Forest Policy and Economics 159 (2024) 103127

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

A trading market for uncertain carbon removal by land use in the EU

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ARTICLE INFO

JEL codes:
Q54
Q57
Q58

Keywords:
Carbon removal
Uncertainty
Cost-efficiency
Trading market
EU

ABSTRACT

This paper designs a trading market for uncertain carbon removal from uptake and reduced leakage by restoration of drained peatland, forest management and afforestation in the EU countries. A cost-efficient design of the quantification of carbon removals takes uncertainty into account by introducing a risk premium that differs between countries and measures. Given the cost-efficient design with risk premiums, the marginal and total costs of achieving carbon removal targets for the EU are higher with reliability concern than without because of the larger carbon removals in order to ensure the achievement of a target at a given probability. The results show large differences in costs after trading where some countries meet high costs and other countries make net gains by selling carbon credits on the market. An evaluation of the EU's regulation on legally binding carbon sink assignments for different countries shows that the total cost of a cost-efficient flexibility with trade could be reduced by 50% compared with no trade, and that all countries benefit from such a change.

1. Introduction

On a global scale, carbon removal by forests from capturing CO_2 from the atmosphere and storing in soils and products amounts to approximately 7.6 Gt CO_2e, corresponding to 22% of total emissions (Harris et al., 2021). Numerous suggestions have been made to increase nature based measures for carbon removal in order to achieve national and international climate targets. Austin et al. (2020) highlight a potential of additional 5.2 Gt CO_2e from improved forest management and avoided deforestation on a global scale. Although promising, this should be considered with caution because of the uncertainty in carbon removal or reduced leakage due to weather conditions and difficulties to measure, monitor and verify carbon removals, which is a disadvantage compared with reductions in CO_2 emissions (e.g. Anderegg et al., 2020). Given the concern in society with achieving climate targets, uncertainty of this kind implies a cost. This has been recognised in the literature on policies for carbon removals and in the design of policies in practice since early 1990s (see Gren and Aklilu (2016) for a review).

In practice, carbon removal was introduced as an offset option under the Kyoto Protocol, and has been covered in programmes for grants or trading markets in several countries, including New Zealand, Australia and the USA (Grafton et al., 2021). Uncertainty in carbon removal has been taken into consideration in different ways, but a common practice has been to follow recommendations from the literature and reduce payments depending on the degree of uncertainty (Gren and Aklilu, 2016). Despite the large body of literature on policies for carbon removal and experiences in practice, and the early construction of the largest emission trading market, the introduction of carbon removal is in its early stages in the EU. The amended LULUCF (Land Use, Land Use Change and Forestry) regulation went into force in May 2023 to increase carbon removal by approximate 17% from the total level of 263 Mt. CO_2e per year (EC, 2023a). The regulation sets legally-binding carbon removal targets for each member state, with a flexibility to trade assignments between countries. It is well known in economics that such a trade is likely to result in lower total costs compared with those of no trade.

Costs of increasing carbon removal have been calculated since early 1990s (reviews in Richard and Stokes, 2004; van Kooten et al., 2009). Several studies have shown that the cost of achieving the target of reducing GHG emissions at a global scale and within EU can decrease considerably when introducing carbon removal as an offset option (e.g. Pohjola et al., 2003; Michetti and Rosa, 2011; Munnich-Vass et al., 2013), but that the cost savings can decrease when accounting for uncertainty (Gren et al., 2012; Gren and Carlsson, 2013).

Regarding policy design, several studies simulate the effects on carbon removal of implementing a payment per tonne CO_2e removal but do not consider uncertainty (e.g. Sohngen and Mendelsohn, 2003; Sjølie et al., 2013; Griscom et al., 2017; Guo and Gong, 2017; Austin et al., 2020; EC, 2021a). A few studies have suggested risk discounting of the prices of carbon removal to account for differences in risk between

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https://doi.org/10.1016/j.forpol.2023.103127
Received 9 June 2022; Received in revised form 3 August 2023; Accepted 4 December 2023

climate mitigation measures (e.g. Kurkalova, 2005; Kim and McCarl, 2009; Gren et al., 2012). This has also been suggested and implemented in practice in the USA for trading of credits between water polluters (e.g. Milon, 1987; McSweeny and Shortle, 1990).

The purpose of this study is to design and calculate the costs of a trading market for carbon removal at the EU level that account for differences in uncertainty in carbon removal between countries and measures, which has not been made before. Carbon removal is then not regarded as an offset for emission reductions within the EU ETS, but as a separate trading market. There are two main reasons for such a separate market. One is the existing LULUCF regulation with country targets on carbon removal, and the other is the need for reducing emissions from fossil fuels and increasing carbon removal. A separate trading market does not affect the targets for emissions from fossil fuel, although it would, in principle, be possible to enlarge the current EU ETS market to include carbon removal measures.

A chance-constrained programming model is developed to account for uncertainty, which has a long tradition in economics of cost-efficient and uncertain achievement of production targets (e.g. Tesler, 1955). This method has been used in several other studies designing policies for carbon removal under uncertainty (e.g. Kurkalova, 2005; Kim and McCarl, 2009; Gren et al., 2012). A given carbon removal target is then achieved only with a certain probability, and the regulator has to choose the target and the reliability level of its achievement. The numerical model includes three main options for each EU country: forest management, afforestation, and restoration of drained peatland. Simplifications are made by developing a static numerical model, with probabilistic targets based on marginal abatement cost (MAC) and uncertainty for each measure and country. The motivation for the simple MAC approach is to ensure that uncertainty in carbon removal is considered in the decision problem.

The paper is organised as follows. The model for the cost-efficient design of the carbon removal market is presented in Section 2, and data retrieval is described in Section 3. The results of cost-efficient trading are presented in Section 4, which are discussed in Section 5. The study ends with the main conclusions in Section 6.

2. Model of cost-efficient market design

A basic premise is that the regulator wishes to design a trading market that minimizes the costs of achieving given targets for uncertain carbon removal at the EU level. Three different measures are included – forest management, afforestation, and restoration of drained peatland – which are described in more detail in Section 3. Avoidance of deforestation is suggested in the literature as a low-cost measure with high potential (e.g. Austin et al., 2020), but is not included in this study since deforestation is relatively minor and corresponds to approximately 0.1% of the forest area in the EU (Frank et al., 2020). Although avoidance of deforestation in countries outside the EU could be a promising measure, it is not included in this study owing to the focus on land use in the EU.

