Peatland Restoration in Germany: A Dynamic General Equilibrium Analysis

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Abstract

While drained peatland currently represents only 7.7 percent of Germany's total utilized agricultural area, it contributes more than 40 percent of total national greenhouse gas emissions from agriculture and agricultural land use. The National Peatland Projection Strategy adopted by the German government in 2022 recognizes that these emissions need to be reduced significantly to meet the country's climate change mitigation commitments. The present study employs a global dynamic computable general equilibrium model to assess the economic and greenhouse gas emission impacts of alternative agriculture-focused peatland restoration scenarios for Germany up to 2030. In contrast to partial-analytic approaches, the global general equilibrium approach allows to take consistent account of economic ripple-on effects and carbon leakage effects triggered by peatland restoration. The results suggest that in the medium term towards 2030 a reduction in annual emissions from agricultural peatland use by up to 45 percent are attainable at marginal private abatement costs between 27 and 61 Euro/tCO_2e. Carbon leakage effects due to induced indirect land use change in Germany and the rest of the European Union reduce the global net emission reduction impact by 0.7 to 1.0 percent of the direct emission reduction. The effects on food prices remain small in all scenarios. In conclusion, a sizable reduction of Germany's land-use-related emissions is achievable at a low macroeconomic cost by moving beyond the moderate ambitions of the National Peatland Restoration Strategy.

Keywords: Greenhouse gas abatement; Climate change mitigation; Organic soils; Computable general equilibrium analysis; Abatement costs; Scenario analysis.

1. Introduction

Peatlands cover around 3 percent of the global land area and store more carbon than the planet's entire forest biomass (Humpenöder et al, 2019; Tanneberger et al, 2020; Leifeld and Menichetti, 2018; Günther et al, 2018). When peatland is drained for agriculture, forestry, peat extraction or human settlement, the organic matter stored in peat soils comes into contact with oxygen and the resulting decomposition process leads to significant CO_2 and N_2O emissions for decades to centuries. Degraded peatlands cover about 0.3% of the global land area and are estimated to contribute up to 5 percent of global anthropogenic CO_2 emissions (Günther et al, 2020; Olsson et al, 2019).[1]

In Germany, there are 1.8 million hectares (ha) of peatland and 92 percent of this area has been drained. Annual greenhouse gas (GHG) emissions from drained peatland amounted to 53 million tCO_2e in 2020, that is 7.5 percent of Germany's total 2020 GHG emissions (UBA, 2022; BMU, 2021). 77 percent of the drained peatland area is used for agricultural production, which accounts for over 80 percent of the GHG emissions from Germany's drained peatlands. While agricultural peatland represents only 7.7 percent of Germany's total utilized agricultural area in 2020, it contributes a disproportionate 40 percent of Germany's total GHG emissions from agriculture and agricultural land use (Grethe et al, 2021; Hirschelmann et al, 2020).

Under the amended Climate Change Act 2021, the German government is committed to reduce GHG emissions by 65 percent relative to 1990 level by 2030 and to reach climate neutrality by 2045. The National Peatland Projection Strategy (NPPS) (BMU, 2021) - adopted in 2022 after protracted political debate about potential adverse economic impacts - recognizes that without a reduction in peatland emissions, these climate change mitigation targets will not be achievable. The target set out in the NPPS is to reach an initial reduction in annual peatland

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[1] For a discussion of uncertainties surrounding these global estimates see Leifeld and Menichetti (2018) and Leifeld et al (2019).

emissions of 5 million tCO_2e by 2030. While some contributors to the discourse on peatland restoration in Germany criticise the NPPS target for its lack of ambition (e.g. GMC, 2021; Grethe et al, 2021), others point to high implementation costs and raise questions concerning the achievability of the target (e.g. Hofer and Köbbing, 2021).

Against this backdrop, the present study employs a global dynamic computable general equilibrium (CGE) model to assess the economic and greenhouse gas (GHG) emission impacts of alternative peatland restoration scenarios for Germany. The adoption of a global general equilibrium approach allows to assess the price effects, demand effects and international trade effects triggered by a reduction in the availability of agricultural land, and so allows to quantify the international carbon leakage effects due to induced changes in exports and imports.

In this respect, the approach serves to overcome the limitations of previous related research based on a partial-analytic framework: Röder et al (2015) use a fixed-price agricultural supply-side model for Germany with a differentiated representation of land use, agricultural production and income across 326 NUTS Level 3 regions to compare agricultural peatland restoration with other land-use-based GHG abatement measures. The results of this earlier study suggest that up to an annual emission reduction level of 20 million tCO_2e, peatland restoration is the most cost-effective (in terms of abatement cost per tCO_2e) and area-efficient (in terms of CO_2e reduction per ha) option among the land-based measures covered by the analysis. While this approach cannot take account of carbon leakage effects, the spatially disaggregated analysis provides valuable information about the size orders of the opportunity costs of agricultural peatland restoration in terms of foregone income as a function of area rewetted.

The scenario design for the present study draws upon this information. With respect to methodology development, the study thus suggests a novel way to link a CGE model with the results of a sectoral model that operates at a higher level of spatial and commodity resolution in order to capture the advantages of both approaches.[2]

Section 2 provides a concise non-technical description of the CGE model, outlines the dynamic baseline calibration process and explains the specification of the simulation scenarios. Section 3 presents and discusses the simulation results. Section 4 recapitulates and draws conclusions.

2. Materials and Methods

2.1. Analytic Framework

The main analytical tool for the policy scenario analysis is a dynamic five-region computable general equilibrium (CGE) model of the German economy and its trade relations with the rest of the European Union, Other High-Income Countries, Africa, and Other Low/Middle-Income Countries. The model distinguishes 20 production sectors and corresponding commodity groups including seven agricultural and six food processing sub-sectors (Table SI-1).

