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Restoring organic soils under agriculture: cost-effective portfolios in the context of European climate and biodiversity policies

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Abstract

Drained organic soils in agricultural use in the European Union (EU) contribute approximately 80% of Cropland and Grassland greenhouse gas (GHG) emissions released to the atmosphere, which makes their restoration highly relevant for achieving climate change mitigation targets in the EU. However, the cost-effectiveness of different restoration measures and their synergies with economic incentives remain poorly understood. Here, we provide an EU-wide assessment of the economic potential of restoring drained organic soils used for agriculture through 2050 using the economic land-use model GLOBIOM-EU. We investigate the climate benefits of three restoration measures—full rewetting, rehabilitation, and full rewetting with paludiculture—and evaluate their cost-effectiveness by developing marginal abatement cost curves (MACCs). Our results indicate that under a GHG price of 100 EUR tCO_2e^{-1}, 38.2–44.4 $MtCO_2e\ yr^{-1}$ could be mitigated in 2050. Demand for paludiculture products would substantially improve the attractivity of full rewetting, enabling up to 2 Mha of drained organic soils to be restored even without additional climate policy incentives, delivering 17 $MtCO_2e\ yr^{-1}$ mitigation in 2050. In addition, meeting the 2050 targets of the EU Nature Restoration Regulation (NRR) alone could mitigate emissions by 20–26 $MtCO_2e\ yr^{-1}$, equivalent to 23%–29% of current emissions from drained agricultural organic soils in the EU. These findings demonstrate that restoring drained organic soils represents a substantial mitigation opportunity for the EU agricultural sector, with synergies for bioeconomy development and nature restoration. An integrated approach to policy design is needed to ensure efficiency in delivering multiple co-benefits.

1. Introduction

Organic soils, which are naturally wet soils rich in organic matter, represent the largest terrestrial reservoir of organic carbon, storing 450 000–650 000 megatons (Mt) of carbon globally (Joosten *et al* 2016, UNEP 2022). Peatlands, categorized as lands with specific organic soils (Hiraishi *et al* 2014), cover only 3%–4% of the global land area but hold about one-third of global soil carbon, approximately twice the amount held in all forest biomass (UNEP 2022). Drainage dries and degrades wet organic soil states and accelerates aerobic decomposition, which releases large amounts of CO_2 and N_2O from oxidized peat and CH_4 from ditches (Hiraishi *et al* 2014, Joosten *et al* 2016, Evans *et al* 2021, Ma *et al* 2022). Stopping further drainage, restoring organic soils and protecting intact peatlands are therefore key climate change mitigation strategies (Leifeld and Menichetti 2018, Günther *et al* 2020, Ma *et al* 2022, Zou *et al* 2022).

In the European Union (EU), drained organic soils occupy only about 2% of agricultural land, but they contribute approximately 80% of Cropland and Grassland greenhouse gas (GHG) emissions released to the atmosphere in 2023 (EEA 2025, UNFCCC 2025). As the EU faces a declining carbon sink from forestry (UNFCCC 2024, 2025), reducing emissions from drained agricultural organic soils presents a potentially effective opportunity to advance the Land Use, Land-Use Change and Forestry (LULUCF) goals with minimal land-use change.

EU policy has increasingly targeted organic soil conservation and restoration. Incentives and regulations addressing restoration of organic soils now appear in multiple policy frameworks, including the Good Agricultural and Environmental Conditions (GAEC) standards, the Carbon Removals and Carbon Farming Regulation (CRCF), the National Energy and Climate Plans (NECPs), and the Nature Restoration Regulation (NRR). The NRR alone requires restoring 1.25 Mha of drained organic soils in agricultural use by 2030, 1.66 Mha by 2040, increasing to 2.08 Mha by 2050, equivalent to about 1.4% of agricultural land in EU countries reporting drained agricultural organic soils (figure S1). This growing policy focus underscores the need to quantify the mitigation potential of restoration under different policy and market conditions.

Existing research provides important insights into the mitigation potential of drained organic soil restoration, but significant knowledge gaps remain. Many studies quantify the biophysical mitigation potential of restoration without considering economic implications or land-use management (Günther *et al* 2020, Zou *et al* 2022, Mander *et al* 2024). Agroeconomic models can explicitly capture interactions between socioeconomic developments, markets, and land-use dynamics (Leclère *et al* 2020, Roe *et al* 2021, Fujimori *et al* 2022). However, most modeling studies assessing organic soil restoration focus primarily on full rewetting as a single measure (Humpenöder *et al* 2020, Doelman *et al* 2023, Willenbockel 2024). This limited focus risks over- or underestimating mitigation potential, because restoration can occur through multiple measures with different costs, emission reductions, and implications for agricultural production. In particular, the productive use of rewetted soils through paludiculture, which can produce biomass while maintaining wet conditions, has rarely been integrated into large-scale economic assessments, and the cost-effectiveness of combining different restoration measures has not been systematically evaluated at the EU scale.

To address these gaps, this study provides an EU-wide assessment of the economic potential of restoring drained agricultural organic soils through 2050, using the economic land-use model GLOBIOM-EU (IBF-IIASA 2023). We evaluate three restoration measures with distinct functions in mitigation and land use: *full rewetting* restores high water tables and terminates conventional agricultural use, with net climate benefits generally positive; *rehabilitation* involves partial restoration, which lowers emissions while maintaining agricultural production; *full rewetting with paludiculture* refers to the productive use of rewetted soils, which does not necessarily increase mitigation beyond full rewetting but can improve the attractiveness of rewetting by producing biomass. For paludiculture, we assume reed canary grass (*Phalaris arundinacea L.*) as the primary paludiculture species, which has been successfully cultivated in multiple European countries and used for biofuels and industrial applications (Abel and Kallweit 2022, Nielsen *et al* 2024). An overview of the study setup is shown in figure S2.

