). Taking a 5% timber loss into account in the model, the total cost increases by 0.5%.

Finally, we analyse the implications of using a linear function for standing biomass volume, as previously done by e.g. Hedenus and Azar (2010). Here, we use the mean annual increment in each European country in 2010 (Appendix D, Table D1). This leads to a reduction in the additional sequestration, which means that the total abatement cost increases by 85%.

Discussion and conclusions

We set out to analyse whether forest carbon sequestration should be increased at the expense of bioenergy and forest products in a cost-efficient EU climate policy by 2050. We compare two different scenarios: with and without additional sequestration above the BAU level. We show a cost saving of 23% when recognising the costs and net carbon impacts of sequestration, bioenergy and forest products. The additional sequestration corresponds to approximately 4.7% of the total emissions reduction required for the policy period. We also show that the cost-efficient level of sequestration in forests increases during the study period, with variations between countries in both level and rate of increase. This increase comes mainly at the expense of reductions in bioenergy. Forest carbon sequestration is also increased at the expense of forest products due to the fact that these products decay over time and hence release emissions. In addition, the dynamics in forest carbon sequestration sometimes mean that it is worth having a higher cost today to reach a higher sequestration level in the future.

Our results are in line with those in the general literature, which point towards cost efficiency in using forest carbon sequestration as an abatement method (e.g. Richards and Stokes, 2004; Van Kooten et al., 2004; Kindermann et al., 2008; Murray et al., 2009; Bosetti et al., 2009; Sohngen, 2009). To some extent, earlier studies draw contrasting conclusions. Hedenus and Azar (2009) found that forest resources should be used for bioenergy production rather than sequestration in a cost-efficient climate policy when strict long-term targets are applied, while Gielen et al. (2002), Schneider and McCarl (2003) and Eriksson (2015) found that sequestration is more cost-efficient than bioenergy. The main explanations for the diverging results in Hedenus and Azar (2009) are that they assume energy demand to be exogenously fixed. Bioenergy with comparatively low emissions is then used to meet this demand at the expense of forest carbon sequestration. In addition, they assume that bioenergy is carbon neutral, which gives an advantage to bioenergy compared with our study, where it is assumed that bioenergy implies net emissions, as suggested by e.g. Johnson (2009), Hudiburg et al. (2011), Holtsmark (2012) and Schulze et al. (2012).

The implication of our results for policy development is that forest carbon sequestration could potentially be a cost-efficient abatement option in EU climate policy. There are a number of possibilities available to incorporate sequestration into EU climate policy, including inclusion in the existing emissions trading scheme (ETS) framework and member state targets or in a separate framework (European Commission, 2012a,b; Gren et al., 2012). Kuikman et al. (2011) propose a separate framework for carbon sequestration and discuss different policy instruments closely related to the Common Agriculture Policy (CAP), which could cover the whole land use sector. The economics literature (e.g. Alig et al., 2010) generally proposes market-based instruments for emissions and sinks in the agricultural and forestry sectors. However, more research is needed to find the appropriate instrument for forest carbon sequestration in the EU, and it should take into consideration that sequestration is accompanied by uncertainties and dynamic effects that affect their overall potential. Furthermore, any policy instrument must fit into the existing frameworks and instruments for reducing carbon emissions and incentivising ecosystem services in the land use sector.

The model used in our study has limitations. For example, we only include one type of forest management option – longer rotation periods – in addition to fossil fuel abatement. The inclusion of other options, such as thinning and conversion of land to and from forestry, could be relevant as carbon abatement measures. Inclusion of renewable energies and carbon sequestration in the agricultural sector could also affect the results. Due to these limitations, the results should be interpreted with caution.

Acknowledgements

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Appendix A. Derivation of abatement cost functions

The costs, defined as reductions in producer and consumer surpluses, are calculated in an equal manner for all abatement options in the model. Note, however, that costs for reducing fossil fuels are only calculated as reductions in consumer surplus. The reduction in producer surplus is calculated as follows, where bioenergy is used as an example. The reduction in consumer surplus is described further down.

