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Should forests be used as uncertain carbon sinks or uncertain fossil fuel substitutes in the EU Roadmap to 2050?

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Abstract

This study investigates the contribution of forest carbon sequestration to a cost-efficient EU climate policy from 2010 to 2050 under conditions of uncertainty. We note that there is a trade-off between sequestration and alternative uses of forests such as bioenergy and timber production. A dynamic and probabilistic cost-minimization model is developed, which includes fossil fuel use within the EU Emissions Trading System and forest management in the EU-27 countries. The results suggest that if policy makers wish to meet emissions targets with 80% certainty, this goal will be eight times more expensive than when they were unconcerned with uncertainty. Policy makers' risk attitudes affect forest management strategy primarily through the inclusion of wood products, where potential carbon emissions reductions are high but also highly uncertain. Excluding wood products from a climate strategy can be expensive if policy maker are insensitive to uncertainty.

Keywords: uncertainty; carbon sequestration; bioenergy; wood products; climate policy; cost-efficiency; EU.

JEL codes: Q23, Q28, Q48, Q54.

Introduction

Carbon sinks have received attention for their climate change mitigation potential. Several studies indicate that forest-related activities account for 10-50% of the emission reductions in a cost-effective climate policy (Sohngen, 2009; Bosetti et al., 2009, Murray et al., 2009; Gren et al., 2012). Despite high potential benefits and relatively low costs, countries can only partially take credit for carbon sequestration in relation to national commitments under the Kyoto protocol. No crediting of sequestration is allowed within the EU climate policy on CO_2 burden allocation. Policy instruments intended to increase carbon sequestration are applied to a limited extent, e.g., through the so-called REDD (Reduced Emissions from Deforestation and Degradation) scheme, which supports the conservation of forests in developing countries (Sandbrook et al., 2010; Angelson et al., 2009). In contrast, policies to promote fossil fuel reduction, i.e., the EU ETS (Emissions Trading Scheme) and to increase the use of bioenergy are well established (Kim et al., 2010). Policies for bioenergy are motivated by the potential to substitute fossil fuels, which implies a reduction in carbon emission provided that bioenergy is carbon neutral in the longer run (Cook and Beyea, 2000; Kim et al., 2010). Bioenergy is, however, not the only way to use wood in a manner that affects carbon emissions. The potential for industrial timber production to simultaneously replace fossil fuel products and serve as a carbon sink has been highlighted by researchers (Sathre and O'Connor, 2010), but policies promoting such behavior have not been introduced.

Arguments against the introduction of instruments to enhance carbon sinks in the European Union include the uncertainty about carbon sinks stocks and development in the short and long term and the difficulty of designing appropriate incentive structures. Instead, the EU has introduced permit trading in fossil fuel CO_2 emissions for the industry and energy sectors, which is the only policy instrument that contributes to a cost-efficient allocation of abatement efforts across countries. Additionally, there is an EU-wide target for 20 percent of all EU energy consumption to be provided by renewable energy sources by 2020. Biomass already accounts for about half of the renewable energy used in the EU (Schlegel and Kaphengst, 2007). Whereas the reduction of CO_2 emissions from reductions in fossil fuel use is achieved with a high degree of certainty (Gren et al., 2012), the same does not hold for bioenergy where there is a large amount of variation in the efficiency of combustion technologies and subsequent displacement of fossil fuels. The reduction of CO_2 from the displacement of fossil fuel products by industrial timber products is also uncertain because it is highly dependent on the type of products which timber products replace.

The purpose of this paper is to analyze the cost-efficiency contribution of forest carbon sequestration to EU climate policy from 2010 to 2050, taking into account uncertainty and the trade-off between carbon sequestration and other uses of forests. Evaluating this trade-off implies taking into account the costs of adjusting carbon sequestration, bioenergy and timber use and the corresponding stochastic impact on CO_2 emissions. To analyze this issue, we develop a dynamic cost-minimization model including the EU-27 countries. The model includes four different measures that all affect carbon dioxide emissions: fossil fuel reductions, carbon sequestration, bioenergy use, and timber use. Uncertainty is taken into account using probabilistic constraints; it is assumed that targets for annual CO_2 reductions should be achieved with a minimum probability. The major contribution of our study is the analysis of the trade-off in cost-efficiency under uncertainty and over time between carbon sequestration and the supply of forest products, which can displace fossil fuels.

The literature on carbon sequestration and the trade-offs between different technologies includes assessments of the impact on carbon emissions; cost-efficiency studies, which maintain substantial detail in the modeling of technical interdependences between alternative measures; and general equilibrium models, which take into account inter-sectoral interdependences and international trade (Povellato et al., 2007). Our study investigates cost-effectiveness in a partial equilibrium framework. This design is motivated by our interest in analyzing the role of the trade-offs between sequestration and the supply of forest products, which can displace fossil fuels, and the role that risk considerations play in the choice of a strategy within a dynamic framework. Previous economic work has paid limited attention to the trade-off between carbon sequestration and alternative uses of the forest such as bioenergy and timber. Some economic studies assume that all carbon contained in forest products is immediately released upon harvest, whereas others assume that forest allocated to sequestration turn into a "carbon graveyard," i.e., there is no harvesting or natural release of carbon (Richards and Stokes, 2004). Modifications to these approaches can be found in Stavins (1999), where wood products are assumed to gradually release carbon as they decay, and in Newell and Stavins (2000), where different sequestration rates are used for harvested and non-harvested forests. Münnich-Vass and Elofsson (unpublished) investigate the trade-off between bioenergy and sequestration in a deterministic dynamic cost-efficiency model over EU climate policy, allowing for bioenergy to replace fossil fuels. Additionally, the role of uncertainties about the impact on carbon emissions is largely neglected. Exceptions include the work of Gren et al. (2012) and Gren and Carlsson (2013) where the role of uncertain carbon sequestration in a cost-efficient European climate policy is investigated within a static framework; however, the interdependence between sequestration and forest product supply is ignored.

Structure of the numerical model

Consider all EU countries *i*, where *i*=1,…,27 different countries. The countries have agreed on a CO_2 emissions reduction path for the whole union until 2050, which they wish to implement at a minimum cost. They can meet the emissions reduction target by either reducing consumption of fossil fuels within the ETS or by implementing changes in forest management. The ability to use forests for different purposes is determined by the existing forest biomass and its development over time. The development of standing forest biomass on one hectare of land is defined by:

$$V_{t+1}^i = V_t^i + G_t^i(V_t^i) - H_t^i \quad (1)$$

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

where all variables are measured in cubic meters. Here, V_t^i is the standing biomass at time t in country i, $G_t^i\left(V_t^i\right)$ is the annual growth of biomass, and H_t^i is the harvest, which is assumed to take place in the end of the year. Total forest biomass in a country is $A^i V_t^i$, where A^i is the number of hectares of forest land in that country. Net annual carbon sequestration in country i, $\tilde{S}_t^i$, is obtained by multiplying net forest biomass growth by a parameter, η, which converts forest biomass in cubic meters into kilo CO_2-equivalents removed from the atmosphere. The net annual carbon sequestration is assumed to be stochastic, as sequestration is determined by weather and local soil conditions. We thus have:

$$\tilde{S}_{t+1}^i = \eta A^i (V_{t+1}^i - V_t^i) + \varepsilon^i, \tag{2}$$

where ε^i is an additive stochastic component, which is assumed to be normally distributed. We then have expected carbon sequestration and variance thereof defined by $E\left(\tilde{S}_t^i\right)$ and $Var\left(\tilde{S}_t^i\right)$, respectively. The harvested forest biomass is used for two different purposes, bioenergy or timber:

$$A^i H_t^i = B_t^i + T_t^i, \tag{3}$$

where B_t^i and T_t^i are the total volume of bioenergy and timber, respectively.

Bioenergy and timber are each assumed to each have one certain and one stochastic impact on CO_2 emissions. When forests are used for bioenergy, the carbon content of the wood is released into the atmosphere. We assume that this consumption occurs during the same time period as the wood harvesting. The amount of CO_2 released is determined by wood carbon content, which can be measured with a high degree of accuracy. The CO_2 released from one cubic meter of wood is captured by a deterministic conversion factor, η. The CO_2 released into the atmosphere by bioenergy is, however, offset by replacing fossil fuels. The net release of CO_2 emissions from bioenergy can be considered stochastic due to variability in the degree of displacement of fossil fuels. This variability is explained by differences in the relative efficiency of bioenergy systems and displaced fossil systems (Schlamadinger and Marland, 1996). The uncertain displacement of fossil fuels is captured by a stochastic parameter $\tilde{\tau}$, with expectation $E(\tilde{\tau})$ and variance $Var(\tilde{\tau})$, which expresses net carbon emissions per unit of carbon in bioenergy after taking fossil fuel displacement into account. The net release of CO_2 emissions can then be expressed as $\tilde{\tau}\eta B_t^i$.