The global CGE model is an extended recursive-dynamic version of the comparative-static GLOBE model originally developed by McDonald, Thierfelder and Robinson (2007) which incorporates capital accumulation, population growth, labour force growth, and technical progress. The individual country or region blocs that together provide complete coverage of the global economy are linked through international trade and capital flows. Each region bloc represents the entire economy of that region at a sectorally disaggregated level. The economic interactions among producers, consumers, and the government as well as economic transactions with other regions are explicitly captured. Producers in each region combine primary factors (skilled and unskilled labor, physical capital, land, and other natural resources) with intermediate inputs obtained from the same and other production sectors at home and

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[2] See Delzeit (2020) for a review or the current state of the art in linking CGE models with agricultural sector models for scenario analysis.

abroad to produce output. The output is sold to domestic households, the domestic government, to domestic producers (for use as intermediate input or as an addition to the productive capital stock), and to other regions of the world. In all traded commodity groups, imports and goods of domestic origin are treated as imperfect substitutes in both final and intermediate demand.

The production process generates factor income in the form of wages, land and natural resource rents, and returns to capital as well as production tax income for the government. The factor income flows to households. Households use their income to pay income taxes, to buy consumer goods, and to save for future consumption. The government receives additional tax revenue from sales taxes including revenue from import duties.

Domestic producers in the model are price-takers in output and input markets and maximise intra-temporal profits subject to technology constraints. The technologies for the transformation of inputs into real outputs are described by sectoral constant-returns-to-scale production functions with a constant elasticity of substitution between primary factors and a Leontief technology for intermediate inputs. Consumer behaviour is derived from intra-temporal utility-maximising behaviour subject to within-period budget constraints, whereby consumer preferences are represented by a Stone-Geary utility function.

A detailed technical exposition of the dynamic GLOBE model is provided in Willenbockel et al (2018: Appendix). The model is initially calibrated to the GTAP10 database (Aguiar et al, 2019). This data set provides a detailed and internally consistent representation of the global economy-wide structure of production, demand, and international trade at a regionally and sectorally disaggregated level for the benchmark year 2014.

2.2. Baseline Calibration

As the benchmark year for the GTAP10 database is 2014, while the time horizon for the policy scenario analysis is 2023-2030, the model is first used to generate a new updated benchmark equilibrium for 2022 which reflects observed / estimated population growth and economic growth over the period 2014-2022. In a next step, a dynamic baseline scenario up to 2030 is constructed which serves as the reference for comparison with the food system transition scenarios. The baseline development uses SSP2 assumptions for population and GDP growth beyond 2027 (Dellink et al, 2017) and IMF / World Bank projections for GDP growth up to 2027 (Tables SI-2 and SI-3). Further information on data sources for the baseline calibration process is provided in the Supplementary Information.

2.3. Scenario Specification

The scenario specifications take account of Germany's National Peatland Protection Strategy (BMU, 2021), the respective recommendations by the Climate Neutrality Foundation (Grethe et al, 2021) and WBAE /WBW (2016), and the latest data on organic soil area (~ peatland) use and associated GHG emissions from Germany's 2022 National GHG Inventory Report (BUA, 2022) displayed in Table 1.

Table 1: Peatland Area by Use and GHG Emissions Germany 2020

Use	Area	GHG Emissions	Emission Factor
	k ha	*Million t CO2e /Year*	*t CO2e/ha*
Cropland	331.2	13.2	39.8
Grassland	951.8	29.3	30.8
Forest Land	278.0	3.1	11.1
Peat Extraction	17.7	0.1	5.6
Other	243.4	5.4	22.4
Total	**1822.1**	**51.2**	
Total Crop + Grassland	***1283.0***	***42.5***	***33.1***

Source: BMU (2022), Tables 345, 263, 362, 394, 409 and author's calculations.
Emissions comprise CO_2, N_2O and CH_4.

Three abatement scenarios in which peatland users are incentivised to reduce these emissions on a voluntary basis are considered. All scenarios assume that the treated areas are fully rewetted by raising the water table permanently to less than 0.1m below ground level to achieve maximum emission impact. In this case, annual emissions drop to 5.5 tCO_2e/ha (Tiemeyer et al, 2020) and consist primarily of methane emissions. Full rewetting entails that these areas become unsuitable for conventional agriculture and conversions to paludicultural uses are not considered in these medium-run scenarios to avoid speculative assumptions about the speed of development of commercial value chains, required new infrastructure investments and so forth.[3]

As the emission factor for cropland in Table 1 is an average over cropland with varying drainage levels and deeper draining entails higher emissions, the specification of the RewetLo and RewetHi scenarios follows WBAE/WBW (2016) in assuming that rewetting starts on deeply drained cropland with above-average baseline submissions. Specifically, it is assumed that the first 100 kha of fully rewetted cropland reduces emissions by 39.7 tCO_2e/ha, the next 100 kha by 34.8 tCO_2e/ha, and the final 133.1 kha by 29.8 tCO_2e/ha. These rates are set such that the integral under this stepwise linear emission function is consistent with the figures in Table 1, given the 5.5 tCO_2e/ha emission factor under complete rewetting.

The National Peatland Protection Strategy (NPPS) and the associated Target Agreement (2021) between the Federation and the Länder sets an aim to reduce annual peatland emissions by 5 million tCO_2e for 2030, but both documents are short on concrete policy detail and silent on prospective funding levels to support this aim. It is assumed that rewetting measures on 30 percent of the forest peatland area (that is the state-owned share of forest peatland according to Nitsch / Schramek, 2020) and the complete phasing-out of peat extraction and use (as envisaged in the Climate Act 2030) contribute respectively annual reductions in emissions of 0.467 million tCO_2e and 1.0 million tCO_2e (based on Höfer and Kobbing, 2021) by 2030. These non-

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[3] Partial rewetting measures that allow some form of conventional agricultural income generation to continue, such as the conversion of deeply drained cropland into medium drained extensive grassland are not considered here, because the empirical evidence suggests that abatement costs per tCO_2e tend to be significantly higher compared to complete rewetting – i.e., the opportunity cost reduction tends to be dominated by the drop in the mitigation effect – see e.g. Schaller (2014), WBAE/WBW (2016: 150), Krimly et al (2016).

agricultural peatland restoration measures will have negligible economy-wide effects and are subsumed in the baseline scenario, while all measures on agricultural peatland are included in the policy scenarios. This approach allows to consider a ‘clean’ agriculture-focused NPPS implementation scenario (RewetLo) that can be contrasted with more ambitious agricultural peatlands scenarios that go beyond the NPPS target.