For each country i, where $i = 1, \dots n$ countries, carbon removal measures k are included where $k = 1,2,3$ (1 forest management, 2 afforestation, 3 restoration of drained peatland). The carbon removal from each of the measure depends on land areas devoted to the measure, A^{ik}, and the carbon removal per area, s^{ik}, which is stochastic with $s^{ik} = \mathrm{\mu}^{ik} + \varepsilon^{ik}$ where μ^{ik} is the mean removal per unit of A^{ik} and ε^{ik} is an additive stochastic term with $E[\varepsilon^{ik}] = 0$ and $Var(\varepsilon^{ik}) = \sigma^{ik}$. Total increase in carbon removal, S, from a base level depends on the area of the carbon removal measure and carbon removal intensity, which is written as:

$$S = \sum_i \sum_k A^{ik} \left(\mu^{ik} + \epsilon^{ik} \right) \tag{1}$$

The regulator is assumed to set a target for a minimum increase in carbon removal from the baseline, S^{Min}. The target is regarded as given in this paper, which can be determined by international negotiations and political processes, such as the international agreement on biodiversity (UN, 2022) and the regulation on carbon removals in the EU (EC, 2023a). Uncertainty in achieving the target is accounted for by applying the safety-first decision framework (e.g. Tesler, 1955). This means that a decision-maker has to decide on the target S^{Min} and the minimum probability, α, at which the target should be achieved, which is written as:

$$prob\left(S \geq S^{Min}\right) \geq \alpha \tag{2}$$

Chance-constrained programming is used to solve the cost-minimisation problem with a probabilistic constraint, and eq. (2) is then transformed into a deterministic equivalent as (e.g. Taha, 2007);

$$\mu - \phi^{\alpha} \sigma^{1/2} \geq S^{Min} \tag{3}$$

where $\mu = \sum_i \sum_k A^{ik} \mu^{ik}$ is the overall mean. Simplifications are made by assuming independence between the variances for each country and measure. The total variance σ is then written as:

$$\sigma = \sum_i \sum_k \left(A^{ik} \right)^2 \sigma^{ik} \tag{4}$$

Eq. (3) shows that the removal target becomes tighter with uncertainty because of the second term on the left-hand side of eq. (3). This means that more expected carbon removal is needed in order to ensure achievement of the target compared with certainty, which is illustrated in Fig. 1 for a normal probability distribution.

For a normal probability distribution $S^{Min} = \mu$ when $\alpha = 0.5$, but for $\alpha > 0.5$ the carbon removal is larger. The extra carbon removal to ensure the achievement of S^{Min} is then $\mu^{\alpha > 0.5} - S^{Min} = \phi^{\alpha > 0.5} \sigma^{1/2}$, which entails a cost of uncertainty. The magnitude of this cost is determined by the level of ϕ^{α} and σ. The parameter ϕ^{α} reflects the decision-maker's risk aversion to non-attainment of the carbon removal target. When $\phi^{\alpha} \neq 0$, the decision-maker is concerned about achieving the target and $\phi^{\alpha} = 0$ otherwise.

A cost function is associated with each measure and country, $C^{ik}(A^{ik})$, which is assumed to be continuous and non-decreasing in $A^{ik.}$. For afforestation and restoration of drained peatlands, the cost includes opportunity cost of land. costs for planting trees or restoring the peatlands by e.g. removing ditches, which is discussed in more detail in Section 3.2. Given the static model, each measure is subject to capacity constraints, such as maximum land areas suitable for afforestation and rewetting of drained peatland.

The EU planner's decision problem is then formulated as choosing the allocation of A^{ik} that minimizes the total cost, C, for achieving the probabilistic carbon removal target in eq. (3) under the capacity constraints of each measure according to:

$$\begin{gathered} Min\ C = \sum_i \sum_k C^{ik} \left(A^{ik} \right) \\ \text{s.t.} \\ \sum_i \sum_k \mu^{ik} A^{ik} - \phi^{\alpha} \left(\sum_i \sum_k \left(A^{ik} \right)^2 \sigma^{ik} \right)^{1/2} \geq S^{Min} \\ A^{ikMax} \geq A^{ik} \end{gathered} \tag{5}$$

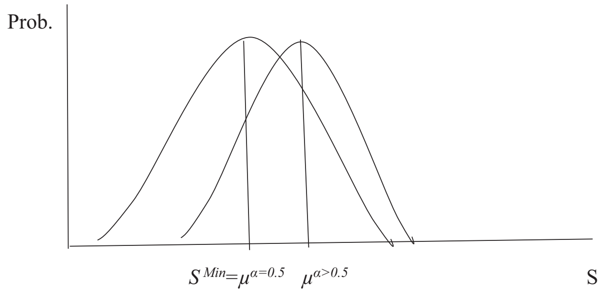

Fig. 1. Illustration of S^{Min} and μ at different levels of α.

where A^{ikMax} is the maximum land area for a carbon removal measure. The first-order conditions for a cost-efficient solution are obtained by constructing a Lagrange expression and differentiating it with respect to A^{ik}, which gives (Appendix A):

$$C^{ik}_{A^{ik}} = \lambda\left(\mu^{ik} - r^{ik}\right) - \lambda^{ik} \tag{6}$$

where subscripts denote partial derivatives, $\lambda \geq 0$ is the Lagrange multiplier, which shows the change in total cost for a marginal change in the target, r^{ik} is the marginal risk premium, and λ^{ik} is the Lagrange multiplier on the capacity constraint of the carbon removal measures. The expression in parentheses on the right-hand side of eq. (6) shows the impact of the measure on the target. For all measures, this consists of two parts: the effect on average emissions and the effect on variability. The impact on expected carbon removal is reduced by the marginal risk premium, r^{ik}, defined as (Appendix A):

$$r^{ik} = \phi^{\alpha} A^{ik} \frac{\sigma^{ik}}{\sigma^{1/2}} \tag{7}$$

The level of r^{ik} is thus determined by ϕ^{α}, A^{ik}, and the share of the measure's variance of the total standard deviation.

For an interior solution (where $\lambda^{ik} = 0$), eq. (6) states the well-known condition for a cost-efficient solution that the marginal costs of achieving the target are equal for all measures and countries and correspond to λ:

$$\frac{C^{ik}_{A^{ik}}}{(\mu^{ik} - r^{ik})} = \lambda = \frac{C^{jl}_{A^{jl}}}{(\mu^{il} - r^{jl})} \qquad \text{for all } i = j - l, ..n \text{ and } k = l = 1, 2, 3 \tag{8}$$

Note the difference between marginal cost at source, $C^{ik}_{A^{ik}}$, and for the same measure at target, $\frac{C^{ik}_{A^{ik}}}{(\mu^{ik} - r^{ik})}$. This implies that the marginal cost at target is high when the marginal risk premium is high, which gives cost advantages to measures with a low marginal risk premium. When $r^{ik} = \mu^{ik}$ the marginal cost at the target is infinite, and the measure in question will not be included in a cost-efficient solution. The case of $r^{ik} > \mu^{ik}$ would imply a net release of carbon instead of removal, and such a measure is, by definition, not included.

The cost-efficient solution described by eq. (8) will be obtained on a competitive market for carbon removal assignments if the EU planner:

i) sets the target $S = S^{Min}$ and distributes removal assignments to each country, S^{iMin}, where $\sum_i S^{iMin} = S^{Min}$, and

ii) announces quantification criteria for removal of each measure as $(\mu^{ik} - r^{ik})$ per unit A^{ik} (proofs in Appendix A).

