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Economic value of land use for carbon sequestration: An application to the EU climate policy.

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Economic value of land use for carbon sequestration: An application to the EU climate policy.

Abstract:. This paper applies the replacement cost method for calculating the value of stochastic carbon sequestration in the EU climate policy for mitigating carbon dioxide emissions. Minimum costs with and without carbon sequestrations are then derived with a safety-first approach in a chance-constrained framework for two different scenarios; one with the current system for emission trading in combination with national allocation plans and one with a hypothetical system where all sectors trade. The theoretical results show that i) the value of carbon sequestration approaches zero for a high enough risk discount, ii) relatively low abatement cost in the trading sector curbs supply of permits on the ETS market, and iii) large abatement costs in the trading sector create values from carbon sequestration for meeting national targets. The empirical application to the EU commitment of 20% reduction in carbon dioxide emissions shows large variation in carbon sequestration value depending on risk discount and on institutional set up. Under no uncertainty, the value can correspond to approximately 0.45% of total GDP in EU under current policy system, but it is reduced to one third if all sectors are allowed to trade. The value declines drastically under conditions of uncertainty and approaches zero for high probabilities in achieving targets. The allocation of value among countries depends on scenario; under the current system countries make gains from reduced costs of meeting national targets, under a sector-wide trading scheme buyers of permits gain from reductions in permit price and sellers make associated losses.

Key words: carbon sequestration, value, replacement cost method, uncertainty, safety-first, chance-constrained programming, EU emission target

1. Introduction

In principle, the threats of climate change due to increased carbon content in the atmosphere can be mitigated in two ways; by reducing carbon dioxide emissions from fossil fuels and/or by increasing the uptake of carbon from the atmosphere by growing biomass, denoted carbon sequestration or sink. While costs of reducing carbon dioxide emissions have been addressed and calculated since early 1990s in a large number of studies, where Nordhaus (1994) is a seminal contribution, there are only a few studies comparing these costs with costs of measures increasing carbon sequestration (e.g. Pohjola et al., 2003; Lubowski, et al., 2006, Bosetti et al., 2009; Michetti and Rosa, 2011; Gren et al., 2012). For example, Lubowski, et al. (2006) showed that approximately 1/3 of the US carbon abatement commitment would be achieved by forest carbon sequestration in a cost effective solution. Michetti and Rosa (2011) presented results where the inclusion of carbon sink could reduce cost of meeting EU 2020 CO_2 commitment in an emission trading system (ETS) by at least 25%.

Despite these results, hesitations remain with respect to the inclusion of carbon sequestration in the EU climate policy, the main argument being the stochastic nature of carbon sequestration (EC, 2008). Gren et al. (2012) showed that the economic value in terms of cost savings approaches zero when reliability in reaching EU climate targets is if great concern. Similar results are obtained in Gren (2012), who accounts for uncertainty in emission reductions from fossil fuel and in abatement costs in addition to the stochastic carbon sink. However, both studies of stochastic carbon sink in the EU policy consider only actual forest sink and increases from conversion of arable land into forest. Undoubtedly, these sink sources are important and correspond to approximately 15% of forecasted emissions in 2020 (Gren et al., 2020). However, it might be difficult to implement carbon sink as ‘by-products’ from forestry into any

EU policy due to the requirement of ‘additionality’, i.e. that the carbon sink would not have been implemented without the policy in question. Further, the potential for increasing sinks may not be of the same order of magnitude as actual carbon sink, and uncertainty in sink can differ among land use options. The purpose of this paper is to investigate whether stochastic carbon sink has positive values in the EU climate change program for increases in carbon sink. The land uses included are increased rotation in forestry, conversion of arable land into forests, and changed land use practices for agricultural land.

This paper applies the same approach for assessing the value of carbon sinks in climate change mitigation programs as Gren et al. (2012) and Gren (2012). This implies the use of the so-called replacement cost method for assigning values to non-market environmental goods. The basic principle guiding the method is that the value of the technology under investigation is determined by its cost savings for reaching specific environmental targets. In order to account for policy makers relative risk aversion with respect to non-attainment of stipulated targets the safety-first criterion in the framework of chance constrained programming is applied. Different variations of the safety-first criterion have a long tradition in economics for dealing with urgent targets, such as minimum food supply (e.g. Tesler, 1955; Pyle and Turnovsky, 1970; Bigman, 1995). The suggested approach has partly been applied by Gren et al. (2012) and Gren (2012) for evaluating the potential of forest carbon sink in the EU ETS and national commitment program, and by Byström et al. (2000) and Gren (2010) for valuing ecosystems’ water cleaning function under stochastic conditions.

Similar to several empirical studies on the evaluation of the costs of reducing carbon dioxides, we apply a partial equilibrium modeling framework which is based on marginal control costs for emission reduction and carbon sequestration in different countries (e.g., Böhringer and Löschel, 2009). The main contribution of this paper is the calculation of value of different land uses for carbon sequestration, which extends the possibilities included in Gren et al. (2012) and Gren (2012).

The paper is organized as follows: In section 2 we describe the chance-constrained programming model, which is used for identifying conditions for a positive value of carbon sinks and determinants of the size of the value. Data sources are briefly described in section 3. Section 4 presents the results and the paper ends with a brief summary and some tentative conclusions.

2. The model

EU consists of *i=1,..,27* countries each of which faces costs of reducing carbon dioxide emissions by decreasing the use of fossil fuels, *f=1,..,n*. In addition, atmospheric content of carbon can be reduced by construction of carbon sinks with *s=1,..,k* sink options such as sequestration in forest, or conversions of alternative land into forests. Each of the carbon sink options deliver carbon sink only with uncertainty due to climate impact on carbon sequestration (e.g. Janssens et al., 2005).

The countries face different regulations with regard to carbon dioxide emissions. In this paper we focus on two directives: the EU ETS (Official Journal, Directive 2009/29/EC) and national commitments (Official Journal, Decision 406/2009/EC). The EU ETS is the cornerstone of the EU's strategy for fighting climate change. It is the first and largest international trading system for carbon dioxide emissions in the world and has been in operation since 2005. In addition to the EU ETS, member states face individual targets expressed as reductions in percent from the 2005 emission level, which in the following are denoted as national allocation plans (NAP).

When both fossil fuel reductions and carbon sinks are allowed, total emissions in each country from the trading, T^{iTr}, and non-trading sectors, T^{iNtr}, is written as initial or business as usual (BAU) use of fossil fuels, $T_{if}^{Tr}{}'$ and $T_{if}^{Ntr}{}'$ minus reductions achieved by decreasing fossil fuel uses, A_{if}^{Tr} and A_{if}^{Ntr}, and by introduction of land use for carbon sinks, A_{is}^{Tr} and A_{is}^{Ntr}, according to

$$T^{iTr} = \sum_f D_{if}(T_{if}^{Tr}{}' - A_{if}^{Tr}) - \sum_s F_{is}(A_{is}^{Tr}, \sigma_{is}^{Tr}) \tag{1}$$

$$T^{iNtr} = \sum_f D_{if}(T_{if}^{Ntr'} - A_{if}^{Ntr}) - \sum_s F_{is}(A_{is}^{Ntr}, \sigma_{is}^{Ntr}) \tag{2}$$

where D_{if} is the conversion of fossil fuel into carbon dioxide, F_{is} converts land use practices into carbon sequestration, and σ_{is}^{Tr} and σ_{is}^{Nr} measure the uncertainties associated with carbon sequestration in the trading and non-trading sectors.