We develop multiple combinations of these measures to analyze their mitigation potential and their cost-effectiveness by constructing marginal abatement cost curves (MACCs), which are evaluated under three policy and market instruments: GHG prices, biomass demand, and restoration targets. Exploring these instruments individually and in combination, we identify how economic incentives could support, accelerate and deepen restoration beyond the minimum required, and deliver co-benefits for climate change mitigation and biodiversity restoration. By capturing interactions between climate benefits, economic viability, and restoration goals, this study provides insights into assessing the role of restoring drained organic soils in climate mitigation strategies, implementing the NRR, and designing integrated restoration management portfolios that align EU climate and biodiversity goals.

2. Methods

2.1. GLOBIOM-EU

The Global Biosphere Management Model (GLOBIOM, https://iiasa.ac.at/models-tools-data/globiom) is a partial equilibrium model designed to assess land-use dynamics, integrating agriculture (including livestock), forestry, and bioenergy sectors in detail (Havlík *et al* 2014). In this study, the regionally enhanced model GLOBIOM-EU (Frank *et al* 2015) extended to represent organic soils is used. GLOBIOM-EU operates at a 10-year time step within NUTS2 administrative boundaries (Nomenclature of territorial units for statistics, a classification developed by the EU to reference countries' regions for statistical purposes; NUTS2 level divides each EU country into basic regions used for regional policies). The model simulates land-use allocation

Table 1. Cost ranges of restoration measures.

Management type	Cost type	Average	Lower bound	Upper bound
Full rewetting, rehabilitation	One-time implementation (EUR ha^{-1})	3553	955	4735
	Annual maintenance (EUR ha^{-1} yr^{-1})	175	29	470
Paludiculture	Establishment (EUR ha^{-1})		500	15 000

Source: Artz *et al* 2018, Günther *et al* 2018, European Commission 2022, Wichmann *et al* 2022, Willenbockel 2024.

and market equilibrium by maximizing producer and consumer surplus under constraints related to resources, technologies, demand and policies. In addition, GLOBIOM-EU endogenously represents major mitigation mechanisms in the agricultural sector: technological mitigation options such as silvopastoral systems (Frank *et al* 2024), structural changes such as switches in production systems or international trade, and feedback on the demand side through consumers' response to price changes (Frank *et al* 2018). GLOBIOM-EU has been extensively used for EU policy impact assessments and continuously refined over time in response to the European Commission's needs and Member States' feedback (European Commission 2024).

2.2. Agricultural organic soils implementation

2.2.1. Area of agricultural organic soils

The area of drained organic soils in agricultural use across Europe implemented in this study is derived from several sources. First, we use the distribution of organic soils based on the area identified as peatland in the European Wetland Map (Tegetmeyer *et al* 2025). Second, we overlay the CORINE Land Cover 2018 system (EEA 2019) to identify cropland and grassland on organic soils. Such areas used for agricultural production are assumed to represent drained organic soils. These areas are then aggregated at the EU NUTS2 region level and implemented in the GLOBIOM-EU (figure S3). Finally, to ensure consistency with official inventories and reduce discrepancies across data sources, the national drained organic soil area is harmonized to the values as reported in the UNFCCC CRTs 2025 submission (UNFCCC 2025). Specifically, the 'Area of organic soil' in table 4.B Cropland and 4.C Grassland in CRTs for each country is retrieved as the national drained organic soil area for each land-use type (table S1).

2.2.2. Emission factors for drained and rewetted organic soils

Net GHG mitigation from restoration is computed as the avoided emissions from drained organic soils minus the additional emissions from rewetted organic soils, both calculated by multiplying their respective emission factors by the restored area. In this study, we extracted emission factors for CO_2 and N_2O from drained soils from UNFCCC CRTs. For CH_4 from drained soils and for all GHGs from rewetted soils, emission factors are retrieved from Wilson *et al* (2016), which are largely based on the 2013 IPCC Wetland Supplement (Hiraishi *et al* 2014). All emission factors for organic soils are calculated at the country level. Specific data sources, detailed calculation steps, and results of emission factors by country, emission type, organic soil management type, and land-use type are presented in table S2.

2.2.3. Restoration cost and productivity

Restoring drained organic soils involves investment, maintenance, opportunity, and transaction costs (European Commission 2022, Agora Agriculture 2024). Based on published literature and reports (table 1), we calculate an average one-time implementation cost of 3553 EUR ha^{-1} and an annual maintenance cost of 175 EUR ha^{-1}. These values fall within the ranges proposed by the European Commission (2022): 955–4735 EUR ha^{-1} for the average upfront costs and 29–470 EUR ha^{-1} yr^{-1} for maintenance. Assuming consistent establishment requirements for restoration, we use the average implementation and annual maintenance cost across all restoration measures, except for rehabilitating Cropland, for which the maintenance cost is set at the lower bound of the cost range to reflect its retained economic value from potential biomass production. Opportunity costs from foregone agricultural production are modeled endogenously within GLOBIOM-EU.

Practicing paludiculture requires additional costs after full rewetting, including surface preparation, seeding, planting (Wichmann *et al* 2022). We adopt the lower bound and upper bound of establishment costs for reed (*Phragmites australis*) and cattails (*Typha latifolia, T. angustifolia*) from Wichmann *et al* (2022) as the potential cost range for practicing paludiculture (table 1). Because of the large range and the biased sample size, we do not calculate the average cost for paludiculture.

Regarding agricultural productivity of rehabilitation, we assume that rehabilitated Cropland is used exclusively for biomass production, while rehabilitated Grassland (shallow-drained Grassland) retains the same productivity as Grassland on drained organic soils. Yield estimates of reed canary grass under paludiculture are based on Abel and Kallweit (2022), who summarize 3–13 t DM ha^{-1} yr^{-1} from various case studies across the EU. For modeling purposes, we adopt an average value of 7 t DM ha^{-1} yr^{-1} for all countries, representing yields that are typically achievable across a wide range of climatic conditions in Europe.