Let P^i and B^i denote the producer price and the quantity of bioenergy supplied in country i. The supply functions of bioenergy are assumed to be linear and are written as:

$$B^i = a^i + b^i P^i \tag{A1}$$

where a^i is a constant that represents the intercept of the supply curve and b^i is a coefficient that represents the slope of the supply curve. An estimate of the coefficient is derived from the definition of the supply elasticity of bioenergy as:

$$b^i = \frac{\hat{B}^i \varepsilon^i}{\hat{P}^i} \tag{A2}$$

where $\hat{B}^i$, $\hat{P}^i$ and ε^i are the observed bioenergy output and price under BAU and the supply elasticity of bioenergy, respectively. When inserting (A2) in (A1) and solving for the intercept, we obtain:

$$a^i = (1-\varepsilon^i)\hat{B}^i \tag{A3}$$

The cost function is given by the inverse supply function:

$$P^i = \frac{B^i - a^i}{b^i} \tag{A4}$$

where the intercept is $-a^i/b^i$ and the slope coefficient is $1/b^i$. By using (A1) and (A3), we obtain an expression for P^i in terms of B^i and for the exogenous parameters $\hat{B}^i$, $\hat{P}^i$ and ε^i as:

$$P^i = \frac{\hat{P}^i}{\varepsilon^i}\left[\frac{B^i}{\hat{B}^i} - (1-\varepsilon^i)\right] \tag{A5}$$

The cost function for reductions in B^i, expressing costs for decreases in producer surplus, is obtained by integrating (A5) over B_t^i and deducting that from $\hat{P}^i(\hat{B}^i - B_t^i)$ as follows:

$$\begin{aligned} C_t^{iB}(\hat{B}^i - B_t^i) &= \hat{P}^i(\hat{B}^i - B_t^i) - \int_{B_t^i}^{\hat{B}^i} \frac{\hat{P}^i}{\varepsilon^i}\left[\frac{B_t^i}{\hat{B}^i} - (1-\varepsilon^i)\right] dB_t^i \\ &= \hat{P}(\hat{B} - B_t) - \frac{\hat{P}}{\varepsilon}\left[\frac{(\hat{B}-B_t)^2}{2\hat{B}} - ((\hat{B}-B_t) - \varepsilon(\hat{B}-B_t))\right] \end{aligned} \tag{A6}$$

where the country suffix, i, has been omitted in the last part of (A6) to facilitate reading.

Reductions in consumer surplus are calculated in a similar fashion as reductions in producer surplus, but we now use the inverse demand functions instead of the inverse supply functions. This cost is calculated as follows:

$$\begin{aligned} C_t^{iB}(\hat{B}^i - B_t^i) &= \int_{B_t^i}^{\hat{B}^i} \frac{\hat{P}^i}{\varepsilon^i}\left[(1-\varepsilon^i) - \frac{B_t^i}{\hat{B}^i}\right] dB_t^i - \hat{P}^i(\hat{B}^i - B_t^i) \\ &= \frac{\hat{P}}{\varepsilon}\left[((\hat{B}-B_t) + \varepsilon(\hat{B}-B_t)) - \frac{(\hat{B}-B_t)^2}{2\hat{B}}\right] - \hat{P}(\hat{B}-B_t) \end{aligned} \tag{A7}$$

where, again, the country suffix, i, has been omitted in the last part.

Appendix B. First-order conditions

$$\frac{\partial L}{\partial B_t^i} = \rho^t\left[\frac{\partial C_t^{iB}(\hat{B}^i - B_t^i)}{\partial B_t^i} + \rho\mu_{t+1}^i + \lambda_t(1+\varphi-\gamma)\right] = 0 \tag{B1}$$

$$\frac{\partial L}{\partial F_t^i} = \rho^t \left[\frac{\partial C_t^{iF}(\hat{F}^i - F_t^i)}{\partial F_t^i} + \rho\mu_{t+1}^i - \lambda_t \left((1-\varphi) + \sum_{\tau=t+1}^{T} \rho^{\tau-t}\lambda_t\theta(1-\theta)^{\tau-1-t} \right) \right] = 0 \tag{B2}$$

$$\frac{\partial L}{\partial X_t^{ij}} = \rho^t \left[\frac{\partial C_t^{iX}(\hat{X}^{ij} - X_t^{ij})}{\partial X_t^{ij}} + \lambda_t \right] = 0 \tag{B3}$$

$$\frac{\partial L}{\partial V_t^i} = \rho^t \left[\mu_t^i - \rho\mu_{t+1}^i \left(1 + \frac{\partial G^i}{\partial V_t^i} \right) + \lambda_t - \rho\lambda_{t+1} \right] = 0 \tag{B4}$$