The first condition is fulfilled by the EC (2023a) regulation, which also offers flexibility where countries can exchange assignments in their achievements of the targets. Calculations are therefore made of costs of achieving the EU target with and without trade between the countries. In both cases, each country is assumed to minimize costs for achieving its carbon removal target S^{iMin} (Appendix A). The costs of achieving the overall target S^{Min} is reduced by the introduction of trade with the quantification criteria in *ii)* as long as there are differences in marginal removal costs between the countries (Appendix A). Countries with high costs will then demand assignments which are supplied by actors with relatively low costs.

3. Description of data

Data are needed on mean and standard deviation in carbon removal intensity, maximum land use areas, and cost of each carbon removal measure and country. In addition, carbon removal targets and reliability levels have to be quantified. Unless otherwise stated, all data refers to year 2020.

3.1. Carbon removal and uncertainty

Increases in carbon removal from a base line by changes in forest management can be made by various measures, such as delayed harvest, thinning practice, and fertilization (e.g. Ameray et al., 2021). According to Kaipainen et al. (2004) increases in the carbon sink from European boreal forests range between 20% and 100% depending on tree species and climate region when the rotation length is increased by 20 years. However, the static model used in this study is appropriate for relatively short periods of time (<10 years). Guo and Gong (2017) showed that an annual increase in carbon sequestration from delayed harvest of standing forest in Sweden could by approximately 15% within a 10 year perspective. Calculations by EC (2021a) indicated an increase by 12% in carbon removal from different measures (delayed harvest, thinning) in standing forests in the EU countries. In this study, a simplification is made by assuming a maximum increase by 15% in carbon removal from improved forest management from the base line by standing forest in all EU countries. Mean and variance in carbon removal by forest management are calculated with data on annual removal by forests during 2009–2020 (Eurostat, 2023; UNFCCC, 2022). The impact of forest management is then calculated as an increase in carbon removal by 15% per unit land area from the base line with a constant removal coefficient and standard deviation per unit forest area for each country (Tables S1 and S2 in Supplementary material).

Afforestation, i.e. the conversion of agricultural land to forest, generally has a positive net effect on carbon removal, particularly if the converted agricultural land has a low content of soil organic matter. This is obtained by accumulation of biomass during the conversion and an eventual increase of the carbon stock in the soil (e.g. Degryze et al., 2004). The impact on GHG emissions depends on a number of different factors including the choice of tree species and soil conditions. In the present study, carbon removal by afforestation was calculated as the sum of carbon removal by forest and emissions from cropland. Mean and standard deviation of emissions from crop land are calculated with data during 2009 and 2020 from UNFCCC (2022) and Eurostat (2023). The variance for afforestation is the sum of the variance in carbon removal by forests and that in emission from crop land (Table S2 in Supplementary material).

However, the full potential of the afforestation is not obtained within a relatively short period of about 10 years as fast-growing trees require at least 20 years, and calculations indicate that approximately 60% of the potential can be obtained within 10 years (EC, 2021b). Simplifications were therefore made by assuming that this can be achieved in all EU countries. It was further assumed that afforestation can be made on a maximum of 10% of the crop land area in each country due to requirements of e.g. crop rotation.

Restoration of drained peatlands has been suggested as a measure with a high potential (Tanneberger et al., 2021). Drainage of peatlands delivers oxygen to the soil, which releases CO_2 and N_2O. Emissions from drained peatland on agricultural land amount to 220 Mt. CO_2e per year in the EU (GMC (Greifswald Mire Centre), 2019). Rewetting of the drained peatlands by restoring water levels near to the surface reduces the emission of CO_2, which can amount to 30 t CO_2/ha, but creates emission of CH_4.

Data on areas of drained peatlands and CO_2e removal from restored peatlands for forestry and agriculture are obtained from Joosten (2009) for most countries, which are completed with available country specific data. The potential removal coefficients for restoration of drained peatland range between 18 and 33 tCO_2e/ha for cropland and between 6 and 24 tCO_2e/ha for forests (Table S2 in Supplementary material). However, restoration through rewetting requires between 10 and 30 year to yield the ecosystem functions similar to pristine peatlands (Escobar et al., 2022). Some studies show that peatlands drained for agricultural purposes can lead to a quick recovery of key microbial processes (Emsens et al., 2020). Therefore, it is simply assumed that the 0.5 of the full carbon removal effect displayed in Table S2 in

Supplementary material can be obtained within 10 years for peat restoration of crop and forest land in all countries.

Very few studies quantify uncertainty in carbon removal by restored peatlands. According to Koch et al. (2023), the standard deviation related to the mean carbon removal for restored peatlands for crop land in Denmark amounts to 0.23, which is used for restoration of peatlands with forest and agriculture in Denmark. Estimates for other countries were obtained from a meta-analysis of 48 studies of effects of restoring peatlands at the global scale (Darusman et al., 2023). They found relatively smaller ranges in removal of CO_2 per area unit for peatlands restored in boreal than in temperate zones. Accounting for study characteristics and other sources of heterogeneity between the studies, the result indicated that the standard deviation related to the mean carbon removal within a 90% confidence interval amounts to 0.28 and 1.12 for boreal and temperate zones, respectively. These estimates are used in this study and assumed to be the same for all GHG and for restoration of peatlands drained for cropland and forest. The boreal zone includes Sweden, Finland, Estonia, Latvia and Lithuania, and the rest of the EU countries are in the temperate zone (Table S2 in Supplementary material).

Given all the assumptions, the total maximum carbon sequestration amounted to approximately 170 Mt. CO_2e, but there was a wide variation between measures and EU countries (Fig. 2).

Restoration of peatland accounts for 60% of the total potential, and afforestation and forest management for 11% and 29%, respectively. Six countries – Germany, Finland, France, Poland, Romania and Sweden – account for approximately 70% of the total potential. The large capacity in Germany, Poland, and Romania is explained by the potential of restoring peatland on agricultural land and that in Finland and Sweden by restoration of forested peatland.

3.2. *Cost of measures*

The cost of carbon removal measures consists of two main parts; opportunity cost of land use, and investment and operational cost. The opportunity cost is the loss of net benefits from the alternative land use. Investment and operation costs of afforestation include plantation and management of trees and those for restoration of drained wetlands consist of hydrological changes such as filling ditches. Following the literature (e.g. Tabeau et al., 2017), the opportunity cost is estimated by means of supply elasticities of land and it is assumed to be quadratic in the area of land. The investment and operational costs are converted into annual costs and assumed to be linear in the area of land. The cost function for each measure then consists of either a quadratic term or a linear and quadratic term according to:

$$C^{ik} = a^{ik}A^{ik} + b^{ik}\left(A^{ik}\right)^2 \qquad (9)$$

where the linear term reflects the annualized investment and operational cost and the quadratic term the opportunity cost of land use. The cost function for forest management includes only the quadratic term and those of afforestation and restoration of drained peatlands consist of both terms.

The quadratic term in the cost function for forest management is the foregone profits from delayed harvest, or changed thinning and fertilization practices. There exists no such calculations for each EU country, but only for entire EU (EC, 2021a). The study shows that an increase in the carbon removal price by approximately € 7.5/tCO_2eq from € 5/t CO_2eq would increase carbon removal by approximately 13 MtCO_2e, which corresponds to an increase by approximately 100% from the carbon removal at the initial price. This gives a carbon removal supply elasticity of 0.7, which is used to evaluate the b^{ik} for forest management at the initial price and assumption of the same percentage carbon removal at the initial price of the base line carbon removal. The percentage is calculated by relating the initial carbon removal of 13 MtCO_2e to the baseline of 290 MtCO_2e (UNFCCC, 2022), which gives 5% of the carbon removal baseline by forests in each EU country (details in Table S3 in Supplementary material).

