Towards net zero CO_2 in 2050: An emission reduction pathway for organic soils in Germany

Franziska Tanneberger[1,2], Susanne Abel[1,2], John Couwenberg[1], Tobias Dahms[1], Greta Gaudig[1,2], Anke Günther[3], Jürgen Kreyling[1], Jan Peters[2], Julia Pongratz[4], Hans Joosten[1]

[1] Institute of Botany and Landscape Ecology, Greifswald University, partner in the Greifswald Mire Centre, Germany
[2] Michael Succow Foundation for the Protection of Nature, partner in the Greifswald Mire Centre, Germany
[3] Faculty of Agricultural and Environmental Studies, Landscape Ecology, University of Rostock, Germany
[4] Department of Geography, Ludwig-Maximilians-Universität München and Max Planck Institute for Meteorology, Hamburg, Germany

---

SUMMARY

The Paris Agreement reflects the global endeavour to limit the increase of global average temperature to 2 °C, better 1.5 °C above pre-industrial levels to prevent dangerous climate change. This requires that global anthropogenic net carbon dioxide (CO_2) emissions are reduced to zero around 2050. The German Climate Protection Plan substantiates this goal and explicitly mentions peatlands, which make up 5 % of the total area under land use and emit 5.7 % of total annual greenhouse gas emissions in Germany. Based on inventory reporting and assumptions of land use change probability, we have developed emission reduction pathways for organic soils in Germany that on a national level comply with the IPCC 1.5 °C pathways. The more gradual pathway 1 requires the following interim (2030, 2040) and ultimate (2050) milestones: Cropland use stopped and all Cropland converted to Grassland by 2030; Water tables raised to the soil surface on 15 % / 60 % / 100 % of all Grassland, on 50 % / 75 % / 100 % of all Forest land, and ultimately on 2/3 of all Settlements and on 100 % of all Wetlands. Also a more direct pathway 2 without interim 'moist' water tables and the climate effect (radiative forcing) of different scenarios is presented.

KEY WORDS: agriculture, climate change, greenhouse gases, land use, mitigation, peatlands, transformation

---

INTRODUCTION

With the Paris Agreement, parties to the United Nations Framework Convention on Climate Change (UNFCCC) have agreed to keep the increase of global average temperature well below 2 °C and to pursue efforts to limit the increase to 1.5 °C above pre-industrial levels (UNFCCC 2015). The IPCC (2018) Special Report states that limiting global warming to 1.5 °C requires that global net carbon dioxide (CO_2) emissions from anthropogenic activities have been reduced to zero around the year 2050, implying a strong reduction of emissions to the atmosphere as well as, depending on scenario assumptions, creation of additional carbon sinks to certain extents. For the land use sector, the report calls for preservation of land carbon stocks, e.g. through reduced deforestation and through afforestation. Transforming the land sector and deploying measures in agriculture and forestry, including wetland management and bioenergy production, could contribute about 30 %, or 15 Gt CO_2e per year, of the global mitigation needed in 2050 to deliver on the 1.5 °C target (Roe *et al*. 2019). The IPCC (2019) Special Report on climate change and land stresses, among other options, the importance of conservation and restoration of peatlands, and, though likely subordinate to some forest-based mitigation measures, peatland restoration features prominently as a natural climate solution with considerable potentials (Griscom *et al*. 2017).