$$\frac{\partial L}{\partial \mu_{t+1}^i} = \rho^t[-V_t^i - G^i(V_t^i) + H_t^i + V_{t+1}^i] = 0 \tag{B5}$$

$$\frac{\partial L}{\partial \lambda_t} = \rho^t \left[\sum_j X_t^{ij} + L_t^i - M_t^i - S_t^i - E_t^{MAX} \right] = 0 \tag{B6}$$

where $\mu_t^i \pm 0$ and $\lambda_t > 0$ are the Lagrange multipliers. The multiplier μ_t^i is the shadow value for the stock of standing biomass volume and λ_t is the shadow cost of the emission target. The latter can be used to illustrate cost-efficient design of economic instruments because it is equal to the efficient carbon tax, or, equivalently, the allowance price under a cap-and-trade system.

Appendix C. Conversion parameters

The carbon content of wood is calculated according to Table 4.5 in IPCC (2006). The calculation is based on the average of pine and other coniferous and hardwood species in temperate forests and the average of pine, fir, spruce and hardwood in boreal forests. Finland and Sweden have boreal forests, and the rest have temperate forests. Table C1 shows the parameter values for carbon content in temperate and boreal forests. Net emissions from bioenergy use are calculated based on the following three parameters, and net carbon storage in forest products is calculated based on the first two parameters: (1) The carbon content of wood; (2) φ, harvesting, transporting and processing emissions, released to the atmosphere; and (3) γ, bioenergy replacing coal in CHP plants, implying an emission offset. The parameter φ is calculated by dividing the emissions from harvesting, transporting and processing bioenergy (Petersen, 2006), measured in tonnes CO_2/m^3, by the carbon content of wood. The substitution effect, γ, is calculated following the approach in Van Kooten (1999). First, the volume of bioenergy, measured in m^3, is converted into tonnes of oil equivalent (toe), the measurement unit of coal, using the conversion factor 0.18 toe per solid m^3 (Forest Sweden, 2012). Second, this is multiplied by the CO_2 content of coal. Third, the product is divided by the carbon content of wood. The emissions factors for different fossil fuels stem from Gren et al. (2009). Table C1 contains the resulting parameters.

Table C1
Conversion parameters used in the model.

Parameter	Value
Carbon content of wood (tonne CO_2/m^3)	1.459/0.912[a]
φ, harvesting, transporting and processing emissions (tonne CO_2/m^3)	0.016/0.026[a]
γ, fossil fuel substitution (tonne CO_2/m^3)	0.506/0.809[a]
Emissions from oil (tonne CO_2/toe)	3.019
Emissions from coal (tonne CO_2/toe)	4.1
Emissions from gas (tonne CO_2/toe)	2.349

[a] The first number refers to all countries with temperate forest and the second to countries with boreal forests.

Appendix D. Data related to forest resources

Table D1
Average age, biomass volume, forest area and increment in 2010.

	Average age, years[a,g]	Model average age, years	Forest volume, m^3/ha[b,g]	Model forest volume, m^3/ha	Real increment, m^3/ha/yr	Model increment, m^3/ha/yr[g]	Forest area, ha[g]
Austria	65	65	292	292	7.5	9.7	3851
Belgium[e]	35	58	248	192	7.9	8.1	678
Bulgaria	55	55	167	167	5.1	7.6	3927
Cyprus[c]	–	47	151	151	–	8.13	173
Czech Rep.	64	64	290	290	9.9	10.0	2657
Denmark	40	40	193	193	10.0	11.8	587
Estonia	45	45	200	200	5.6	10.7	2203
Finland	67	67	99	99	4.6	4.0	22 084
France	76	76	162	162	6.2	5.4	15 954
Germany	68	68	315	315	10.1	10.0	11 076
Greece[c]	–	47	151	151	–	8.1	3903
Hungary	40	40	174	174	6.4	10.7	2039
Ireland[f]	16	50	100	132	5.8	7.0	738
Italy	47	47	151	151	4.0	8.1	9149
Latvia	48	48	189	189	5.8	9.6	3354
Lithuania	51	51	221	221	5.7	10.1	2165
Luxembourg	89	89	299	299	7.5	7.4	87
Malta[c]	–	47	151	151	–	8.1	0.3
Netherlands	58	58	192	192	7.6	8.1	365
Poland	54	54	247	247	8.0	10.4	9319
Portugal	27	27	53	53	10.5	5.6	3437
Romania	58	58	212	212	6.5	8.6	6391
Slovakia	64	64	189	189	7.4	7.1	2713
Slovenia	90	90	301	301	7.8	7.1	1243
Spain[d]	–	27	50	50	3.1	5.4	18 173
Sweden	59	59	113	113	4.7	5.1	28 605
UK	50	50	132	132	8.6	7.0	2881

