Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Economics

WORKING PAPER
07/2014

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Economics

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ISSN 1401-4068
ISRN SLU-EKON-WPS-1207-SE

Working Paper Series 2014:7
Uppsala 2014

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Abstract
The purpose of this paper is to investigate policy instruments for interdependent carbon pools and how they can be applied in the EU climate policy to 2050. Cost-effective policy instruments for forest products which are adjusted for the impact on carbon pools are identified. A numerical, dynamic, chance-constrained model including the EU-27 countries shows that inclusion of only one forest carbon pool can reduce costs and increase emission reductions. Results also suggest that decentralized policy instruments for both carbon pools are less costly than uniform instruments at the EU level.

Keywords: EU; climate policy; carbon sequestration; bioenergy; timber; policy instruments.

JEL codes: Q23, Q28, Q48, Q54.

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Introduction

Terrestrial carbon pools[1] have received attention for their climate change mitigation potential. The associated costs for carbon mitigation is comparatively low, and increased carbon pools in natural ecosystems could thus be an alternative to other measures such as increased use of renewable energy and reduced fossil fuel use (Sohngen, 2009; Bosetti et al., 2009, Murray et al., 2009). Despite high potential benefits and relatively low costs, countries can only partially take credit for increases in carbon pools in relation to national commitments under the Kyoto protocol. Policy instruments are rarely applied, with an exception for the United Nations initiative on Reducing Emissions from Deforestation and forest Degradation (REDD), restricted to developing countries, and the inclusion of reforestation as an abatement option in New Zealand's carbon emission trading system (Lawrence and Dudley, 2012). Within the European Union (EU), crediting of increases in carbon pools against the CO_2 burden allocation is not allowed in spite of the substantial cost savings it could entail (Gren et al., 2012; Michetti and Rosa, 2012). Arguments against the introduction of policies to enhance carbon sinks include the complexity in each of the forest carbon pools and their interdependence, uncertainty about carbon stocks and sequestration in the short and long term, and the associated difficulty of designing appropriate incentive structures (Kuikman et al., 2011). The EU's policy against greenhouse gas emissions is, instead, focused on CO_2 emission trading for fossil fuel use, in combination with a target to have 20 percent renewable energy by 2020. The latter has implications for carbon sequestration as increased use of biomass can is likely to reduce carbon sequestration in forest ecosystems.

Instead of dealing with carbon policy design, the debate on carbon pools within the EU mainly concerns the rules for reporting different land use related activities. Under the Kyoto Protocol, countries are obliged to account for a limited set of land use related activities and their impact on net carbon emissions; afforestation, reforestation and deforestation. It is optional to record the impact of ongoing forestry activities as well as activities in the agricultural sector

[1] We use the IPPC (2001) definitions as presented by FAO (2014) where carbon pool refers to carbon reservoirs with the capacity to accumulate or release carbon, carbon stock to the amount of carbon in the pools at a specific point of time, sequestration as the process of increasing the carbon content in the pools, and carbon sink as a process for removing carbon content from the atmosphere.

(Kuikman et al., 2011). A few Member States report on carbon emissions from all land use management, and only two thirds report on the effects of forest management. However, the EU Commission has recently introduced harmonized rules for carbon accounting, implying that reports should capture all relevant effects from land use, land management, and harvested wood products (EU, 2013)[2].

Given the magnitude of forest carbon flows and stocks, it can be risky to ignore those when developing strategies against climate change. Carbon is stored in both biomass and soil, and the relative importance of these pools varies depending on climate, soil conditions and forest management practices. In Europe, the soil carbon stock is about three times larger than the corresponding stock in living biomass, and total carbon sequestration in biomass and soil corresponds to 8-10% of the total emissions (Lal, 2005; Kuikman et al., 2011). Sequestration in European forests has gradually increased since the 1950s (Kauppi, Mielikäinen and Kuusela, 1992), and can be expected to increase also over the next decades (Liski, Perruchoud, and Karjalainen, 2002), suggesting that forest management choices have a considerable climate impact.

Several economic studies have included more than one forest carbon pool (e.g. Lubowski, Plantinga, and Stavins, 2006; van Kooten et al., 1999; Sohngen and Mendelsohn, 2003). However, in spite of the inclusion of only one pool in most official reports and actual policies there is, to our knowledge, no earlier study which compares the policies applied to only one carbon pool compared with the first best policy where both carbon pools are included. On the other hand, several studies analyze policy instruments applied to only one of the pools (Lecocq et al., 2011; van Kooten et al., 1995; Mason and Plantinga 2013; Guthrie and Kumareswaran 2007). Using a French forest sector model, Lecocq et al. (2011) compare separate and combined uses of policy instruments, showing that a pure sequestration subsidy leads to larger carbon emission reductions, whereas this is not achieved by a subsidy to bioenergy, or a combination of the two. Van Kooten et al. (1995) show that a combination of carbon taxes and subsidies, applied to the sequestration in forest biomass, can be used to achieve optimal forest rotation when sequestration is valuable to society. Comparing uniform carbon subsidies to a contract scheme, Mason and Plantinga (2013) conclude that the former imply higher costs for achieving sequestration under asymmetric information if forest owners have different sequestration costs. Using a real options model with uncertain future timber prices, Guthrie and Kumareswaran (2007) compare subsidies paid in proportion to the actual amount of carbon sequestered to credits that are allocated according to the long-run potential to sequester carbon

[2] Exceptions are permitted when sequestration is positive.

on the land and show that the first scheme generates more sequestration. In addition, there are a number of studies on the role of carbon sequestration in a cost-effective EU climate policy. Michetti and Rosa (2012) use a static general equilibrium model, while Gren et al. (2012) and Gren and Carlsson (2013) apply a static, chance-constrained framework covering a larger set of sequestration options. Münnich-Vass and Elofsson (2013) investigate the trade-off between bioenergy and sequestration in a dynamic cost-effectiveness framework.

The purpose of this paper is to analyze the design of policy instruments to enhance carbon sequestration in interdependent carbon pools. We analyze the value of including carbon sequestration in forest biomass and soils in the EU climate policy from 2010 to 2050, and investigate how this value depends on the choice of carbon pool to be included in the policy. Inclusion of only one carbon pool can be seen as a feasible alternative if there is disagreement on the links between forest management activities and the associated impact on both carbon pools. We therefore compare separate and complete inclusion of biomass and soil sequestration in the policy decision, with an aim to assess whether separate inclusion is a step in the right direction, or even counterproductive. In addition, we investigate the cost-efficient economic incentives for achieving increased carbon sequestration. This is done with an aim to evaluate the potential for common policy instruments at the EU level to promote carbon sinks. To this end, we develop a dynamic, numerical, chance-constrained cost-minimization, which includes five different measures to reduce CO2 emissions in the EU-27 countries; carbon sequestration in forest biomass and forest soil, bioenergy and timber use, and fossil fuel reductions. In our view, the main contribution of this paper is the analysis and comparison of a separate policy where only a single sink is included, to one with a broader coverage of carbon pools and flows. It also adds to the literature through investigation of policy instruments for forest products, i.e. bioenergy and timber, while implicitly taking short and long run impact on sequestration in biomass and soils into account.

Numerical model

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

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

$$V_0^i = \overline{V_0^i}, \tag{1}$$

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 standing tree biomass in a country is $A^i V_t^i$, where A^i is the area of forest land, measured in hectares. Forest carbon sequestration occurs in standing biomass and in forest soil. Net annual carbon sequestration in tree biomass, $\tilde{W}_t^i$, is assumed to be stochastic, as sequestration is determined by weather and local soil conditions, and defined by:

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

where η is a parameter for conversion of tree biomass to ton CO_2-equivalents removed from the atmosphere, and ε^{Wi} is an additive stochastic component, assumed to be normally distributed.