2.3. Scenarios

2.3.1. Restoration portfolios

In this study, we consider three restoration measures with distinct functions:

Full rewetting raises the water table to or near the surface, shallower or equal to 30 cm below the surface (Hiraishi *et al* 2014), restoring wet conditions, and terminates existing agricultural use. This sharply reduces CO_2 and N_2O emissions while increasing CH_4 emissions (Hiraishi *et al* 2014), but net climate benefits are generally positive (Barthelmes *et al* 2015, Andersen *et al* 2017, Günther *et al* 2020). GHG emission reductions from rewetting drained organic soils are estimated at 26.1–32.9 $tCO_2e\ ha^{-1}\ yr^{-1}$ for Cropland and 18–23.4 $tCO_2e\ ha^{-1}\ yr^{-1}$ for deep-drained Grassland in boreal and temperate climate zones (Wilson *et al* 2016).

Rehabilitation involves partial restoration without full rewetting, such as converting cropland to permanent grassland or reducing drainage intensity on grassland (European Commission 2025a), delivering moderate GHG mitigation and retaining agricultural use. For example, GHG emissions from organic soils under shallow-drained Grassland may be reduced by approximately half compared with deep drainage (e.g. from 27.8 to 15.6 $tCO_2e\ ha^{-1}\ yr^{-1}$; Wilson *et al* 2016). Critically, rehabilitation can serve as a transitional step towards full rewetting.

Full rewetting with paludiculture, the productive use of organic soils after rewetting, produces biomass while stopping peat oxidation and maintaining related ecosystem services (Joosten *et al* 2015, Wichmann *et al* 2016). It is assumed not to provide additional mitigation beyond full rewetting, but to offer sustainable income opportunities, acting as an additional incentive for restoration (de Jong *et al* 2021, Tanneberger *et al* 2022).

To quantify the economic potential of different restoration measures, we develop four portfolios combining these measures: *Full Rewet Only (FO), Full Rewet + Rehabilitation (FR), FO + Paludiculture, FR + Paludiculture*. For portfolios involving paludiculture, both the lower- and upper-bound costs from table 1 are modeled and represented as 'Palu_lowCost' and 'Palu_highCost'. In all scenarios, restoration measures are initiated in 2030 and implemented over the modeling horizon to 2050. The maximum area eligible for restoration is limited to the current extent of drained organic soils reported in the UNFCCC CRTs 2025 submission, assuming no additional drainage over the simulation period.

2.3.2. Policy scenarios

The restoration portfolios are simulated around three policy and market instruments:

GHG prices: an increasing LULUCF GHG price on drained organic soil emissions. Increasing from 5 to 200 EUR tCO_2e^{-1}, GHG prices are applied to all portfolios from 2030 onwards to assess the cost-effectiveness of restoration measures. Restoration measures are endogenously triggered when economically competitive.

Biomass demand: three hypothetical biomass prices (5, 10, and 15 EUR GJ^{-1}) to reflect different market demand levels for biomass, including paludiculture products. These price levels correspond to biomass supply levels of approximately 4–13 EJ yr^{-1} in 2050 in the EU, ranging from current primary biomass use (EUROSTAT 2026) to projected maximum biomass use in 2050 under pathways towards climate neutrality assessed by ESABCC (2023). Biomass prices are applied only in portfolios that include paludiculture to evaluate the impacts of paludiculture on restoration.

NRR targets: according to the Article 11.4 of the NRR mandating the restoration of organic soils in agricultural use constituting drained peatlands (European Commission 2025a), the restoration measures are in place on as follows:

- 30% of drained organic soils restored by 2030, with at least 25% of the restored area rewetted.
- 40% restored by 2040, with at least 33% rewetted.
- 50% restored by 2050, with at least 33% rewetted.

We model two interpretations of how NRR targets could be achieved:

- Full Rewet Only (FO): all restoration areas, including the minimum rewetting fraction, are fully rewetted.
- Full Rewet + Rehabilitation (FR): minimum rewetting targets met by full rewetting; remaining restoration by rehabilitation.

Paludiculture is not included because it is a market-driven measure in this study. Without explicit demand for paludiculture products specified in NRR, paludiculture will not be adopted and therefore does not alter the optimal restoration portfolio.

To reflect different policy contexts and potential applications in practice, we simulate four combinations (table 2): *GHG prices only, GHG prices + biomass demand, NRR targets only*, and *GHG prices + biomass demand + NRR targets*. These

Table 2. Scenario design for assessing the economic potential of restoration measures under different instruments.

	GHG prices	GHG prices + biomass demand	NRR targets	NRR targets + GHG prices + biomass demand
Full Rewet Only (FO)	x		x	
Full Rewet + Rehabilitation (FR)	x		x	
Full Rewet Only + Paludiculture		x		x
Full Rewet + Rehabilitation + Paludiculture		x		x

combinations allow to investigate the integrated impacts of policy frameworks on restoration.

3. Results

3.1. Cost-effectiveness of restoration measures in GHG mitigation

Figure 1 presents the economic potential of restoring drained agricultural organic soils for mitigating GHG emissions under two portfolios excluding paludiculture, Full Rewet Only (FO) and Full Rewet + Rehabilitation (FR). In both portfolios, restoration begins at a GHG price of 10 EUR tCO_2e^{-1} (figure 1(a)), initially driven by countries with relatively high reported emission factors, such as Romania, based on national-level data (table S2). In the FO portfolio, the restoration area remains below 1% under 40 EUR tCO_2e^{-1} due to high opportunity costs of full rewetting. As GHG prices rise, restoration expands rapidly, delivering substantial emission reductions. At 100 EUR tCO_2e^{-1}, FO restores 48% of agricultural organic soils, achieving 38.2 $MtCO_2e$ yr^{-1} of mitigation in 2050, which is about 43% of current GHG emissions from drained agricultural organic soils in the EU, and equivalent to 70% of net Cropland and Grassland GHG emissions in EU countries reporting organic soils in 2023.