[a] Initial age is calculated from data on forest area by age class for 2010. For Austria, Luxembourg, Portugal, Romania and Slovenia, the 2005 age and volumes are used due to missing data for 2010.
[b] Initial volumes are calculated from data on total volume and forest area for 2010.
[c] The C–R function is the same as for Italy.
[d] The age is the same as for Portugal.
[e] The C–R function is the same as for the Netherlands.
[f] The C–R function is the same as for the UK.
[g] Forest age, volume and area from UNECE (2013) and real increment from Eurostat (2011).

Table D2
Calibrated parameters of the Chapman–Richards function.

	k^i	m^i	n^i
Austria	0.000179	3.824	0.02552
Belgium[c]	0.000135	3.824	0.02327
Bulgaria	0.000137	3.824	0.0238
Cyprus[a]	0.000214	3.824	0.02677
Czech Rep.	0.0001788	3.824	0.025045
Denmark	0.000557	3.824	0.03371
Estonia	0.00039	3.824	0.03129
Finland	0.00002985	3.824	0.01581
France	0.0000367	3.824	0.016555
Germany	0.0001638	3.824	0.02448
Greece[a]	0.000214	3.824	0.02677

Table D2 (*Continued*)

	k^i	m^i	n^i
Hungary	0.000491	3.824	0.033222
Ireland[b]	0.0001333	3.824	0.02319
Italy	0.000214	3.824	0.02677
Latvia	0.000279	3.824	0.02866
Lithuania	0.000283	3.824	0.02877
Luxembourg	0.00005344	3.824	0.018264
Malta[a]	0.000214	3.824	0.02677
Netherlands	0.0001333	3.824	0.02319
Poland	0.0002735	3.824	0.02851
Portugal	0.000422	3.824	0.03197
Romania	0.0001613	3.824	0.024835
Slovakia	0.0000923	3.824	0.021459
Slovenia	0.0000546	3.824	0.018725
Spain	0.000395	3.824	0.03142
Sweden	0.00005835	3.824	0.01885
UK	0.000135	3.824	0.02327

The three parameters of the Chapman–Richard function are calibrated as explained in the main text (Section "Abatement in the forest sector").

[a] Cyprus, Greece and Malta same C–R function as Italy.

[b] Ireland same C–R function as UK.

[c] Belgium same C–R function as NL.

Table D3
Prices and elasticities for bioenergy and forest products.

	Bioenergy price in €/m[a]	Forest product price in €/m[b]	Bioenergy demand elasticity[c]	Bioenergy supply elasticity[d]	Forest product demand elasticity[e]	Forest product supply elasticity[e]
Austria	51	75	−0.55	0.45	−0.34	1.000
Belgium	45	69	−0.42	0.45	−0.542	1.498
Bulgaria	9	45	−0.55	0.45	−0.34	1.000
Cyprus	49	56	−0.42	0.45	−0.271	0.242
Czech Republic	8	48	−0.42	0.45	−0.542	1.498
Germany	18	59	−0.42	0.45	−0.542	0.733
Denmark	38	71	−0.42	0.45	−0.542	1.498
Estonia	15	42	−0.55	0.45	−0.34	1.000
Finland	24	68	−0.35	0.55	−0.723	1.084
France	30	55	−0.42	0.45	−0.542	1.498
Greece	49	56	−0.42	0.45	−0.271	0.242
Hungary	25	53	−0.55	0.45	−0.34	1.000
Ireland	45	69	−0.42	0.45	−0.542	1.498
Italy	49	367	−0.42	0.45	−0.271	0.242
Lithuania	15	37	−0.55	0.45	−0.34	1.000
Luxembourg	45	69	−0.42	0.45	−0.542	1.498
Latvia	15	37	−0.55	0.45	−0.34	1.000
Malta	49	56	−0.42	0.45	−0.271	0.242
Netherlands	23	41	−0.42	0.45	−0.542	1.498
Poland	16	63	−0.55	0.45	−0.34	1.000
Portugal	23	54	−0.42	0.45	−0.271	0.242
Romania	9	45	−0.55	0.45	−0.34	1.000
Slovakia	9	45	−0.55	0.45	−0.34	1.000
Slovenia	9	53	−0.42	0.45	−0.271	0.242
Spain	21	56	−0.42	0.45	−0.271	0.242
Sweden	28	44	−0.35	0.55	−0.187	1.084
UK	34	43	−0.42	0.45	−0.542	1.498

[a] Refers to logging residues; Lundmark and Mansikkasalo (2009).