The development of the soil carbon stock is mainly determined by forest tree growth, which increases the soil carbon stock as litter falls to the ground, and forest harvest, which causes a release of soil carbon due to to disturbances in the soil structure, shifts in abundance of woody and herbaceous vegetation, and altered soil water and temperature regimes which accelerate decomposition. (Jandl et al., 2005; Kuikman et al., 2011). The development of the soil carbon stock on an average hectare of forest land, $\tilde{P}_t^i$, is assumed to be defined by a function

$$P_{t+1}^i = P_t^i - \nu P_t^i \gamma \frac{H_t^i}{V_t^i} + \kappa^i \eta V_t^i - \vartheta^i P_t^i \tag{3}$$

where ν the share of the soil carbon stock lost at the time of harvesting, γ is a factor converting the share of forest volume harvested into share of forest area harvested[3], and H_t^i / V_t^i is the share of forest volume harvested. The second term on the r.h.s. then expresses soil carbon losses due to final felling. The third term is the impact of forest biomass on soil carbon, where κ^i is the litter coefficient, expressing the unit increase in the soil carbon stock as tree biomass increases. The parameter ϑ in the last term is the decay of soil carbon, i.e. the release of soil carbon to the atmosphere. Total annual carbon sequestration in forest soil can then be expressed as the incremental change in the soil carbon stock:

$$\tilde{M}_{t+1}^i = A_{t+1}^i \left(P_{t+1}^i - P_t^i \right) + \varepsilon^{Pi} \quad (4)$$

where ε^{Pi} is an additive stochastic term, assumed to be normally distributed. Uncertainty arises because soil sequestration is strongly dependent on the site specific soil conditions, climate, tree species type and forest management practice (Jandl et al., 2005; Lal, 2005). Due to the large variation in carbon density between different soil layers and across space, this uncertainty can be of considerable magnitude (Lal, 2005). Total carbon sequestration in forest soil and trees can then be expressed as

$$\tilde{S}_{t+1}^i = \tilde{W}_{t+1}^i + \tilde{M}_{t+1}^i . \quad (5)$$

The harvested forest biomass is used for two different purposes, bioenergy or timber:

$$A^i H_t^i = B_t^i + T_t^i , \quad (6)$$

[3] The factor γ is typically less than one, as the standing biomass volume on a hectare subject to final felling is larger than the average.

where B_t^i and T_t^i are the total volume of bioenergy and timber, respectively. Bioenergy and timber both affect CO_2 emissions. When forests are used for bioenergy, the CO_2 content, ηB_t^i, is assumed to be released to the atmosphere in the same time period as it is harvested. The released CO_2 is, however, partly offset by displacement of fossil fuels, where displacement depends on the relative efficiency of bioenergy and replaced fossil systems (Schlamadinger and Marland, 1996). The parameter τ expresses net CO_2 emissions per unit of CO_2 in bioenergy after taking fossil fuel displacement into account, implying that net CO_2 emissions from bioenergy are equal to $\tau\eta B_t^i$.

When used as timber, carbon is stored in wood products and hence removed from the atmosphere. The annual increase in the CO_2 stock of wood products is calculated as ηT_t^i. Timber products have a limited life span (cf. Eggers, 2002) of k_i years, after which they are assumed to be used to be combusted for energy purposes, and the CO_2 content is released. Like bioenergy, timber that is combusted is assumed to replace fossil fuels, hence the emissions are partially offset, implying that the net release of CO_2 after k_i years is $\tau\eta T_{t-k_i}^i$. The contribution of bioenergy and timber to CO_2 emissions in a given year, L_t^i, can then be summarized as:

$$L_t^i = -\eta T_t^i + \tau\eta\left(T_{t-k_i}^i + B_t^i\right), \qquad (7)$$

where the first term is the incremental increase in the carbon pool of timber, 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 CO2 emissions given the displacement of fossil fuels. The net reduction of CO_2 in the atmosphere, $\tilde{R}_t^i$, due to forest carbon sequestration and the different uses of forest products can then be summarized as:

$$\tilde{R}_t^i = \tilde{S}_t^i - L_t^i. \qquad (8)$$

The combustion of fossil fuels in each country contributes to CO_2 emissions. Emissions of CO_2 from fossil fuels are determined by the quantities of fossil fuels consumed, X_t^{ij}, with j=1,…,6, different types of fuel[4] and an emission coefficient for each fuel type, α^j. Consequently, emissions from a given type of fossil fuel in a country, E_t^{ij}, are equal to $\alpha^j X_t^{ij}$. Total emissions in all countries from fossil fuels and forest management, E_t, are then:

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

where expressions for the expectation and variance of E_t can be found in the Appendix.

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., $\underline{X}_t^{ij} \le X_t^{ij} \le X_{BAU}^{ij}$.

Changes in the production of timber and bioenergy also give rise to costs. The use of timber and bioenergy can be reduced or increased in order to increase forest biomass and hence carbon 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. We assume that B_t^i is subject to lower and upper bounds, such that $\underline{B}^i \le B_t^i \le \overline{B}^i$. In a corresponding manner, changes in the production of timber is associated with a cost, $C_t^{Ti}(T_{BAU}^i - T_t^i)$, where T_{BAU}^i is the unregulated production of timber, and upper and lower bound apply, i.e. $\underline{T}^i \le T_t^i \le \overline{T}^i$. The cost functions for bioenergy and timber are assumed to be continuous, convex, and decreasing in B_t^i and T_t^i below the business-as-usual level, but increasing in B_t^i and T_t^i above these levels. We assume costs to be separable in X^{ij}, B_t^i and T_t^i. For bioenergy and timber, this assumption is motivated by the large variation in the share of

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

forest harvest used for bioenergy and timber in European countries, implying that simply assuming that bioenergy is a by-product seems incorrect, even though this is sometimes assumed in national and regional models (Carlsson, 2012; Trømborg and Sjølie, 2011). Fossil fuel and forest product costs are assumed to be separable given the relatively small role of bioenergy and timber combustion for total energy consumption.

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 (EUCOM, 2012). The sequence of emission targets can be met by reductions of the consumption of fossil fuels, and changes in forest management which affect bioenergy and timber production as well as carbon sequestration in biomass and soils. Policy makers are assumed to be concerned with risk, and, therefore wish to meet the targets 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

$$E\left(E_t\right) + K_\beta \sqrt{Var(E_t)} \leq E_t^{MAX}, \tag{10}$$

see Charnes and Cooper (1959). The formulation in (10) 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, and therefore also the cost, required to reach the same target. If $K_\beta = 0$, policy makers attach no weight to variations in loads and (10) 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 (10) at a minimum cost. The decision problem is then to:

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

s.t. (1)-(10) and the upper and lower bounds on the decision variables. The dynamic discrete time Lagrangian for this problem, and the associated necessary conditions for an interior solution, are included in the Appendix. In the following section, we present the efficient policy instruments which can be derived from the necessary conditions. For simplification, we assume that there is no covariance between soil and biomass sequestration, or in sequestration between different countries.

Efficient policy instruments

The cost-efficient solution can be achieved through efficient taxes on fossil fuels, bioenergy and timber. Those will take into account the indirect effect of the changes in bioenergy and timber production on sequestration in forest biomass and soils. The efficient tax can be derived from the necessary conditions, which can be found in the Appendix. For fossil fuels, the efficient tax is defined by:

$$\frac{\partial C_t^{ij}(X_{BAU}^{ij}-X_t^{ij})}{\partial X_t^{ij}}=\lambda_t\alpha^j \qquad (12)$$

i.e., each fuel is taxed in proportion to the carbon emissions per unit of fuel. Thus, the same tax is applied to a fuel type, independently of where it is emitted. Equivalently, all fuels can be taxed in proportion to the carbon emissions, implying that the tax is equal to λ_t, i.e. the shadow cost of the emission constraint. The shadow cost increases over time due to increased target stringency, and consequently the tax on fossil fuel consumption increases over time. The shadow cost λ_t

depends jointly on the costs for reducing carbon emissions by means of fossil fuel reductions and changed forest management. Hence, it is also determined by the potential and cost for adjusting forest management to achieve sequestration at different points in time.