The FR portfolio responds more quickly to rising GHG prices due to the economic benefits of rehabilitation. At prices below 60 EUR tCO_2e^{-1}, rehabilitation (dotted green line) accounts for 70%–80% of mitigation. Above this threshold, full rewetting (dashed green line) becomes more prominent, where the climate benefits of full rewetting outweigh the economic returns from continued agricultural activities on rehabilitation, making full rewetting the preferred option for ambitious mitigation. In 2050, at 100 EUR tCO_2e^{-1}, FR restores 73% of the total area and mitigates 44.4 $MtCO_2e$ yr^{-1}. Above 150 EUR tCO_2e^{-1}, rehabilitation areas are progressively rewetted, increasing both restored area and mitigation from full rewetting (figure 1(b)). The dominant mitigation process at higher GHG prices converges between FR and FO toward full rewetting, leading to greater GHG mitigation, and their total mitigation levels become increasingly similar. At 150 EUR tCO_2e^{-1}, FO overtakes FR in total GHG reductions despite restoring 0.6 Mha less area, which reflects the greater mitigation potential per hectare of full rewetting. Although its total mitigation is slightly lower than FO, FR restores a larger area, creating the ecological conditions needed for biodiversity recovery across more land, and thus potentially delivering greater biodiversity benefits (Minayeva *et al* 2016).

3.2. Impacts of paludiculture practices in drained organic soil restoration

Paludiculture substantially accelerates and expands full rewetting by providing an economic use for rewetted land (figures 2 and S4). With paludiculture, FO begins restoration at lower GHG prices, and FR shifts toward a higher share of full rewetting in 2050. This reduces mitigation potential difference between two portfolios across the GHG price range. Without paludiculture, full rewetting becomes competitive only at higher GHG prices. Practicing paludiculture therefore lowers the economic threshold for adopting full rewetting.

The strength of paludiculture depends on both paludiculture product demand and the paludiculture cost. Across biomass price levels, scenarios involving paludiculture achieve higher mitigation potential than the no-paludiculture scenarios, with differences more pronounced as biomass prices increase (figure 2). Remarkably, under high biomass demand (15 EUR GJ^{-1}), substantial restoration occurs even without GHG price incentives. In the Palu_lowCost scenario, 2 Mha of organic soils are fully rewetted, corresponding to approximately 48% of the current drained soil area (figure S4). This delivers 17 $MtCO_2e$ yr^{-1} of mitigation at zero GHG price, which is equivalent to 19% of current emissions from drained organic soils. Even when paludiculture costs are high (Palu_highCost), the highest biomass demand supports the restoration of 0.6 Mha, corresponding to about 14% of current drained soils. Depending on the paludiculture costs, 29%–96% of the 2050 NRR restoration area targets could already be achieved under high biomass demand and in the absence of GHG price incentives. This indicates that strong market impacts alone can stimulate restoration under favorable economic conditions, i.e., a high market demand for paludiculture products. Under low biomass demand (5 EUR GJ^{-1}), the biomass market does not provide a sufficient incentive to cover the high costs of paludiculture (figure S5). As a result, in the Palu_highCost scenario, paludiculture is not

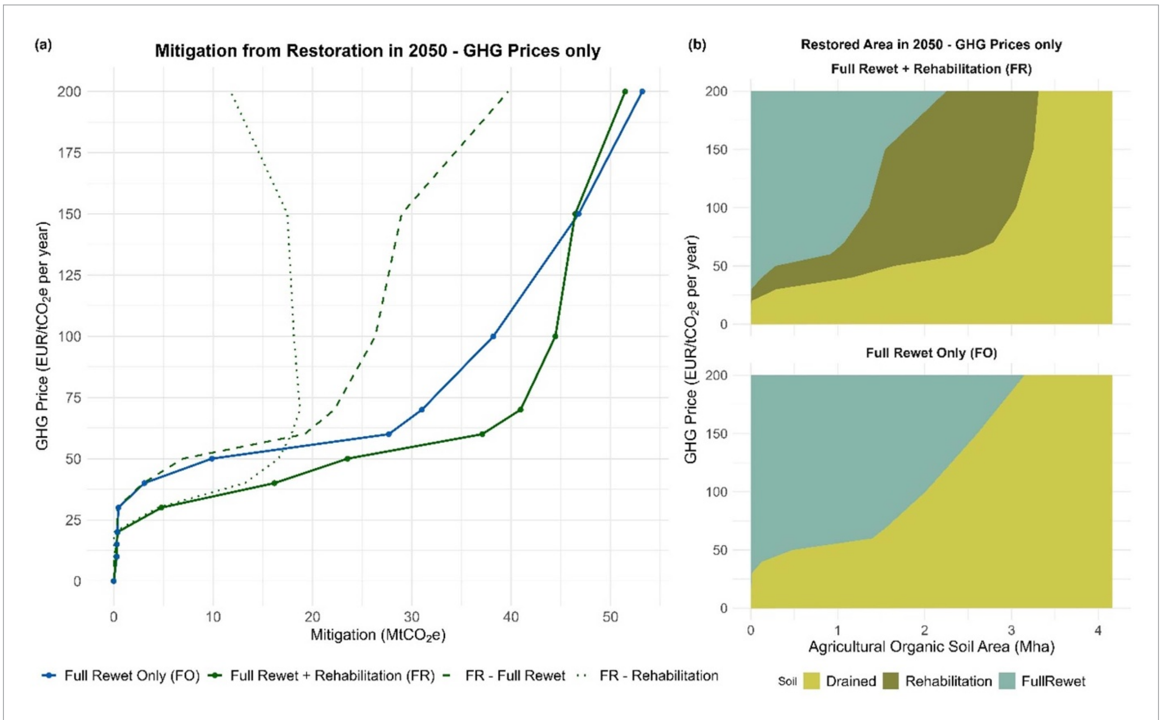

Figure 1. GHG mitigation (a) and restored area (b) from restoring currently drained organic soils in agricultural use across different GHG prices in the EU in 2050. Panel (a) shows marginal abatement cost curves (MACCs) for the two restoration portfolios: Full Rewet Only (FO, blue) and Full Rewet + Rehabilitation (FR, green). The dashed green line represents the contribution of full rewetting within the FR portfolio, and the dotted green line represents the contribution of rehabilitation (i.e. the decomposition of the FR portfolio into its component measures). Panel (b) shows the corresponding restored organic soil area under different GHG price levels, separately for FR (top) and FO (bottom).