[b] Refers to roundwood; Lundmark and Mansikkasalo (2009).

[c] Temperate Oceanic and Mediterranean counties, data from Couture et al. (2009); Boreal countries, data from Ankarhem (2005); Temperate Continental countries, data from Dornburg et al. (2007).

[d] All countries except Boreal countries, data from Sacchelli et al. (2013); Boreal countries, data from Geijer et al. (2011).

[e] All countries have data from Kangas and Baudin (2003).

Table D4
Production quantities of forest products and bioenergy in 2010.

Country	Ind. roundwood (thousand m^3)	Fuel wood (thousand m^3)
Austria	13 281	4550
Belgium	4114	714
Bulgaria	3011	2657
Cyprus	5	4
Czech Rep.	14 771	1965
Denmark	1590	1080
Estonia	5256	1944
Finland	45 977	4975
France	29 634	26 174
Germany	45 388	9031
Greece	336	711
Hungary	2746	2994
Ireland	2437	181
Italy	2647	5197
Latvia	10 222	2312
Lithuania	5154	1943
Luxembourg	258	17
Malta	0	0
Netherlands	791	290
Poland	31 343	4124
Portugal	9048	600
Romania	10 548	2564
Slovakia	9089	510
Slovenia	1841	1104
Spain	10 969	5120
Sweden	66 300	5900
UK	8337	1381

Source: Eurostat (2013a).
Forest products are industrial roundwood and bioenergy is fuel wood.

Appendix E. Data related to fossil fuels

Table E1
Total consumption, prices and demand elasticities in all sectors of fossil fuel products in 2010.

	Consumption natural gas (1000 toe)	Consumption oil products (1000 toe)	Consumption coal products (1000 toe)	Oil price (€/toe)	Natural gas price (€/toe)	Oil products demand elasticity	Coal products demand elasticity	Natural gas demand elasticity
Austria	8214	13 091	3397	820	543	–0.45	–0.41	–0.46
Belgium	16 960	25 630	3186	863	489	–0.63	–0.40	–0.37
Bulgaria[c]	2241	4027	6887	682	390	–0.80	–0.59	–0.58
Cyprus[a]	0	2592	17	784	589	–0.51	–0.62	–0.55
Czech Rep.	8019	9335	18 474	785	474	–0.60	–0.49	–0.39
Germany	73 406	114 204	77 120	1023	783	–0.58	–0.61	–0.35
Denmark	4437	6886	3809	697	376	–0.47	–0.68	–0.45
Estonia[c]	563	1055	3917	905	773	–0.80	–0.59	–0.58
Finland	3837	10 271	6878	882	510	–0.58	–0.58	–0.64
France	42 540	83 925	12 046	901	541	–0.52	–0.37	–0.30
Greece	3234	15 064	7863	821	589	–0.51	–0.62	–0.55
Hungary[c]	9815	6832	2730	900	500	–0.80	–0.59	–0.58
Ireland	4696	7604	2095	878	462	–0.58	–0.67	–0.53
Italy	68 057	70 513	14 170	1042	572	–0.44	–0.42	–0.37

Table E1 (*Continued*)