For timber, the efficient tax can be obtained from the necessary conditions as:

$$\frac{\partial C_t^{Ti}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i} = \rho\mu_{t+1}^{Vi}\frac{1}{A_t^i} + \rho\mu_{t+1}^{Pi}\nu\gamma\frac{P_t^i}{V_t^i A_t^i} - \lambda_t\eta + \rho^{t+k_i-1}\lambda_{t+k_i}\tau\eta\,, \tag{13}$$

which shows that the optimal tax on timber is set such that the marginal cost, i.e. the foregone current return due to changed timber production, equals the marginal benefit. The marginal benefit of changed timber supply equals the sum of the discounted value of changed forest biomass and soil carbon stock, plus the value of the current and discounted future impact on the emission targets. If the shadow cost λ_t increases at a faster rate than the discount factor, and at the same time, fossil fuel displacement is small such that τ is close to one, the fourth term on the r.h.s. of (13) can be larger than the third term. This implies that the negative cost of future emissions is larger than the positive benefits of storing carbon in timber in the current time period. In that case, there is a strong motive to sequester carbon in the forest, and timber taxes are higher. Whereas the two last terms in equation (13) are equal across all countries, the two first terms on the r.h.s. differ across countries, implying that taxes may differ across countries in both sign and magnitude. These two terms are the marginal user cost of timber, i.e. the value of the impact of harvesting on standing biomass and on the soil carbon stock. The marginal user costs can be negative or positive, depending on the shape of the forest growth and soil stock functions and on whether timber supplies increase or decrease. The sign of the tax, positive or negative, then depends jointly on biomass and soil carbon growth functions, the chosen path of emission targets, and discount rates.

The corresponding efficient tax on bioenergy is defined by:

$$\frac{\partial C_t^{Bi}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i} = \rho\mu_{t+1}^{Vi}\frac{1}{A_t^i} + \rho\mu_{t+1}^{Pi}\nu\gamma\frac{P_t^i}{V_t^i A_t^i} + \lambda_t\tau\eta \tag{14}$$

where the interpretation of the two first terms on the right hand side is the similar as in equation (13) above. The last term on the r.h.s. is the shadow cost of the emission constraint in the same year, multiplied by the net impact of bioenergy on emissions. Given positive net emissions from bioenergy, this term is negative as $\lambda_t < 0$, hence motivating a decrease in bioenergy use, and the term is identical for all countries. The two first terms on the r.h.s. differ across countries, and comparing equations (13) and (14) we find that the efficient tax on bioenergy and timber are, in a similar manner, determined by the country specific impact on biomass and carbon soil stock development. Therefore, taxes on bioenergy and timber in a given country differ only with regard to their impact on carbon emissions.

To further understand how the efficient tax is set, we will have a closer look at the determinants of the marginal user costs. Using the necessary condition for the forest biomass stock we have that:

$$\rho\mu_{t+1}^{Vi} = \frac{1}{\left(1+\frac{\partial G_t^i}{\partial V_t^i}\right)}\left[\begin{array}{l}\mu_t^{Vi} - \rho\mu_{t+1}^{Pi}\left(-\nu P_t^i \gamma \frac{H_t^i}{\left(V_t^i\right)^2} + \kappa\right) + \\ \lambda_t\left(\eta A^i - K_\beta \frac{\partial\sqrt{Var\left(\tilde{W}_t^i\right)}}{\partial V_t^i}\right) + \rho\lambda_{t+1}\left(-\eta A^i - K_\beta \frac{\partial\sqrt{Var\left(\tilde{W}_{t+1}^i\right)}}{\partial V_t^i}\right)\end{array}\right] \tag{15}$$

Equation (15) shows that the marginal user cost of forest biomass depends on forest biomass growth: if a reduction in forest biomass increases forest growth, the marginal user cost is lower, as can be seen in the first term on the r.h.s. Thus, harvesting in the current time period makes it possible to sequester more carbon in the future. Within the parenthesis we have first the marginal value of the current stock, followed by the value of the impact of forest biomass on the soil carbon stock. This impact is larger if litter production, κ_i, is large or if the term $P_t^i H_t^i / \left(V_t^i\right)^2$ is small. The latter term expresses the impact of the biomass stock on the magnitude of soil carbon loss from final felling. This loss is larger if the harvested share of the forest biomass falls rapidly when the biomass volume is increased, and if the soil carbon stock is larger. In sum, the marginal user cost associated with an increase in forest biomass is smaller if *(i)* there is a larger positive effect on forest growth, *(ii)* soil carbon stocks are small and a small share of forest biomass is harvested, *(ii)* litter production is large, and *(ii)* the discounted future shadow cost is relatively small compared to the current shadow cost. Under these circumstances, larger sequestration in living biomass will optimally be carried out. The marginal user cost can be negative or positive depending on whether forest growth and soil sequestration are positively or negatively affected by the increased biomass volume, and depending on whether the discounted and risk-adjusted value of the impact on emission target is larger or smaller in the future.

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

$$\rho\mu_{t+1}^{Pi} = \frac{1}{\left(\left(1-\vartheta^{i}\right)-\nu\gamma\frac{H_{t}^{i}}{V_{t}^{i}}\right)}\left[\begin{array}{l}\rho\mu_{t}^{Pi}+\lambda_{t}\left(A^{i}-K_{\beta}\frac{\partial\sqrt{Var\left(\tilde{M}_{t}^{i}\right)}}{\partial P_{t}^{i}}\right)+\\ \rho\lambda_{t+1}\left(-A^{i}-K_{\beta}\frac{\partial\sqrt{Var\left(\tilde{M}_{t+1}^{i}\right)}}{\partial P_{t}^{i}}\right)\end{array}\right] \quad (16)$$

The marginal user cost of the soil carbon stock is affected by stock development, captured in the first term. A high decay rate ϑ^{i} increases the marginal user cost as a soil carbon stock increase in the current time period will be partly lost to the atmosphere in the following time period. A high harvested share of biomass, i.e. a high H_{t}^{i}/V_{t}^{i}, implies that an increase in the carbon soil stock will to larger extent be lost in the following time periods due to final felling. Both a high decay rate and a high harvested share will therefore imply that there is less reason to sequester soil carbon. The two last terms in (16) show that the marginal user cost depends on the relative target stringency at time *t* and *t+1* and on the discount rate. The sum of these terms is negative if the discounted future shadow cost is higher than the current. Increased soil carbon sequestration is thus less advantageous if future emission targets are more stringent, discount rates are low, and current sequestration reduces the future sequestration possibilities.

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), where the costs of reducing fossil fuel consumption are calculated as the associated decrease in consumer surplus. Emission coefficients for each type of fossil fuel have been obtained from the same source. Cost functions for decreases and increases in bioenergy and timber are calculated as changes in producer surplus, i.e. reflect the cost to producers in terms of profits foregone (in the case of a reduction) and costs above the market price payment (in the case of an increase)[5]. Inverted, linear supply functions were calculated based on estimates of price elasticities, price data and input use data, following the approach in Elofsson and Gren (2013).

Forest growth functions are obtained from Elofsson and Gren (2013), where functions are estimated from Eurostat forestry statistics. The gross increment per hectare is then modeled as a quadratic function of standing biomass, using dummies to control for different growth rates in boreal and Mediterranean countries due to cold winters and dry summers, respectively. The functions are estimated for commercial forests but are assumed to apply also for non-commercial forests, given that those might, in the future, be used as commercial ones. Based on data in Trømborg and Sjølie (2011), the CO_2 content per cubic meter of wood is assumed to be 0.8 tons[6]. Uncertainty about biomass carbon sequestration is obtained from Gren et al. (2009) as the coefficient of variation for sequestration in living biomass on “forest land remaining forest land,” as reported to UNFCCC (2009). This coefficient of variation ranges between 0.1 and 1.04 for different countries, and the coefficient of variation for aggregate sequestration in standing biomass in EU under current forest management practice is 0.41.