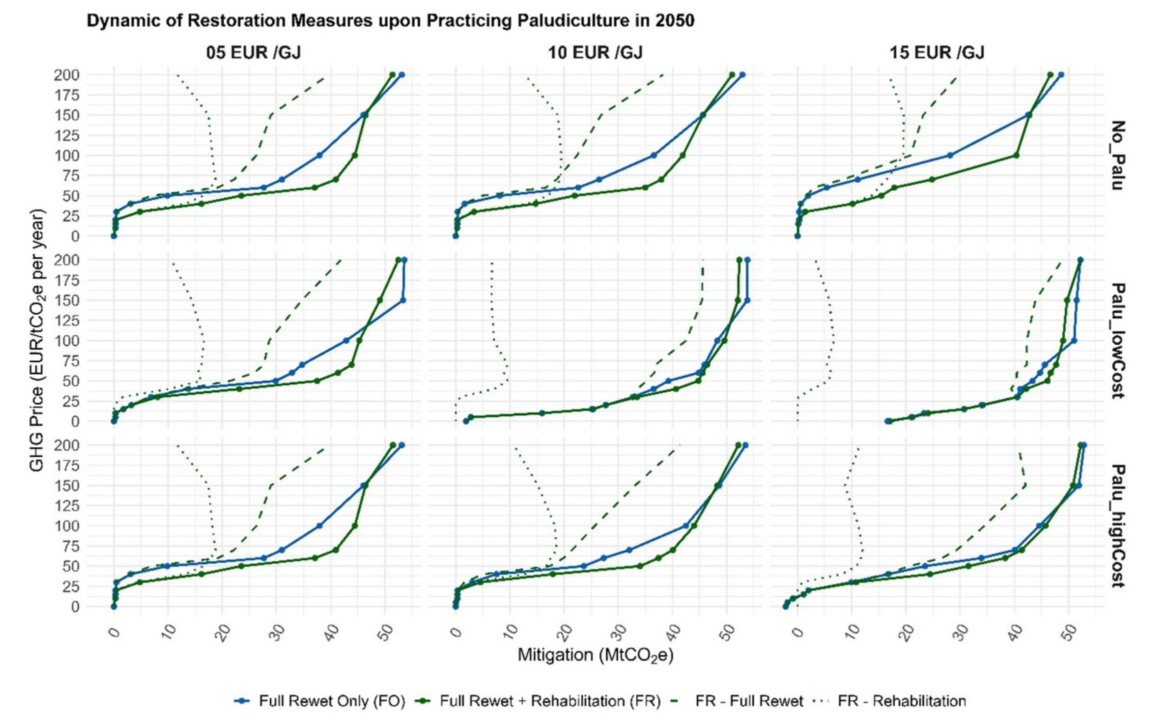

Figure 2. Comparison of GHG mitigation from drained organic soil restoration upon practicing paludiculture at different biomass demand levels under different GHG price levels in 2050.

adopted, and full rewetting proceeds without biomass production.

The impact of paludiculture on full rewetting is not uniformly positive across all conditions. In the FR portfolio under moderate biomass demand (10 EUR GJ^{-1}) and the low paludiculture costs, the full rewetted area declines from 3.3 Mha at 100 EUR tCO_2e^{-1} to 2.8 Mha at 150 EUR tCO_2e^{-1},