Table 2: Agricultural Peatland Transformation Pathway by Scenario

	2023	2024	2025	2026	2027	2028	2029	2030
Rewetted Peatland Area					**RewetLo**			
Cropland (kha)	11.0	22.0	33.0	44.1	55.1	66.1	77.1	88.1
Grassland (kha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (kha)	**11.0**	**22.0**	**33.0**	**44.1**	**55.1**	**66.1**	**77.1**	**88.1**
Rewetted Peatland Area					**RewetHi**			
Cropland (kha)	41.4	82.8	124.2	165.6	207.0	248.4	289.8	331.2
Grassland (kha)	17.8	35.7	53.5	71.4	89.2	107.1	124.9	142.8
Total (kha)	**59.2**	**118.5**	**177.7**	**237.0**	**296.2**	**355.5**	**414.7**	**474.0**
Rewetted Peatland Area					**RewetHi+**			
Cropland (kha)	86.3	172.7	259	331.2	331.2	331.2	331.2	331.2
Grassland (kha)	0.7	1.3	2.0	16.8	72.0	174.0	276.0	378.0
Total (kha)	**87.0**	**174.0**	**261.0**	**348.0**	**403.2**	**505.2**	**607.2**	**709.2**

Table 3: Direct Greenhouse Gas Emission Reduction by Scenario

	2023	2024	2025	2026	2027	2028	2029	2030
Direct GHG Reduction					**RewetLo**			
Cropland (million tCO2e)	-0.4	-0.9	-1.3	-1.8	-2.2	-2.6	-3.1	-3.5
Grassland (million tCO2e)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (million tCO2e)	**-0.4**	**-0.9**	**-1.3**	**-1.8**	**-2.2**	**-2.6**	**-3.1**	**-3.5**
Direct GHG Reduction					**RewetHi**			
Cropland (million tCO2e)	-1.6	-3.3	-4.8	-6.3	-7.7	-8.9	-10.1	-11.4
Grassland (million tCO2e)	-0.5	-0.9	-1.4	-1.8	-2.3	-2.7	-3.2	-3.6
Total (million tCO2e)	**-2.1**	**-4.2**	**-6.2**	**-8.1**	**-9.9**	**-11.6**	**-13.3**	**-15.0**
Direct GHG Reduction					**RewetHi+**			
Cropland (million tCO2e)	-2.6	-5.2	-7.7	-9.6	-9.6	-9.6	-9.6	-9.6
Grassland (million tCO2e)	0.0	0.0	-0.1	-0.4	-1.9	-4.4	-7.0	-9.5
Total (million tCO2e)	**-2.6**	**-5.2**	**-7.8**	**-10.0**	**-11.5**	**-14.0**	**-16.6**	**-19.1**

Thus, scenario *RewetLo* assumes that the remaining abatement effort of 3.5 million tCO$_2$e required to reach the 5 million tCO$_2$e NPPS target – given the aforesaid non-agricultural measures subsumed in the baseline scenario - is realized by fully rewetting a suitable fraction of cropland. Under the stated assumptions about 88,000 ha of cropland need to be rewetted by 2030 to reach the NPPS target.

Scenario *RewetHi* is a substantially more ambitious abatement scenario, in which all drained cropland is rewetted and in addition 15 percent of drained grassland is fully rewetted by 2030 (Table 2). Annual emissions from agricultural peatland use drop by 15 million tCO_2e towards 2030 in this scenario (Table 3). In terms of mitigation outcomes – though not in the details of the pathway – this scenario is similar to 'scenario C' to 2030 of WBAE/WBW (2016) and to the 'Pathway 1' scenario to 2030 in Tanneberger et al (2021). In both RewetLo and RewetHi, the rewetting process takes place over the period 2023 to 2030 according to a linear expansion path as shown in Table 2.

The specification of scenario *RewetHi+* draws upon the aforementioned model-based spatially explicit simulation analysis by Röder et al (2015), which assumes that peatland use by an agricultural activity in a NUTS3 region of Germany is abandoned in favour of full rewetting once the reward payment received for rewetting exceeds the short-run opportunity cost measured in terms of gross value added foregone. The analysis suggests that at a reward level of 5 Euro/ tCO_2e, an area of 261,000 ha (primarily cropland in areas of East-Central Germany with low value added per ha due to unfavourable soil and climatic conditions), while at 10 Euro/ tCO_2e (20 Euro/ tCO_2e) the total rewetted area rises to 405,000 ha (729,000 ha).

The RewetHi+ scenario modifies this abatement cost schedule by adding planning and engineering costs and by scaling up the implied schedule of opportunity costs per to arrive at an updated valuation of foregone income in Euros of 2020 purchasing power and to reflect the conjecture that probably a stronger financial incentive beyond the compensation for lost income is required to induce the level of voluntary participation in rewetting schemes assumed in this scenario. Furthermore, since the rewetted cropland area in Röder et al (2015) exceeds the total available organic soil cropland area according to the more recent BMU (2022) data used in the present study (Table 1) by 20,000 ha, the rewetted area figures have been adjusted accordingly. Thus, under the RewetHi+ scenario 709,000 ha are completely rewetted by 2030 (Table 2). Annual emissions from agricultural peatland use drop by 19.1 million tCO_2e towards 2030 in this scenario (Table 3)[4].