To obtain parameter values for the soil carbon stock equation, we make use estimates of soil carbon stock and sequestration in Liski, Perruchoud, and Karjalainen (2002). Their soil carbon stock estimates apply to the tree-originating carbon in the organic soil plus the topmost 20 cm mineral soil layer. National estimates for 1990 are available for 14 countries of those included here. We adjust these estimates for the average stock change 1990-2010 in the region, to which the country belongs; North, Northwest, Central or South Europe. For the 13 countries not included in their study, we use the average stock for the corresponding region. We use annual sequestration estimates reported in Liski, Perruchoud, and Karjalainen (2002) for 1990, and assume they apply also in 2010, while for countries not included in their study, we use the average for the region. Furthermore, we assume that 50 per cent of the soil carbon is lost on

[5] Consumer side welfare effects are not taken account because for bioenergy, demand is highly politically determined, and because trade in forest products is not easily incorporated in a partial model.
[6] Trømborg and Sjølie (2011) report CO_2 content to be 0.7-0.92 depending on tree species.

forest land subject to final felling, as suggested in early studies on the subject (Yanai et al., 2003; Covington, 1981; Federer, 1984). Later studies have shown that the magnitude of soil carbon loss can sometimes be much smaller, even zero (Yanai et al., 2003; Covington, 1981; Federer, 1984; Johnson and Curtis, 2001), and that the harvesting method and the extent of site preparation are important for the magnitude of the losses (Jandl et al., 2005), wherefore the case with zero losses is investigated in the sensitivity analysis. Building on Swedish data for 2010 (Swedish Forest Agency, 2013), γ is calculated to be 0.6, which we assume to apply for all countries. Decay rates are calculated from the functions for decomposition rates for slow and fast humus presented in Liski, Perruchoud, and Karjalainen (2002), where decomposition is modeled as functions of annual mean temperature. We use the average of the decomposition rates for fast and slow humus. The rate of litter fall, κ^i, is used to calibrate the functions to such that the above-mentioned sequestration is achieved in the initial year. Calibrated values then range from 0.00129 to 0.0358, which can be compared with Liski, Perruchoud, and Karjalainen (2002), where, e.g., the rate of litter fall to stem biomass is reported to be 0.0043 for coniferous forests and 0.0087 for deciduous trees. The variation in obtained litter coefficients seems reasonable given that the impact of tree growth on soil carbon accumulation differs between tree species (Jandl et al., 2005). The soil carbon loss at the time of harvest on a particular site is uncertain as losses depend on forest floor carbon content, which varies among different stands of the same age, and because it is difficult to measure the soil carbon stock, where carbon appears in different layers; forest floor and mineral soil, and where these layers can be more or less mixed (Jandl et al., 2005). It is here assumed that the coefficient of variation of carbon sequestration in soils equals one. This high assumed uncertainty is motivated by the small number of studies which provide information on soil sequestration across European numbers, in combination with the variation in estimates across studies (Liski, Perruchoud, and Karjalainen, 2002).

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

BAU. Also, it assumed that bioenergy and timber production can at the most be increased by 75%, which is reasonable compared to short and long term increases in renewables discussed by the EU Commission (EUCOM, 2012, 2013a).

The EU emissions target is interpreted as a successive reduction of CO_2-emissions by 80 percent until 2050. This target is assumed to be tightened by the same percentage each year from 2010 to 2050, taking into account that 2010 emissions are eleven percent below those in the reference year 1990 (EUCOM, 2012). A discount rate of 3% is applied, as suggested by Boardman et al. (2011) to be an appropriate level for public undertakings.

Results

We will consider five different policy scenarios. The first is an efficient scenario, called ALL, which includes fossil fuel reductions, emissions from forest products, as well as sequestration in biomass and soil. The second scenario, FPRO, includes emissions from fossil fuels and forest products, but sequestration is completely ignored. In the third scenario, BIO, emissions from fossil fuels and forest products, and biomass sequestration is included, but consequences for soil sequestration are ignored. The fourth scenario, SOIL, is similar to the third, but instead of biomass sequestration, soil sequestration is included. The fifth scenario, FOSSIL, is one where emission targets have to be achieved by only reductions in fossil fuel consumption. Forest harvest is constant, but forest biomass and soil carbon stock change over time.

The motive for the FOSSIL and FPRO scenarios is their similarity with current EU climate policy, where fossil fuel reduction is the major focus, but combustion of bioenergy and used timber product is part of the strategy for renewables. The scenarios BIO and SOIL, where only one carbon sink is included, are included because of the perceived difficulties to include all types of carbon sinks in a policy due to, e.g., measurement problems and difficulties to design adequate policy instruments. The ALL scenario can be seen as a benchmark, to which the outcome of the other policies can be compared.

To calculate the minimum costs for the above scenarios, it is necessary to define an "equally stringent target" for all scenarios. This is done as follows: In the FOSSIL scenario, baseline emissions used to calculate E_t^{MAX} are based only on fossil fuel consumption and the E_t^{MAX}-targets can only be achieved by reductions in fossil fuels. In the FPRO scenario, baseline emissions are calculated based on fossil fuel consumption and forest product emissions, L_{BAU}^i, and the E_t^{MAX} -targets can be achieved by reductions fossil fuel consumption and in L_t^i, the latter implying changes in bioenergy and timber production. Targets in the BIO, SOIL and ALL scenarios are calculated in a corresponding manner. For tractability, the model is aggregated into 5-year time periods. The model is run for 20 years beyond 2050, requiring that emissions then remain constant and equal to those in 2050, in order to end-of-period effects.

The minimum cost and achieved emission reduction

The minimum cost of meeting the EU Roadmap targets is calculated for each scenario. The cost savings that occur when including sequestration and forest product emissions, compared to the FOSSIL scenario, is achieved by allowing for changed forest management, compared to having B_t^i and T_t^i fixed at the business-as-usual level.

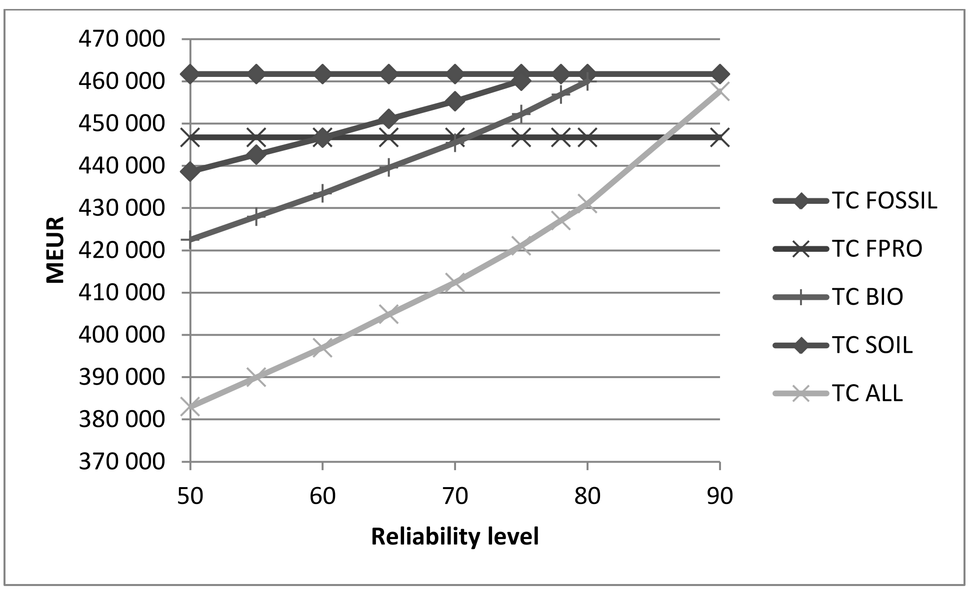

Figure 1. Total net presents cost in EUR of meeting emission target in different scenarios.