Regarding the parameter a^{ik} for the linear term in eq. (9), plantation of trees and regular harvest are the main investment and operational costs of afforestation, and a constant annualized cost per ha is obtained for the EU countries from EC (2021b). The investment and management cost of restoration of peatlands includes preparation of the land by removing plants, regular harvesting of restored land and control, which is calculated to be € 410/ha per year (in 2020 prices) in Sweden, most of which is salary costs (SBA (Swedish Board of Agriculture), 2018). Moxey and Moran (2014) estimated a total average cost of £ 830/ha for rewetting of peatland in Scotland, but did not convert this cost into an annual basis. Therefore, the estimate of the annual management cost of € 410/ha for Sweden is used in this study, which is transferred to other EU countries by using purchasing power parities for the countries (Table S3 in Supplementary material).

The quadratic term for afforestation and restoration of peatland on cropland reflects foregone profits from the land in agricultural use, which is approximated by the rental value per ha (Table S3 in Supplementary material). The value of b^{ik} for afforestation and restoration of peatlands on cropland is calculated by means of data on supply elasticity and rental value of land per ha and area of agricultural land in 2020 (details in Supplementary material Table S3). Supply elasticities of agricultural land were obtained from Tabeau et al. (2017) for the EU

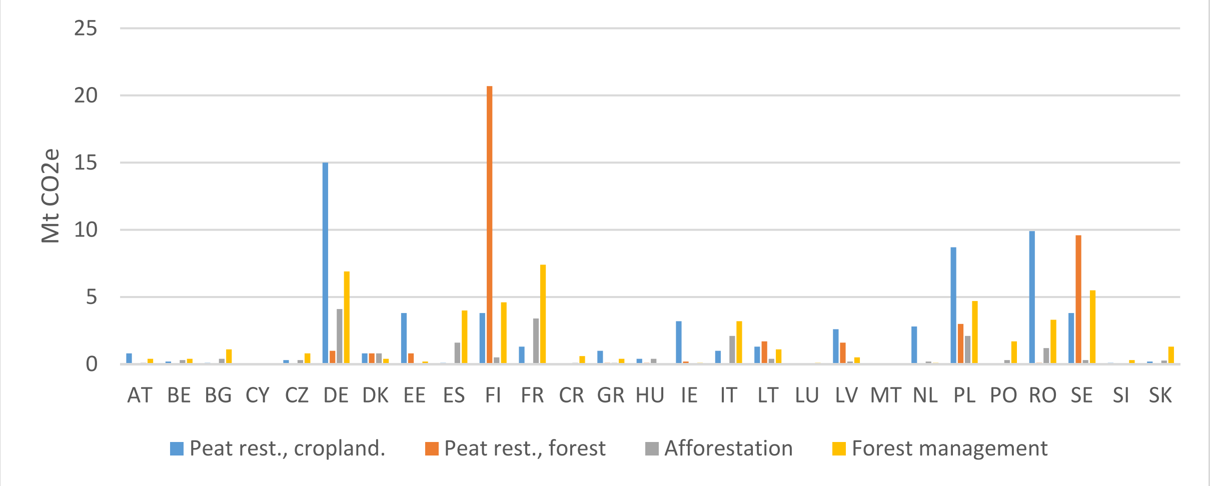

Fig. 2. Maximum carbon removal by different measures and countries, Mt. CO_2e (Table B1 in Appendix B).

countries.

There exist no data on supply elasticities of forest land for the calculation of b^{ik} for restoration of forested peatlands. Similar to agricultural land, the supply at different prices is determined by the marginal value of land. This is, in turn, calculated as the discounted current and future annual streams of cash flows from the forest land, an important source of which is timber harvest (e.g. Conrad and Rondeau, 2020). Changes in timber prices will then affect the value of land, the magnitude of which depends on several factors such as ownership, type of forest, and interest rate. The elasticity of timber supply is therefore used as an approximation of the supply elasticity of land. In a meta-analysis with 25 studies at the global scale, Tian et al. (2017) found a variation in supply elasticities which ranged between 0.35 and 0.71 for European countries, but provided no country specific values. The responses in timber supply to price changes can be larger than responses in forest land area to changes in prices of land. Therefore, the b^{ik} parameter for restoration of forested peatland is estimated by assuming the lower level of 0.35 at the level of forest profits and areas in 2020 (Table S3 in Supplementary material).

3.3. *Scenarios, reliability and distribution of assignments*

Calculations of total costs and for different countries are made for cost-efficient trading between countries at overall carbon removal targets ranging from 25 Mt. CO_2e to the maximum of 150 Mt. CO_2e. In addition, costs are calculated of the EC (2023a) regulation, which aims at increasing the carbon removal from the average of 268 Mt. CO_2e during 2016–2018 to 310 Mt. CO_2e to be achieved in 2030. To this end, binding carbon removal assignments are distributed between the countries based on the area of productive forest and arable land, and average carbon removal during 2016–2018 (Table B1 in Appendix B). The regulation offers flexibility in the achievement of the country requirements where surplus from compliance with the ESR (Effort Sharing Regulation) can be used to meet the carbon removal target, and vice versa. Another option is to trade carbon removal assignments between the EU countries. In this study, it is assumed that surpluses for trade with the ESR are not used, but the option of trading in carbon removal is exercised. Given that each country minimizes costs for meeting its EU requirement, trading will generate a cost-efficient solution (Appendix A). Costs of the regulation are calculated with and without the option to trade.

Regarding the choice of reliability level under these scenarios, there is no explicit consideration of uncertainty when formulating the target in the EU regulation, although the uncertainty in carbon removal is well recognised. Canada is the only country for which a reliability level has been quantified, which amounts to a probability of 0.9 (Kim and McCarl, 2009). This level will therefore be used in this study, but calculations are also made for prob. = 0.7. It is also assumed that the probability distribution is normal, which implies that the level of $\phi^{\alpha}$is obtained from the student's t-table. When calculating costs of the EU regulation it is assumed that the reliability level is the same in all countries. Owing to the limited carbon removal potential in some countries, a reliability level of prob. = 0.6 is used for illustrative purposes.

In order to calculate the net costs for different countries after trade in both scenarios, the distribution of the initial carbon sequestration requirements needs to be determined. In the EU Emissions Trading System (EU ETS), the initial emission permits are determined in relation to historical emissions. It is more difficult to issue carbon assignments in relation to past carbon removal since some countries show negative sequestration and others positive. Instead, the distribution of carbon removal assignments determined by the EC (2023a) is used. The increase of carbon by 42.3 Mt. CO_2e is distributed between the countries where the largest share is allocated to France, Spain, and Sweden with 16%, 13%, and 9% of the total requirement, respectively (Table B1 in Appendix B). It is assumed that the distribution of initial assignments follows these country shares for all carbon removal targets.