When used as timber, carbon is stored in wood products and removed from the atmosphere. Again, we know the CO_2 content of timber, captured by the deterministic conversion factor, η. We can thus calculate the annual increase in the CO_2 stock of wood products as ηT_t^i. Timber products can displace fossil fuel-based materials, e.g., in the construction sector or elsewhere. The magnitude of displacement depends on the ratio of energy required to produce one unit of a component from wood and non-wood materials and the ratio of the mean lifetimes of the wood and non-wood products (Schlamadinger and Marland, 1996). These ratios can vary considerably for different components, therefore, we model the displacement as stochastic. The stochastic displacement is captured by a parameter $\tilde{\varphi}$, with expectation $E(\tilde{\varphi})$ and variance $Var(\tilde{\varphi})$, which expresses the units of carbon emissions displaced by one unit of carbon in timber. At time *t*, when the forest is harvested and used for timber products, $\tilde{\varphi}\eta T_t^i$ units of CO_2 are removed from the atmosphere due to the production of timber. However, we assume that timber products have a limited life span (c.f. Eggers, 2002) of k_i years after which they are used for energy purposes, i.e., they are combusted and the carbon content in the timber, ηT_t^i, is released into the atmosphere. Like bioenergy, timber that is combusted is assumed to replace fossil fuels, partially offsetting the CO_2 emissions from combustion. We assume that the displacement of fossil fuel from the combustion of timber products is identical to that of bioenergy. The net release of carbon after k_i years is $\tilde{\tau}\eta T_{t-k_i}^i$. The contribution of forest products to carbon dioxide emissions in a given year, L_t^i, can then be summarized as:

$$\tilde{L}_t^i = -\tilde{\varphi}\eta T_t^i + \tilde{\tau}\eta T_{t-k_i}^i + \tilde{\tau}\eta B_t^i, \quad (4)$$

where the first term is the increase in the carbon pool of timber, multiplied by $\tilde{\varphi}$ to account for the simultaneous displacement of fossil fuels. The second term is the delayed release of carbon from wood products combusted at the end of their lifetime, and the third term is the net contribution of bioenergy to carbon dioxide emissions given the displacement of fossil fuels.

Accordingly, the net reduction of carbon in the atmosphere, $\tilde{R}_t^i$, due to forest carbon sequestration and the different uses of forest products can be summarized as:

$$\tilde{R}_t^i = \tilde{S}_t^i - \tilde{L}_t^i, \qquad (5)$$

where all terms are measured in terms of carbon dioxide equivalents.

The combustion of fossil fuels in each country contributes to carbon dioxide emissions. Emissions of carbon dioxide from fossil fuels are determined by the quantity of fossil fuels consumed in different countries, X_t^{ij}, where *j*, with *j*=1,…,6, is the type of fuel (hard coal, lignite, natural gas, light fuel and heating oil, heavy fuel oil and jet fuel) and the emission coefficient for each fuel type, α^j. Consequently, emissions from a given type of fossil fuel in a country, E_t^{ij}, are defined by $E_t^{ij} = \alpha^j X_t^{ij}$. Total emissions in all countries from fossil fuels and forest management, E_t, are then:

$$E_t = \sum_i (\sum_j \alpha^j X_t^{ij} - \tilde{R}_t^i) \qquad (6)$$

with

$$E(E_t) = \sum_i (\sum_j \alpha^j X_t^{ij} - E(\tilde{R}_t^i)) = \sum_i \sum_j \alpha^j X_t^{ij} - \sum_i E(\tilde{S}_t^i) + \sum_i E(\tilde{L}_t^i) = \\ \sum_i \sum_j \alpha^j X_t^{ij} - \sum_i E\left[\eta A^i (V_{t+1}^i - V_t^i)\right] - \sum_i E(\tilde{\varphi}) \eta T_t^i + \sum_i E(\tilde{\tau}) \eta T_{t-k_i}^i + \sum_i (\tilde{\tau}) \eta B_t^i \qquad (7)$$

and

$$Var\left(E_t\right)=\sum_i Var\left(\tilde{R}_t^i\right)=\sum_i Var\left(\tilde{S}_t^i-\tilde{L}_t^i\right)=\sum_i Var\left(\tilde{S}_t^i+\tilde{\varphi}\eta T_t^i-\tilde{\tau}\eta T_{t-k_i}^i-\tilde{\tau}\eta B_t^i\right)=$$
$$\sum_i Var\left(\tilde{S}_t^i\right)+\sum_i Var\left(\tilde{\varphi}\right)\left(\eta T_t^i\right)^2+\sum_i Var\left(\tilde{\tau}\right)\left(\eta T_{t-k_i}^i\right)^2+\sum_i Var\left(\tilde{\tau}\right)\left(\eta B_t^i\right)^2+\sum_i\sum_{j\neq i} Cov\left(\tilde{S}_t^i,\tilde{S}_t^j\right)+$$
$$\sum_i\sum_{j\neq i}2\eta T_t^i Cov\left(\tilde{\varphi},\tilde{S}_t^j\right)+\sum_i\sum_{j\neq i}2\eta T_{t-k_i}^i Cov\left(\tilde{\tau},\tilde{S}_t^j\right)+\sum_i\sum_{j\neq i}2\eta B_t^i Cov\left(\tilde{\tau},\tilde{S}_t^j\right)+\sum_i 2\eta^2 T_t^i T_{t-k_i}^i Cov\left(\tilde{\varphi},\tilde{\tau}\right)$$
$$+\sum_i 2\eta^2 T_t^i B_t^i Cov\left(\tilde{\varphi},\tilde{\tau}\right)$$
.

(8)

where in the following, the covariance terms are assumed to be equal to zero. We do not explicitly model the substitution between fossil fuels and bioenergy in final use; but simplify this by modeling bioenergy as a measure with lower net emissions due to the displacement of fossil fuels. This simplification is motivated by our desire to analyze the role of uncertainty for the trade-off between forest product use and sequestration. A more elaborate analysis of the substitution between bioenergy and fossil fuels would require more detailed modeling of supply and demand in different industries, i.e., a general equilibrium approach, which is outside the scope of this paper.

There are costs associated with reduced fossil fuel consumption and a changed supply of forest products. The cost from 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 unregulated, business-as-usual consumption of the fossil fuel in question. It is assumed that the cost function is twice differentiable, decreasing and convex. Furthermore, it is assumed that fossil fuel consumption cannot fall below a given minimum level, $\underline{X}_t^{ij}$, i.e., $\underline{X}_t^{ij}\leq X_t^{ij}\leq X_{BAU}^{ij}$.

Costs also arise when the use of timber or bioenergy changes. The use of forest products can be reduced in order to achieve increased carbon sequestration by maintaining forests. Alternatively, the use of timber or bioenergy can be increased if it is more beneficial to combat CO_2 emissions through these products compared to forest sequestration. The cost of changing bioenergy production is defined as $C_t^{Bi}(B_{BAU}^i - B_t^i)$, where B_{BAU}^i is the business-as-usual, unregulated production of forest bioenergy. It is assumed that B_t^i can be lower than or exceed B_{BAU}^i, but that the deviation from business-as-usual production is subject to lower and upper bounds, $\underline{B}^i \leq B_t^i \leq \overline{B}^i$. Correspondingly, changing the use of timber products is associated with a cost, $C_t^{Ti}(T_{BAU}^i - T_t^i)$, where T_{BAU}^i is the unconstrained production of timber. It is assumed that $\underline{T}^i \leq T_t^i \leq \overline{T}^i$, i.e., timber production can be smaller or larger than the unconstrained quantity. The cost functions for bioenergy and timber are assumed to be continuous, convex, and decreasing in B_t^i and T_t^i below the business-as-usual levels, but increasing B_t^i and T_t^i above the business-as-usual levels. We assume costs to be separable for bioenergy, timber and fossil fuels. For bioenergy and timber, the separability assumption is motivated by the large variation in the share of forest harvest used for bioenergy and timber in European countries, see table A1 in the Appendix; implying that assuming that fixed proportions of the harvest are used for bioenergy is not adequate, even when such assumptions could be reasonable in a national or regional setting (Carlsson, 2012; Trømborg and Sjølie, 2011). A possible explanation for the variations in forest use includes the extent to which forest residues are used for bioenergy purposes or left to decay in the forest. Information on the use of forest residues are necessary to analyze the degree of cost separability between timber and bioenergy, see, e.g., Read and Lermit (2005), Galik et al. (2009) and Abt et al. (2010). Such data are, however, not available for the EU countries.