Decision makers at the international level are assumed to apply a safety-first approach in reaching maximum emission target with respect to total emission in the EU ETS, $T^{Tr} = \sum_i T^{iTr} \leq \overline{T}^{Tr}$. National authorities make similar decisions on achievement of the national allocation plans where $T^{iNtr} \leq \overline{T}^{iNtr}$. Both types of decision makers formulate a minimum probability, α and β^i for EU and national authorities respectively, of achieving the maximum emission target, which is written as

$$prob(T^{Tr} \leq \overline{T}^{Tr}) \geq \alpha \tag{3}$$

$$prob(T^{iNtr} \leq \overline{T}^{iNtr}) \geq \beta^i \tag{4}$$

In order to facilitate calculations, these constraints are rewritten in terms of deterministic equivalents (see e.g. Taha, 1976). This is made in the same way for both restrictions, and it is presented for the EU target as

$$prob\left[\frac{T^{Tr}-\mu_{T^{Tr}}}{o^{1/2}_{T^{Tr}}} \leq \frac{\overline{T}^{Tr}-\mu_{T^{Tr}}}{\sigma^{1/2}_{T^{Tr}}}\right] \geq \alpha \qquad (3')$$

where $\mu_{T^{Tr}} = E\left[T^{Tr}\right]$, $\sigma_{T^{Tr}} = Var(T^{Tr})$, and the term $\frac{T^{Tr}-\mu_{T^{Tr}}}{o^{1/2}_{T^{Tr}}}$ shows the number of standard errors, ϕ, that T deviates from the mean. By the choice of α, there is thus a level of acceptable deviation, and the expression within brackets in (3') then holds only if

$$\mu_{T^{Tr}} + \phi^{\alpha}\sigma^{1/2}_{T^{Tr}} \leq \overline{T}^{Tr}. \qquad (5)$$

where ϕ^{α} is the critical value associated with α, which is determined by the distribution of the random variable and the chosen level of α. The left hand side of (5) shows that reliability in achieving the target is obtained at a cost, which is increasing in reliability concern or higher probability of achieving the target, i.e. in ϕ^{α}, and in $\sigma_{T^{Tr}}$. The deterministic equivalents of the national targets in (3) are derived in the same way, which gives

$$\mu_{T^{iNtr}} + \phi^{\beta^i}\sigma^{1/2}_{T^{iNtr}} \leq \overline{T}^{iNtr} \qquad (6)$$

Carbon dioxide emission are reduced by abatement in the trading and non-trading sectors, A^{Tr}_{if} and A^{NtTr}_{if} respectively, and carbon sink is increased by implementation of measures in each sector, A_{is}^{Tr} and A_{is}^{Ntr}. Cost functions for reductions in each fossil fuel type are written as $C_{if}^{Tr}(A_{if}^{Tr})$ and $C_{if}^{Ntr}(A_{if}^{NtTr})$, and for carbon sink management as $C_{is}(A_{is}^{Tr})$ and $C_{is}(A_{is}^{Ntr})$. It is thus assumed that the costs for carbon sink are the same irrespective of its use as offsets in the ETS of for meeting national allocation plans. All cost functions are assumed to be increasing and convex in their arguments. It is also assumed that the area of land suitable for different land uses is limited in each country according to

$$\sum_s A_{is}^{Tr} + A_{is}^{Ntr} \leq \overline{A}^i \tag{7}$$

The decision problem is formulated as the choice of abatement measures that minimizes total costs, which is written as

$$Min \qquad C = \sum_i \left[\sum_f C_{if}^{Tr}(A_{if}^{Tr}) + C_{if}^{Ntr}(A_{if}^{Ntr}) + \sum_s C_{is}(A_{is}^{Tr}) + C_{is}(A_{is}^{Ntr}) \right] \tag{8}$$

$s.t.$ (1)-(2), (5)-(6)

The first-order necessary conditions are:

$$\frac{\partial C_{if}^{Tr}}{\partial A_{if}^{Tr}} = \lambda \frac{\partial \mu_{T^{Tr}}}{\partial A_{if}^{Tr}} \tag{9}$$

$$\frac{\partial C_{is}}{\partial A_{is}^{Tr}} = \lambda \left(\frac{\partial \mu_{T^{Tr}}}{\partial A_{is}^{Tr}} + \psi \frac{\partial \sigma_{T^{Tr}}}{\partial A_{is}^{Tr}} \right) + \gamma^i \tag{10}$$

$$\frac{\partial C_{if}^{Ntr}}{\partial A_{if}^{Ntr}} = \varphi^i \frac{\partial \mu_{T^{iNtr}}}{\partial A_{if}^{iNtrr}} \tag{11}$$

$$\frac{\partial C_{is}}{\partial A_{is}^{Ntr}} = \varphi^i \left(\frac{\partial \mu_{T^{iNtr}}}{\partial A_{is}^{Ntr}} + \omega^i \frac{\partial \sigma_{T^{iNtr}}}{\partial A_{is}^{NtTr}} \right) + \gamma^i \tag{12}$$

where $\psi = \frac{\phi^{\alpha}}{2(\sigma^{Tr})^{1/2}}$, $\omega^{i} = \frac{\phi^{\beta^{i}}}{2(\sigma^{iNtr})^{1/2}}$, $\lambda<0$ is the Lagrange multiplier on the EU emission restriction in (3), $\varphi^{i}<0$ on the national target restrictions in (4), and γ^{j} on the land use restrictions in (5). In a competitive trading market, the equilibrium permit price is set at $-\lambda$.

By comparing equations (9) and (11) with (10) and (12) we can derive conditions for when carbon sink has a cost advantage compared to emission reduction, which occurs when the marginal abatement cost is lower than that of emission reduction. In a cost effective solution for reaching the EU ETS target, the marginal costs weighted by their impacts, i.e. the left hand sides of (9) and (10) divided by the expression within parentheses at the right hand sides, are equal and correspond to the Lagrange multiplier λ. A positive value of carbon sink then occurs if, at any $A_{is}>0$, the weighted marginal cost of carbon sink is lower than that of emission reductions, which is written as

$$\frac{\frac{\partial C_{is}}{\partial A_{is}^{Tr}}}{\frac{\partial C_{if}^{Trr}}{\partial A_{if}^{Tr}}} < \frac{\frac{\partial \mu_{T^{Tr}}}{\partial A_{is}^{Tr}} + \psi \frac{\partial \sigma_{T^{Tr}}}{\partial A_{is}^{Tr}}}{\frac{\partial \mu_{T^{Tr}}}{\partial A_{if}^{Tr}}} \tag{13}$$

According to (13), carbon sink has a cost advantage when the marginal impact on the target is relatively high and the sink provision cost low. The marginal target impact consists of two parts; reduction in expected sink and increase in variability. The latter implies a marginal risk discount, the level of which depends on the chosen reliability level and on the marginal impact on the total standard deviation. When $\psi \frac{\partial \sigma_{T^{Tr}}}{\partial A_{is}^{Tr}} \geq \left| \frac{\partial \mu_{T^{Tr}}}{\partial A_{is}^{Tr}} \right|$ carbon sink is not an interesting option since the right hand side of (13) then becomes negative. When this is not the case, the value of carbon sink is determined by the abatement costs for all trading sectors in the EU.

The conditions for a positive value of carbon sink for meeting the national allocation plans are derived in a similar way, but the marginal cost of carbon sink is then compared to abatement costs of fossil fuel reductions within a country. Carbon sink is then of higher interest for meeting national allocation plans then the EU ETS target when the country in question faces relatively high abatement costs. This can be seen when comparing (10) and (12), and solving for γ^i, which gives the optimal allocation of carbon sink for meeting EU ETS and NAP as

$$\frac{\lambda}{\varphi^i} = \frac{\left(\frac{\partial \mu_{T^{iNtr}}}{\partial A_{is}^{Ntr}} + \omega^i \frac{\partial \sigma_{T^{iNtr}}}{\partial A_{is}^{Ntr}} \right)}{\left(\frac{\partial \mu_{T^{Tr}}}{\partial A_{is}^{Tr}} + \psi \frac{\partial \sigma_{T^{Tr}}}{\partial A_{is}^{Tr}} \right)} \tag{14}$$

Carbon sink is used for meeting national allocation plans when the right hand side of (14) exceeds the left hand side. The costs of meeting NAP are then reduced more than if the sink is offered at the market at the equilibrium permit price of $-\lambda$. Thus, if abatement in the trading sector is obtained at a lower cost than in the non-trading sector carbon sink will be used for meeting NAP. Similar result was obtained by Gren et al. (2012).