All calculations are made with the mathematical programming code GAMS, using the Conopt solver designed for nonlinear models (Rosenthal, 2008).

4. Results

4.1. *Costs of different carbon removal targets*

With a competitive trading market, the minimum total costs start to increase relatively rapidly at carbon removal levels exceeding 100 Mt. CO_2e for all probability levels (Fig. 3).

The cost increases for a given target at high reliability levels because of the need to provide more carbon removal to achieve the probability constraint (Table B2 in Appendix B). For example, at the 100 Mt. CO_2e target with prob. = 0.7 and prob. = 0.9 the extra carbon removal amounts to 10 and 23 Mt. CO_2e, respectively.

The equilibrium carbon removal prices also differ between removal targets and probability levels (Fig. B1 in Appendix B). Without uncertainty, the equilibrium price increases from € 11/t CO_2e to € 184/t CO_2e when the removal target increases from 25 to 150 Mt. CO_2e. However, with uncertainty, the equilibrium price increase at a given S^{Min} can be large. For example, at $S^{Min} = 100$ Mt. CO_2e the price under certainty is € 56/t CO_2e, which increases to € 141/t CO_2e when prob. = 0.9.

The equilibrium prices at different removal targets and probabilities are determined by the marginal costs of the carbon removal measures. Forest management is a relatively low cost measure, which is included at the maximum capacity at $S^{Min} \geq 100$ Mt. CO_2e. The use of the other removal measures increases at higher targets and under uncertainty, which is exemplified for two removal targets and probability levels in Table 1.

The risk premium for each measure and country depends on the chosen target and reliability level. It is relatively low, $r^{ik} < 0.01$, for most measures and countries when $S^{Min} = 100$ MtCO_2e and prob. = 0.9 (Table S5 in Supplementary material). Premiums where $r^{ik} > 0.10$ are imposed on measures in Germany, France, and Poland because of their relatively large variances.

The setting of the overall carbon removal target, distribution of initial assignments, and the introduction of risk premiums under conditions of uncertainty determine the cost-efficient allocation of carbon removal and associated trade flows. Countries with measures with marginal costs below the equilibrium price will sell, and vice versa. The allocation of costs after trade between countries also differs depending on reliability choices. The cost for a country includes costs of carbon removal and cash flows of trade. This is shown for $S^{Min} = 100$ Mt. CO_2e in Fig. 4 without uncertainty and with uncertainty when prob. = 0.9.

The net cost after trade is positive for most countries, but a few countries make net gains from sales of assignments in the certainty and/or the uncertainty case (Germany, Denmark, Estonia, Lithuania, Poland, Romania, Slovenia and Slovakia). The cost under uncertainty is higher than without uncertainty for all countries with a positive cost, but the net income can be larger for sellers because of their relatively low risk premiums and high market price. France and Spain are the largest buyers of assignments with and without uncertainty, and Poland is the largest seller (Table S5 in Supplementary material).

4.2. *Costs of the EU regulation*

The calculations indicate a total cost under certainty of the EU regulation with and without trade of 284 million € and 567 million €, respectively (Table 2).

Total cost savings of moving from no trade to cost-efficient trading are 283 and 413 million € under certainty and uncertainty, respectively. The relatively large costs of the EU proposal under uncertainty is partly explained by the extra carbon removals which amount to 0.7 Mt. CO_2e and 3.2 Mt. CO_2e with and without trade, respectively. The equilibrating price with trade and without uncertainty amounts to 19.8 €/t CO_2e.

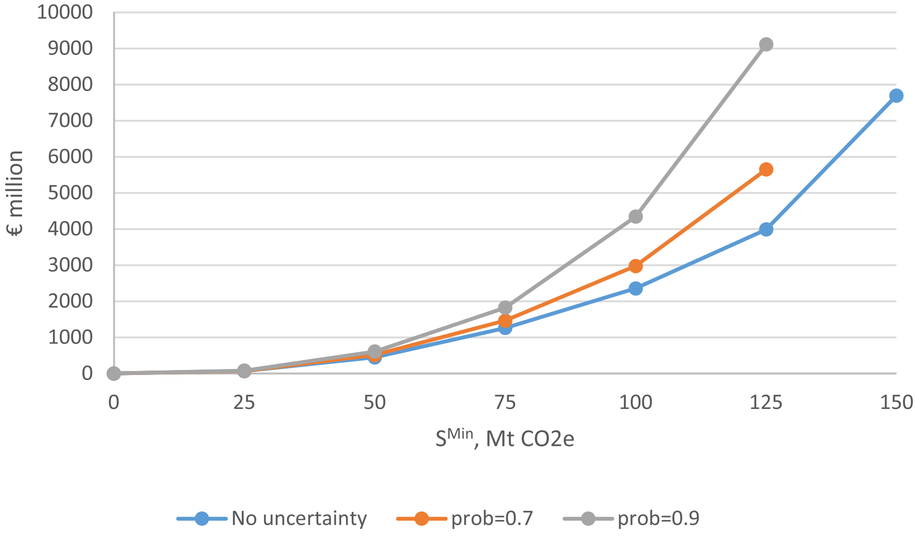

Fig. 3. Minimum costs at different EU carbon removal targets, S^{Min}, and reliability levels.

Table 1
Cost-efficient allocation of carbon removal measures at different S^{Min} and probabilities, $MtCO_2e$.

	Peat restoration;		Affore station	Forest manag.	Total
	Cropland	Forest			
S^{Min} = 100 $MtCO_2e$;					
Certainty	32.18	6.26	12.04	49.52	100.00
Prob = 0.9	48.48	9.32	15.73	49.52	123.05
S^{Min} = 125 $MtCO_2e$;					
Certainty	53.25	7.80	14.43	49.52	125.00
Prob = 0.9	55.30	31.98	16.38	49.52	153.18

The allocation of costs between countries with and without trade depends on the target and availability and costs of carbon removal measures. The costs differ considerably between the countries with and without trade (Fig. 5).

The cost of the EU proposal without trade is highest for Spain and France, which face the largest removal targets. For Spain, the EU assignment is close to the calculated maximum removal capacity (Table B1 in Appendix B). The high cost is also revealed by the shadow costs, i.e. the increase in removal cost from a unit increase in the target, of the EU assignments, which is largest for Spain and amounts to € 135/ tCO_2e (Table S7 in Supplementary material).

All countries gain from the suggested trading scheme by buying (selling) assignments if the shadow cost exceeds (is below) the equilibrium price of € 19.8 /tCO_2e. Spain obtains the largest gains from trade by a reduction in removal cost by approximately 104 million €. Eight countries (Belgium, Denmark. Poland, Lithuania, Luxemburg, Portugal, Slovakia, Slovenia) make net gains from selling assignments at the equilibrium price (Table S7 in Supplementary material).

Table 2
Total costs of EU regulation with and without trade for S^{Min} = 42.3 Mt. CO_{2e} with and without uncertainty, million €.