It is assumed that EU policy makers want to meet a sequence of annual emissions targets, E_t^{MAX}, which are based on EU's roadmap for moving to a low-carbon economy by 2050 (EU Commission, 2011a). A target can be reached by reducing the consumption of fossil fuels and changing the production of bioenergy and timber, taking into account the interdependence between forest products and carbon sequestration. Policy makers are assumed to be concerned with risk, and, therefore, they wish to meet the target with at least a given probability β, i.e.,

$$P\left\{E_t \leq E_t^{MAX}\right\} \geq \beta$$
$$\beta \in (0,1)$$

If $\beta=0.9$, this means that at least nine times out of ten, total emissions must be less than E_t^{MAX}. The deterministic equivalent of the above expression can be written as

$$E(E_t)+K_\beta\sqrt{Var(E_t)}\leq E_t^{MAX} \tag{9}$$

(see, *e.g.*, Charnes and Cooper, 1959). The formulation in (9) implies that the random loads in the probabilistic expression are replaced by estimates of their values given by their expected value plus the quantity $K_\beta\sqrt{Var(E_t)}$. In this expression, K_β can be interpreted as the weight that policy makers attach to the standard deviation of total emissions. The higher the β, the larger the K_β, and the greater the effort required to reach the same target. Thus, a larger β implies that the costs of compliance with the environmental target are higher. If $K_\beta=0$, policy makers attach no weight to variations in loads and (9) can be interpreted as a deterministic constraint. The difference in minimum costs between the deterministic and chance-constrained outcomes depends on the subjective level of β, assumptions about the distribution of emissions, and the estimated $Var(E_t)$.

It is assumed that the policy maker wants to meet (9) at a minimum cost. The decision problem is then to:

$$\underset{X_t^{ij},B_t^i,T_t^i}{Min} \quad TC=\sum_t\sum_i\rho_t\left[C_t^{Bi}(B_{BAU}^i-B_t^i)+C_t^{Ti}(T_{BAU}^i-T_t^i)+\sum_j C_t^{Xij}(X_{BAU}^{ij}-X_t^{ij})\right](10) \qquad (11)$$

s.t. (1)-(9) and the upper and lower bounds on the decision variables. The dynamic discrete time Lagrangian for the above problem in (11) is then:

$$L=\sum_t\sum_i\rho^t\begin{bmatrix}C_t^{Bi}(B_{BAU}^i-B_t^i)+C_t^{Ti}(T_{BAU}^i-T_t^i)+\sum_j C_t^{Xij}(X_{BAU}^{ij}-X_t^{ij})+\\ \rho\mu_{t+1}^i\left(V_{t+1}^i-V_t^i-G_t^i(V_t^i)+H_t^i\right)-\\ \lambda_t\left[E_t^{MAX}-E(E_t)-K_\beta\sqrt{Var(E_t)}\right]\end{bmatrix}$$

where $\rho = \dfrac{1}{(1+r)}$ is the discount factor and, *r*, is the discount rate. The necessary conditions for an interior solution are:

$$\rho^{-t}\frac{\partial L}{\partial X_t^{ij}} = \frac{\partial C_t^{ij}(X_{BAU}^{ij} - X_t^{ij})}{\partial X_t^{ij}} - \lambda_t \alpha^j = 0 \tag{12}$$

$$\rho^{-t}\frac{\partial L}{\partial B_t^i} = \left[\frac{\partial C_t^{Bi}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i} + \rho\mu_{t+1}^i \frac{\partial H_t^i}{\partial B_t^i} - \lambda_t\left(-\frac{\partial E\left(E_t\right)}{\partial B_t^i} - K_\beta \frac{\partial\sqrt{Var(E_t)}}{\partial B_t^i}\right)\right] = 0 \tag{13}$$

$$\rho^{-t}\frac{\partial L}{\partial T_t^i} = \begin{bmatrix} \dfrac{\partial C_t^{Ti}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i} + \rho\mu_{t+1}^i \dfrac{\partial H_t^i}{\partial T_t^i} - \lambda_t\left(-\dfrac{\partial E\left(E_t\right)}{\partial T_t^i} - K_\beta \dfrac{\partial\sqrt{Var\left(E_t\right)}}{\partial T_t^i}\right) \\ -\rho^{t+k_i-1}\lambda_{t+k_i}(-\dfrac{\partial E\left(E_{t+k_i}\right)}{\partial T_t^i} - K_\beta \dfrac{\partial\sqrt{Var\left(E_{t+k_i}\right)}}{\partial T_t^i} \end{bmatrix} = 0 \tag{14}$$

$$\rho^{-t}\frac{\partial L}{\partial V_t^i} = \left[\rho\mu_{t+1}^i\left(1 + \frac{\partial G_t^i}{\partial V_t^i}\right) - \mu_t^i - \lambda_t\left(-\frac{\partial E\left(E_t\right)}{\partial V_t^i} - K_\beta \frac{\partial\sqrt{Var\left(E_t\right)}}{\partial V_t^i}\right) - \lambda_{t+1}\left(-\frac{\partial E\left(E_{t+1}\right)}{\partial V_t^i} - K_\beta \frac{\partial\sqrt{Var\left(E_{t+1}\right)}}{\partial V_t^i}\right)\right] = 0 \tag{15}$$

where μ_t^i and λ_t are the Lagrange multipliers for the stock of biomass volume and the emissions target, respectively. Equation (12) states that for fossil fuels, the marginal cost of a reduction in consumption must equal the marginal impact on the target multiplied by the target shadow cost, λ_t, in the same year. Equation (13) requires that the sum of the marginal cost of a change in the supply of bioenergy and the marginal user cost of bioenergy, where the latter is determined by the impact on forest growth until the following time period, equal the risk-weighted marginal impact of bioenergy on the emission constraint in the same year multiplied by the shadow cost, λ_t. Equation (14) requires that for timber, the marginal cost of a change in the supply plus the marginal user cost equal the sum of the risk-weighted impact on the probabilistic constraint in the same year and the discounted impact on the probabilistic constraint k_i years later. In both (13) and (14) the marginal user cost can be negative or positive, depending on the shape of the growth function and on whether bioenergy and timber supplies increase or decrease. The forest stock condition in Equation (15) is determined by two factors. First, it is determined by the relationship between the shadow value of the forest stock in the current time period and the discounted shadow value of the future stock and stock growth. These terms reflect the additional cost of a reduction in the forest stock in the current time period due to the impact on the stock available for bioenergy and timber production in the following time period, on stock growth, and, hence, on sequestration in the next time period. Second, the two last terms in equation (15) express the direct impact of the forest stock on sequestration at time *t* on risk-weighted emissions at times *t* and *t+1*, both multiplied by the shadow cost of meeting the emission constraints in the corresponding years.

Using (12) and (13) we find that efficiency requires that

$$\frac{\dfrac{\partial C_t^{ij}(X_{BAU}^{ij}-X_t^{ij})}{\partial X_t^{ij}}}{\dfrac{\partial C_t^{Bi}\left(B_{BAU}^{i}-B_t^{i}\right)}{\partial B_t^{i}}}=\frac{\lambda_t\alpha^j}{\rho\mu_{t+1}^{i}\dfrac{\partial H_t^i}{\partial B_t^i}-\lambda_t\left(-\dfrac{\partial E\left(E_t\right)}{\partial B_t^i}-K_\beta\dfrac{\partial\sqrt{Var(E_t)}}{\partial B_t^i}\right)}, \tag{16}$$

i.e., the ratio of the marginal costs of reducing fossil fuels and bioenergy at time *t* must equal their relative impacts on targets as shown by the r.h.s. ratio, where the numerator is the Lagrange multiplier of the emission constraint at time t, λ_t, multiplied by the emission coefficient for the fossil fuel in question. The denominator consists of two terms, where the first term is the discounted value of impact of biofuels on forest biomass and the second term is λ_t multiplied by sum of the impact of biofuels on the expectation and variance of emissions. The impact on variance is weighted by K_β, which is determined by the policy makers' attitudes toward risk.

Using (13) and (14), we have that:

$$\frac{\dfrac{\partial C_t^{io}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i}}{\dfrac{\partial C_t^{io}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i}} = \frac{\left[\rho\mu_{t+1}^i \dfrac{\partial H_t^i}{\partial B_t^i} + \lambda_t\left(-\dfrac{\partial E\left(E_t\right)}{\partial B_t^i} - K_\beta \dfrac{\partial\sqrt{Var(E_t)}}{\partial B_t^i}\right)\right]}{\left[\rho\mu_{t+1}^i \dfrac{\partial H_t^i}{\partial T_t^i} + \lambda_t\left(-\dfrac{\partial E\left(E_t\right)}{\partial T_t^i} - K_\beta \dfrac{\partial\sqrt{Var\left(E_t\right)}}{\partial T_t^i}\right) + \rho^{t+k_i-1}\lambda_{t+k_i}\left(-\dfrac{\partial E\left(E_{t+k_i}\right)}{\partial T_t^i} - K_\beta \dfrac{\partial\sqrt{Var\left(E_{t+k_i}\right)}}{\partial T_t^i}\right)\right]}, \quad (17)$$

which demonstrates that the ratio of marginal costs of reducing bioenergy and other forest products must equal the right hand side ratio, where the numerator is, as before, the sum of the marginal user cost of bioenergy and the risk weighted marginal value of the impact on the emission constraint. The denominator consists of the marginal user cost of timber, which is equal to that of bioenergy, and the risk weighted marginal value of the impact on the emission constraint in the same time period as well as k_i periods later.