Peatlands belong to the 'organic soils', which also include shallow peat soils and peaty soils. Peatlands cover only 3 % of the world's land surface (about 4 million km^2), but contain some 500 Gt of carbon within their peat - substantially more than the carbon stock of the entire current global forest biomass (Joosten *et al*. 2016). Although most of the global peatland area is still in a natural state, some 650,000 km^2 have been drained (Joosten 2009), and the majority of this land is still drained. Drainage allows oxygen to enter the peat, resulting in decomposition of the organic material and emissions of CO_2 - and often also of nitrous oxide (N_2O). These emissions continue as long as the soil remains drained or until all peat has been oxidised (Joosten *et al*. 2016). Emissions can be curbed by restoring the water table to pre-drainage levels (IPCC 2014, Wilson *et al*. 2016) and rewetting of drained peatlands is therefore recognised as an important climate change mitigation option in the land use and agriculture sectors (Hawken 2017, Roe *et al*. 2019). Drained peatlands are currently responsible for emissions of about 2 Gt CO_2 per year (Joosten 2009, Joosten *et al*. 2016). In other words, only 0.4 % of the world's land surface cause almost 5 % of the world's anthropogenic CO_2 emissions (43 Gt CO_2; Friedlingstein *et al*. 2019). The European Union (EU) is, after Indonesia, the second largest emitter of CO_2 from drained peatlands worldwide, with Germany being the largest emitter within the EU (Joosten 2009, GMC 2019). The total area of organic soil in Germany is 18,239 km^2 (5 % of the area under land use), of which more than 98 % is drained (Trepel *et al*. 2017) and responsible for 47 Mt CO_2e (or 5.4 %) of the total annual greenhouse gas (GHG) emissions (UBA 2019).

Germany ratified the Paris Agreement in 2016. In the same year, the German federal government adopted its "Climate Protection Plan 2050", which substantiates the long-term goal to make Germany carbon-neutral until 2050. This goal has been reinstated recently by supporting the European Commission's proposal for a legally binding target of net zero GHG emissions by 2050 as part of the European Climate Law (European Commission 2020). The German Climate Protection Plan also establishes interim reduction targets for individual sectors to reach in total a 55 % reduction by 2030 compared to 1990 levels (BMU 2016). The Climate Protection Plan explicitly mentions peatlands and addresses peatland related CH_4 and N_2O emissions mainly under the UNFCCC reporting sector 'Agriculture', and CO_2 mainly under 'Land use, land-use change and forestry (LULUCF)'. Although the Plan's LULUCF target is only to preserve the net sink at its current strength (cf. "no-debit rule" of EU's 2018 LULUCF Decision), substantial emission avoidance is required as the sector is expected to become a net source already in 2020 due to reduced sequestration in forests (BMU 2019a).

National emission reduction pathways show the magnitude and possible timing of transitions needed to achieve globally agreed climate protection goals. As such, they provide policy with actionable interim and long-term targets (van Vuuren *et al*. 2011) and are powerful in communication. Next to illustrating the ultimate aim, pathways stratified by sectors (e.g. Roe *et al*. 2019) also allow us to set the framework for comparing and swapping emission reduction efforts between sectors and in time. For 'top down' pathways, a clear link to the background logic of targets must be made. The Paris Agreement (UNFCCC 2015) provides such a clear target in terms of warming, which has been translated into corresponding cuts in GHG emissions in the IPCC (2018) special report and for Germany in its Climate Protection Plan 2050 (BMU 2016). Whereas the ultimate target is thus fixed, the intermediate steps are open for (some) flexibility with respect to timing, nature and extent of measures.

For the land use sector, global pathways have been developed by taking an *a priori* warming (e.g. 1.5 °C) target and deducing the magnitude and timing of actions needed to contribute to the global mitigation needed until 2050 to deliver on this target (Roe *et al*. 2019). Pathway studies for the land sector at a national level (e.g. Gao & Bryan 2017 for Australia) are, however, still rare and the potential role of individual land uses in these pathways remains often unexplored. Which considerations should be made when preparing, for example, a 1.5 °C target pathway for organic soils, and what would emission trajectories for the different land use categories look like? In this study, we provide the first national emission reduction pathways for organic soils in Germany and explain the underlying assumptions and resulting emission reductions and climate effects. We further explore strengths and weaknesses of analysing 'peatland pathways' and provide guidance for developing such pathways for other European countries with high peatland GHG emissions.

METHODS

We used data on organic soil cover for all land use categories (incl. peatlands and shallow peat soils, Roßkopf *et al*. 2015) and country-specific emission factors (see Table A1 in the Appendix, Tiemeyer *et al*. 2020) from the National Inventory Reporting of Germany to the UNFCCC (UBA 2019). In addition, we used water table depth classes ('dry'=deep-drained=mean annual water table lower than 30 cm below soil surface, 'moist'=shallow-drained=mean annual water table at ~30 cm below soil surface, 'wet'=undrained/rewetted=mean annual water table at the soil surface) based on IPCC (2014). For peat extraction areas (a subset of the land use category Wetlands), off-site emissions are included (UBA 2019). Emission factors for rewetted peatlands under paludiculture were assumed similar to that of rewetted sites without paludiculture (Günther *et al*. 2015, Kaiser & Tanneberger 2020).