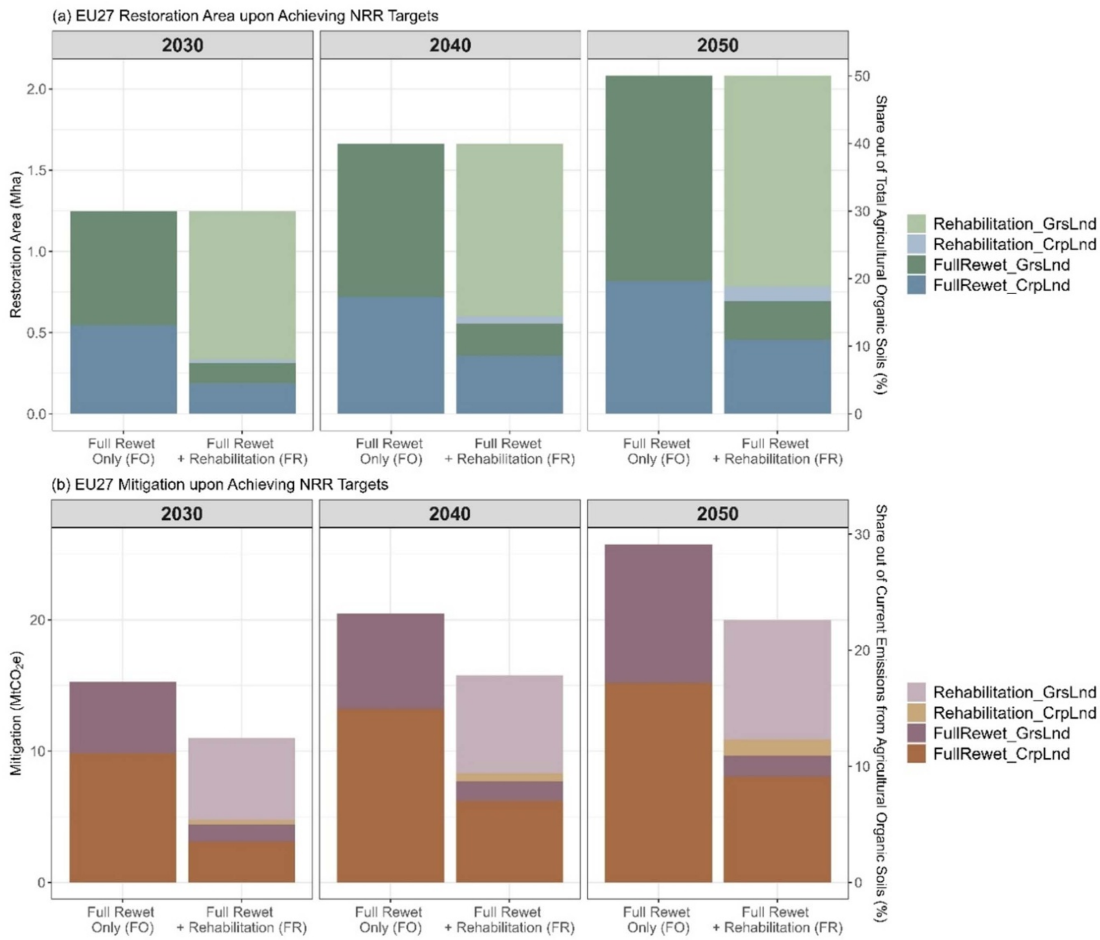

Figure 3. EU restoration results upon achieving NRR targets. (a) Restoration area under various restoration measure combinations to achieve NRR targets for specific years; (b) GHG mitigation from restoring drained organic soils under various restoration measures upon achieving NRR targets for specific years.

while the mitigation potential attributed to full rewetting increases from 42.5 $MtCO_2e\ yr^{-1}$ to 45.4 $MtCO_2e\ yr^{-1}$ in 2050. This is due to the heterogeneous data sources of emission factors for drained and rewetted soils: UNFCCC CRTs (CO_2 and N_2O) and the IPCC wetland supplements (CH_4). In Poland and Estonia, reported GHG emission factors for drained Grassland are lower than those for rewetted soils (table S2), resulting in net negative climate benefits from fully rewetting Grassland. Therefore, when climate benefits outweigh economic returns of biomass production at high GHG prices, fully rewetting Grassland and the paludiculture practice in these countries are eliminated, which sharply reduces restored area while increasing overall mitigation.

3.3. Dynamics of restoration measures to achieve NRR targets

While both restoration portfolios meet the same NRR restoration targets each year, the composition of restoration measures varies substantially (figure 3(a)). In the FR portfolio, full rewetting is applied only to meet the minimum rewetting requirement compared to achieving all NRR targets in FO. The choice of restoration measures strongly influences GHG mitigation outcomes (figure 3(b)). Achieving NRR 2050 targets reduces emissions by 20–26 $MtCO_2e\ yr^{-1}$, equivalent to 23%–29% of current emissions from drained agricultural organic soils in the EU. Because drained Cropland exhibits higher emissions, rewetting Cropland delivers a disproportionate share of mitigation: about 59% of total mitigation in FO and 40% in FR is attributed to rewetting Cropland. Throughout the analysis, we constrain trade flows to the baseline scenario levels to prevent emission leakage through bilateral trade. Thus, the associated agricultural production loss upon meeting NRR targets can be compensated through intensifying production on remaining agricultural land to maintain overall supply. The corresponding increase in agricultural emissions is negligible relative to mitigation from restoration.

NRR targets can be achieved by applying economic incentives, and our cost-effectiveness analyses (figures 1 and 2) provide reference for the level of incentives required. The results show that NRR 2050 area targets can be met at a compensation level of

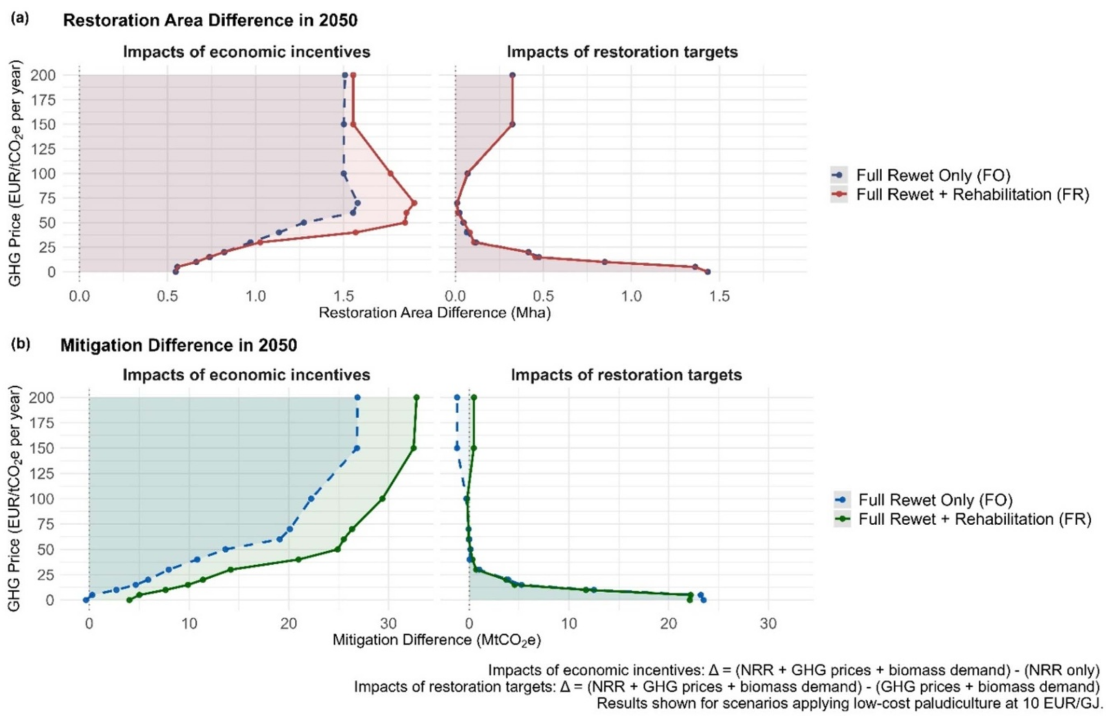

Figure 4. Differences in restoration area (a) and mitigation potential (b) between different instruments in 2050 under low-cost paludiculture scenarios ('Palu_lowCost') at 10 EUR GJ^{-1}. Each panel indicates alternative policy comparisons: 'Impacts of economic incentives' compares economic incentives with NRR (NRR + GHG prices + biomass demand) with NRR-only cases, and 'Impacts of restoration targets' compares economic incentives with NRR (NRR + GHG prices + biomass demand) with those without NRR (GHG prices + biomass demand). Positive values represent additional restoration area or mitigation achieved under NRR-inclusive policy combinations.