The right hand side of equations (16) and (17) specify the rate at which the different measures should be traded against each other in an emissions trading system, i.e., the so-called trading ratio (Malik et al., 1993). For a scheme with annual emissions targets, trade across time periods is not possible. Consequently, an emissions trading system with annual emissions targets, as indicated by the EU Roadmap, would be one where fossil fuel reductions are traded against changes in bioenergy and timber production at different ratios in different years. For example, reductions in bioenergy production in one country can be traded against increases in bioenergy production in another.

Data

The costs of reductions in the consumption of different fossil fuels used in the EU Emissions Trading System have been obtained from Gren et al. (2009). The costs are calculated as the decrease in consumer surplus when fossil fuels consumption is reduced. Inverted linear demand functions are calculated based on available estimates of price elasticity, business-as-usual prices, and consumption. The consumer surplus is calculated as the area under the demand curve and above the price line. The emission coefficients for each type of fossil fuel have been obtained from the same source.

Separate cost functions are calculated for decreases and increases in bioenergy and timber, respectively. These cost functions are based on the supply function for each goods. The cost of a reduction in the good, compared to the business-as-usual level, is calculated as a reduction in producer surplus for that good, i.e., the area under the price line but above the supply curve. The cost of an increase in the production of a good, compared to the business-as-usual level, is calculated as the increase in production cost minus the price for the product, i.e., the area under the supply curve and above the price line. Inverted, linear supply functions have been calculated based on estimates of price elasticities, price data and input use data. Supply elasticities for timber and bioenergy are not available for all EU countries. Based on Swedish data, Geijer et al. (2010) estimate the own price elasticities to be 0.28 for sawn wood, 0.14 for pulpwood 0.14 and 0.55 for fuel wood. Using Finnish data, Toppinen and Kuuvalainen (1997) estimate the short run supply elasticity of pulpwood and sawlogs to be 0.41 and 0.16 (but insignificant), respectively, whereas Kuuvalainen et al. (1988) estimate supply elasticity of pulpwood and sawlogs to be 0.59 and 0.53, respectively. We apply the estimates in Geijer et al. (2010) to all European countries. For timber, the average of the estimates for sawn wood and pulp wood are used, and for bioenergy, the fuelwood estimate is used. The data on forest production and prices used to calculate the cost functions are available in the Appendix.

Aggregate forest growth functions on national level are not available. A forest growth function is therefore estimated from Eurostat forestry statistics on biomass per hectare and gross increment for commercial forests. A quadratic function, which allows for different growth rates in regions with different climates, is estimated. The results imply that maximum forest growth occurs when average biomass per hectare is 266 m^3, which, compared to results in Vilén et al. (2012), occurs when the average stand age is 50-60 years. Given that average age of EU forests is 60 years (Vilén et al., 2012), increasing average forest age as a result of efforts to increase sequestration could therefore lead to reduced sequestration over time unless sequestration is allocated across countries in a cost-efficient manner. Given that corresponding data are not available for non-commercial forests, and given that non-commercial forests might, in the future, be used as commercial ones, we apply the estimated growth function to all forest land in the EU. Details on the estimations, as well as the data on forest stock, growth and harvests are available in the Appendix.

Based on data in Trømborg and Sjølie (2011), the CO_2 emissions per cubic meter of wood are assumed to be 0.8 tons[1]. Uncertainty about carbon sequestration is incorporated using data on the coefficient of variation for carbon sequestration, obtained from Gren et al. (2009). There are different sources of uncertainty associated with the measurements of forest carbon sequestration. The uncertainty estimates here apply to sequestration in the living biomass of "forest land remaining forest land," as reported to UNFCCC (2009). The coefficient of variation for individual countries ranges between 0.1 and 1.04. The aggregate uncertainty in European forest sequestration in the BAU scenario can be measured as the coefficient of variation for aggregate sequestration, which is 0.41.

Because the productions of bioenergy requires fossil fuels use in the refinement process, and this process is typically less energy efficient than for refining fossil fuels, the carbon displacement is, at best, one-to-one but typically less than one. Schlamadinger and Marland (1996) suggest that 0.6 is a reasonable estimate of the displacement value of bioenergy with current technology but that a 1.0 displacement is possible with improved technologies. Sathre and O'Connor (2010) conclude based on several studies that, for wood used directly as biofuel, the 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) argues 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 have calculated the expected displacement and standard deviation of bioenergy assuming that displacement is normally distributed and that 95 percent of observations fall between 0.5 and 1.0. Given that $\tilde{\tau}$ is one minus the displacement, this implies that $E\left(\tilde{\tau}\right)=0.25$ and that the standard deviation is also 0.25.

In their meta-analysis of 21 case studies, Sathre and O'Connor (2010) observe that wood products' displacement factors range from a low of -2.3 to a high of 15. Most estimates lie in the range of 1.0 to 3.0. Many of the studies reviewed include both pessimistic and optimistic estimates of displacement. We use all of the presented estimates, pessimistic, realistic and optimistic, collected in the meta-analysis to calculate mean and standard deviation of the

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

displacement[2]. The mean displacement is 2.5 and the standard deviation is 2.8. The mean displacement factor value of 2.5 means that for each tC in a wood product substituted for a non-wood product, there is an average emission reduction of 2.5 tC. The average lifetime of timber products was obtained from Eggers (2002).

The EU emissions target is expressed as the successive reduction of 1990 levels of emissions of greenhouse gases by 80 percent until 2050. This target is interpreted as the reduction by the same percentage each year from 2010 to 2050, taking into account that 2010 emissions are eleven percent below 1990 emissions (EU Commission, 2011b). Moreover, we take into account that current forest management implies that net sequestration is positive every year and that timber and bioenergy production together displace carbon dioxide emissions. Business-as-usual carbon sequestration and displacement of fossil fuels by forest products are therefore deducted from the EU emission target for all time periods. Thereby, the addition of forest carbon sequestration and fossil fuel displacement from forest products to the analysis does not imply that the stringency of the targeted is reduced compared to a target met only by reductions in fossil fuel emissions and where sequestration and forest product are ignored.

Restrictions are applied to the different decision variables. It is assumed that fossil fuel consumption and bioenergy and timber production can, at most, be reduced by 80% and that bioenergy and timber production can be increased by 100% (compared with BAU). Finally, five years are aggregated into one time period in order to make the numerical model more tractable. A discount rate of 3% is used in the calculations, as suggested by Boardman et al. (2011) to be a reasonable discount rate for public projects.

Results

We first demonstrate how the total net present cost of achieving the EU target for 2050 depends on the policy makers' attitudes towards uncertainty. This step is followed by an analysis of the role of forest sequestration and forest products as a cost-efficient strategy to meet the EU Roadmap targets, taking into account their mutual interdependence. Five different scenarios are then considered (see Table 1). In scenario A, the impacts of sequestration and forest products on carbon emission are treated as certain, and in scenario B, all of these impacts are treated as uncertain. Scenario A provides a benchmark to which scenario B can be compared to understand the effects of uncertainty. Scenario B then serves as to the benchmark for the remaining

[2] Calculated from table 2 in Sathre and O'Connor (2010)

scenarios, where we examine in further detail the effects of making different assumptions about uncertainty and the possibility of introducing new policies. In scenario C, the impacts of sequestration are treated as uncertain, but the impacts of forest products are considered certain, assumptions with some similarity to the assumptions currently made in formulating EU policies. In scenario D, the impacts of sequestration and forest products on carbon emission are considered uncertain but timber production is fixed at the BAU levels. Examination of this scenario is motivated by the fact that there is currently no climate-related policy in place that provides incentives for timber products. Scenario D illustrates a situation where no such policy can be introduced. In scenario E, the impacts of sequestration and forest products on carbon emissions are treated as uncertain, but uncertainty about the displacement of fossil fuels by timber is assumed to be twice as large as in the previous scenarios. This scenario is motivated by the difficulties in quantifying the level of uncertainty about the displacement of fossil fuels compared to the uncertainties of other variables.

[Table 1 about here]

The total cost of meeting the annual reduction targets in scenario A, where there is no uncertainty, is approximately 100 billion Euros. This cost increases under different reliability requirements and assumptions about uncertainty combinations, which are illustrated in figure 1. The costs are highest when a high probability of target achievement is required and the displacement of fossil fuels by timber is assumed to be highly uncertain, i.e., in scenario E. If policy makers want to meet emissions targets with 80% certainty, i.e., 8 years out of 10, it will be almost 8 times more expensive to achieve emissions targets in scenario E than when policy makers are not concerned with uncertainty, i.e., policy makers only require that the targets are met with 50% probability given the assumed normal probability distributions. If policy makers dislike uncertainty and wish to meet targets with 80% certainty, doubling the uncertainty of the fossil fuels displacement of timber will increase the cost of meeting the target 2.5 times compared to scenario B. Holding the certainty requirement constant, ignoring the uncertainty of the impact of forest products on carbon emissions (scenario C) would lead to a policy with 70% lower costs compared to a scenario that accounts for all uncertainties (scenario B). If policy makers require a high level of certainty, the target cannot be met in several scenarios.