As a basic orientation, we assumed that all land use categories on organic soils will follow the global IPCC (2018) trajectories, which implies that CO_2

emissions are reduced to net zero around the year 2050 (and become negative afterwards), whereas methane (CH_4) emissions must be halved, and N_2O emissions must be reduced by 20 %. We calculated emissions for all three GHGs separately per land use category for a pathway including a 'moist' interim stage (pathway 1) and a pathway omitting a 'moist' stage (pathway 2), respectively.

Conservatively, we did not include net soil carbon sequestration in any land use category. We primarily targeted CO_2 emissions because this greenhouse gas has by far the highest contribution (> 90 %) to the total GHG emissions from organic soils in Germany (Tiemeyer *et al*. 2020, Günther *et al*. 2020) and because it needs to be reduced to net zero (see above), but determine the corresponding changes in N_2O and CH_4 as well. Whereas CO_2 and N_2O emissions will decrease after rewetting, CH_4 emissions will actually increase (Wilson *et al*. 2016, Kandel *et al*. 2020, Tiemeyer *et al*. 2020). To better understand the climate effect of the three gases and their respective different atmospheric life-time (12.4 yrs for CH_4, 121 yrs for N_2O, up to thousands of years for CO_2; Myhre *et al*. 2013) we calculated the radiative forcing (following Günther *et al*. 2020) of four pathways: i) 'no change', ii) 'pathway 1' = all rewetted by 2050 including a 'moist' stage, iii) 'pathway 1(slow)' = all rewetted by 2080 including a 'moist' stage, and iv) 'pathway 2' = all rewetted by 2050 omitting a 'moist' stage.

We modified the drainage status of (part of) the organic soil area in 10-year steps such that the net zero CO_2 target for the area of organic soils is reached. Informed by literature and expert judgement (expressed during the 2015–2018 'German Peatland Conservation Dialogue', see Abel *et al*. 2019), we started the iterative sequence of temporal and spatial assumptions with peat extraction areas (implied emission factor of 108 t CO_2e ha^{-1} a^{-1}, see UBA 2019; reported together with other lands under Wetlands, see Table A1) and Cropland, being the most climate-harmful land use types on peatlands. We proceeded with (other) Wetlands, Forest land and Settlements, and finally addressed the land use category Grassland until the projected CO_2 emissions for the years 2020–2050 best reflected the shape of the global IPCC trajectories. We assumed a strong increase in peatland rewetting from 2020 onwards, in particular on agricultural land, as this is regarded as one of the most cost-efficient land use based GHG abatement measures for Germany (Röder *et al*. 2015, SABAFC and SABF 2016; cf. Moxey & Moran 2014 and Humpenöder *et al*. 2020) and is currently gaining substantial political support (BMU 2019b). We assumed that rewetted areas will remain productive as paludicultures (i.e. 'wet' agriculture/forestry, Wichtmann *et al*. 2016, Geurts *et al*. 2019) and that all land use categories reduce their GHG emissions simultaneously, i.e. we do not consider the potential impact of indirect land use change caused by the rewetting.

RESULTS

The German peatland use transformation pathway 1 is shown in Figure 1. The resulting cumulative CO_2 emission reduction trajectory from the different land use categories fit the general global IPCC (2018) 1.5 °C pathways (Figure 2). The pathway shows for 2030 a complete fading-out of domestic peat extraction and water tables raised to the surface on 100 % of the 2020 peat extraction area. By 2030, all Cropland on organic soils (the land use with the highest emissions per hectare, Table A1) is turned into Grassland, and all Wetlands is rewetted. For Forest land on drained organic soil, water tables are raised to surface on 50 % of the land by 2030, on 75 % by 2040, and on 100 % by 2050. Settlements on organic soils are included with an emission reduction of 1/3 in 2040 and of 2/3 by 2050. For Grassland water tables are at an annual average of -30 cm ('moist') over the entire area and at the soil surface on a subset of 2,000 km^2 (~15 %) by 2030, whereas water tables are at the soil surface on 60 % of all Grassland by 2040 (8,500 km^2, which by 2030 also includes the current area of Cropland), and on 100 % by 2050.