To assess the minimum compensation payment levels required to induce a voluntary switch from agricultural production to the harvesting of carbon credits, an estimate of the short-run private abatement costs is required. These comprise the opportunity cost of full rewetting in terms of agricultural income foregone plus the annualized planning, construction, maintenance and monitoring costs (net of avoided baseline drainage costs) associated with permanently raising the water tables on the peatlands designated for rewetting.[5] Existing empirical studies for Germany[6] measure the opportunity cost component by the gross margin (foregone revenue including subsidies minus short-run variable cost) or gross value-added at factor cost. For the RewetLo and RewetHi scenarios the annual opportunity cost component is set at a uniform rate of 900 Euro/ha[7]. Following Isermeyer et al (2019: 46-47) and Grethe et al (2021: 72), the average annualized engineering costs are set at 500 Euro/ha (i.e. 10,000 Euro/ha over 20 years). The engineering costs enter the general equilibrium model in the form of additional exogenous government-financed purchases of construction services and other services. It is assumed that these rewetting costs consist of upfront planning and construction costs of 8000 Euro/ha in the first year and recurrent annual maintenance and monitoring costs of 100 Euro/ha for 20 years.

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[4] Emission figures in for RewetHi+ in Table 3 are based on emission reduction factors (29.9 to 25.0 tCO_2e/ha) backed out from Röder (2015: Supplementary Information Table A.2).

[5] In the following these latter costs are referred to as ‘engineering costs’ for brevity’s sake.

[6] See Bonn et al (2015) for a concise review.

[7] This figure is slightly above the range for the private opportunity cost of rewetting suggested by Grethe et al (2021: 72).

The annualized short-run private abatement including engineering costs is thus 1400 Euro/ha, which equates to marginal private abatement costs of 35 Euro/tCO_2e under RewetLo and 40 to 50 Euro/tCO_2e under RewetHi (Table 4). These figures are within the mid-range of existing abatement cost estimates for fully rewetted agricultural peatland in Germany.

In the RewetHi+ scenario, the upscaled opportunity costs derived from Röder et al (2015) rise from 308 Euro/ha for the first 261 ha to 529 Euro/ha for the next 142 ha and to 1030 Euro/ha for the last 306 ha of rewetted peatland, and thus the marginal private abatement costs including annualized engineering costs rise from 808 Euro/ha to 1029 Euro/ha and 1530 Euro/ha respectively. The corresponding marginal abatement costs per tCO_2e are shown in Table 4. It is assumed that reward payments at the initial low rate are offered from 2023 to 2025 and then rise to higher levels in 2026 and 2028.

Table 4: Private Abatement Costs by Scenario

		2023	2024	2025	2026	2027	2028	2029	2030
					RewetLo				
Marginal short-run cost	*Euro/tCO2e*	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2
Funding requirement	*Million Euro*	98.0	107.9	117.8	127.8	137.7	147.6	157.5	167.4
					RewetHi				
Marginal short-run cost	*Euro/tCO2e*	39.6	39.6	42.0	43.9	44.7	49.2	49.2	49.2
Funding requirement	*Million Euro*	528.4	582.8	637.2	691.7	746.1	800.5	854.9	909.4
					RewetHi+				
Marginal short-run cost	*Euro/tCO2e*	27.0	27.0	27.0	40.1	40.1	61.2	61.2	61.2
Funding requirement	*Million Euro*	728.7	761.4	794.1	846.2	626.8	1112.2	1223.2	1334.2

Funding requirement in year t equals upfront engineering cost for additional area rewetted *in* t plus recurrent annual payments (maintenance / monitoring costs and compensation for foregone agricultural income) for the area rewetted *up to* t.

2.4. Scenario Implementation in the CGE Model

In the CGE model the reductions in the availability of agricultural land in the peatland restoration scenarios are implemented as exogenous shifts of the German aggregate land supply function. Land supply is specified as an iso-elastic function of the real returns to land to allow for endogenous increases in the utilization of mineral soil land in response to the rice effects triggered by peatland restoration. As the peatland restoration is assumed to take place on land with below-average productivity in terms of baseline value added per ha, the size of the annual land supply functions shifts are specified by transforming the UAA reductions into equivalent changes in units of average-productivity land. The compensation payments for foregone agricultural income enter the model as recurrent additional annual transfer payments from the government to the private household sector. As noted in section 2.3, the upfront and recurrent engineering costs enter in the form of additional exogenous government-financed purchases of construction services and other services. The net increase in government expenditure in the peatland restoration scenarios is by assumption financed through a marginal increase in the household income tax rate. Technically, the time paths of government savings and real government expenditure (other than the government payments related to peatland restoration) are kept frozen at baseline levels, and the income tax adapts endogenously to satisfy the government budget constraint. An alternative government sector closure under which the additional government expenditure is debt-financed has been considered as part of the sensitivity analysis.

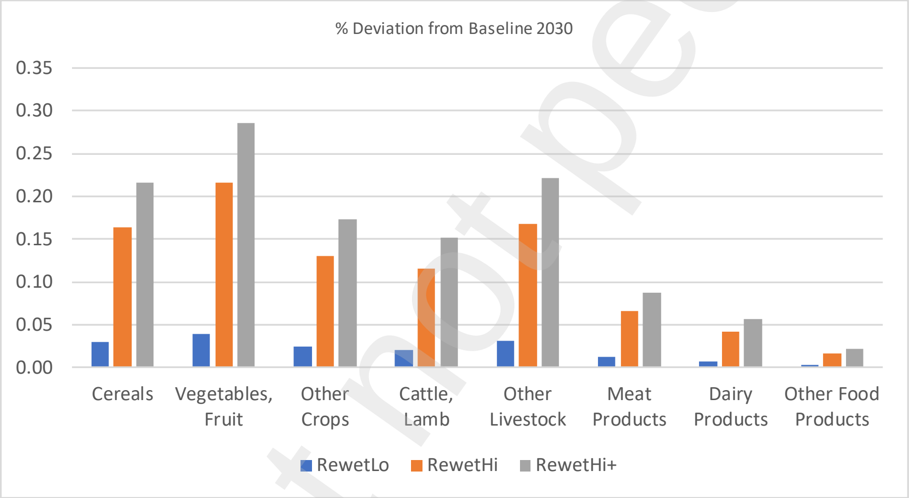
3. Results and Discussion

3.1. Economic Impacts

In the RewetLo scenario, which reflects the moderate ambitions of Germany’s National Peatland Protection Strategy, the rewetted peatland area withdrawn from agricultural production by 2030 amounts to 0.31 percent of the 2030 baseline UAA in productivity-adjusted terms. In the more ambitious RewetHi and RewetHi+ scenarios, the corresponding productivity-adjusted shares are respectively 1,69 and 2.21 percent.