3. Data retrieval

The data needs for empirical assessment consist of abatement costs for all measures, emissions from fossil fuel sources, and mean and variance in carbon sequestration of different land uses for all member states. In addition, we need forecasts on emissions in 2020 since the EU commitment of 20% reductions of CO_2 from the 1990 emission level is supposed to be achieved at the latest this year. Since the focus of this paper is on the role of carbon sinks for meeting EU commitments, we present data for calculations of carbon sinks and quantification of uncertainty in more detail than for the other classes of data. Gren et al. (2012) give references to more detailed presentation of all data on abatement costs for reductions in energy-related emissions and calculations of emissions from different energy sources.

3.1 Calculation of actual and potential carbon sink from different land uses

Carbon sequestration is associated with biomass growth, which, in turn, depends on a number of different factors such as forest management, climate conditions and soil quality (see e.g. van Kooten et al. 2004). This paper makes use of the assessment presented by Janssens et al., (2005), which contains systematic measurement of carbon sequestration for all EU countries and several classes of land uses. The carbon emission intensities presented in Janssens et al. (2005) for forests, arable land, grassland, and peatland are used for calculating both actual and potential carbon sinks in the EU countries. The calculated total amount of carbon sink as measured in carbon dioxides equivalents (CO_2e) from forests amount to 513 million of ton, but this is counteracted by the carbon sources provided by other land uses, see Figure 1.

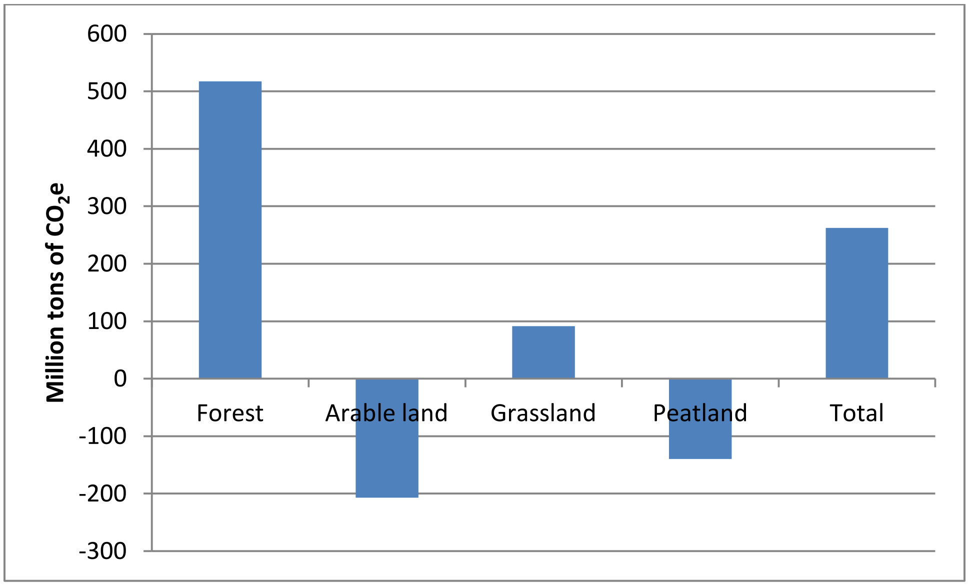

Figure 1: Allocation of existing carbon sink/source in the EU.
Source: calculations based on data in Table A1 in appendix.

Net carbon sink in the EU countries amounts to 262 million tons of CO_2e. Arable land is the main carbon source. Depending on allocation of land uses, the contribution to sink/source among the EU countries shows a large variation, see Figure 2.

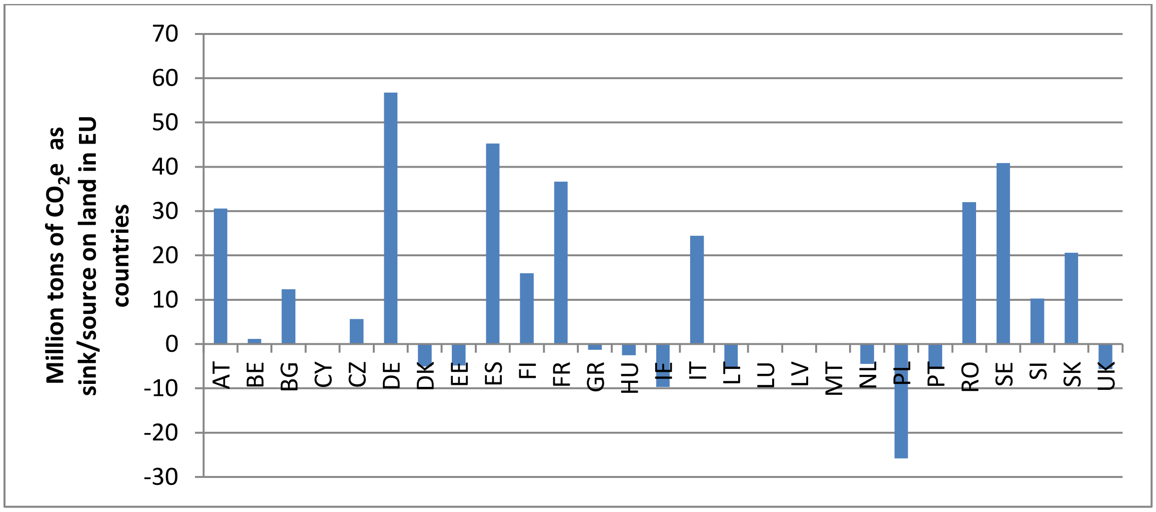

Figure 2: Allocation of existing carbon sink/source among EU countries from forests, arable land, grassland, and peatland. (See Table 1 for acronyms.)
Source: Calculations from Table A1 in appendix

Countries with relatively large areas of forest and grassland provide carbon sinks where Germany, Spain, France, and Sweden are the largest contributors. The carbon source countries are Poland and Ireland, which arise from their relatively high emission intensities from arable land and peat land.

The potential of raising the amount of total net carbon sinks includes increases in carbon sink rich countries and reductions in carbon source from other countries. In principle, changes in carbon sink compared with the baseline presented in Figures 1 and 2 can be made by increasing the rotation period of forests which prolongs the growth period and thereby sequestration, converting areas to forest, and changing land uses practices in agriculture and peat land. With respect to the first type of measure, Kaipanen et al. (2004) estimate that increases in carbon sink from European boreal forests range between 20% and 100% when the rotation period is increased by 20 years. The variation depends on tree species and climate region in Europe. In this paper we assume that the forest sink increases by 40% when the rotation period is increased by 20 years, compared with the baseline for each country presented in Figure 2. The lower range is chosen because of the difficult to transfer results to deciduous forests in other parts of Europe.

According to Weiske (2007) carbon sources from arable land could be decreased by approximately 75-105 Mt CO_2e if a range of practices are implemented, such as reduced tillage, better use of organic amendments, more perennial crops, improved rotations and irrigation. This paper applies a lower range of 30% decrease in carbon source from arable land compared with the baseline presented in Figure 1, and assumes this to be the same for all EU countries. Since much of the reductions in emission are obtained from improved management practices on drained peat land, specific measures on peat land are not included. Finally it is allowed for conversion of agriculture land into forest. Given the short period until 2020, afforestation requires fast-growing tree varieties to provide carbon sequestration. Assuming this can be accomplished, the corresponding net effect on carbon sequestration per unit of land area is calculated as the difference in emission coefficients between the land uses (see Table A1 in appendix). Given all assumptions the total change in carbon sink corresponds to a net increase of approximately 407 Mt CO_2e, which is allocated on the different land uses for entire Europe as shown in Figure 3.