150 EUR tCO_2e^{-1} in FO, and 60 EUR tCO_2e^{-1} in FR. To reach the same level of mitigation potential upon achieving NRR 2050 targets, the required support levels fall to 60 EUR tCO_2e^{-1} for FO and 50 EUR tCO_2e^{-1} for FR, because the cost-effective mechanism prioritizes restoring regions with highest emissions from drained organic soils. The presence of a viable paludiculture market further lowers these incentive levels: under high biomass demand (15 EUR GJ^{-1}), the NRR 2050 area targets can be met at 5–70 EUR tCO_2e^{-1} depending on production costs and restoration measures, and mitigation-equivalent outcomes can be achieved at 5–60 EUR tCO_2e^{-1}.

3.4. Integrated impacts of multiple policy frameworks on restoration

Figure 4 shows how restoration outcomes change when NRR targets, GHG prices, and biomass demand operate together, illustrated for the low-cost paludiculture scenario with a biomass price of 10 EUR GJ^{-1}. Compared with achieving only NRR targets, combining NRR with economic incentives increases restoration area by 0.55 Mha at 0 EUR tCO_2e^{-1} in both portfolios, responding to the market incentives to produce paludiculture biomass (Impacts of economic incentives in figure 4(a)). The difference between two policy frameworks peaks at 1.6 Mha in FO and 1.9 Mha in FR at 70 EUR tCO_2e^{-1}. FR achieves a larger increase because rehabilitation allows more area to be restored at intermediate GHG price levels. Such portfolio difference narrows at higher GHG prices, where restoration patterns converge, and both portfolios shift towards full rewetting. Compared to economic incentives only (GHG prices + biomass demand), NRR contributes about 1.4 Mha of additional restoration at zero GHG price in the combined-policy scenario (NRR + GHG prices + biomass demand, Impacts of restoration targets in figure 4(a)). Its influence declines as GHG prices increase, where climate benefits dominant the choices of restoration measures. The magnitude and direction of this effect of NRR are consistent across both restoration portfolios.

Mitigation outcomes follow similar patterns (figure 4(b)). Relative to NRR alone, combined policies deliver substantially higher mitigation. In FR, paludiculture-driven restoration increases mitigation by 4 $MtCO_2e\ yr^{-1}$ at zero GHG price in 2050. In contrast, despite more area restored at zero GHG price under the combined-policy setting, FO mitigates less because in some countries restoration shifts towards cheaper land-use types to produce biomass, yet with net negative climate benefits. However, as GHG prices increase and restoration choices prioritize greater climate benefits, the mitigation advantage of combined policies becomes more pronounced. Simultaneously achieving NRR targets with economic incentives allow mitigating additional 22–23.5 $MtCO_2e\ yr^{-1}$

at 0 EUR tCO_2e^{-1} compared to without NRR. As GHG prices exceed 30 EUR tCO_2e^{-1}, the influences of NRR becomes marginal, as economic incentives dominate restoration decisions in both portfolios, and mitigation outcomes converge.

The impacts of integrated policies on both restoration area and GHG mitigation potential vary by biomass demand levels, as presented in figures S6–7. Our results show that the interaction of restoration targets and economic incentives jointly shape the scale and composition of optimal restoration portfolios. NRR targets deliver substantial restoration and mitigation where economic incentives are weak, while rising GHG prices and biomass demand expand restoration beyond regulatory minima.

4. Discussion

Our estimates of restoration area and GHG mitigation are broadly comparable with existing modeling studies on organic soil restoration. However, model-based estimations of restoration outcomes are highly sensitive to underlying input data and scenario assumptions. Humpenöder *et al* (2020) estimated that by 2050, about 3–4 Mha agricultural peatland could be restored across the EU and the UK at the GHG price of 227 EUR tCO_2e^{-1} (192 USD_{2005}). Similarly, Doelman *et al* (2023) showed that about 5–6 Mha agricultural peatland could be restored across 42 European countries by 2100. Both studies consider full rewetting as the only restoration measure, corresponding to our FO scenario, where we estimate that 3.1 Mha drained agricultural organic soils could be restored by 2050 at the GHG price of 200 EUR tCO_2e^{-1} in the EU. One major reason to cause such difference is the variances of input data. Specifically, this study relies on national organic soil areas and emission factors reported in UNFCCC CRTs, whereas Humpenöder *et al* (2020) and Doelman *et al* (2023) used different peatland maps and IPCC emission factors. Agora Agriculture (2024) assessed both full rewetting and shallow-drained grassland (one of the rehabilitation measures in this study) for the EU using UNFCCC CRTs. They reported that by 2045, restoring 3.5 Mha agricultural peatland in EU countries would be able to reduce 72 $MtCO_2e$ emissions. However, this assessment was based on 2020 data. Using updated data from the 2025 UNFCCC submission, our FR scenario indicates that at the GHG price of 200 EUR tCO_2e^{-1}, 3.3 Mha organic soils could be restored, delivering 51.5 $MtCO_2e$ mitigation by 2050.