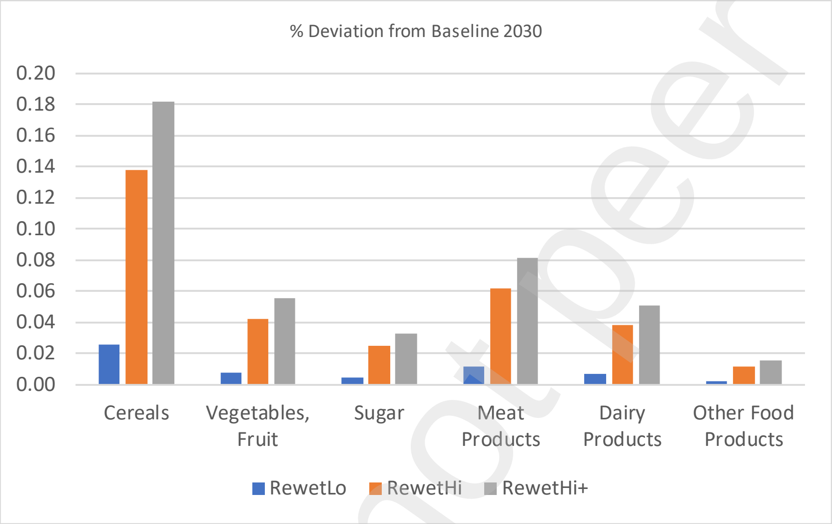
The effective agricultural land supply reduction entails upward pressure on agricultural land rents in Germany and this pushes domestic agricultural production costs and hence producer prices up to some extent (Figure 1). However, since the rewetted areas are small in relation to Germany's total UAA (16.6 million ha in 2020), the size order of this cost-push effect is small under the RewetHi scenarios and negligibly small under the RewetLo scenario. The resulting increases in consumer prices for food in Germany at the 2030 endpoint of the transformation pathway remain well below 0.05 percent under RewetLo and well below 0.2 percent under RewetHi+ (Figure 2). Correspondingly, the impact on domestic food consumption quantities is virtually nil in RewetLo and remains below 0.1 percent in RewetHi+ across all food commodity groups (Table SI-6).

Figure 1: Impact on Producer Prices 2030 in Germany



The increase in prices for food commodities of German origin relative to the rest of the world induce a rise in German imports and a drop in German exports of agricultural commodities and processed food products (Table 5). In percentage terms, the export reduction in the RewetHi+ scenario is most pronounced for fruit and vegetables (Table SI-3) – which is the sector with the highest share of land rents in total cost and the strongest increase in producer prices (Figure 1). However, in absolute volume terms the strongest decline in exports is registered by the meat processing sector (Table SI-4), as the baseline export volume of German processed meat products is far higher than the baseline export volume of German fruit and vegetable exports. From a macroeconomic perspective, the trade volume effects reported in Table 5 are tiny in relation to Germany's total trade volumes: The total reduction in agricultural and processed food exports for 2030 in the RewetHi+ scenario amounts to 0.012 percent of Germany's projected total 2030 baseline exports of goods and services. On the import side, the sum of the volume reductions amounts to around 0.009 percent of Germany's projected total 2030 baseline imports of goods and services.

Figure 2: Impact on Consumer Prices 2030 in Germany



Note: Prices are measured relative to the consumer price index. The figure shows changes in composite price indices over domestic and imported commodities.

The resulting impacts on Germany's agricultural and processed food output by commodity group at the endpoint of the simulation horizon are shown in Figure 3. Vegetable and fruit production registers the strongest decline relative to the baseline. This is the commodity group with the highest producer price increase (Figure 1) and a commodity group with a relatively high baseline export-output ratio. For all other commodity groups, the output reductions remain well below 0.6 percent of 2030 baseline production in the RewetHi scenarios and below 0.1 percent in the RewetLo scenario.

Table 5: Impact on German Export and Import Volumes in 2030

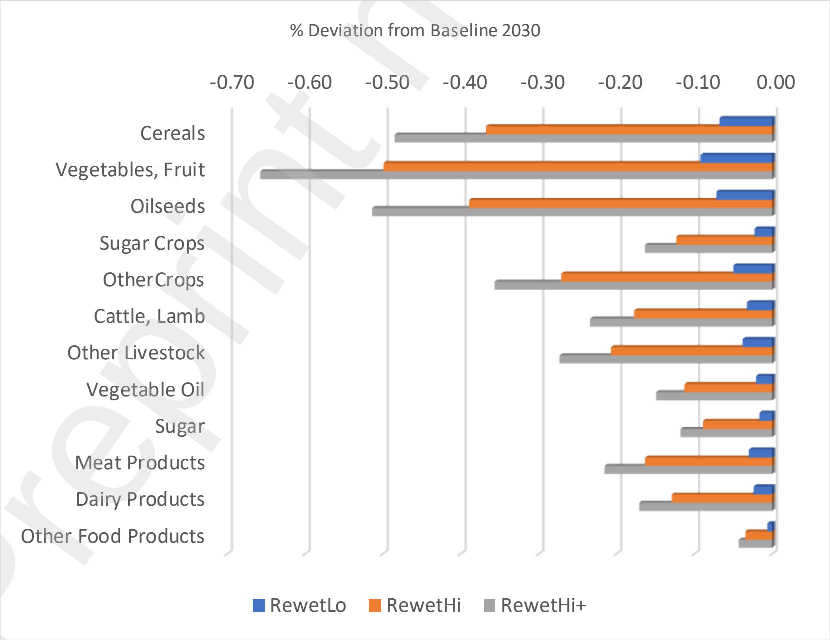
(Deviation from Baseline 2030)