Figure 1 shows the net present costs in all scenarios and how it relates to the reliability β required. As can be seen in the Figure, inclusion of more alternative abatement options reduces the cost of meeting the targets. The net present cost in the FOSSIL scenario corresponds to approximately 0.1% of GDP, which is consistent with results in Capros et al. (2014)[7]. When uncertain abatement options as biomass and soil sequestration are included, a larger cost reduction is achieved if lower reliability is required. The reason is that higher reliability requires either a larger reduction in expected emissions and/or a reallocation from less to more certain abatement, e.g., a reallocation of sequestration from countries where it is cheap but uncertainty, to countries where it is more expensive but also more certain. Total net present costs is 17% lower in the ALL scenario compared to the FOSSIL scenario when policy-makers ignore risk, i.e. when the reliability level is 50, which can be compared to Michetti and Rosa (2012), who estimate the cost savings from carbon sequestration to be around 30%, and Gren et al. (2012), who conclude that sequestration could reduce EU climate policy costs by two thirds under certainty. The lower cost reduction obtained here is explained by analysis of the 2050 target, instead of the 2020 target, that the fact that the two studies allow for afforestation, while Gren et al. (2012) include also the non-trading sector[8], factors that together have a larger impact on minimum cost than our inclusion of several carbon pools. Cost savings from inclusion of carbon sequestration are reduced to nil when 70, 80 and 90 percent reliability is required in the SOIL, BIOMASS and ALL scenarios, respectively. Beyond these reliability levels, the negative effect of the increased uncertainty due to increased carbon sequestration exceeds the cost savings.

[7] Capros et al. (2014) compare three large-scale energy-economy models with regard to the least-cost strategy for meeting 2050 targets, and conclude such a strategy can reduce GDP by 0.0-0.5%. Different to this study, their calculations include also the non-trading sector, which is larger than the trading sector and abatement costs are higher, see e.g. Böhringer, Rutherford and Tol (2011).

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

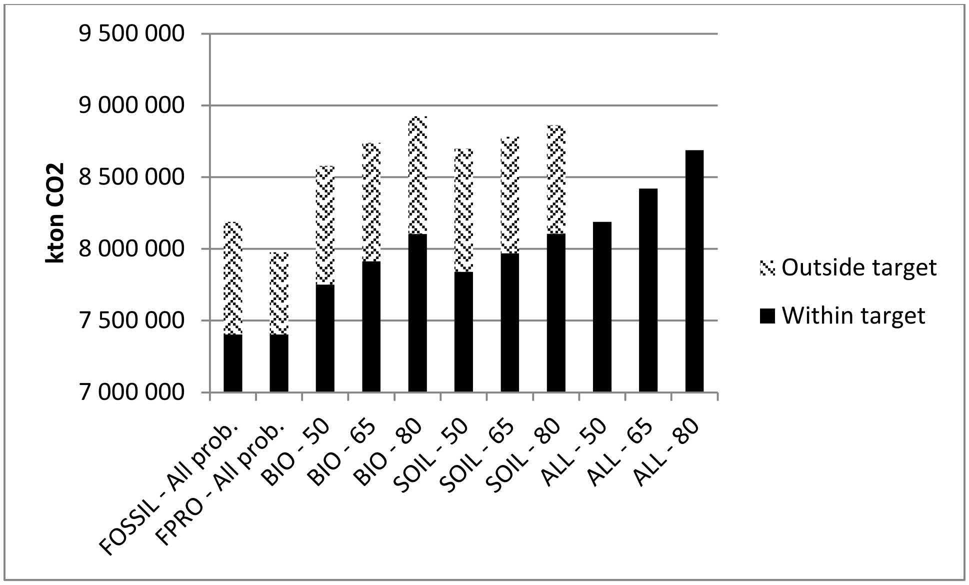

Figure 2. Reductions achieved under different target, within target and outside. X-axis labels indicate scenario and reliability level.

Except for the ALL scenario, the targets in the different scenarios do not capture all effects on emissions that results from the measures being undertaken. To compare the different policy scenarios, it is therefore necessary to identify emission reductions made within and outside the emission target constraint, see Figure 2. First, note that the total emission reduction in the FOSSIL scenario equals the emission reduction within the emission constraint in the ALL scenario under certainty. This is because business-as-usual sequestration is included in the target in the ALL scenario, whereas it is not in the FOSSIL scenario, even though it is actually achieved. Emission reductions within the emission target constraint in all the other scenarios are, in a corresponding manner, directly determined by the procedure used to calculate an "equally stringent target", described above.

Total emission reductions in the FPRO scenario are smaller than in other scenarios, because of less abatement outside the constraint. Bioenergy is reduced less, and timber is increased more, than in other scenarios because the impact on sequestration is not taken into account. In contrast, total emission reductions in the BIO and SOIL scenarios are large because of considerable abatement being made outside the emission constraint. When only one of either biomass or soil sequestration is included in the target, the other carbon pool will still increase. Inclusion of biomass sequestration leads to larger tree volumes and, hence, larger quantities of litter which increases the soil carbon pool. Conversely, inclusion of soil sequestration requires larger tree volumes in order to increase litter production and hence soil sequestration, implying also increased biomass sequestration. However, it matters which of the carbon pools is included: inclusion of biomass sequestration implies a lower minimum cost, see Figure 1, because biomass sequestration is cheaper to achieve than soil sequestration. The reason is that the carbon sequestered in soils is partially lost through decay and at the time of harvesting. Consequentially, biomass and soil sequestration are both larger in the BIO scenario.

The largest total emission reduction is achieved in the BIO scenario with 80 percent reliability, as higher reliability implies both further fossil fuels reductions and more sequestration. The net present cost is equal to that in the FOSSIL scenario, but the total emission reduction exceeds the one in the FOSSIL scenario by 9 percent. Even though the largest total emission reduction is obtained in the BIO scenario with 80 percent reliability, the largest total sequestration is achieved in the ALL scenario with the same reliability requirement. In the BIO scenario, sequestration in biomass is seen as having a smaller impact on emissions that it actually has, given its impact on soil sequestration. More carbon is instead stored in timber, and larger reductions in fossil fuel emissions are made in order to meet the emission targets.

Policy instruments

Both carbon taxes on fossil fuels and taxes on bioenergy and timber can, in principle, be applied to meet the climate targets for the EU as shown above. Figure 3 shows the cost-effective CO_2-tax on fossil fuels in the FOSSIL and ALL scenarios. The CO_2-tax increases over time throughout the policy period as the emission target becomes more stringent, and is always higher in the FOSSIL scenario, and higher for higher reliability levels. In the ALL scenario, carbon taxes will increase from €25 per tCO_2 in 2010 to €63 in 2050. This can be compared with actual carbon price, which ranged between €8 and €29 per tCO_2 between 2008 and 2010 (Chen, Wang and Wu, 2013). Also, our result can be compared with permit prices 2020 estimated by Böhringer, Rutherford and Tol (2011) from three different CGE-models. They calculate the permit price for the EU ETS, in the absence of additional efforts to promote renewables, to be €50-75/tCO_2. Our estimate in the FOSSIL scenario, €47 per tCO_2 in 2020, is in the lower end of their estimated price interval, which could reflect the fact that we do not take into account economy-wide dispersal effects. Capros et al. (2014) estimate that carbon prices will reach €243-€565 in 2050.

Our result in the FOSSIL scenario is only half of this, which is mainly explained by their estimates including also the non-trading sector, where abatement costs are higher than in the trading sector. Michetti and Rosa (2012) estimate that the carbon price is reduced by 30% in 2020 when forest sequestration is included. For that time period, we get a corresponding carbon price reduction by 16%, where the lower reduction can be explained their inclusion of land use changes and structural impacts.