Figure 1 also suggests that a scenario that does not allow for the increased use of timber products will be more costly compared to scenarios that include this measure in the policy mix. The exclusion of timber from the policy mix increases the cost of meeting emissions targets by 2.5 times under conditions of certainty, but when 90% certainty is required, the exclusion of timber only increases costs by approximately 35% compared to scenario B. This difference is explained by the lower value of increased timber use with regard to emissions target achievement when a higher level of certainty is required, given the high level of uncertainty about the carbon impact of timber.

[Figure 1 about here]

The sequence of emissions targets is met through a combination of reductions in fossil fuels, increased carbon sequestration, and increased timber production. The composition of these measures is adjusted over time due to the increasing stringency of annual emissions targets.

Figure 2 below displays the development of carbon sequestration in forests in different scenarios over time given a probabilistic emissions constraint with 80% reliability. The business-as-usual curve illustrates carbon sequestration as it would develop if business-as-usual bioenergy and timber use remained constant over the whole time period. In all scenarios, sequestration is below the business-as-usual curve for the first 20 years. Afterwards, sequestration exceeds the business-as-usual level only when timber use is fixed (scenario E). In that case, reduced bioenergy production contributes to the positive sequestration. In all other scenarios, sequestration is below the benchmark level during the whole policy period. The amount of carbon sequestration in scenarios A and C is similar, i.e., the inclusion of uncertainty about sequestration only has a limited impact on sequestration. When the uncertainty about forest products is considered (scenario B), sequestration reaches a higher level after 10 years and 30-35 years, while dipping during the beginning, middle and end of the policy period. A similar development pattern is observed in scenario C but with lower sequestration towards the second half of the policy period when bioenergy and timber use is continually adjusted to meet the increasingly stringent annual emissions targets. When the high level of uncertainty about timber product impacts is considered (scenario E), sequestration is higher than in scenario B and remains relatively stable after the first 10 years.

[Figure 2 about here]

The cost-efficiency of bioenergy use varies considerably over time and between scenarios. Figure 3 illustrates this variation for a probabilistic emission constraint with 80% reliability. Net increases in bioenergy, on the aggregate, are cost-efficient only in the first time period when reliability levels are low. Given that bioenergy is associated with positive net emissions of carbon, increases in bioenergy use are explained by their impact on future forest carbon sequestration. The net increase in bioenergy during the first time period reflects both increases and decreases in different countries. By definition of the cost functions, the increases and decreases in bioenergy are equally expensive in a given country. Decreases are therefore made in countries where harvest reductions lead to greater future forest growth and hence increased sequestration, whereas increases are made in countries with opposite conditions. Net reductions occur in all other time periods.

For bioenergy, the difference between scenarios A and C is minor, implying that acknowledging uncertainty about sequestration has little impact on the cost-efficiency scale of bioenergy use. In these scenarios, bioenergy use is reduced by up to 20% towards the end of the policy period compared to business-as usual-levels. In contrast, bioenergy use is radically reduced after several time periods in the scenarios where bioenergy and timber uncertainty are taken into account. Scenario E implies that bioenergy use is radically reduced by the period 2015-2020, whereas the reduction in bioenergy use occurs later in scenarios B and D. These reductions are explained by the positive net emissions from bioenergy in combination with more stringent emissions targets over time. Greater reductions are made in the presence of more uncertainty (scenario E) and when timber use cannot be altered (scenario D). In both of these scenarios, forest sequestration increases.

[Figure 3 about here]

The use of timber products increases above initial levels in all scenarios where this is possible, but the cost-efficient level varies over time (see Figure 4). For timber, scenarios A, B and C yield similar results. The higher level of uncertainty about the timber carbon impact in scenario E implies less variability in the cost-efficient use of timber over time. This stability is explained by the fact that the risk-weighted standard deviation of total emissions increases as timber use rates increase, which can be seen by differentiating Eq. (8). Given that target stringency is increasing over time, successively more abatement is necessary and increased timber use could be motivated. At the same time, however, uncertainty about the associated carbon impact needs to be offset either by further increases in timber use or by other, more certain, measures such as carbon sequestration or reduced fossil fuel emissions. The cost of these additional reductions in expected emissions are increasing in reductions.

The net increase in timber use reflects decreases as well as increases at the national level. Countries that decrease their timber use make successively larger decreases over time. Increases are made in different countries during different time periods. Timber use increases are cost-efficient in countries where the costs of adjusting timber production are low and forest growth is little affected by a reduction in forest stock, implying that the amount of sequestration is little affected. Timber use decreases are also cost-efficient in countries where the costs of adjusting timber production is low and future forest growth is positively affected by an increase in forest stock, implying that the amount of future sequestration will be larger. Timber use can increase and decrease in the same country over different time periods, and the choice between the two strategies is determined by both forest growth and emissions target stringency. The results demonstrate that timber production is not continuously increasing over time but that, due to the interdependence of timber production and forest sequestration, it can both increase and decrease.

[Figure 4 about here]

The net effect of changes in bioenergy and timber production is that carbon dioxide emissions from forest products fall (see Figure 5). A comparison of Figure 5 to Figures 3 and 4 suggests that forest product emissions are largely determined by the use of timber products. This is clear when comparing the substantial reduction in bioenergy use in scenario D with the small corresponding impact on total forest product emissions. Notably, the lagged effect of timber production on carbon emissions, from the combustion of timber products after their lifetime, has a limited impact on the cost-efficiency because timber use and emissions from timber products are, largely, mirror curves. This pattern confirms the small role that bioenergy plays in total carbon emissions compared to timber.

[Figure 5 about here]

Even when sequestration and forest products are included in the analysis of EU climate policy, it is clear that reductions in fossil fuel emissions are the dominant measure for meeting the EU 2050 target in terms of CO_2 reductions made (see Figure 6). For scenarios with higher levels of assumed uncertainty, larger fossil fuel reductions are undertaken to achieve greater reductions in expected emissions. The difference in emissions between scenarios A and C, where in the latter only sequestration is assumed to be uncertain, is modest. In contrast, fossil fuel reductions increase substantially when uncertainty about the impact of forest products is acknowledged. The largest fossil fuel emissions reductions are made in scenario E, where a higher level of uncertainty about the timber product effects is assumed. In scenarios A and C, the emissions from fossil fuels are relatively constant during the middle of the policy period 2020-2035, which can be explained by the substantial reductions in carbon emissions from increased timber production in the same period. Despite a similar level of timber use in scenario B during the period 2020-2035, fossil fuel emissions are successively reduced over time to compensate for the smaller reductions in bioenergy and sequestration.

[Figure 6 about here]

Whether the inclusion of uncertain carbon sequestration and carbon replacing forest products could motivate a change in the EU Roadmap for 2050, i.e., in the emissions reduction path, is a relevant question. Given that our model does not include investment costs, e.g., alternative energy sources, improved energy efficiency and carbon capture and storage, we cannot directly compare the EU Roadmap to an optimal roadmap including sequestration and forest products. In the absence of investment costs, the optimal roadmap without sequestration and forest products reduces fossil fuel use at a constant rate over the whole time period due to the convexity of cost functions. To establish whether uncertain sequestration and carbon replacement motivates a change in the optimal emissions reduction path, we compare two cases, one where fossil fuel reductions are the only abatement option and no attempts are made to adjust forest and forest product management, and one where sequestration and forest products are included. In both cases, the total amount of emissions over the whole time period 2010-2050 is the same as above, but we now assume that policy makers are free to allocate emissions over time.

The calculations demonstrate that the discounted cost of the optimal emission path with free adjustment of sequestration and forest products would be 30-50% of the cost when sequestration and forest products cannot be adjusted compared to business-as-usual, and a smaller cost difference results when a higher level of certainty is required. The costs of meeting the EU Roadmap targets when sequestration and forest products can be adjusted would be lower than those of an optimal emissions reduction path with no adjustment if the required reliability is below 80%. Thus, there are high costs to meeting the stringent EU Roadmap targets towards to end of the policy period, but the cost savings from adjustments in sequestration and forest product use more than outweigh these costs provided that the policy maker is modestly risk averse. Comparing abatement strategies under the EU Roadmap and the optimal path, given that sequestration and forest products are adjustable, demonstrates that the major reason for the lower cost under an optimal path results from the change in sequestration and forest product use, which is smooth under the optimal path in contrast to the jumps in the path shown above (see Figures 2 and 5). The jumps in the path are expesive because they are associated with large changes in the production of bioenergy and timber in the same time period. Reducing the discount rate from 3 to 1% can generally be expected to shift abatement towards earlier time periods. Our calculations demonstrate that this change mainly affects fossil fuel reductions, where early reductions fall and late reductions increase by approximately 10 and 15%, respectively. The impact on forest sequestration and forest product use is close to zero and 3%, respectively.