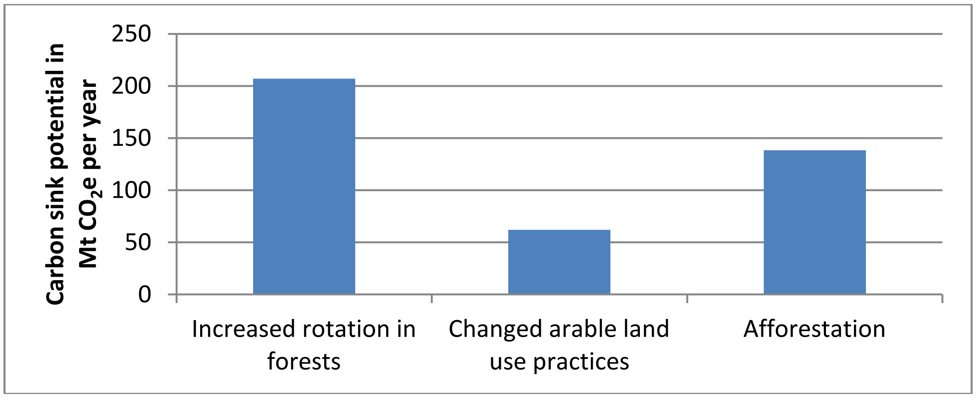

Figure 3: Potential increase of carbon sinks in EU for different land uses as change from the baseline in Figure 1.
Source: Table A2 in appendix.

Undoubtedly, the main increase in carbon sink is obtained from increased rotation period in actual forestry, which accounts for one half of the total potential increases. The allocation of potential carbon sink increase among countries indicates that almost half of the potential is found in four countries; Germany, France, Poland, and Romania, see Figure 4.

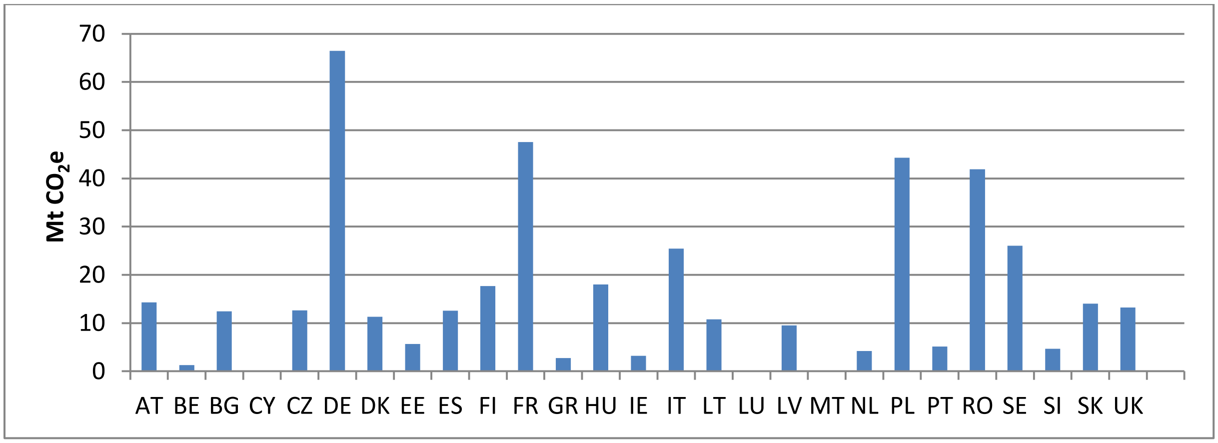

Figure 4: Carbon sink change potential in EU countries a change from the baseline in Figure 2, Mt CO_2e. (See Table 1 for acronyms.)
Source: Table A2 in the appendix.

With respect to restrictions on the total area available and on areas of agriculture land that can be converted to forests, it is assumed that the total area of land uses cannot be changed. For all EU countries, land use is affected by a number of common policies, such as the common agricultural policy and by national interests for food security, rural development, and countryside amenities. However, country-specific investigations of maximum conversion of agriculture land in a short time perspective are not available, and we therefore follow Gren et al. (2012) and assume that the maximum conversion of agriculture land into forests is 20% of the actual arable land area in all countries.

Carbon sink for each of the land uses presented in Figure 4 is associated with a risk, which is measured as their variances. Such data are obtained from Janssens et al (2005) who report standard deviations in carbon sink for each land use. Because of lack of data it is assumed that there is no co-variation in emissions and carbon sequestration among countries and the total risk is then calculated as the sum of all country variances. Table 1 shows the calculated emission, and allocations of risk in carbon sink.

Table 1: CO_2 emission from fossil fuel (thousand tons), carbon sink as share of forecasted emission in 2020 per country and in total, and allocation of risk in total carbon sink when all measures are implemented.

Acronyms and countries		*Emissions in 2006 from fossil fuel per country and in total, kton CO2e* [1]	*Max share in % of potential sink of 2020 emissions per country and in total*[2]	*Allocation of total EU sink risk, in %*[3]
AT	Austria	69675	0.18	1.07
BE	Belgium	128396	0.01	0.09
BG	Bulgaria	46934	0.24	0.59
CY	Cyprus	8441	0.00	0.00
CZ	Check Republic	117617	0.11	1.16
DE	Germany	816432	0.08	32.01
DK	Denmark	60944	0.23	0.34
EE	Estonia	14851	0.32	0.24
ES	Spain	355472	0.03	6.86
FI	Finland	67425	0.32	1.57
FR	France	383634	0.12	13.14
GR	Greece	103986	0.03	0.05
HU	Hungary	53547	0.28	2.59
IE	Ireland	47363	0.06	0.15
IT	Italy	446523	0.05	3.82
LT	Lithuania	13149	0.65	1.12
LU	Luxembourg	12383	0.01	0.00
LV	Latvia	8788	0.83	0.67
MT	Malta	2709	0.00	0.00
NL	Netherlands	225081	0.02	0.22
PL	Poland	310308	0.13	15.92
PT	Portugal	58795	0.07	0.37
RO	Romania	93080	0.35	11.53
SE	Sweden	52514	0.42	2.98
SI	Slovenia	15613	0.25	0.14
SK	Slovakia	35411	0.32	1.05
UK	United Kingdom	567793	0.02	2.32
	Total	4116864	0.10	100

Source: 1) Gren et al., (2012) Table 1; 2) Coefficient of variation calculated from the data in Table A1 in appendix.

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In total, maximum increase in carbon sequestration compared to the baseline in Figure 1 amounts to approximately 10% of total calculated forecasted emissions in the target year 2020. This is considerable when comparing with the target reduction of 20% in 1990 emission which requires a reduction of 24% in forecasted emissions (Gren et al., 2012). For several countries, the potential carbon sink corresponds to at least 30% of the forecasted emissions in 2020.

In addition there is a need to describe the uncertainty with respect to type of probability distribution. The choice will affect the level of the discounting ϕ^{α} and $\phi^{\beta^{i}}$ in equations (5)-(6) in Section 2. A standard practice is to assume a normal probability distribution and ϕ^{α} is then a standard number such that $\int_{-\infty}^{\phi\alpha} f(\phi)d\phi = \alpha$, where ϕ is the standardized distribution of the sink and $f(\phi)$ is the probability density function for ϕ (see e.g., Taha, 1976). This approach is frequently applied in the literature on policy instruments for stochastic water pollution (McSweeny and Shortle, 1990; Shortle, 1990; Byström, et al., 2000; Gren, 2010). In this paper we follow the practice of using the normal probability distribution. For alternative specifications, see McCarl and Spreen (2010), Gren et al. (2012) and Gren (2012). It is also assumed that the assigned probabilities are the same for all countries and for the trading market.