Policy scheme	Certainty		Uncertainty with prob. = 0.6		
	Cost Mill. €	Price €/tCO_2e	Cost Mill. €	Price €/tCO_2e	Removal, Mt. CO_2e
No trade	567		712		45.5
With trade	284	19.8	299	21.2	43.0

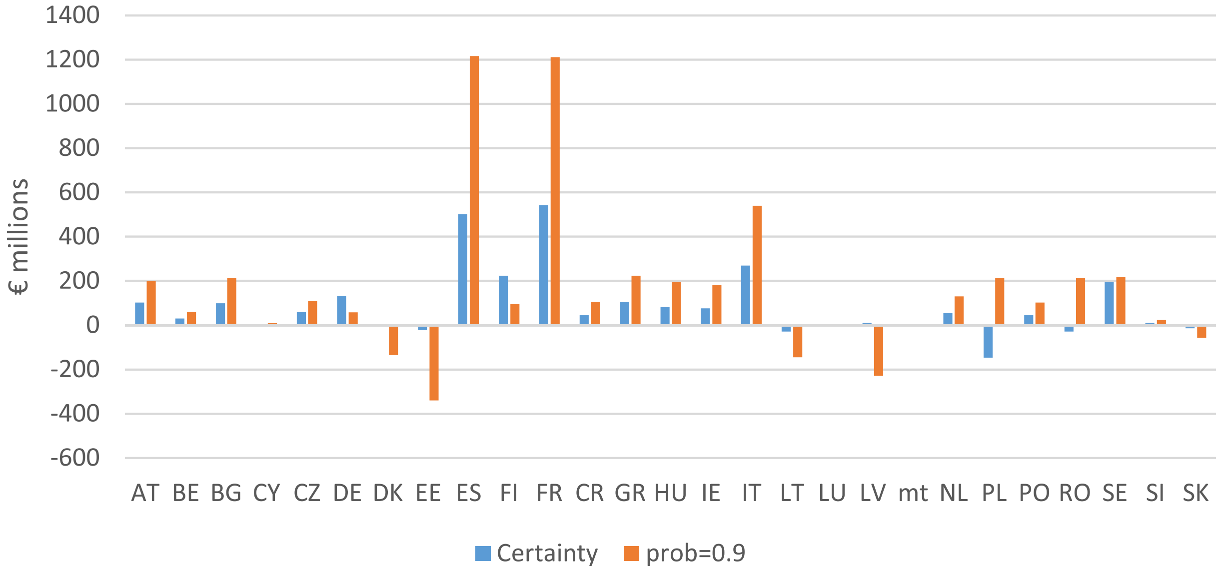

Fig. 4. Country cost after trade in cost-efficient solutions for S^{Min} = 100 Mt. CO_2e with and without uncertainty with a reliability level of 0.9.

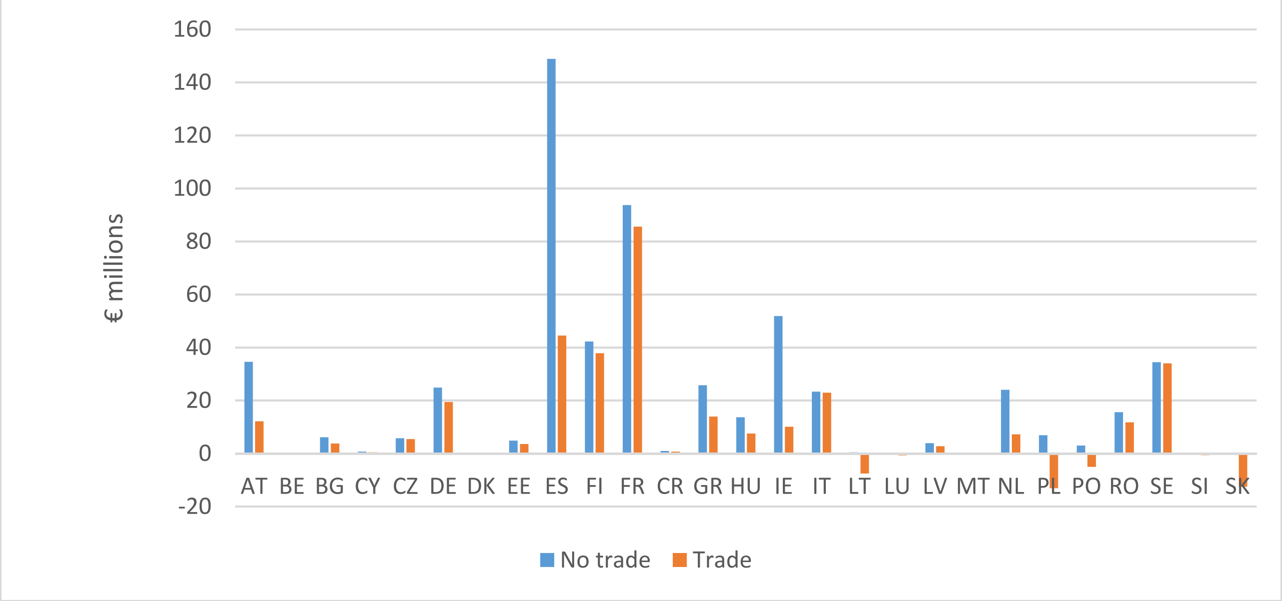

Fig. 5. Costs of the EU regulation with and without trade for different countries with a total carbon removal target of 42.3 Mt. CO_2e and no uncertainty.

The costs under the EU proposal without trade increase for all countries under condition of uncertainty with prob. = 0.6, but the pattern of cost allocations remains the same (Table S7 in Supplementary material). Similar to the certainty scenario, all countries gain from trading but the market price increases to € 21.2 /t CO_2e. The magnitude of the cost savings for buyers and net incomes for sellers of assignments is slightly reduced.

5. Discussion

The results from this study are based on several assumptions regarding the choice of removal measures and associated parameter values. Since no study has designed and calculated the effects of trading carbon removal at the EU level with uncertainty, only partial comparisons can be made between the results and those of other studies. A few studies have calculated the effects of carbon prices on the supply of carbon removal applied to the EU (Gren and Carlsson, 2013; EC, 2021a). Gren and Carlsson (2013) used a similar MAC approach as in this study and estimated an increase by approximately 150 Mt. CO_2e at the price of € 100/t CO_2e. At the same price, EC (2021a) found that carbon removal increased by 110 Mt. CO_2e by combining partial equilibrium models of the forest and agricultural sectors. In the present study, the price of € 100/t CO_2e carbon removal would generate a carbon removal of 125 Mt. CO_2e under certainty, which is in between the estimates by EC (2021a) and Gren and Carlsson (2013).

However, the results are based on several assumptions about the choice of probability distribution and parameter values. A normal distribution was assumed, but a change to a range of distributions based on Chebyshev’s theorem would increase cost for providing 100 Mt. CO_2e at prob. = 0.7 by 15% and the achievement of the EU proposal without trade is not feasible with this distribution.