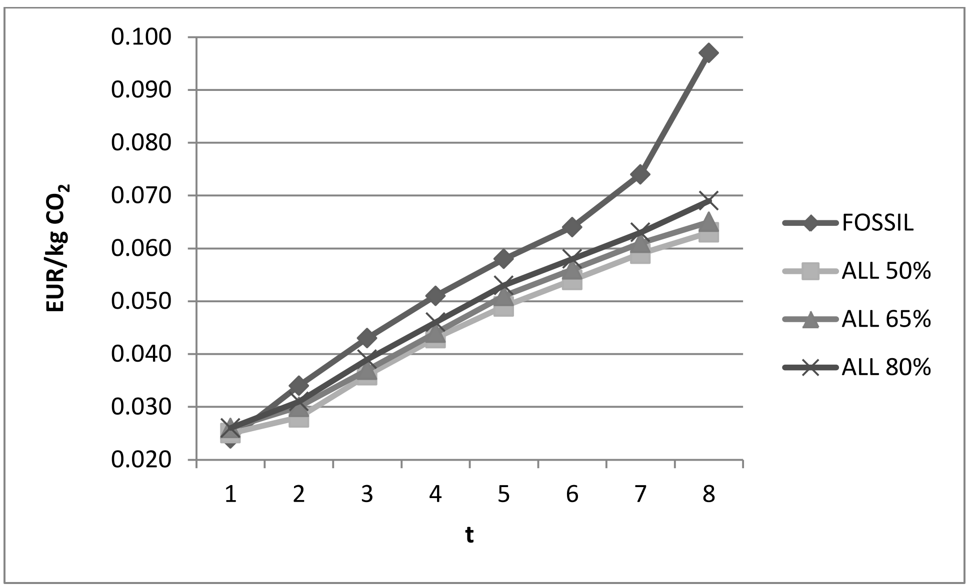

Figure 3. CO2-tax on fossil fuels in current value in FOSSIL and ALL scenarios.

Taxes and subsidies on bioenergy and timber

When investigate results for the taxes on bioenergy and timber in three countries; Germany, Finland and Spain, chosen because of their large forest area and, hence, potential importance to the overall EU climate policy in this context. We first briefly summarize forest data for these countries in table 1. The forest area is the largest in Spain, followed by Finland and then Germany. Per hectare standing biomass is the largest in Germany, almost three times the European average, whereas that in Finland is close to the average, and that in Spain is far below. Forest growth is high in Germany, but lower in Finland and Spain because of their less suitable climate in combination with the smaller biomass stock. The soil carbon stock is large in

Germany and Finland, but small in Spain, and sequestration is high in Germany, moderate in Finland and low in Spain.

	Total forest and other wooded land area	Growing stock	Forest growth, modeled	Soil C stock	Soil C sequestration	Coeff. of var. in biomass sequester.	Coeff. of var. in soil sequester.
	1000 ha	m^3/ha	m^3/ha	t CO_2-eq/ha	ton CO_2-eq/ha		
Germany	11076	315	7.6	220	0.183	0.3	1
Spain	28214	32	0.8	48	0.029	0.4	1
Finland	23116	96	3.3	180	0.084	0.37	1

Table 1. Forest data 2010 for Germany, Finland and Spain.

For all the three countries, the efficient tax on bioenergy[9] is set on a level where bioenergy in reduced by the maximum amount. This tax is then equal across countries because of the underlying assumption about equal price and price elasticity, used for the calculation of bioenergy cost function. Efficient taxes on timber production are shown in Figure 4. In Spain, the tax is positive and high for all time periods and all levels of reliability, and implies a reduction of timber by the maximum amount. This leads to an increase in biomass and soil carbon sequestration, given the low initial standing biomass and, hence, low growth. Accordingly, biomass volume as well as litter production increases. Increased biomass decreases the harvest to volume ratio, but this is of small importance for protection against soil carbon losses from final felling, given the small soil carbon stock.

For Finland, the tax on timber is high and leads to the maximum reduction over the first 25-30 years, but then declines successively as forest growth falls. The decline is faster when higher reliability is required and, hence, sequestration is a less attractive option. It is cost-effective to build up forest biomass in order to increase sequestration in both biomass and soil, albeit not as efficient as in Spain, given the higher initial Finnish biomass and soil carbon stock.

[9] The efficient tax is here calculated as the marginal cost of reducing bioenergy, but without adding the marginal value of the capacity constraint. The calculated tax is thus the one that would be necessary to achieve a reduction to the capacity constraint, but does not reflect the marginal value of being able to lower the constraint in question.

Given the larger soil carbon stock there is also reason to build up biomass volume in Finland, in order to decrease the harvest to volume ratio and so protect from soil carbon losses.

In Germany, timber is first taxed at a low rate over the first five years, which is explained by the large initial biomass stock and, hence, low biomass growth. Timber harvesting is increased in order to increase sequestration. In the following time periods, timber is taxed at a low rate, which maintains high biomass sequestration, and reduces the harvest to volume ratio. The latter is of considerable importance as the soil carbon stock is large so a lower harvest to volume ratio reduces soil carbon losses substantially.

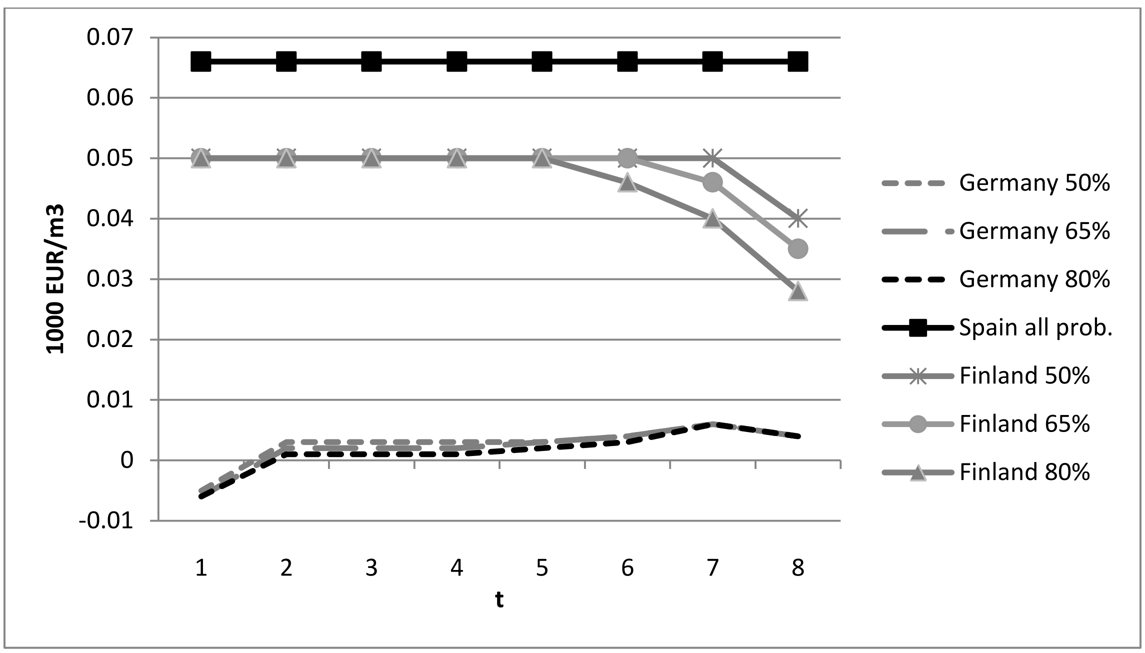

Figure 4. Efficient tax on timber products in the ALL scenario, in current value. Legend shows country and reliability level.

From Figure 4, it is clear that cost-effective timber taxes differ substantially between countries, suggesting that common timber taxes at the EU level would not be cost-effective. There is no clear pattern in the figure showing whether taxes converge or diverge over time of when higher certainty is required. However, uncertainty is, in principle, likely to add to the heterogeneity between countries with regard to the impact of harvesting on the certainty equivalent of future sequestration, given that there is no obvious reason for expected sequestration, and variability thereof, to be negatively correlated.