Conclusions and discussion

We analyze EU climate policy in a spatially disaggregated model using four different measures including two where the expected net emissions are positive, fossil fuels and bioenergy, and two where they are negative, forest carbon sequestration and timber. We recognize that the impact on carbon emissions from carbon sequestration, bioenergy and timber is uncertain and that a trade-off between alternative forest uses exists. We use a chance-constrained dynamic model of cost-efficient EU climate policy until 2050 to analyze how the cost-efficient combination of measures over time is affected by assumptions about uncertainty. Our results illustrate that uncertainty about forest carbon sequestration plays a minor role in the choice of forest and forest product management in a cost-efficient policy. The reason is that the additional uncertainty implies that further fossil fuel reductions are undertaken compared to a situation with complete certainty. The addition of uncertainty about the carbon impact of bioenergy and timber products to the analysis, however, has significant effects for the results. Bioenergy is successively abandoned over time in order to increase carbon sequestration and timber product use, where the balance between the two latter is determined by the policy maker's attitude towards risk: a policy maker with a low level of concern for risk will prefer timber products over sequestration and *vice versa*.

Our paper contributes to the analysis of the climate policy trade-offs among sequestration, bioenergy and timber more generally. These trade-offs have received comparatively little attention in the economic literature. Although a couple of studies model the development of carbon pools in both forests and forest products at a relatively detailed level, harvests are assumed to be exogenous and trade-offs are never modeled (Alig et al., 1997, 2010). An exception is Sjølie et al. (2013) who use a regionalized forest sector model for Norway and explicitly analyze the trade-off between bioenergy and sequestration while allowing harvest levels and wood markets to adjust. Carbon impacts are modeled taking into account sequestration and the displacement of fossil fuels from forest products. These authors demonstrate that harvest level adjustments are crucial to the carbon reduction impact when economic incentives to reduce carbon emissions are introduced and that a flexible policy benefits society as well as forest owners. Our results confirm the importance of including not only carbon sequestration but also forest products in the analysis.

The results indicate that timber products and sequestration both play a significant role not only for the current net emissions of carbon into the atmosphere but also in a cost-effective EU policy; bioenergy plays a smaller role. Moreover, the results suggest that it could be cost-efficient to reduce bioenergy use over time as carbon reduction targets are successively tightened; despite small net emissions of bioenergy use the addition of uncertainty about bioenergy carbon displacement makes uncertain sequestration a more attractive choice if policy makers care about uncertainty.

References

Abt, R.C., Abt, K.L., Cubbage, F.W., Henderson, J.D. 2010. Effect of policy-based bioenergy demand on southern timber markets: A case study of North Carolina. Biomass and Bioenergy 34(12): 1679-1686.

Angelson, A., Brown, S., Loisel, C., Peskett, L., Streck, C., Zarin, D. 2009. Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment. Report Prepared for the Government of Norway by the Meridian Institute, March 2009. Available for download at http://www.REDD-OAR.org; ISBN: 978-0-615-28518-4

Alig, R., Adams, D., McCarl, B., Callaway, J. M., Winnett, S. 1997, Assessing Effects of Mitigation Strategies for Global Climate Change with an Intertemporal Model of the U.S. Forest and Agriculture Sectors. Environmental and Resource Economics 9: 259–274.

Alig, R., Latta, G., Adams, D., McCarl, B. 2004. Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices. Forest Policy and Economics 12: 67-75.

Boardman A., D. Greenberg, A. Vining, Weimer, D. 2011. Cost-benefit analysis - concepts and practice. 4th ed. Pearson Education, Boston, pp. 238-273.

Bosetti, V., Lubowski, R., Golub, A., Markandya, A. 2009. Linking Reduced Deforestation and Global Carbon Market: Impact on Costs, Financial Flows, and Technology Innovation. Working Paper No. 2009:56, Fondazione Eni Enrico Mattei, Milano.

Cannell, M.G.R. 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass and Bioenergy 24: 97–116.

Charnes, A., Cooper, W.W. 1959. Chance-Constrained Programming. Management Sciences. 6(1): 73-79.

Cook, J., Beyea, J. 2000. Bioenergy in the United States: progress and possibilities. Biomass and Bioenergy 18: 441–455.

Eggers, T. 2002. The Impacts of Manufacturing and Utilisation of Wood Products on the European Carbon Budget. European Forestry Institute. Joensuu, Finland.

EU Commission. 2011a. A Roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission to the European parliament, the council, the European Economic and Social Committee and the Committee of the Regions, COM/2011/0112 final.

EU Commission. 2011b. Climate actions – milestones. As available 2013-02-15 at http://ec.europa.eu/clima/policies/roadmap/milestones/index_en.htm.

Eurostat. 2009. Forestry statistics. Available 2013-03-20 at http://epp.eurostat.ec.europa.eu/portal/page/portal/forestry/data/database

Finnish Forest Research Institute. 2011. Finnish Statistical Yearbook of Forestry. Available 2013-02-15 at http://www.metla.fi/metinfo/tilasto/julkaisut/vsk/2011/vsk11_13.pdf

Galik, C.S., Abt, R., Wu, Y. 2009. Forest biomass supply in the Southeastern United States–Implications for industrial roundwood and bioenergy production. Journal of Forestry, 107(2): 69–77.

Geijer, E., Bostedt, G., Brännlund, R. 2011. Damned if you do, damned if you do not – reduced climate impact vs. sustainable forests in Sweden. Resource and Energy Economics, 33: 94-106.

Gren, I.-M., Münnich, M., Carlsson, M., Elofsson, K., 2009. A numerical model for cost effective CO2 mitigation in the EU with stochastic carbon sink. Working Paper No. 2009:4. Department of Economics, SLU, Uppsala.

Gren, I.-M., Munnich, M., Carlsson, M., Elofsson, K., 2012. Stochastic carbon sink for combating carbon dioxide emissions in the EU. Energy Economics 34(5): 1523–1531.

Kim, Y.H., Sohngen, B., Golub, A., Hertel, T.W., Rose, S. 2010. Impact of US and European biofuel policies on forest carbon. Paper presented at the Agricultural & Applied Economics Association's 2010 AAEA, CAES & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27, 2010. Available 2013-04-04 at: http://ageconsearch.umn.edu/bitstream/61456/2/AAEA_11359_0503.pdf

Kuuluvainen, J., Hetemiki, L., Ollonqvist, P., Ovaskainen, V., Pajuoja, H., Salo, J., Seppila, H., Tervo, M. 1998. The Finnish Roundwood Market: An Econometric Analysis. Finnish Economic Papers 1: 191-201.

Malik, A.S., Letson, D., Crutchfield, S.R. 1993. Point/nonpoint source trading of pollution abatement: choosing the right trading ratio. American Journal of Agricultural Economics 75: 959–967.

Münnich-Vass, M. Elofsson, K. Forest sequestration or bioenergy for combating climate change to 2050 in the EU. (unpublished)

Murray, B., Lubowski, R., Sohngen, B. 2009. Including International Forest Carbon Incentives in Climate Policy: Understanding the Economics. Nicholas Institute for Environmental Policy Solutions at Duke University, USA.

Newell, R., Stavins, R. 2000. Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration. Journal of Environmental Economics and Management 40(3): 211–235.

Povellato, A., Bosello, F., Giupponi, C. 2007. Cost-effectiveness of greenhouse gases mitigation measures in the European agro-forestry sector: a literature survey. Environmental Science & Policy 10: 474-490.

Read, P., Lermit, J. 2005. Bio-energy with carbon storage (BECS): A sequential decision approach to the threat of abrupt climate change. Energy 30: 2654–2671.

Richards, K.R., Stokes, C. 2004. A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research. Climatic Change 63(1-2): 1-48.

Sandbrook, C., Nelson, F., Adams, W.M., Agrawal, A. 2010. Carbon, forests and the REDD paradox. Oryx 44: 330–334.

Sathre, R., O'Connor, J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science & Policy 13: 104–114.

Schlamadinger, B., Marland, G. 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 10(5/6): 275-300.

Schlegel, S., Kaphengst, T. 2007. European Union policy on bioenergy and the role of sustainability criteria and certification systems. Journal of Agricultural & Food Industrial Organization 5(2).

Sjølie, H.K., Latta, G.S., Solberg, B. 2013. Potentials and costs of climate change mitigation in the Norwegian forest sector – does choice of policy matter? Canadian Journal of Forest Research (published online).

Sohngen, B. 2009. An Analysis of Forestry Carbon Sequestration as a Response to Climate Change. Copenhagen Consensus Center, Copenhagen Business School, Frederiksberg, Denmark. http://fixtheclimate.com/component-1/the-solutionsnew-research/forestry/.

Stavins, R. 1999. The Costs of Carbon Sequestration: A Revealed Preference Approach. American Economic Review 89: 994-1009.