The total area rewetted by 2050 is 16,569 km^2, i.e. 91 % of the total area of drained organic soils in 2020 (Table 1). Highest CO_2 emission reductions occur on Grassland and in the decade 2020–2030 (Table 2). In this pathway 2 % of total CO_2 emissions in 2020 remain in 2050 (Table 2). To achieve net zero in 2050, this amount needs to be compensated by sequestration, e.g. in the categories Grassland or Wetlands. CH_4 emissions increase substantially between 2020 and 2050 (from 34.4 kt to 452.1 kt; Table A2) whereas N_2O emissions decrease (from 7.2 kt to 0.1 kt; Table A3).

The area rewetted (Table 3) and emission reduction (Table 2) in pathway 2 differ from pathway 1 for Grassland in (the period until) 2030 and 2040, respectively. CH_4 emissions (Table A2) occur earlier, whereas N_2O emissions (Table A3) are more rapidly reduced. Land use transformation in pathway 2 is shown in Figure 3. The resulting CO_2 emission reduction trajectories for the different land use categories in pathway 2 are very similar to that of pathway 1 (Figure 2) and not depicted.

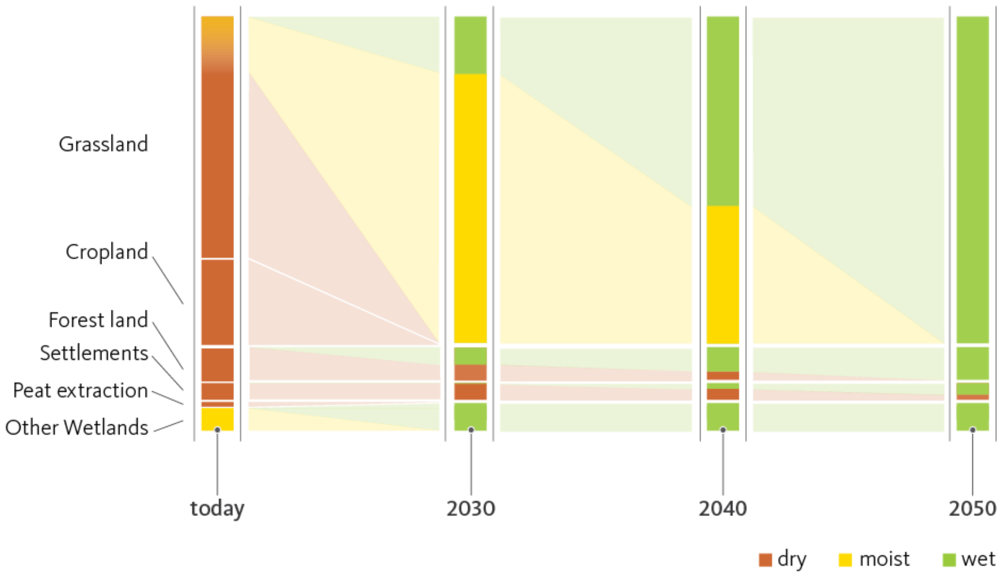

Figure 1. Net zero CO_2 emission pathway for organic soils in Germany visualising transformation by land use category (in % of total area of organic soils) over the period 2020–2050 (pathway 1). Dry=deep-drained, moist=shallow-drained (mean annual water table ~30 cm below soil surface), wet=undrained/rewetted (mean annual water table at the soil surface).