3.2 Carbon sequestration and emission reduction costs

The carbon sink can increase, and hence incur costs, by changing timber management and the allocation of land from low- to high-sink land intensities (see van Kooten et al., 2005, for a review and meta-analysis of carbon sequestration options and costs). Ideally, cost functions for providing carbon sequestration would be available for each country, showing the allocation of sequestration by different options, which minimizes total costs for each sequestration level.

Unfortunately, such cost functions are not available. Relatively simple estimates are therefore used for assessing costs of increasing the rotation period in forests, converting arable land to forests, and reducing carbon dioxide emissions from arable and peat land. Costs for increasing rotation period are defined as the associated decreases in optimal profits. They are determined by a number of different factors, such as expected prices on timber and saw logs, discount rate, and biomass growth. According to Kaipanen et al., (2007) there is only minor impact on profits from prolonged rotation period. However, a delay in harvesting by 20 years impacts profits as measured in present terms, the magnitude of which depends on the discount rate. In this paper it is assumed in the reference case that profits, which are measured as incomes from forestry obtained in UNECE (2012), decrease by 20%. Incomes from forestry per ha in different countries are shown in Table A4 in appendix.

Similarly, there are no data on costs of changed practices on arable land in the EU. Enkvist et al. (2007) report a range in cost between 15 and 50 Euro/ton CO_2e reduction depending on which practices are implemented. Changes in manure treatment are relatively inexpensive and conversion of land use for energy production expensive. These costs are related to the profit from arable land under business as usual conditions, and will therefore differ between the EU countries. When measuring these profits as rents for arable land, they vary between 33 and 466 Euro/ha (see Table A4 in appendix). The higher cost for reducing carbon emissions reported by Enkvist et al. (2007) would correspond to approximately 25% of these profits. Due to lack of better data, it is assumed that this percentage on profit reduction is the same for all EU countries, and, hence, generates constant marginal costs for reducing emission from arable land in each country. Costs of converting arable land to forests are obtained from Gren et al. (2012), where the costs are calculated as associated decreases in producer surplus. These costs are derived from estimated linear supply functions of agriculture land, which are calculated based on point estimates of rental value and supply of agriculture land and the elasticity of 0.2.

Data on costs of emission reductions are obtained from Gren et al., (2012), which are calculated as corresponding decreases in consumer surplus derived from energy demand functions for three main classes of energy products: oil products (heavy fuel oil, light fuel oil/heating oil, gasoline, diesel, and jet kerosene), coal (hard coal and lignite), and natural gas. These demand functions are, in turn, assumed to be linear and are calculated by means of data on input price elasticities, price level, and input use for the year 2006. Separate demand functions are calculated for three different sectors; the industry sector, the power sector, and the households.

4. Results

The value of carbon sequestration is calculated as the difference in total abatement costs with and without the inclusion of the sequestration options. Calculations are made for the EU independent commitment of reducing total emission by 20% in 2020 under assumptions of two different institutional settings. One is the program from 2005 which is modeled in Section 2 with a market for emission trading (ETS) and national allocation plans. The other is a hypothetical setting, which is a plausible future scenario, where all sector are allowed to trade. Given the large number of simplifying assumptions presented in Section 3 in particular with respect to costs and effects of the included land use changes, Monte Carlo simulations are carried out for ranges in these parameter values in order to investigate the implications of parameter uncertainty for the results. GAMS' solver Conopt2 is used for all calculations (Brooke et al., 1998).

4.1 Results in the reference case

As shown in Section 2, the higher the abatement cost without carbon sink and the lower cost of carbon sink, the higher is the value of the sink. This is the reason for the relatively high value under the system with EU ETS and national allocation plans, denoted EU2020, compared to a system where all sectors trade, denoted Market, see Figure 5.

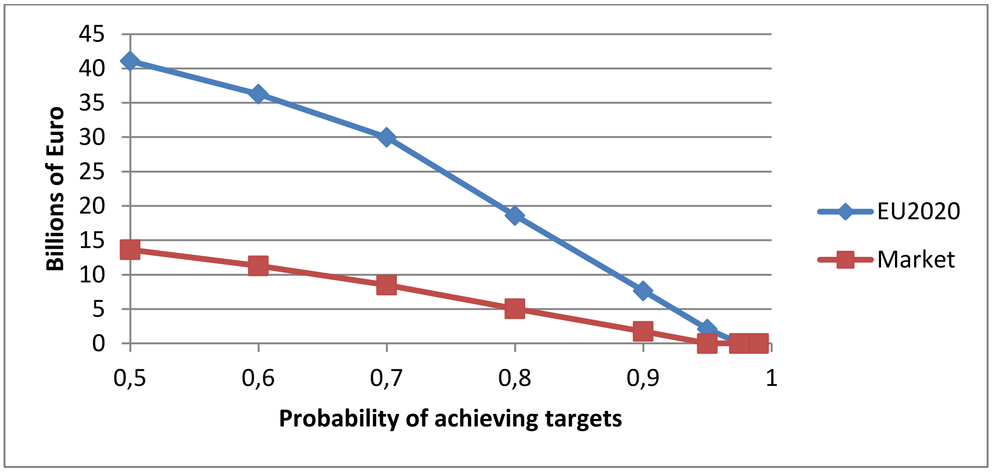

Figure 5: Value of carbon sink for different probabilities of achieving the target of reducing emissions by 20% in 2020, and EU2020 (ETS and NAP) and Market (ETS for all sectors)

The total cost for reaching the EU2020 under deterministic and no sink cases is found for the probability of 0.5 for the normal distribution; it amounts to 98 billion Euro/year which corresponds to approximately 0.9 % of total GDP in the EU countries in 2006. The associated allowance price is 46 Euro/ton CO_2 emission. When we compare these estimates with the results of other studies, we note that they fall in the upper level of the range (e.g. Capros et al., 2008; Stankeviciute et al., 2008; Böhringer et al., 2009). The total estimated costs in Capros et al. (2008), who used a general equilibrium model of the EU countries, range between 75 and 111 billion Euro/year, which correspond to approximately 0.6 % and 1 % respectively of the sum of GDP in all EU countries in 2006. When all sectors trade, the total cost of achieving the 20% target is reduced to about one half, to 46 billions of Euro, which is a result in line with the literature (see Börhinger et al. 2009 for a review).

The difference in costs for achieving targets under the no sink cases between the institutional settings explains corresponding difference in the value of carbon sink. The cost of carbon sink is the same regardless if it is used at the market or for meeting NAP. The costs for most countries are higher under EU2020 because of the allocation of NAP where marginal abatement costs differ in the non-trading sectors among the countries and exceed the allowance price on the trading market. They therefore use most of the carbon sink for meeting the NAP, and the value of carbon sink is almost three times as large as when there is an overall trading market. However, under both institutional settings, the value declines for higher reliability levels because of the risk discount, and approaches zero when the chosen probability for achieving the targets is 0.95

However, the value is unevenly distributed among the countries under both institutional settings, but in different ways. Under EU2020 most countries make gains from reducing costs of meeting NAP, and relatively little sink is offered on the ETS. This is shown in the price of ETS that is reduced from Euro 42/tCO_2 in the no sink case under EU2020 to Euro 40/tCO_2 with sink and a p=0.8, and to Euro 35/tCO_2 under deterministic conditions when p=0.5 . Then, a few countries, Germany, France, Italy, and Sweden, account for almost one half of the total value of carbon sinks, see Figure 6.