	Imports to Germany			Exports from Germany		
	RewetLo	**RewetHi**	**RewetHi+**	**RewetLo**	**RewetHi**	**RewetHi+**
			Million Euro			
Agricultural Products	7.4	40.0	75.9	-11.7	-63.8	-84.2
Processed Food	5.0	26.9	54.4	-13.9	-75.3	-100.0
Total Agri-Food	**12.3**	**67.0**	**130.3**	**-25.6**	**-139.1**	**-184.2**
			%			
Agricultural Products	0.02	0.12	0.22	-0.10	-0.53	-0.69
Processed Food	0.01	0.04	0.08	-0.02	-0.11	-0.15
Total Agri-Food	0.01	0.07	0.13	-0.03	-0.17	-0.23

Note: Export and import volumes are quantities valued at 2030 baseline prices. Disaggregated trade effects by commodity group are shown in Tables SI-4 and SI-5.

The impacts on real GDP and net real household income are negligibly small in all scenarios: Under RewetHi+, 2030 real GDP is -0.023 percent lower than in the baseline and under RewetLo the GDP effect for 2030 is -0.003 percent. Results for net household income are of the same order of magnitude. The temporary household income tax increases required to finance the additional government expenditure are 0.036 (2023) to 0.064 (2030) percentage-points under RewetHi+, 0.027 to 0.045 percentage-points under RewetHi, and 0.005 to 0.008 percentage-points under RewetLo.

Figure 3: Impact on Domestic Production in 2030 in Germany



3.2 Leakage Effects

Table 6 reports the effects on agricultural land use suggested by the simulation analysis. The net land use reductions in Germany are lower than the assumed agricultural peatland area reductions (Table 2), because the model allows for an endogenous land supply response to the rise in agricultural land rents triggered by the peatland restoration.

Table 6: Change in Utilised Agricultural Area

	Germany			RoEU	Germany	RoEU	EU27
	Organic Soil	**Mineral Soil**	**Total**	**Total**	**Total**	**Total**	**Total**
	kha	*kha*	*kha*	*kha*	*% Deviation from Baseline*		*kha*
RewetLo							
2023	-9.4	2.4	-7.0	0.5	*0.0*	*0.00*	-6.5
2024	-18.7	4.8	-13.9	0.9	*-0.1*	*0.00*	-12.9
2025	-28.1	7.3	-20.8	1.3	*-0.1*	*0.00*	-19.4
2026	-37.4	9.7	-27.7	1.8	*-0.2*	*0.00*	-25.9
2027	-46.8	12.2	-34.6	2.2	*-0.2*	*0.00*	-32.5
2028	-56.1	14.6	-41.6	2.6	*-0.3*	*0.00*	-39.0
2029	-65.5	17.0	-48.5	3.0	*-0.3*	*0.00*	-45.6
2030	-74.8	19.4	-55.5	3.4	*-0.4*	*0.00*	-52.1
RewetHi							
2023	-59.2	17.8	-41.5	2.7	*-0.3*	*0.00*	-38.8
2024	-118.5	35.8	-82.7	5.0	*-0.5*	*0.00*	-77.7
2025	-177.7	53.8	-123.9	7.3	*-0.8*	*0.01*	-116.6
2026	-237.0	71.9	-165.1	9.5	*-1.1*	*0.01*	-155.5
2027	-296.2	89.8	-206.5	11.8	*-1.3*	*0.01*	-194.7
2028	-355.5	107.6	-247.9	13.9	*-1.6*	*0.01*	-234.0
2029	-414.7	125.3	-289.5	16.1	*-1.9*	*0.01*	-273.4
2030	-474.0	142.8	-331.1	18.3	*-2.1*	*0.01*	-312.9
RewetHi+							
2023	-87.0	10.4	-76.6	1.9	*-0.5*	*0.00*	-74.7
2024	-174.0	21.1	-152.9	3.2	*-1.0*	*0.00*	-149.7
2025	-261.0	31.9	-229.1	4.5	*-1.5*	*0.00*	-224.6
2026	-348.0	50.5	-297.5	6.9	*-1.9*	*0.00*	-290.6
2027	-403.2	62.1	-341.1	8.2	*-2.2*	*0.01*	-332.9
2028	-505.2	104.2	-401.0	14.0	*-2.6*	*0.01*	-387.0
2029	-607.2	145.9	-461.3	19.2	*-3.0*	*0.01*	-442.1
2030	-709.2	187.3	-521.9	24.4	*-3.4*	*0.02*	-497.4

Both the increases in German agri-food imports and the decreases in German agri-food exports entail a rise in agricultural land use in the rest of the world. This indirect land use effect occurs again predominantly in the rest of the EU[8]. Thus, in comparison to the 2030 baseline level Germany's UAA drops by 522 kha in the RewetHi+ scenario – which is the net effect of the reduction in peatland use by 709 kha and a rise in mineral-soil land use by 187 kha in response to the agricultural produce price increase - while the UAA in the RoEU rises by around 24 kha, so that the EU27 (i.e. RoEU + Germany) UAA drops on balance by around 497 kha.

3.3. GHG Emission Impacts

To assess the total net impact on Germany's GHG emissions from agriculture and agricultural land use suggested by the simulation, Table 7 sets the emission reductions from organic soils directly attributable to the rewetting of drained cropland and grassland from Table 3 in relation to the indirect emission changes due to the induced shifts towards agricultural production on mineral soils reported in Table 6 and the reductions in German cattle and other livestock production (Figure 3) triggered by the rewetting scheme. The assessment of these indirect effects covers the three main components of agricultural emissions in Germany, which together account for 92.5 percent of Germany's total agricultural GHG emissions in 2020 (56.1 million tCO_2e)[9]. These are CH_4 emissions from enteric fermentation (42.5 percent), CH_4 and N_2O emissions associated with manure management (16.7 percent) and N_2O emissions from agricultural soils (33.2 percent).