Trømborg, E., Sjølie, H.K. 2011. Data applied in the forest sector models NorFor and NTMIII. INA fagrapport 17, Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences.

Toppinen, A., Kuuluvainen, J. 1997. Structural changes in the Finnish sawlog and pulpwood markets. Scandinavian Journal of Forest Research 12: 382–389.

UNFCCC. 2009. National inventory submissions Common Reporting Format (CRF) spreadsheets, as reported per February 2009. Available 2013-02-15 at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4303.php

Vilén, T., Gunia, K., Verkerk, P.J., Seidl, R., Schelhaas, M.-J., Lindner, M., Bellassen, V. 2012. Reconstructed forest age structure in Europe 1950–2010. Forest Ecology and Management 286: 203–218.

APPENDIX

[Table A1 about here]

Estimation of the forest growth function

The data on average annual national forest growth per hectare and forest standing biomass in m^3 were collected from Eurostat (2012) for commercial forests in all EU countries. For each country, four observations are available in the database (1990, 2000, 2005 and 2010). A quadratic growth function is assumed. Dummy variables are used to account for the possibility of lower forest growth in *(i)* Sweden and Finland due to their colder climate compared to most other EU countries and *(ii)* the Mediterranean countries (defined as countries with a Mediterranean coastline) due to their dry summers.

Descriptive statistics about here, no. of observations, etc.

We follow the literature in assuming that the forest increment is close to zero when forest age is zero (see, e.g., Newell and Stavins, 2000), therefore, we suppress the intercept. The estimated function is then:

$$G_t^i = \alpha V_t^i + \beta \left(V_t^i\right)^2 + \gamma SC^i + \delta ME^i + \varepsilon_t$$

where G_t^i and V_t^i are national average growth per hectare and standing biomass, respectively, K^i is the intercept, SC^i and ME^i are dummies for Scandinavian and Mediterranean countries, ε_t is the error term, and α, β, γ and δ are the estimated coefficients.

The results from the estimation display the expected signs, (see table A2) and the coefficients for both forest stock and stock squared are significant while the coefficients for the dummies have expected sign but are not significant. The estimated coefficients for stock volume and volume squared imply that maximum growth occurs when forest biomass is 266 m^3 per hectare. According to the available data on forest age and volume in European forests (Vilén et al., 2012), this volume corresponds to an average forest age of 60 to 80 years.

[Table A2 about here]

TABLES AND FIGURES

Table 1. Scenarios used in the empirical calculations and the associated assumptions made about the impact on carbon emissions.

Scenario	**Sequestration**	**Bioenergy**	**Timber**
A	Certain	Certain	Certain
B	Uncertain	Uncertain	Uncertain
C	Uncertain	Certain	Certain
D	Uncertain	Uncertain	Uncertain, fixed quantity
E	Uncertain	Uncertain	Larger uncertainty than in B

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

					Use of domestic forest[1]		Prices[2]	
	Total forest and other wooded land area[1]	Growing stock[1]	Gross increment[1]	Fellin gs[1]	Bio-energy	Other forest products	Bio-energy	Other forest products
	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
BE	706	238	7.9	7.2	15	85	0.0227	0.0728
BG	3927	167	5.1	2.0	47	53	0.0227	0.0742
CY	387	27	0.9	0.2	41	59	0.0227	0.0768
CZ	2657	290	9.9	7.2	12	88	0.0227	0.0708
DE	11076	315	10.1	5.1	18	82	0.0227	0.0723
DK	635	180	10.0	4.6	40	60	0.0227	0.0767
EE	2337	191	5.6	3.6	27	73	0.016	0.0473
ES	28214	32	3.1	1.1	32	68	0.0227	0.0665
FI	23116	96	4.6	2.6	10	90	0.0235	0.0503
FR	17572	148	6.2	3.7	47	53	0.0227	0.0733
GR	6539	31	1.3	0.3	68	32	0.0227	0.0768
HU	2039	174	6.4	3.3	52	48	0.0227	0.0768
IE	788	95	9.8	5.7	7	93	0.0227	0.0768
IT	10916	133	4.0	1.0	66	34	0.0227	0.0743
LT	2249	214	5.7	3.8	27	73	0.0188	0.0453
LU	88	295	7.5	3.2	6	94	0.0227	0.0768
LV	3467	183	5.8	4.0	18	82	0.016	0.0505
MT	0	0	0.0	0.0	--	--	0.0227	0.0768
NL	365	192	7.6	3.7	27	73	0.0227	0.0723
PL	9319	247	8.0	4.2	12	88	0.016	0.0487
PT	3611	52	10.5	5.3	6	94	0.0227	0.0594
RO	6733	207	6.5	2.5	20	80	0.0227	0.0768
SE	30625	106	4.7	3.5	8	92	0.0235	0.0518
SK	1938	265	7.4	5.4	5	95	0.0227	0.0687
SI	1274	327	7.8	2.5	37	63	0.0227	0.0751
UK	2901	131	8.6	4.0	14	86	0.0227	0.0746

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

2 The price of other forest products is the weighted average price of logs and pulp in 2010 where prices are obtained from the Finnish Forest Research Institute (2011). The prices were available for Austria, Estonia, Lithuania and Sweden. These prices 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.

Table A2. OLS estimation, dependent variable, G_t^i, forest growth 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

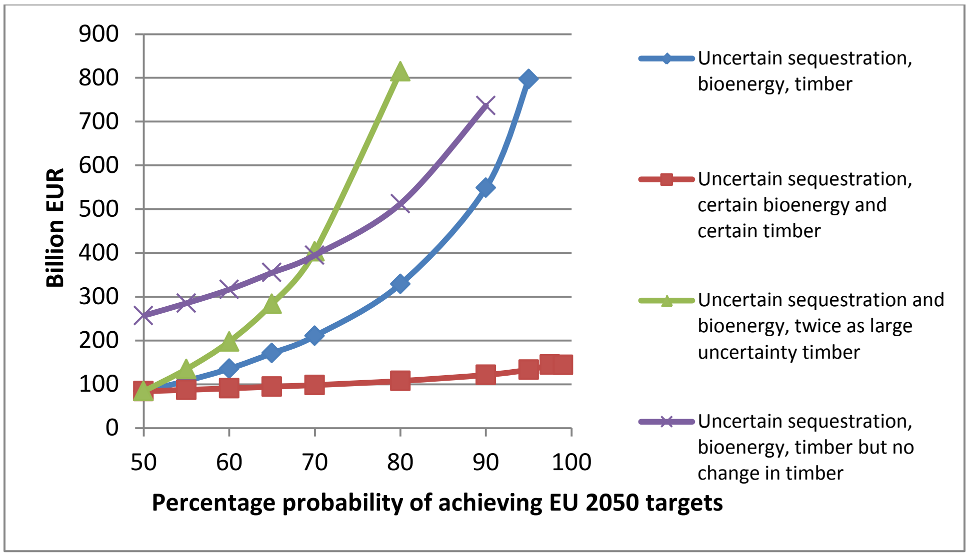

Figure 1. Total net present value of costs of achieving the EU 2050 targets under different assumptions about uncertainty.

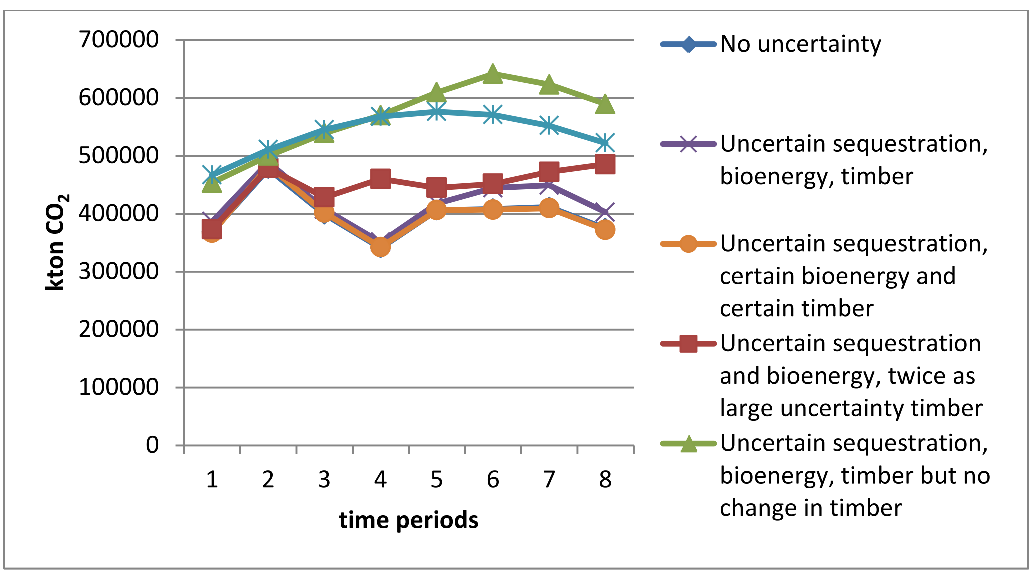

Figure 2. The development of carbon sequestration in forests over time in different scenarios with 80% certainty of emissions target achievement.