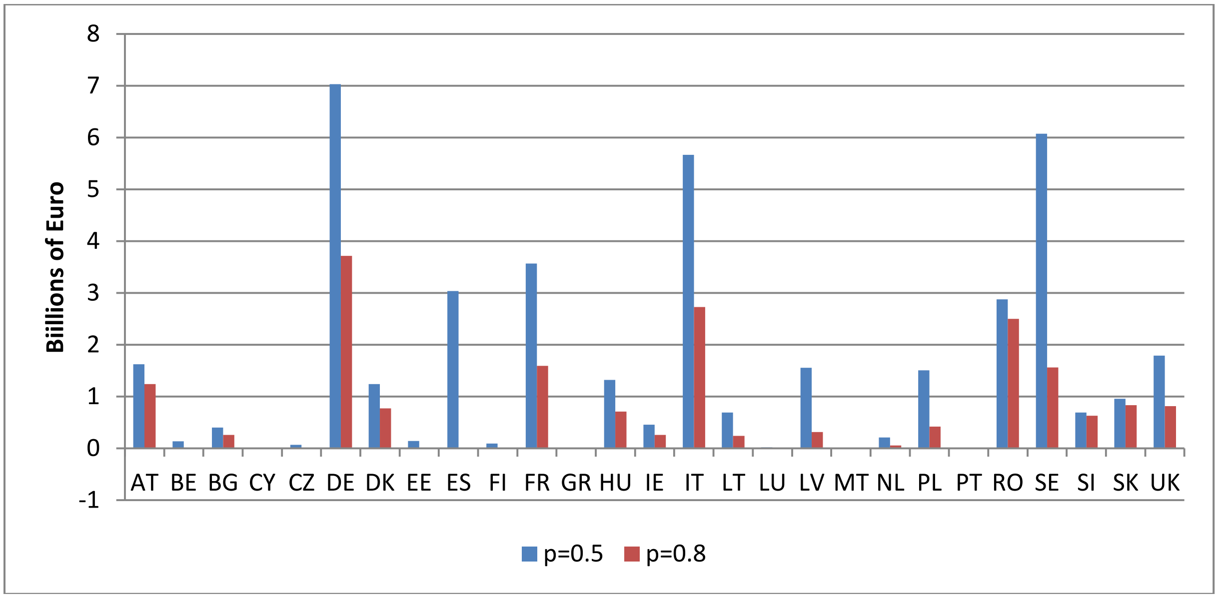

Figure 6: Allocation of values of carbon sink among countries net after trade under EU2020 when probability of achieving the target is 0.5 (p=0.5) and 0.8 (p=0.8). (See Table 1 for acronyms).

As shown in Figure 6, the value of carbon sink is reduced considerably for some countries when reliability is of concern. The overall reduction in the value is approximately 55%, which also corresponds to the reduction in value for Germany, Italy, and France. However, for other countries, such as Sweden and Spain, the value shows a more drastic decline which is due to the risk discount. For Spain, the value is eliminated because of the relatively high risk in reducing emissions from arable land.

The pattern of value allocations among countries is changed when there is a market for all sectors. Gains are then made by lower abatement costs which reduce demand for permits on the market. The price is then reduced by approximately 50% when p=0.5, from approximately 55 Euro/tCO_2 to 27 Euro/tCO_2. Countries purchasing permits gain from this price decrease while countries with relatively low cost options for reducing emissions make losses from lower sales prices, see Figure 7.

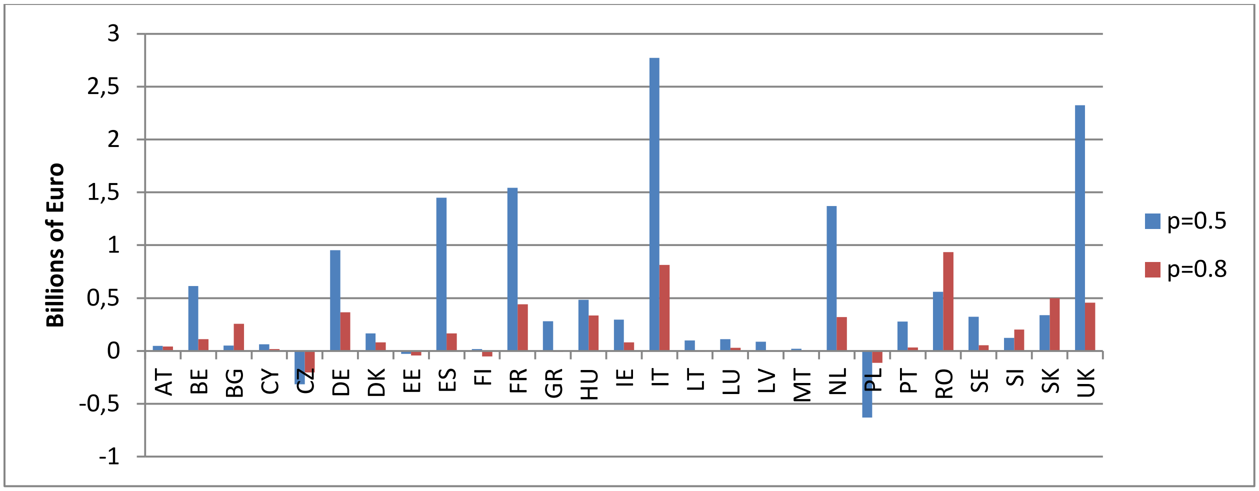

Figure 7: Allocation of values of carbon sink among EU countries net after trade when all sectors trade and the probability of achieving the target is 0.5 (p=0.5) and 0.8 (p=0.8). (See Table 1 for acronyms).

The level of values of carbon sink is considerably lower when all sectors trade compared to EU2020 because of the lower cost of meeting the overall target. Countries making the largest gains from the lower price of permits when p=0.5 are Italy, UUK, France, Spain and the Netherlands. For some countries, the value of carbon sink is negative; Czech Republic, Estonia, and Poland. The equilibrium permit price increases to 41 Euro/tCO_2 when p=0.8, which increases the value of carbon sinks from permit sales for Bulgaria, Romania, Slovenia and Slovakia.

4.2 Monte Carlo simulations

The results presented in Section 4.1 rest on several simplifying assumption with respect to impacts of increased rotation in forests and of arable land use practices, and associated costs. Monte Carlo simulations are therefore carried out where calculations of values are made for a combination of 100 random numbers within ranges for these variables, which are presented in Table 2.

Table 2: Ranges in impact and costs of increased forest rotation and arable land use practices

Variable	*Range*
Carbon sink of forest rotation, in % of actual sink from forest (Table A1)	10 – 80
Decrease in emissions from arable land use change, in % from actual emission (Table A1)	15 – 50
Cost of forest rotation, % of factor income (Table A4)	0 – 100
Cost of arable land change, % of rent (Table A4)	5 - 100

Calculations are carried out for EU2020 and when all sectors trade, but only for risk neutrality when p=0.5 (for a normal probability distribution), because of the relatively high carbon sink values in this case. It can also be argued that the probabilistic constraints account for the uncertainty in carbon sink.

Given the ranges displayed in Table 2, the total value of carbon sink for all EU countries can vary between 3003 and 57555 billions of Euro, and the average value amounts to 31076 billions of Euro under an EU2020 policy, see Table 3. Thus, in spite of zero risk discount, the value can be quite low which occurs when the impact of increased rotation is small and the cost is relatively high.

Table 3: Descriptive statistics for value of carbon sink total EU and for different countries under EU2020, n=100 (See Table 1 for acronyms).