Other assumptions are the choice of parameter values in the chosen model. According to Belassen et al. (2022), the national GHG inventory reports to UNFCCC and EU do not cover all forest and agricultural land, and removal and emissions from peatlands are missing. Since the carbon removal by restoring peat land had considerable impact on the results, sensitivity analysis was carried out for deviations by 10% in the removal coefficients. In addition, impacts on costs were calculated for 10% changes in the land suitable for forest management and afforestation, in the supply elasticities of land, and in the variance in all measures. The results indicated that changes in the potential of peatland removal, forest management and afforestation have the largest relative impact on costs at a target of 100 Mt. CO_2eq and for achieving the EU regulation without trade (Table B3 in Appendix B).

The results are affected not only by parameter values in the existing model, but also by excluded variables and model choice. The model excludes several types of measures in forestry and agriculture, and their inclusion would reduce total cost if their marginal removal costs with the risk premium are lower than those for the included removal measures. Transaction cost is another cost item that is not included. The establishment of trading will require costs for monitoring and verification of assignments and trades. Coria and Jaraité (2019) showed that the median transaction cost for Swedish firms trading on the EU ETS market amounted to approximately € 2.5/t CO_2 emission. Pearson et al. (2014) found that the transaction cost of carbon sequestration in tropical forests can raise the marginal cost by approximately 30%. On the other hand, inclusion of co-benefits in terms of simultaneous environmental improvements, such as biodiversity and water quality enhancement, would reduce the cost (e.g. Bustamante et al., 2014; Grafton et al., 2021).

The relatively simple MAC model, chosen to account for uncertainty, does not consider the dispersal effects in the economies of the carbon removal measures. Such effects are likely to increase the cost through adjustments made by firms and consumers to changes in the prices of outputs from the forest and agricultural sectors. Prolonged forest rotation will reduce the supply of forest products and raise the equilibrium price. Afforestation and restoration of peatland for agricultural purposes can affect up to 10% of agricultural land in the EU, which is likely to affect the prices of agricultural goods that create welfare losses for consumers.

The results also depend on the assumption of a competitive trading market. It is well known that the exercise of market power will not lead to a cost-efficient allocation of abatement in a market (e.g. Carraro et al., 1996). This might be of less concern in the market for carbon removal suggested in this study since no country receives assignments exceeding 16% of the total initial distribution of carbon sequestration.

6. Conclusions

The main purpose of this study was to design a cost-efficient trading market for carbon removal in the EU when considering differences in uncertainty in carbon removal between countries and measures. To this end, chance-constrained programming was used to calculate the cost-efficient risk premium of the measures, the magnitude of which depends on the regulator's risk aversion and variance in carbon removal. It was shown in a conceptual model that consideration of the risk increases the carbon removal and costs for achieving a given target. Another finding was that the prices paid for carbon sequestration by different measures should be reduced by a risk premium which shows the marginal impact on total risk of the measure. A cost-efficient solution will be obtained by a competitive trading market if the EU planners define the overall removal target, allocate country assignments, and set risk premiums for each measure and country.

The empirical application showed that the total cost for a given total carbon removal target can be considerably higher with than without uncertainty. However, not all countries make losses, countries with low marginal removal costs and risk premiums make net gains when selling assignments to high-cost countries. An evaluation of the EU's proposal on country allocation of carbon removal requirements showed that the total ost of the proposal could be reduced by 50% if trade was allowed under conditions of certainty, and by even more when uncertainty was considered.

However, the empirical results should by interpreted with caution because of the lack of data which necessitated a number of assumptions. Nevertheless, the results with respect to carbon removal at different carbon prices under conditions of certainty are in the same order of magnitude as those of other studies. The potential and costs would be affected by changes in the inclusion of alternative removal measures and types of costs, but in different directions. The exclusion of several carbon removal options and co-benefits is likely to overestimate the cost, but the exclusion of transaction cost and dispersal effects are likely to underestimate costs. A specific feature of the present study was the inclusion of the restoration of drained peatlands, which proved to be a cost-efficient measure with relatively large removal capacity.

A carbon removal market was considered that allows for a separate requirement on the total carbon removal without hampering emission reductions from other sectors regulated by the EU ETS or the effort-sharing schemes (Nabuurs et al., 2015). Nevertheless, it could be of interest to estimate the supply of carbon removal at the EU ETS market price, which was approximately € 99/t CO_2 on March 1. 2023 (Carbon Credits, 2023). This is € 86 in 2020 prices (Eurostat, 2022), which would generate approximately 125 Mt. CO_2e on the carbon removal market under certainty, which corresponds to 7% of the total EU ETS cap in 2020 of 1816 Mt. CO_2 (ICAP (International Carbon Action Partnership), 2023).

Given the knowledge and experiences of compensation payments to agriculture, in particular at the EU level within the CAP system, a logical question is whether it would be better to subsidise carbon removal than to construct a carbon removal market. As shown by Evison (2017), forestry owners in New Zealand hesitated entering a trading market for carbon removal because of fluctuating prices. Instead, grants for afforestation and plantation were preferred and had a greater incentive effect. There could also be differences in transaction costs between the market and compensation payment systems. One difference between the suggested market system in this paper and the EU's current compensation payment scheme in CAP is that it is based on results, i.e. quantity of carbon removal, and not on the provision cost.

A results-based system gives higher incentives to landowners for developing carbon removal technologies than a cost-based system. A main challenge is then the lack of consistent data on carbon removal and uncertainty of different carbon removal measures which is necessary for a result-based incentive scheme. Nevertheless, result-based incentive schemes have been implemented in different countries, which have met the challenges in quantifying carbon removals in different ways (reviews in Gren and Aklilu, 2016 and Grafton et al., 2021). A common approach has been to use independent standards such as the Verified Carbon Standard, and risk discounting was implemented in the carbon removal market in New Zealand. Trading of carbon removal at the EU level requires a common standard for all counties, and the recent proposal on a voluntary framework for certifying carbon removals can then be quite useful (EC, 2023b). The framework specifies the processes for monitoring, verifying and reporting carbon removal. Further research on the different incentive systems is needed to evaluate and compare their advantages and disadvantages.

CRediT authorship contribution statement

Ing-Marie Gren: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Valuable comments from the editor and two anonymous reviewers are much appreciated.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2023.103127.

Appendix A. First-order conditions

The Lagrange expression for the cost-efficient solution is obtained from eqs. (1)–(6) as:

$$\mathscr{L} = \sum\nolimits_i \sum\nolimits_k C^{ik}\left(A^{ik}\right) - \lambda\left(\mu - \phi^{\alpha}\sigma^{\frac{1}{2}} - S^{Min}\right) - \lambda^{ik}\left(A^{ikMax} - A^{ik}\right) \tag{A1}$$

where $\mu = \sum_i \sum_k \mu^{ik} A^{ik}$ and $\sigma = \sum_i \sum_k \left(A^{ik}\right)^2 \sigma^{ik}$. Differentiating eq. (A1) with respect to A^{ik} gives:

$$\frac{\partial \mathscr{L}}{\partial A^{ik}} = C^{ik}_{A^{ik}} - \lambda\left(\mu^{ik} - r^{ik}\right) + \lambda^{ik} = 0 \tag{A2}$$

where $r^{ik} = \phi^{\alpha} A^{ik} \frac{\sigma^{ik}}{\sigma^{1/2}}$.