4.1. Limitation of the modeling framework

The presented results should be considered in the context of modeling assumptions and parameter uncertainty. In this study, we apply IPCC emission factors for rewetted organic soils, which do not capture the non-linear dynamic relationship between GHG fluxes and water table depth observed in site studies, where net emissions decline only at the relatively shallower water table depth (Tiemeyer *et al* 2020, Koch *et al* 2023). This limitation can lead to over-/underestimating the benefits of specific restoration measures, particularly of the hybrid ones involving rehabilitation. For drained organic soils, areas and emission factors reported in UNFCCC CRTs carry substantial uncertainty due to divergent definitions, inconsistent methodologies, and limited transparency in country reporting. van Giersbergen *et al* (2025) also pointed out that the use of UNFCCC CRT data may lead to an underestimation of GHG emissions and their mitigation potential, particularly given the underreporting observed in several EU countries. The assumption that all agricultural organic soils are deeply drained simplifies the soil profile and management conditions, which may not fully capture subnational heterogeneity in drainage status and restoration outcomes.

It is also important to note that the cost estimations of restoration and paludiculture are primarily retrieved from projects in Germany and the UK. In practice, restoration costs may vary by geographic locations, management practices, and degradation levels (European Commission 2022, Wichmann *et al* 2022, Agora Agriculture 2024). Applying uniform costs across the EU likely masks regional differences. To evaluate the impacts of costs on restoration, we incorporate the upper and lower cost bounds from table 1 into the cost sensitivity analysis. The results (figure S8) present that restoration costs substantially affect the activation threshold and scale of mitigation. However, at higher GHG prices, the gap of mitigation difference narrows as economic incentives overcome cost barriers, indicating that restoration costs are more impactful as a limiting factor at lower GHG price thresholds. Country-specific restoration costs, though currently unavailable, would further improve model accuracy and policy relevance.

Although this study demonstrates the significant impacts of practicing paludiculture on restoration, the modeling remains at an exploratory stage. While paludiculture is theoretically recognized as a promising practice on fully rewetted soils, both technical and economic challenges to implementing paludiculture remain significant in real life (Tanneberger *et al* 2022, Wichmann and Nordt 2024). The model assumes a hypothetical biomass market for paludiculture products, but the real-world paludiculture market is still emerging, which may lead to the challenges of high upfront investment costs, long payback periods, and instable demand of paludiculture products (Ziegler *et al* 2021, Wichmann and Nordt 2024). Furthermore, our analysis focuses on reed canary grass as a representative paludiculture crop, which might potentially underestimate GHG mitigation in regions where tree species (e.g. black alder, willow) as primary paludiculture options could sequester more carbon over longer timeframes (Bianchi *et al* 2021, Abel and Kallweit 2022). Applying a single average yield of reed canary grass across the EU overlooks heterogeneity in site and management conditions and country-specific economic impacts of paludiculture. Future work could improve assessment of paludiculture by incorporating model-based yield predictions for paludiculture crops, where sufficient data are available.

Furthermore, the model optimizes restoration measures from an economic and emissions-based perspective, neglecting some feasibility and physical constraints of restoration implementation. For example, water availability is not considered, which could restrict rewetting in regions where today's hydrological conditions are unfavorable. Climate change itself can change peat decomposition and GHG release, and can alter restoration dynamics and emissions pathways (Leng *et al* 2019, Strack *et al* 2022). Yet, the current model does not account for future climate risks, potentially underestimating the urgency and benefits of restoration. We also assume that restoring a larger area enables greater potential biodiversity benefits. However, it will take decades to observe the trend towards natural conditions after the restoration, and the biodiversity and ecosystem functioning of restoration is not comparable with the pre-drainage conditions (Minayeva *et al* 2016, Kreyling *et al* 2021). These limitations highlight the need for improved emission data, broader representation of suitable paludiculture species, more detailed economic and ecological modeling, and explicit integration of hydrological and climate feedback to better inform restoration policy under changing environmental conditions.

4.2. Restoration of drained agricultural organic soils in the EU

Nevertheless, our results reveal several implications for how restoration measures interact with existing and emerging EU policy frameworks. NRR's area-based targets can secure substantial restoration, but they may not always maximize climate mitigation efficiency. Policy instruments like CRCF could provide market incentives to reach these targets, and even for additional mitigation beyond regulatory minima. Furthermore, the role of paludiculture in lowering the economic threshold for full rewetting indicates potential synergies between restoration policy and the EU Bioeconomy Strategy (European Commission 2025b). By providing productive uses for rewetted land, it can transform restoration from a policy-dependent measure into a self-sustaining land-use strategy. Unlocking this potential will require coordinated policy support, investment in infrastructure, and development of stable markets for paludiculture products.

5. Conclusion

This study provides an integrated assessment of the economic potential from restoring drained agricultural organic soils in the EU, explicitly evaluating full rewetting, rehabilitation, and full rewetting with paludiculture within the land-use economic model GLOBIOM-EU using the most up-to-date organic soil GIS data from European Wetland Map. We show that as GHG prices increase, restoration portfolios shift toward full rewetting, increasing overall mitigation outcomes. Introducing paludiculture lowers the GHG price threshold for large-scale rewetting, increases the share of fully rewetted soils, and can stimulate restoration even without GHG price incentives under high biomass demand. Achieving the 2050 NRR restoration targets to contribute to EU Biodiversity Strategy requires compensation levels of 60–150 EUR tCO_2e^{-1}, and can mitigate 23%–29% of current emissions from drained agricultural organic soils. These findings show that cost-effective restoration needs to be adaptive to economic conditions, land-use competition, and policy incentives. Aligning climate policy, emerging bioeconomy and biodiversity regulation can substantially increase the efficiency of restoring drained organic soils, advancing climate change mitigation and restoration goals at lower overall cost.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary Data available at https://doi.org/10.1088/1748-9326/ae5fae/data1.

Author Contributions

F J, A D and P H designed the study. F J, A D and J B processed the peatland data with supports from Z A G and M G F J and A D carried out the GLOBIOM modelling. F J performed the analysis and wrote an initial draft. All authors provided feedback and contributed substantially to the interpretation of the results and to the final text.

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