	Average, billions of Euro	*Standard deviation*	*Coefficient of variation*	*Min value, billions of Euro*	*Max value, billions of Euro*
Total EU	31975.57	15033.64	0.47	3003	57553
Countries:					
AT	957.80	655.53	0.68	1.57	2251.10
BE	82.99	95.99	1.16	0.61	341.64
BG	300.09	143.25	0.48	10.55	554.84
CY	2.24	1.94	0.87	0.33	8.18
CZ	30.71	66.98	2.18	-109.80	294.13
DE	4711.62	2554.01	0.54	0.11	9041.75
DK	1126.31	433.21	0.38	133.36	1707.61
EE	96.36	49.10	0.51	12.98	212.39
ES	2466.90	1574.98	0.64	0.21	5709.51
FI	47.90	96.11	2.01	0.51	418.22
FR	1900.78	1722.29	0.91	4.56	5845.12
GR	7.33	27.42	3.74	-0.14	150.29
HU	1188.56	458.82	0.39	124.46	1778.96
IE	448.36	212.72	0.47	24.52	827.46
IT	4870.63	2447.63	0.50	5.60	9500.51
LT	561.93	162.12	0.29	112.95	815.22
LU	15.58	2.58	0.17	11.72	22.25
LV	1380.16	229.73	0.17	695.27	1723.86
MT	0.82	0.84	1.02	-0.03	3.42
NL	167.10	144.53	0.86	1.90	535.16
PL	926.00	594.75	0.64	0.20	2066.52
PT	11.17	52.46	4.69	-2.59	287.03
RO	2654.45	489.06	0.18	1382.65	3345.10
SE	4283.08	1938.10	0.45	19.27	7240.80
SI	589.12	136.35	0.23	208.36	793.71
SK	823.03	223.38	0.27	240.36	1158.41
UK	1704.57	902.65	0.53	17.20	3682.89

The average value is positive for all countries, and Germany, Spain, Italy, Sweden and Romania accounts for almost 2/3 of the total average value. All these countries but Romania make considerable gains from less expensive achievement of their NAP. The low cost of increased forest rotation in Romania (see Table A4 in appendix) generates gains from supplying carbon sink at the trading market. However, the variability in values, measured as the coefficient of variation, differ between the countries, being quite small for Latvia and Romania and high for Portugal and Greece. The low opportunity cost of land conversion in Latvia and low cost of increased forest rotation period in Romania generate incomes from sales of permits also under relatively unfavorable conditions. For other countries, these conditions determine whether carbon sink is used for meeting NAP or offered in the market, which creates larger variations in values.

When all sectors trade, the pattern with respect to winners and losers from carbon sink presented in Figure 7 remains the same; buyers of permits make gains and sellers make losses, see Table 4.

Table 4: Descriptive statistics for value of carbon sink total EU and for different countries under market for all sectors. (See Table 1 for aronyms).

	Average	*Standard deviation*	*Coefficient of variation*	*Min*	*Max*
Total EU	10539.87	6568.32	0.62	111	25956
Countries:					
AT	212.11	157.54	0.74	-52.01	706.46
BE	460.44	268.42	0.58	6.36	929.50
BG	43.07	37.55	0.87	-56.45	105.87
CY	46.85	25.57	0.55	0.69	87.00
CZ	-144.03	114.59	0.80	-384.67	145.02
DE	606.94	832.65	1.37	-518.10	3181.43
DK	95.68	98.90	1.03	-64.72	330.69
EE	-59.48	57.03	-0.96	-180.32	11.99
ES	1059.26	602.32	0.57	15.68	2264.28
FI	14.97	61.72	4.12	-259.92	151.88
FR	1615.84	931.52	0.58	23.70	3609.98
GR	210.87	132.80	0.63	2.06	484.11
HU	360.35	208.24	0.58	2.17	686.76
IE	213.34	120.47	0.56	3.42	429.08
IT	2095.38	1236.87	0.59	30.26	4608.32
LT	2.88	108.87	37.75	-197.65	193.06
LU	83.36	45.52	0.55	1.25	155.82
LV	-2.18	119.02	54.47	-303.60	209.65
MT	16.34	8.97	0.55	0.23	30.53
NL	1015.99	598.05	0.59	12.23	2072.38
PL	-668.21	441.95	0.66	-1485.57	-8.71
PT	206.05	114.15	0.55	2.04	395.47
RO	544.18	267.44	0.49	-243.88	897.22
SE	207.96	182.19	0.88	-217.99	513.82
SI	73.12	67.72	0.93	-71.54	180.00
SK	280.80	144.92	0.52	-190.15	421.01
UK	1700.33	1055.70	0.62	26.50	3837.05

It is interesting to note that, for Poland, even the maximum value of carbon sink is negative because of the decline in permit price. Without sink option, this country make larger gains from offering permits at the market due to the relatively low abatement cost for reducing fossil fuels. For other countries, such as Italy and UK, the results show no negative values because they are always buyers of permits and gain from the lower equilibrium prices compared with a market without carbon sink option. It can also be noted that volatility in values increase for countries being sellers at the market and relying on carbon sinks, such as Latvia and Lithuania, because of the fluctuating equilibrium permit prices.

5. Discussion and conclusion

This paper analyzed and quantified the value of increasing carbon sinks as a climate change mitigation option in the current EU climate policy with a combination of emission trading (ETS) and national allocation plans, and a potential system with one market for all sectors. The replacement cost method was applied which measures the value as the difference in costs for achieving given targets without carbon sink when only reductions from fossil fuel use are included with the costs when carbon sinks are included. Three options for increasing carbon sinks were included; increased rotation in forests, afforestation of arable land, and changed land use practices on arable land. The theoretical analysis, which builds on a safety-first approach where total costs for achieving emission targets are minimized under probabilistic constraints, shows that carbon sink is not included in a cost effective solution for high enough risk discount. It was also shown that the allocation of carbon sink for meeting national targets and the EU ETS target depends on the relation between marginal abatement costs in the trading and non-trading sectors. When costs are relatively high for the non-trading sector, which is the case for many EU countries, carbon sink values arise from reduction in costs for meeting the national allocation plans.

The empirical application to the EU commitment of 20% CO_2 reduction to be achieved in 2020 showed that, the value of all carbon sink options can vary between 0 and 40 Billions of Euro depending on reliability concern and institutional framework. The value is largest under current EU system with national allocation plans and ETS because of the significant cost savings when the sink can used to reduce costs for meeting the currently expensive national targets. However, the value decreases for increased reliability concern and approaches zero when the assigned probability of achieving the targets exceeds 0.9. The value of carbon sink is also lower when all sectors are allowed to trade because costs for meeting targets without carbon sequestraion is lower in that case than under the current system. The allocations of carbon sink values among countries differ for the two institutional settings. Under current EU trading system countries with carbon sink options, such as Germany and Sweden, make gains from reduced cost for achieving national targets. When all sectors trade, countries purchasing permits, like Italy and UK, make the largest gains because of the reduction in equilibrating permit price from the introduction of carbon sinks. On the other hand, sellers of permits then face negative values of carbon sink where Poland is a prominent example,

Admittedly, the results presented in this paper rest on a number of simplifying assumptions. The most challenging data needs have been to find estimates of effects and costs of different carbon sink options. Although there is relatively much information on current land use and carbon sink or source, there is only scattered investigation of measures increasing carbon sink or reducing carbon releases. Monte Carlo simulations were therefore carried out for ranges of impacts and costs of increased forest rotation and changes arable land use practices, which showed great variation in carbon sink values. The simulations were carried out without any risk discount, and even in this case the sink value could be very low, but also very high, depending on impacts and costs of the measures. This calls for more investigations of impacts and costs, preferably in the same study. Although there are some studies estimating impacts of changed land use practices, they usually don't contain any cost estimates. Furthermore, there is little quantification of uncertainty in impacts.