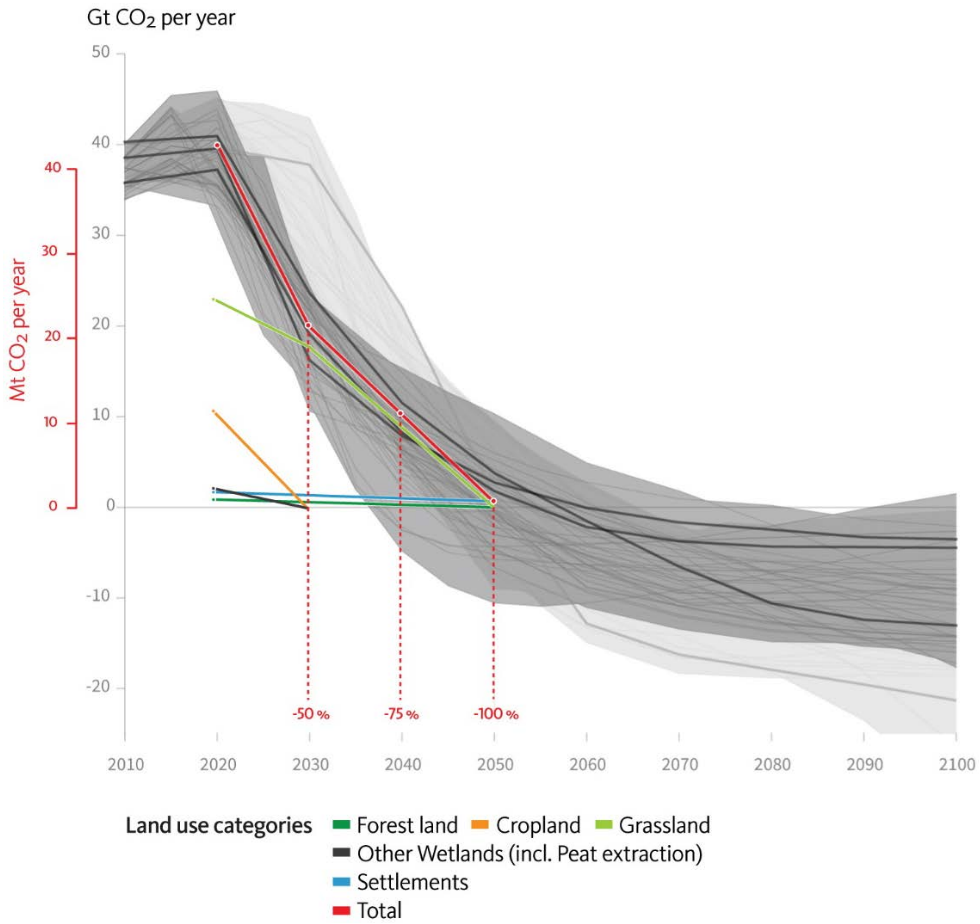

Figure 2. Main graph: Four illustrative global CO_2 emission trajectories with net zero in 2050 (in Gt yr^{-1}; IPCC 2018). Inset: CO_2 emission trajectories with net zero in 2050 for different land use categories on organic soils in Germany, pathway 1 (in Mt yr^{-1}; this study).

Table 1. Drained and rewetted area (km^2) of organic soil per land use category in Germany under the proposed emission reduction pathway 1 (2020 data estimated based on UBA 2019).

year	2020	2030	2030	2040	2040	2050	2050
Land use category	drained	drained	wet	drained	wet	drained	wet
Grassland	10,743	12,576*	2,000	6,076	8,500	0	14,576
Cropland	3,833	0	-	0	-	0	-
Forest land	1,484	742	742	371	1,113	0	1,484
Settlements	785	747**	37	523	262	262	523
Wetlands***	1,394	0	1,394	0	1,394	0	1,394
Total	18,239	14,066	4,173	6,971	11,269	262	16,569

* = $Cropland_{2020}+Grassland_{2020}-2{,}000\ km^2$, this number resulted from the best reflection of the projected CO_2 emissions for the year 2030 in the shape of the global IPCC trajectories; all drained to −30cm
** = logic: this brings CO_2 emissions from 2.1 Mt down to 2.0 Mt; 2040 reduction is 1/3, 2050 2/3
*** = mix category including peat extraction areas (199 km^2), flooded lands and (partially) rewetted lands

Table 2. CO_2 emissions (in Mt) from land use on organic soil in Germany under the proposed emission reduction pathways 1 and 2 (for details, see text).