Given a market with initial distribution of S^{iMin} and quantification of r^{ik}, trade takes place, which results in the equilibrium price p. A competitive market is assumed and the distribution of initial requirements will not then affect the price and the cost-efficient allocation of carbon removal (e.g. Carraro et al., 1996). Each actor is assumed to minimize the cost of carbon removal plus sales/purchases of S^{iMin} according to:

$$Min\ C^i = \sum\nolimits_k C^{ik}\left(A^{ik}\right) + p\left(S^{iMin} - \sum\nolimits_k \left(\mu^{ik} - r^{ik}\right)A^{ik}\right) \qquad \text{(A3)}$$
$$\text{s.t.}A^{ikMax} \geq A^{ik.}$$

If the carbon removal is larger than the requirement, $S^{iMin} < \sum_k \left(\mu^{ik} - r^{ik}\right)A^{ik}$, the surplus can be sold at the price of p and incomes are obtained that counteract the carbon removal costs. If instead the actor faces a high removal cost, requirements can be purchased. The first-order condition for a cost-efficient allocation of carbon removal is then given by:

$$C^{ik}_{A^{ik}} = p\left(\mu^{ik} - r^{ik}\right) - \lambda^{ik} \qquad \text{(A4)}$$

Eq. (A4) is the same as the condition for a cost-efficient solution in eq. (A2) when $p = \lambda$, which is ensured by a competitive trading market. Without trading, countries need to fulfil the requirements S^{iMin} by national measures, and it is assumed that they minimize costs according to:

$$Min\ C^i = \sum\nolimits_k C^{ik}\left(A^{ik}\right)\ \text{s.t.}A^{ikMax} \geq A^{ik}\text{and } \mu^i - \phi^\alpha\left(\sigma^i\right)^{1/2} \geq S^{iMin} \qquad \text{(A5)}$$

The decision problem is solved by constructing a Lagrange expression, and the associated first–order condition is written as:

$$C^{ik}_{A^{ik}} = \lambda^i\left(\mu^{ik} - r^{ik}\right) - \lambda^{ik} = 0 \qquad \text{(A6)}$$

The Lagrange multiplier λ^i reflects the so-called shadow cost of the country target, i.e. the increase in the costs for a country from a unit increase in S^{iMin}, The condition without trade will give a cost-efficient solution only if $\lambda^i = \lambda$ for all countries.

Appendix B. Tables B1–B3, Fig. B1

Table B1
Carbon removal capacity and EU regulation on removal targets, Mt. CO_2e.

Country	Removal capacity[a]; Peat rest: Affor. For. man. Total Agr. Forest					EU removal targets[b]
Austria	0.8		0.1	0.4	1.3	0.9
Belgium	0.2		0.3	0.4	0.9	0.4
Bulgaria	0.1		0.4	1.1	1.6	1.2
Cyprus	0.01		0.05	0.02	0.08	0.06
Czech Republic	0.3		0.3	0.8	1.4	0.8
Germany	15	1	4.1	6.9	26.9	3.7
Denmark	0.8	0.8	0.8	0.4	2.8	0.4
Estonia	3.8	0.8	0.04	0.2	4.84	0.4
Spain	0.1		1.6	4.0	5.6	5.3
Finland	3.8	20.7	0.5	4.6	29.5	2.9
France	1.3		3.4	7.4	12.1	6.7
Croatia	0.01		0.1	0.6	0.74	0.6
Greece	1	0.1	0.1	0.4	1.6	1.1
Hungary	0.4	0.1	0.4	0.5	1.3	0.9
Ireland	3.2	0.2	0.02	0.1	3.4	0.6
Italy	1		2.1	3.2	6.3	3.2
Lithuania	1.3	1.7	0.4	1.1	4.5	0.7
Luxembourg	0.01		0.02	0.1	0.1	0.03
Latvia	2.6	1.6	0.2	0.5	4.8	0.6
Malta	0.014				0.014	0.01
Netherlands	2.8	0.04	0.2	0.1	3.3	0.5
Poland	8.7	3	2.1	4.7	18.4	3.3
Portugal	0.03		0.3	1.7	2.0	1.0
Romania	9.9	0.1	1.2	3.3	14.5	2.4
Sweden	3.8	9.6	0.3	5.5	13.3	3.9
Slovenia	0.1		0.02	0.3	0.4	0.2
Slovakia	0.2		0.27	1.3	1.7	0.5
Total	61.27	39.74	19.32	49.52	169.5	42.3

[a]Tables S1 and S2 in Supplementary material; [b]EC (2023a) Annex IIa.

Table B2
Mean carbon removal under uncertainty for different levels of S^{Min} (Mt CO_2e) and reliability levels.

	0	25	50	75	100	125	150
Prob = 0.7	0	26	52	80	108	136	165
Prob = 0.9	0	27	55	85	118	149	Infeas.

Table B3

Impacts on costs from 10% increase or decrease in peat removal coefficient, price elasticity of land, carbon removal capacity of forest management and afforestation, and variances of all measures with target for 100 Mt. CO_2e on the market and the EU proposal, % change from the base case.

Parameter	No uncertainty;		Uncertainty;	
	Increase	decrease	Increase	decrease
S^{Min} = 100 Mt. CO_2e with trade, prob. = 0.9;				
Price elasticity of land	1.02	−1.23	1.43	−1.68
Peat removal coeff.	8.58	−10.45	11.85	−15.14
Capacity of for. man. and affor.	7.35	−9.09	14.44	−17.45
Variance			3.97	−3.76
EU proposal without trade, prob. = 0.6;				
Price elasticity of land	1.38	−1.54	1.54	−1.80
Peat removal coeff.	6.92	−8.92	7.19	Infeas.
Capacity of for. man. and affor.	8.00	−10.15	8.47	Infeas.
Variance			1.03	−1.03

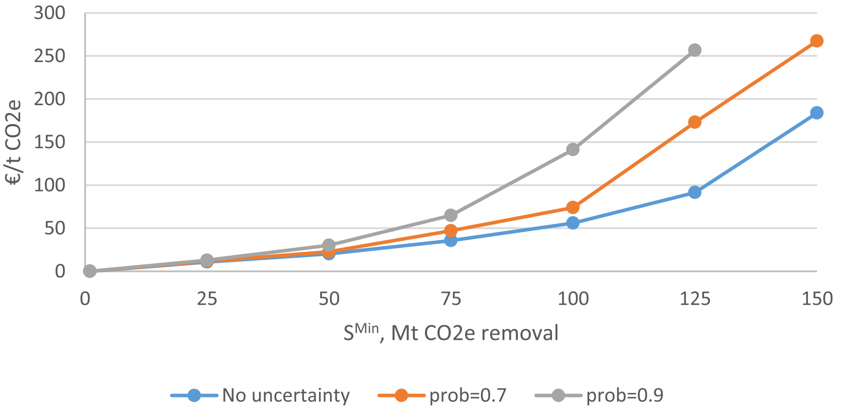

Fig. B1. Equilibrating market prices (€/tCO_2e) of different carbon removal targets S^{Min} (Mt CO_2e) in the EU at different reliability levels.

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