For the calculation of the indirect emission impacts, the annual agricultural land use baseline projection for 2021 to 2030 from the CGE model is applied to the agricultural soils emission data for 2020 from Vos et al (2022b) to obtain the dynamic baseline projection for this category at an annual timestep , and then the deviations in agricultural land use from the baseline under the peatland rewetting scenarios from Table 6 are used to obtain the annual emissions for

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[8] In the RewetHi+ scenario, agricultural land use in 2030 rises by 0.0011 percent in Africa, by 0.0010 percent in RoLMI and by 0.0029 percent in RoHI relative to the baseline.

[9] Vos et al (2022a: Table 2.1). This source and Vos et al (2022b) provide the agricultural GHG emission data for Germany's latest National GHG Report (UBA, 2022).

agricultural soils reported in Table 7. Similarly, for the determination of changes in emissions from enteric fermentation, the 2020 emissions data for cattle, sheep, goats and horses from Vos et al (2022a) are linked to the real output changes for the *Bovine Cattle, Sheep, Goats, Horses* sector of the CGE model, and the emission data for pigs from the same source to are linked to the real output changes for the *Other Livestock Agriculture* sector of the CGE sector. The same approach is used for CH_4 and N_2O emissions associated with manure management, but in this case the emissions for *Other Livestock Agriculture* include poultry in addition to pig manure management emissions.

Table 7: Impact on Germany's GHG Emissions

(Deviations of annual emissions from Baseline in million tCO_2e)

Emissions from	2023	2024	2025	2026	2027	2028	2029	2030	2023-2030
	RewetHi+								
Organic Soils	-2.600	-5.200	-7.800	-10.041	-11.454	-14.075	-16.695	-19.316	**-87.181**
N_2O Mineral Soils	0.011	0.023	0.034	0.054	0.067	0.112	0.157	0.201	**0.658**
Enteric Fermentation	-0.004	-0.007	-0.010	-0.016	-0.019	-0.031	-0.043	-0.056	**-0.186**
Manure Management	-0.002	-0.003	-0.004	-0.007	-0.008	-0.013	-0.018	-0.023	**-0.078**
Total	**-2.594**	**-5.187**	**-7.780**	**-10.008**	**-11.414**	**-14.007**	**-16.600**	**-19.194**	**-86.785**
	RewetHi								
Organic Soils	-2.096	-4.192	-6.168	-8.059	-9.914	-11.599	-13.284	-14.969	**-70.282**
N_2O Mineral Soils	0.019	0.038	0.058	0.077	0.096	0.115	0.134	0.153	**0.692**
Enteric Fermentation	-0.005	-0.011	-0.016	-0.021	-0.026	-0.032	-0.037	-0.042	**-0.191**
Manure Management	-0.002	-0.004	-0.007	-0.009	-0.011	-0.013	-0.015	-0.018	**-0.079**
Total	**-2.085**	**-4.169**	**-6.133**	**-8.011**	**-9.855**	**-11.529**	**-13.202**	**-14.876**	**-69.860**
	RewetLo								
Organic soils	-0.438	-0.875	-1.313	-1.750	-2.188	-2.625	-3.063	-3.500	**-15.750**
N_2O Mineral Soils	0.003	0.005	0.008	0.010	0.013	0.016	0.018	0.021	**0.094**
Enteric Fermentation	-0.001	-0.002	-0.003	-0.004	-0.005	-0.006	-0.007	-0.008	**-0.034**
Manure Management	0.000	-0.001	-0.001	-0.002	-0.002	-0.002	-0.003	-0.003	**-0.015**
Total	**-0.436**	**-0.873**	**-1.309**	**-1.745**	**-2.181**	**-2.617**	**-3.054**	**-3.490**	**-15.705**

Global Warming Potential (GWP) coefficients of 25 for CH_4 and 298 for N_2O are used for the conversion into CO_2 equivalents.

The results indicate that the reduction in emissions from organic soils strongly dominate the increase in emissions from mineral soils. As shown in Table 8, the carbon leakage effects associated with the induced increases in the UAA and in livestock production within the RoEU are likewise small in relation to the direct emission reduction effect.

Table 8: Impact on Rest of European Union GHG Emissions

(Deviations of annual emissions from Baseline in million tCO_2e)

	2023	2024	2025	2026	2027	2028	2029	2030	2023-2030
RewetLo	0.001	0.003	0.004	0.005	0.006	0.007	0.009	0.010	**0.045**
RewetHi	0.008	0.014	0.021	0.028	0.034	0.041	0.047	0.054	**0.246**
RewetHi+	0.006	0.009	0.013	0.020	0.024	0.041	0.056	0.072	**0.242**

3.4. General Equilibrium Assessment of Social Costs and Benefits

Table 9 provides a summary assessment of the social costs and benefits of agricultural peatland rewetting under the three scenarios. The assessment covers the period 2023 to 2049 to take account of the ongoing annual maintenance and monitoring costs and foregone land returns for 20 years after the initial land conversion. For the period 2023 to 2030, the annual social costs for Germany are determined by the Hicksian equivalent variation (EV), which provides a model consistent money-metric measure of the consumer welfare change due to the general equilibrium price and household income changes triggered by the policy reform. The EV measures the hypothetical amount by which the household sector's consumption budget would have to be reduced *in the absence of* the policy reform to generate a welfare effect that is equivalent to that of the policy reform.[10]

The undiscounted cumulated consumer welfare losses as measured by the model-based EV over the period 2023 to 2030 amount to 0.75 billion Euro under RewetLo, 4.0 billion Euro under RewetHi and 5.9 billion Euro under RewetHi+. These figures are close to a simpler alternative social cost estimate obtained by just adding up rewetting costs and foregone land returns over the same period. Together with ongoing annual maintenance and monitoring costs

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[10] See Supplementary Information for a formal definition.

and foregone land returns between 2031 and 2049[11], the total undiscounted social cost up to 2049 ranges from 1 billion Euro (RewetLo) to 8.3 billion Euro (RewetHi) (Table SI-7).