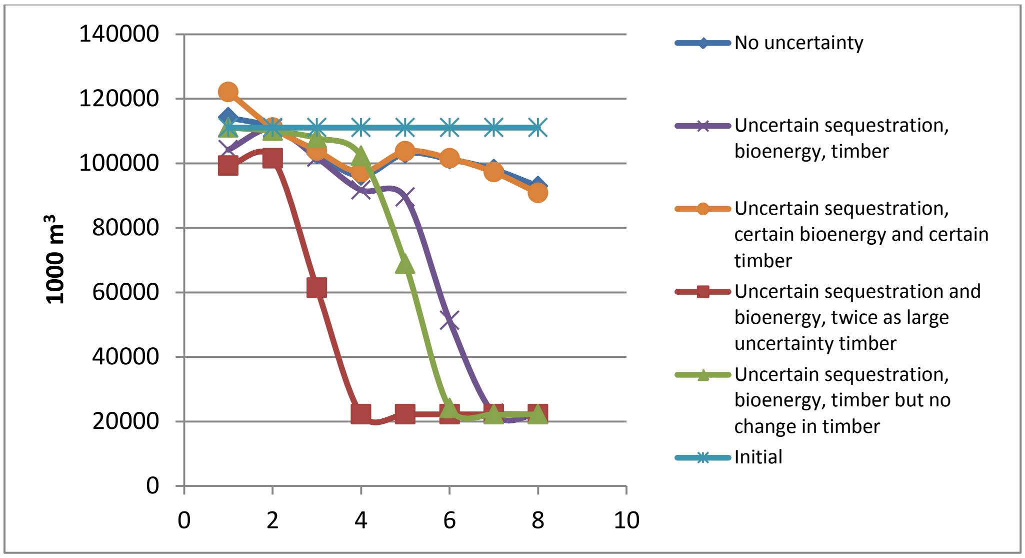

Figure 3. The development of bioenergy use over time under different scenarios with 80% reliability.

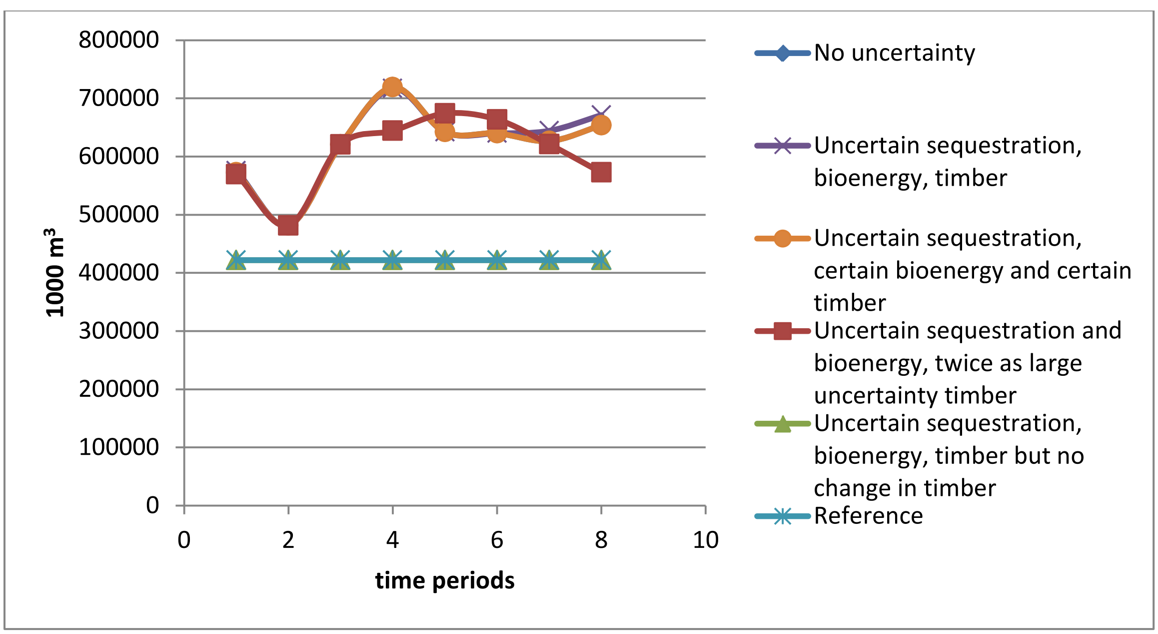

Figure 4. The development of timber use over time in different scenarios with 80% reliability of meeting targets.

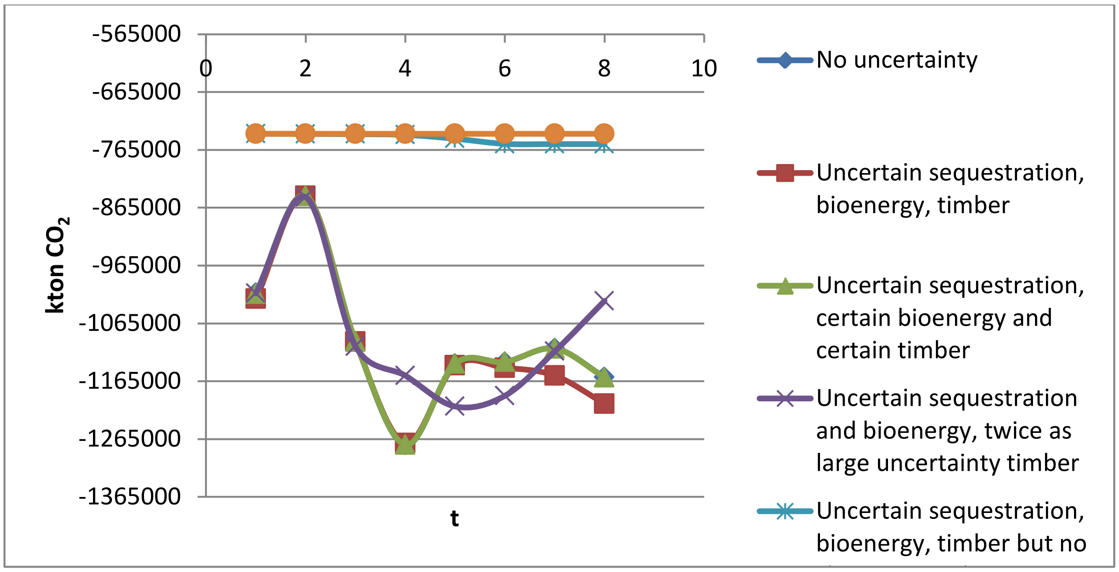

Figure 5. The development of emissions from forest products over time in different scenarios with 80% reliability of meeting targets.

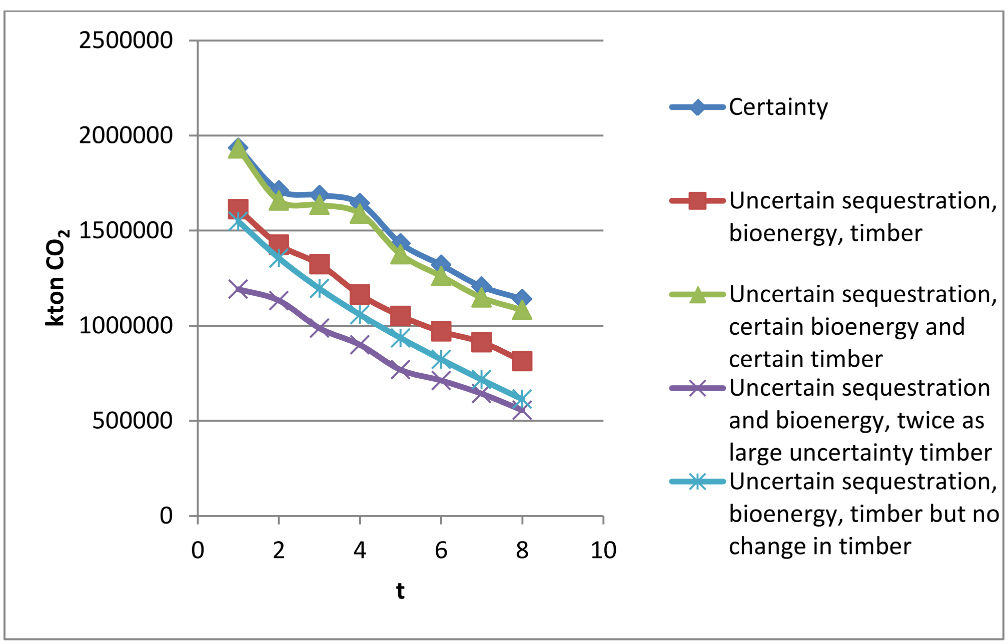

Figure 6. Emissions from fossil fuels in different scenarios with 80% reliability of meeting targets.

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