	Consumption natural gas (1000 toe)	Consumption oil products (1000 toe)	Consumption coal products (1000 toe)	Oil price (€/toe)	Natural gas price (€/toe)	Oil products demand elasticity	Coal products demand elasticity	Natural gas demand elasticity
Lithuania[c]	2492	2587	205	719	376	−0.80	−0.59	−0.58
Luxembourg	1197	2875	66	714	432	−0.63	−0.40	−0.37
Latvia[c]	1462	1293	109	780	491	−0.80	−0.59	−0.58
Malta[b]	0	911	0	811	589	−0.44	−0.42	−0.37
Netherlands	39 309	35 067	7596	1004	531	−0.42	−0.49	−0.33
Poland	12 807	26 400	54 608	761	453	−0.43	−0.57	−0.38
Portugal	4489	12 381	1657	894	532	−0.58	−0.57	−0.50
Romania[c]	10 788	9247	7009	682	246	−0.80	−0.59	−0.58
Slovakia[c]	5006	3689	3897	797	451	−0.80	−0.59	−0.58
Slovenia[c]	863	2573	1458	759	589	−0.80	−0.59	−0.58
Spain	31 221	60 616	7828	804	477	−0.45	−0.60	−0.54
Sweden	1331	14 509	2492	1045	773	−0.56	−0.35	−0.51
UK	84 814	73 919	30 457	996	470	−0.39	−0.58	−0.32

Sources: Consumption quantities Eurostat (2013b).
The price of oil products is the average of light and heavy fuel oil, petrol and diesel with and without taxes and VAT for 2006 Gren et al. (2009).
The price of natural gas is the average of domestic consumers with and without taxes in 2010 Eurostat (2013c).
Demand elasticities Holtsmark and Maestad (2002).

[a] Assumed to have the same elasticity as for Greece.
[b] Assumed to have the same elasticity as for Italy.
[c] Defined as economies in transition with the same elasticities.

Appendix F. Results

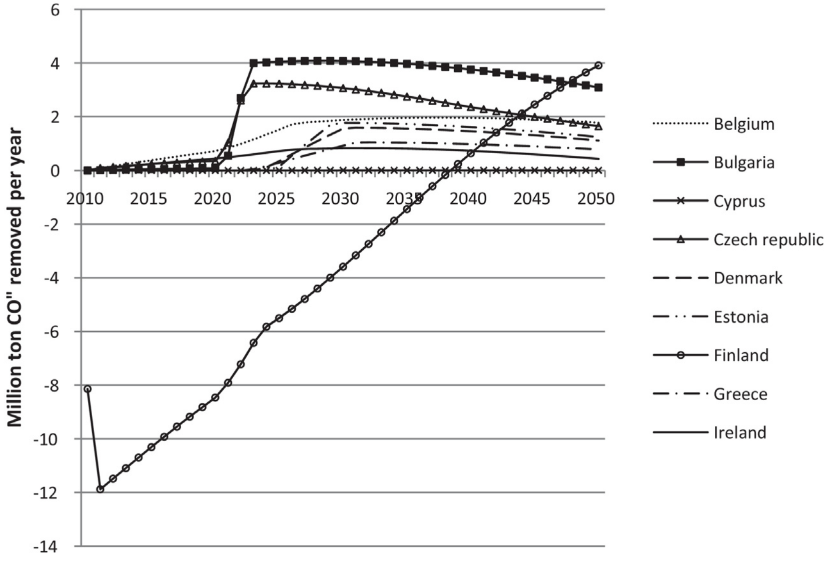

Fig. F1. Development of sequestration in forests and forest products in some European countries in million tonnes CO_2 removed per year.

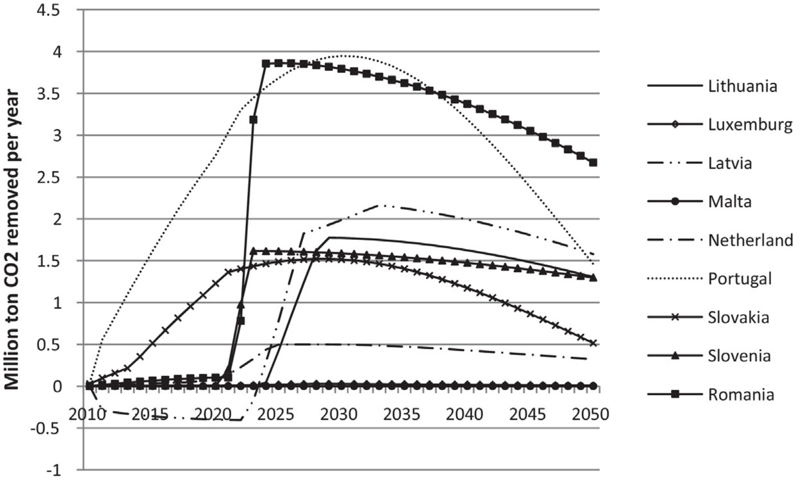

Fig. F2. Development of sequestration in forests and forest products in some European countries in million tonnes CO_2 removed per year.

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