Other simplifications were associated with the calculation or risk and concern of risk in different countries. Level of concern about achievement of emission targets and beliefs with respect to risk in carbon sinks relative to other measures determine the value of carbon sink. This points to the need of careful analyses and quantification of uncertainty extending beyond the simplifications made in this paper. Availability of data which allow for the relaxation of assumptions made with respect to zero co-variation among measures and countries may either enforce or counter act our empirical results. For example, a positive co-variation between carbon sink and carbon emissions from fossil fuels reduces total risk and, hence, increases the value of carbon sink. The sink capacity is then high when carbon emissions are large and forest sink acts as a hedging device. Another limitation of the study is the neglect of transaction cost, which is regarded as a particular disadvantage of carbon sink due to the monitoring difficulties (e.g. Antle et al., 2003; Antinori and Sathaye 2007; Sohngen, 2009). This is partly accounted for in the risk discount of carbon sink used in the paper. Improved monitoring is likely to reduce the uncertainty and thereby the risk discount.

Appendix: Tables

Table A1: Carbon emission intensities and coverage of land use in EU countries. (See Table 1 for acronyms.)

	Carbon emission intensities, tC/ha[1];				*Coverage of land, 1000ha:*				
	Forest	*Arable land*	*Grassland*	*Peat land*	*Forest[2]*	*Arable[2] land*	*Grassland[2]*	*Peat [3] land*	*Total*
AT	2.08	-0.42	0.59	6.66	3620	1375	1854	126	8387
BE	0.62	-0.2	0.47	-2778.2	621	840	528	10	3053
BG	1.19	-0.43	0.2	-666.00	4076	3053	2031	5	11100
CY				0.00	116	93	48	1	925
CZ	1.5	-0.79	0.27	-3.82	2593	2626	970	1445	7887
DE	2.13	-0.59	0.49	-128.02	10799	11890	5106	1785	35705
DK	3.14	-0.63	0.24	-1034.40	476	2478	241	25	4310
EE	0.7	-2.36	0.25	-144.52	2252	556	204	820	4523
ES	0.32	-0.09	0.52	0.00	14191	12482	12634	20	50536
FI	0.39	-0.8	1.87	-43.09	22146	2266	68	10044	33815
FR	0.87	-0.33	0.31	-70.93	16384	21144	11039	542	54919
GR	0.1	-0.38	0.22	-119.96	6560	2072	1412	55	13196
HU	1.93	-0.73	0.26	-583.72	1806	4493	1209	102	9303
IE	0.81	-0.2	0.24	-284.77	554	1153	3114	1301	7030
IT	0.85	-0.44	0.41	-2909.30	11261	7352	5906	29	30132
LT	1.23	-1.47	0.12	-84.71	2030	1835	862	185	6530
LU	1.27	-0.18	0.3	-785.63		61	70	3	259
LV	1.08	-1.55	0.15	-126.93	2929	1188	652	402	6459
MT				0.00		8	1	1	32
NL	1.68	-0.51	0.42	-548.03	479	1042	833	321	3735
PL	1.11	-0.75	0.38	-544.70	8991	11757	3658	1504	31268
PT	0.47	-0.7	-0.1	-680.82	3476	1186	2500	27	9191
RO	1.99	-0.54	0.28	-80.81	6755	8820	4839	59	23839
SE	0.48	-1.07	0.4	1.71	27947	2646	90	10502	44847
SI	2.46	-0.33	0.12	56.31	1174	174	324	18	2027
SK	3.25	-0.64	0.55	-61.29	1932	1343	554	56	4903
UK	1.04	-0.3	0.52	-122.14	2494	5492	5736	5496	24410

1) Janssens et al., 2005; 2) Gren et al., 2012, 3) Montanarella, 2006

Table A2: Potential changes in carbon sinks from alternative land uses, Mt CO_2e. (See Table 1 for acronyms.)

	Increased rotation by 20 years[1]	*Changed arable land use practises*[2]	*Afforestation*[3]	*Total*
AT	11.05	0.64	2.52	14.21
BE	0.57	0.18	0.51	1.26
BG	7.12	1.45	3.63	12.2
CY	0.00	0.00	0.00	0
CZ	5.71	2.28	4.41	12.4
DE	33.77	7.72	23.74	65.23
DK	2.19	1.72	6.86	10.77
EE	2.31	1.44	1.25	5
ES	6.67	1.24	3.76	11.67
FI	12.68	2.00	1.98	16.66
FR	20.92	7.68	18.62	47.22
GR	0.96	0.87	0.73	2.56
HU	5.12	3.61	8.77	17.5
IE	0.66	0.25	0.85	1.76
IT	14.05	3.56	6.96	24.57
LT	3.67	2.97	3.64	10.28
LU	0.00	0.01	0.06	0.07
LV	4.64	2.03	2.29	8.96
MT	0.00	0.00	0.00	0
NL	1.18	0.59	1.67	3.44
PL	14.65	9.71	16.05	40.41
PT	2.40	0.91	1.02	4.33
RO	19.73	5.24	16.38	41.35
SE	19.69	3.12	3.01	25.82
SI	4.24	0.06	0.36	4.66
SK	9.22	0.95	3.83	14
UK	3.81	1.81	5.40	11.02
Total	207.01	62.04	138.3	407.35

1) Kaipanen et al. (2004), 2) Wieske (2007), 3) Difference in sink/source emission intensities between forest and arable land in Table A1

Table A3; Standard deviations in tC ha^{-1} . (See Table 1 for acronyms.)

	Forest	*Arable land*	*Grassland*	*Peatland*
AT	0.83	0.30	1.15	0.67
BE	0.25	0.72	0.72	15.27
BG	0.45	0.19	0.38	22.20
CY	0.00	0.00	0.00	0.00
CZ	0.60	0.66	0.54	0.05
DE	0.85	0.65	0.45	0.60
DK	0.43	0.40	0.46	25.86
EE	0.28	1.67	0.49	0.72
ES	0.13	0.43	0.20	25.27
FI	0.16	0.48	21.38	0.20
FR	0.35	0.21	0.23	1.01
GR	0.04	0.22	0.18	2.40
HU	0.77	0.52	0.49	0.91
IE	0.33	0.30	1.26	1.40
IT	0.34	0.38	0.15	10.39
LT	0.49	1.12	0.25	0.35
LU	N/A	0.84	0.46	4.32
LV	0.43	1.24	0.29	0.64
MT	N/A	0.00	0.00	0.00
NL	0.67	0.75	1.03	2.68
PL	0.45	0.60	0.74	2.70
PT	0.19	1.01	0.18	3.40
RO	0.80	0.46	0.56	4.04
SE	0.19	0.29	16.44	0.04
SI	0.98	0.55	0.23	1.13
SK	1.30	0.55	1.10	0.88
UK	0.41	0.46	0.85	0.58

Source: Calculated from Janssens et al. (2005) and allocation of land in Table A1

Table A4: Rents for arable land and factor incomes from forestry, Euro/ha. (See Table 1 for acronyms.)

	Rent for arable land[1]	*Factor incomes from forestry*[2]
AT	456	515
BE	466	300
BG	100	53
CY	61[7]	104[7]
CZ	33	309
DE	456	332
DK	456	348
EE	33	72
ES	176	99
FI	175	264
FR	176	236
GR	61	104[3]
HU	61	104
IE	183	108[4]
IT	176	150
LT	33	120
LU	466	310
LV	33	120[5]
MT	176	150
NL	466	310
PL	61	120[5]
PT	176	567
RO	100	53[6]
SE	105	187
SI	33	144
SK	33	117
UK	173	108

Sources: 1) Gren et al., (2012), Supplementary material, Table S2, 2) Factor and entrepreneur incomes from UNECE 2012; 3) assumed the same as in Hungary; 4) assumed the same as in UK; 5) assumed the same as in Lithuania; 6) assumed the same as in Bulgaria; 7) assumed the same as in Greece.

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