Given our aim to investigate separate and combined inclusion of carbon sinks, we have also calculated the efficient timber tax in the BIO scenario, see Figure 5, given that this scenario implies cost savings compared to the FOSSIL scenario, while achieving the emission target with substantial margin. Timber taxes are lower in the BIO scenario, explained by benefits of soil carbon sequestration being ignored. Timber is subsidized in Germany throughout the whole policy period. In Spain, timber taxes are at the maximum level for the first 30 years, but are then successively reduced when biomass growth falls and sequestration becomes more expensive. The Finnish timber tax falls throughout the policy period for the same reason. Taxes tend to convergence towards the end of the policy period. Such convergence can be expected when all forests are managed in a cost-effective way taking sequestration into account. This implies that consideration of harmonized policies at the EU-level could, possibly, be relevant in a longer term, beyond 2050.

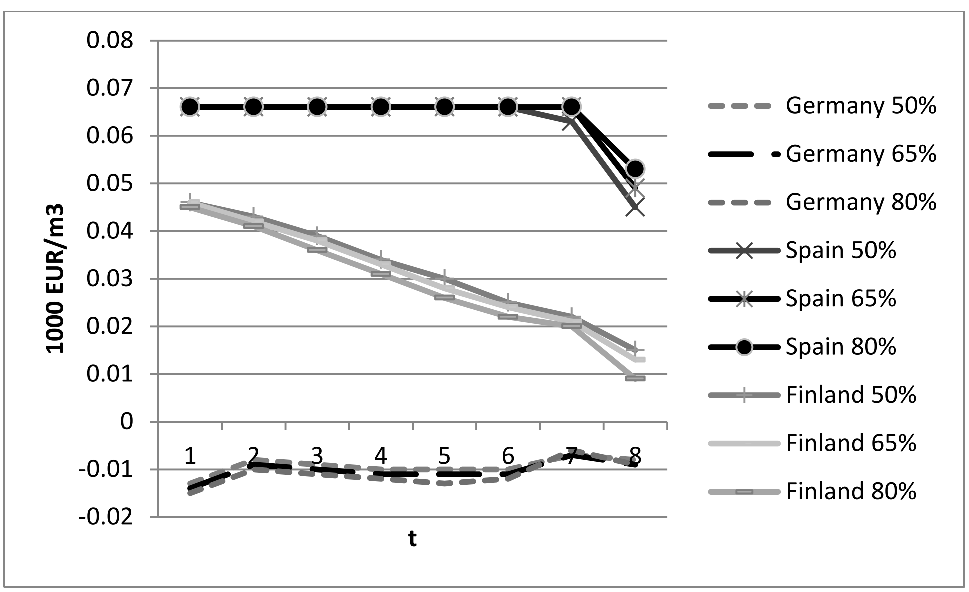

Figure 5. Efficient tax on timber products in the BIO scenario, in current value. Legend shows country and reliability level.

Sensitivity analysis

In the sensitivity analysis, we chose to focus on the role of assumptions made about soil carbon sequestration, given the importance of soil sequestration for our research question. As mentioned above, there is substantial controversy regarding the magnitude of soil carbon losses at the time of harvesting. To investigate the role assumptions about these losses, we recalibrate the soil carbon stock function assuming that losses from harvesting are zero. Moreover, data on the magnitude of uncertainty about carbon soil sequestration are not well known, and we therefore investigate the sensitivity of results with regard to a doubling of soil carbon sequestration uncertainty. Sensitivity analysis is carried out on the ALL scenario. Results from the sensitivity analysis are included in the Table 2.

	Net present cost	Aggregate biomass sequestration	Aggregate soil carbon sequestration	Timber tax at t=1, Germany	Timber tax at t=1, Finland	Timber tax at t=1, Spain
No soil carbon losses from harvesting	1.29	0.97	0.17	2.50	1.00	1.00
Doubled soil carbon sequestration uncertainty	1.04	0.997	0.996	1.00	1.00	1.00

Table 2. Sensitivity analysis in the ALL scenario under 65% reliability. Figures refer to the value of the variable compared to that in the reference scenario.

The sensitivity analysis shows that when the soil stock function is calibrated for zero losses from final felling, which implies a smaller litter coefficient, the net present cost increases and sequestration in both soil and biomass falls, but the fall in soil sequestration is much larger. This is explained by the smaller possibility to enhance soil carbon sequestration through increased biomass volume. This illustrates the large importance of litter production compared to soil carbon losses from final felling for the development of the soil carbon stock. Timber taxes are unaffected in Finland and Spain, but the timber subsidy increases substantially in Germany, as the consequences of harvesting on soil carbon losses are now zero, whereas in the reference scenario, these losses are comparatively large in Germany because of the large soil carbon stock.

The second scenario, with doubled uncertainty, has a minor impact on total net present cost and almost no impact on the other variables. Increased uncertainty is compensated for through additional reductions in fossil fuels. The small changes made to forest management, mainly implying a reallocation of efforts between countries, hardly affects total cost or timber taxes in the three countries.

Summary and discussion

This aim of this paper is to compare the economic and environmental consequences of separate inclusion of one forest carbon pool in the EU's climate policy to that of including two interdependent pools. We also aim to evaluate policy instruments applied to forest product as a means to achieve carbon sequestration in a cost-effective manner. The theoretical analysis shows that if both biomass and soil sequestration could be included in a policy by means of differentiated taxes on bioenergy and timber, which reflect direct emissions from bioenergy and timber, displacement of fossil fuels, and the consequences of on current and future sequestration in forests biomass and in soils.

A numerical model is developed, which includes cost functions for fossil fuels and forest products, forest growth and soil carbon stock development. The model is used to analyze separate and combined inclusion of forest product emissions and forest sequestration compared to a coherent policy where all abatement options are included, and one where fossil fuel reductions are the only means to meet the EU Roadmap targets. The results show that inclusion of only one carbon sink will reduce costs compared to a policy with fossil fuel reductions, and that more than intended emission reductions will be achieved. On the contrary, a policy which only includes fossil fuels and direct emissions from forest product will imply that intended emission targets are not met, because of reduced sequestration. Thus, it is not necessary for a policy to accommodate for all different carbon pool effects of changed forest management to reap at least some benefits from sequestration.

Analysis of the cost-efficient taxes on forest products shows that consideration sequestration in biomass and soils have a considerable impact on the tax level. Lop-sided consideration of fossil fuel displacement resulting from the use of bioenergy and timber therefore seems to be a costly strategy, confirming Eriksson's (2013) observation that sequestration should be prioritized compared to bioenergy. Given the wide variation in biomass and soil carbon stocks and growth, the efficient level and time path of subsidies and taxes varies substantially across countries. Uncertainty aversion further reduces the scope for uniform instruments, as uncertainty adds to the heterogeneity of sequestration impacts. Therefore, uniform EU-wide policy instruments seem to be unsuitable in the foreseeable future. Possibly, common EU-wide policy instruments for forest products could be an alternative beyond 2050, if policies to increase sequestration have been in place for a longer time, and further knowledge on sequestration processes is available.

The above analysis above has limitations, including the partial approach, the exclusion of land use change, and exclusion of the non-trading sector. Also important is the exclusion of transaction costs, likely to arise when developing new policy instruments, implying that results should be interpreted with care.

Acknowledgements

Funding from the Swedish Energy Agency for the research project Incentives for forest and forest land carbon sequestration in EU is gratefully acknowledged.

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APPENDIX

Expected total emissions:

$$E\left(E_t\right)=\sum_i\left(\sum_j\alpha^j X_t^{ij}-E\left(\tilde{R}_t^i\right)\right)=\sum_i\sum_j\alpha^j X_t^{ij}-\sum_i E\left(\tilde{S}_t^i\right)+\sum_i L_t^i=$$
$$\sum_i\sum_j\alpha^j X_t^{ij}-\sum_i E\left[\eta A^i(V_t^i-V_{t-1}^i)\right]-\sum_i E\left[A^i\left(P_t^i-P_{t-1}^i\right)\right]-\sum_i\eta T_t^i+\sum_i\tau\eta\left(T_{t-k_i}^i+B_t^i\right) \quad \text{(A1)}$$

Variance of total emissions:

$$Var\left(E_t\right)=\sum_i Var\left(\tilde{R}_t^i\right)=\sum_i Var\left(\tilde{S}_t^i\right)=\sum_i Var\left(\tilde{W}_t^i+\tilde{M}_t^i\right)=$$
$$\sum_i Var\left(\tilde{W}_t^i\right)+\sum_i Var\left(\tilde{M}_t^i\right)+\sum_i\sum_{j\neq i}Cov\left(\tilde{W}_t^i,\tilde{W}_t^j\right)+\sum_i\sum_{j\neq i}Cov\left(\tilde{M}_t^i,\tilde{M}_t^j\right)+\sum_i\sum_j Cov\left(\tilde{W}_t^i,\tilde{M}_t^j\right)$$

(A2)

where in the empirical application, the covariance terms are assumed to be equal to zero[10].