The present values of the social benefits in the Table are calculated by evaluating the annual net GHG emission reductions (net of leakage effects) using the carbon prices recommended by the German Environmental Agency for use in cost-benefit analysis, which rise from 201 Euro/tCO$_2$e for 2023 to 250 Euro/tCO$_2$e for 2050 (Matthey and Bünger, 2023). The social internal rate of return – that is the discount rate at which the present value of the social costs is equated to the present value of the social benefits – is 102 percent for the RewetLo scenario, 88 percent for the RewetHi scenario and 76 percent for the RewetHi+ scenario.

Table 9: Long-Run Social Costs and Benefits (TY)

	RewetLo	RewetHi	RewetHi+
Present Value of Social Cost 2023-2049			
Discount Rate = 0 *(Million Euro)*	1,052	5,666	8,160
Discount Rate = 0.03 *(Million Euro)*	911	4,906	7,130
Present Value of Social Benefit 2023-2049			
Discount Rate = 0 *(Million Euro)*	15,769	66,997	86,694
Discount Rate = 0.03 *(Million Euro)*	10,506	44,906	57,805
Social Benefit-Cost Ratio			
Discount Rate = 0	15.0	11.8	10.4
Discount Rate = 0.03	11.5	9.2	8.5
Social Rate of Return	1.018	0.878	0.762
Cumulated Net GHG Reduction 2023-2049 (*Million tCO2e)*	-69.5	-295.9	-382.3
Average Social Abatement Cost			
Discount Rate = 0 *(Euro/tCO2e)*	15.13	19.15	21.73
Discount Rate = 0.03 *(Euro/tCO2e)*	13.11	16.58	17.84
Marginal Social Abatement Cost *(Euro/tCO2e)*	15	17 to 23	20 to 27

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[11] For the area rewetted in 2023 (2030) ongoing costs are included up to 2042 (2049) in this social cost-benefit analysis. Correspondingly, emission reduction benefits for the area rewetted in 2023 (2030) are assumed to materialize from 2024 (2031) and are included up to 2043 (2050).

3.5. Sensitivity of Results

To assess the sensitivity of results to assumptions about the average installation and maintenance cost for physical infrastructure required to raise water levels on peatland permanently back to near-surface level, a variation of the RewetHi scenario has been simulated, in which average upfront investment costs were ceteris paribus raised by 25 percent from Euro 8,000/ha to Euro 10,000/ha. However, as this demand component remains small both in relation to the total volume of government expenditure and in relation to total baseline demand for construction and other services, this variation has no noteworthy impact on the results. As further discussed in the Supplementary Information file, the sensitivity of results to variations in the assumptions about financing is likewise low.

4. Conclusions

In 2020, Germany's GHG emissions from drained peatland under agricultural cultivation amounted to 42.5 million tCO_2e, accounting for 5.9 percent of Germany's total GHG emissions. While the peatland area used for agricultural production (1283 kha) represented just 7.7 percent of Germany's total utilized agricultural area in 2020, it contributed over 40 percent of the country's total GHG emissions from agriculture and agricultural land use. The present study considers three abatement scenarios in which peatland users are incentivised to reduce these emissions on a voluntary basis.

In the RewetLo scenario, which reflects the moderate ambitions of Germany's National Peatland Protection Strategy, 88 kha (6.9 percent) of agricultural peatland is rewetted by 2030 to attain a direct annual emission reduction by 3.5 million tCO_2e (-8.2 percent) at private short-run abatement costs of 35 Euro/tCO_2e. In the RewetHi scenario, 474 kha (36.9 percent) of peatland is rewetted by 2030 to attain a direct annual emission reduction by 15 million tCO_2e (-35.2 percent) at marginal private abatement costs between 35 and 49 Euro/tCO_2e. In the RewetHi+ scenario, which draws upon results of an earlier study by Röder et al (2015) for the determination of the private abatement cost schedule, 729 kha (55.2 percent) of peatland is rewetted by 2030 to attain a direct annual emission reduction by 19.3 million tCO_2e (-45.4 percent) at marginal abatement costs between 27 and 61 Euro/tCO_2e. The economy-wide marginal social abatement costs range from 15 Euro/tCO_2e under RewetLo to 27 Euro/tCO_2e under RewetHi+.

The effective agricultural land supply reduction entails upward pressure on agricultural land rents in Germany and this pushes domestic agricultural production costs and hence producer prices up to some extent. Since the rewetted areas are small in relation to Germany's total UAA, the size order of this cost-push effect is small under the RewetHi scenarios and negligibly small under the RewetLo scenario. The resulting increases in consumer prices for food in Germany at the 2030 endpoint of the transformation pathway remain well below 0.05 percent under RewetLo and below 0.3 percent under RewetHi+ Correspondingly, the impact on domestic food consumption quantities is negligible in the RewetLo scenario and remains below 0.1 percent in the RewetHi+ scenario. The increase in prices for food commodities of German origin relative to the rest of the world induce a rise in German agri-food import volumes by 0.01 to 0.13 percent and a drop in German agri-food exports by -0.03 to -0.23 percent towards 2030. The impacts on real GDP and net real household income are negligibly small in all scenarios. Carbon leakage effects due to induced indirect land use change in Germany and the rest of the European Union reduce the global net emission reduction impact by 0.7 to 1.0 percent of the direct emission reduction.

In conclusion, a sizable reduction of Germany's GHG emissions from agriculture and land use appears achievable at a low macroeconomic cost by moving beyond the moderate ambitions of the country's current National Peatland Restoration Strategy.

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