The Lagrangian and the necessary first order conditions

The dynamic discrete time Lagrangian is:

[10] Substitution between fossil fuels and bioenergy in final use is not explicitly modeled. This simplification is motivated by our desire to analyze the role of sink interdependence, uncertainty, and 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, where sink interdependences and uncertainty in a dynamic model are difficult to incorporate.

$$L = \sum_t \sum_i \rho^t \begin{bmatrix} C_t^{Bi}(B_{BAU}^i - B_t^i) + C_t^{Ti}(T_{BAU}^i - T_t^i) + \sum_j C_t^{Xij}(X_{BAU}^{ij} - X_t^{ij}) + \\ \rho\mu_{t+1}^{Vi}\left(V_t^i + G_t^i(V_t^i) - \frac{\left(B_t^i + T_t^i\right)}{A^i} - V_{t+1}^i \right) + \\ \rho\mu_{t+1}^{Pi}\left(P_t^i - \nu P_t^i \gamma \frac{\left(B_t^i + T_t^i\right)}{V_t^i A^i} + \kappa_i V_t^i - \vartheta^i P_t^i - P_{t+1}^i \right) + \\ \lambda_t \left[E_t^{MAX} - E\left(E_t\right) - K_\beta \sqrt{Var(E_t)} \right] \end{bmatrix} \tag{A3}$$

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

$$\rho^{-t}\frac{\partial L}{\partial X_t^{ij}} = \frac{\partial C_t^{ij}(X_{BAU}^{ij} - X_t^{ij})}{\partial X_t^{ij}} - \lambda_t \alpha^j = 0 \tag{A4}$$

$$\rho^{-t}\frac{\partial L}{\partial B_t^i} = \left[\frac{\partial C_t^{Bi}\left(B_{BAU}^i - B_t^i\right)}{\partial B_t^i} - \rho\mu_{t+1}^{Vi}\frac{1}{A_t^i} - \rho\mu_{t+1}^{Pi}\nu\gamma\frac{P_t^i}{V_t^i A_t^i} - \lambda_t \tau\eta \right] = 0 \tag{A5}$$

$$\rho^{-t}\frac{\partial L}{\partial T_t^i} = \left[\frac{\partial C_t^{Ti}\left(T_{BAU}^i - T_t^i\right)}{\partial T_t^i} - \rho\mu_{t+1}^{Vi}\frac{1}{A_t^i} - \rho\mu_{t+1}^{Pi}\nu\gamma\frac{P_t^i}{V_t^i A_t^i} + \lambda_t \varphi\eta - \rho^{t+k_i-1}\lambda_{t+k_i}\tau\eta \right] = 0 \tag{A6}$$

$$\rho^{-t}\frac{\partial L}{\partial V_t^i}=\begin{bmatrix}\rho\mu_{t+1}^{Vi}\left(1+\frac{\partial G_t^i}{\partial V_t^i}\right)-\mu_t^{Vi}+\rho\mu_{t+1}^{Pi}\left(-\nu P_t^i\gamma\frac{H_t^i}{\left(V_t^i\right)^2}+\kappa\right)-\lambda_t\left(\eta A^i-K_\beta\frac{\partial\sqrt{Var\left(\tilde{W}_t^i\right)}}{\partial V_t^i}\right)-\\ \rho\lambda_{t+1}\left(-\eta A^i-K_\beta\frac{\partial\sqrt{Var\left(\tilde{W}_{t+1}^i\right)}}{\partial V_t^i}\right)\end{bmatrix}=0 \tag{A7}$$

$$\rho^{-t}\frac{\partial L}{\partial P_t^i}=\begin{bmatrix}\rho\mu_{t+1}^{Pi}\left(\left(1-\vartheta^i\right)-\nu\gamma\frac{H_t^i}{V_t^i}\right)-\rho\mu_t^{Pi}-\lambda_t\left(A^i-K_\beta\frac{\partial\sqrt{Var\left(\tilde{M}_t^i\right)}}{\partial P_t^i}\right)-\\ \rho\lambda_{t+1}\left(-A^i-K_\beta\frac{\partial\sqrt{Var\left(\tilde{M}_{t+1}^i\right)}}{\partial P_t^i}\right)\end{bmatrix}=0 \tag{A8}$$

where μ_t^{Vi}, μ_t^{Pi} and λ_t are the Lagrange multipliers for the stock of tree biomass, the stock of soil carbon and the emissions target, respectively.

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]**	**Fellings[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. Soil carbon stock and sequestration.

	Soil carbon stock[1]	**Soil carbon sequestration**[1]	**Conversion factor**[2] γ	**Litter coefficient**[3], κ^i	**Decomposition rate**[1], ϑ^i	**Harvest to volume ratio**[4],	**Harvest impact coefficient,** υ	**Coeff of var., soil sequest**
	ton CO2/ ha	ton CO2/ha	% volume to % area harvested	ton CO2/ m^3	%	%	%	
AT	220	0.183	0.6	5.3	4.94E-13	0.019	0.5	1
BE	139	0.213	0.6	7.2	6.07E-13	0.03	0.5	1
BG	220	0.183	0.6	2	4.94E-13	0.012	0.5	1
CY	48	0.029	0.6	0.2	7.80E-13	0.007	0.5	1
CZ	220	0.183	0.6	7.2	4.94E-13	0.025	0.5	1
DE	220	0.183	0.6	5.1	5.43E-13	0.016	0.5	1
DK	180	0.084	0.6	4.6	4.98E-13	0.026	0.5	1
EE	180	0.084	0.6	3.6	4.98E-13	0.019	0.5	1
ES	48	0.029	0.6	1.1	9.24E-13	0.034	0.5	1
FI	180	0.084	0.6	2.6	2.46E-13	0.027	0.5	1
FR	220	0.183	0.6	3.7	6.53E-13	0.025	0.5	1
GR	48	0.029	0.6	0.3	9.16E-13	0.01	0.5	1
HU	220	0.183	0.6	3.3	4.94E-13	0.019	0.5	1
IE	139	0.213	0.6	5.7	5.80E-13	0.06	0.5	1
IT	48	0.029	0.6	1	7.80E-13	0.008	0.5	1
LT	180	0.084	0.6	3.8	4.98E-13	0.018	0.5	1
LU	139	0.213	0.6	3.2	6.07E-13	0.011	0.5	1
LV	180	0.084	0.6	4	4.98E-13	0.022	0.5	1
MT	48	0.029	0.6	0	7.80E-13	NA	0.5	1
NL	139	0.213	0.6	3.7	5.90E-13	0.019	0.5	1
PL	220	0.183	0.6	4.2	5.43E-13	0.017	0.5	1
PT	48	0.029	0.6	5.3	9.39E-13	0.102	0.5	1
RO	220	0.183	0.6	2.5	4.94E-13	0.012	0.5	1
SE	180	0.084	0.6	3.5	2.95E-13	0.033	0.5	1
SK	220	0.183	0.6	5.4	4.94E-13	0.02	0.5	1
SI	220	0.183	0.6	2.5	4.94E-13	0.008	0.5	1
UK	139	0.213	0.6	4	5.43E-13	0.031	0.5	1

1 Own calculation based on Liski, Perruchoud, and Karjalainen (2002).
2 Own calculation based on data from Swedish Forest Agency (2013).
3 From calibration of model.
4 Calculated from data in Table A1.

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