CO_2 (Mt)	Pathway 1				Pathway 2			
Land use category	2020	2030	2040	2050	2020	2030	2040	2050
Grassland	24.4	18.86	9.11	0	24.4	19.83	9.91	0
Cropland	11.4	0	0	0	11.4	0	0	0
Forest land	1.2	0.61	0.31	0	1.2	0.61	0.31	0
Settlements	2.1	2.00	1.40	0.70	2.1	2.00	1.40	0.70
Wetlands	3.9	0	0	0	3.9	0	0	0
Total	43.0	21.47	10.82	0.70	43.0	22.44	11.62	0.70

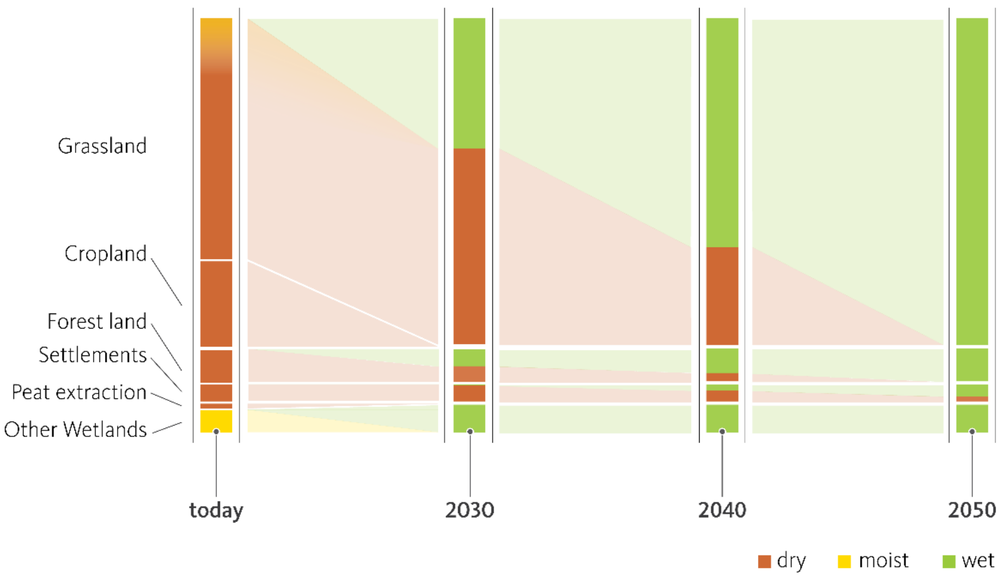

Figure 3. Net zero CO_2 emission pathway for organic soils in Germany visualising transformation by land use category (in % of total peatland area) over the period 2020–2050 and excluding an intermediate ‘moist’ stage (pathway 2). Dry=deep-drained, wet=undrained/rewetted (mean annual water table at the soil surface).

Instantaneous radiative forcing in the period until 2100/2200 is by far highest for the 'no change' scenario (Figures 4 and 5) with almost all climate effect attributed to CO_2 emissions (Figure 4). Due to the long-lived nature of CO_2 in the atmosphere, 'no change' results in continuously increasing forcing. More than half of the 'no change' radiative forcing in 2100 can be avoided by implementing pathway 1 or pathway 2. Radiative forcing of pathways 1 and 2 is dominated by the warming from CH_4 rather than CO_2 emissions. Over time the limited atmospheric lifetime of CH_4 results in a stable forcing for the two pathways. The 'slower' pathway 1 (slow) causes a slightly higher climate effect than the pathways with faster rewetting.

DISCUSSION

Challenges, incentives and barriers for land use change on organic soils in Germany

Changing land use on German organic soils in compliance with international climate agreements seems biophysically, politically, and socio-economically feasible. Peat extraction areas in Germany currently cover 199 km^2 (UBA 2019) from which ~4 Mm^3 of peat is extracted annually (BMEL 2020) mainly as raw material for the production of horticultural growing media. Full substitution of high quality 'white peat' (~3 Mm^3 recently mainly imported) by 2030 will require a net area of ~350 km^2 for producing *Sphagnum* biomass in paludiculture

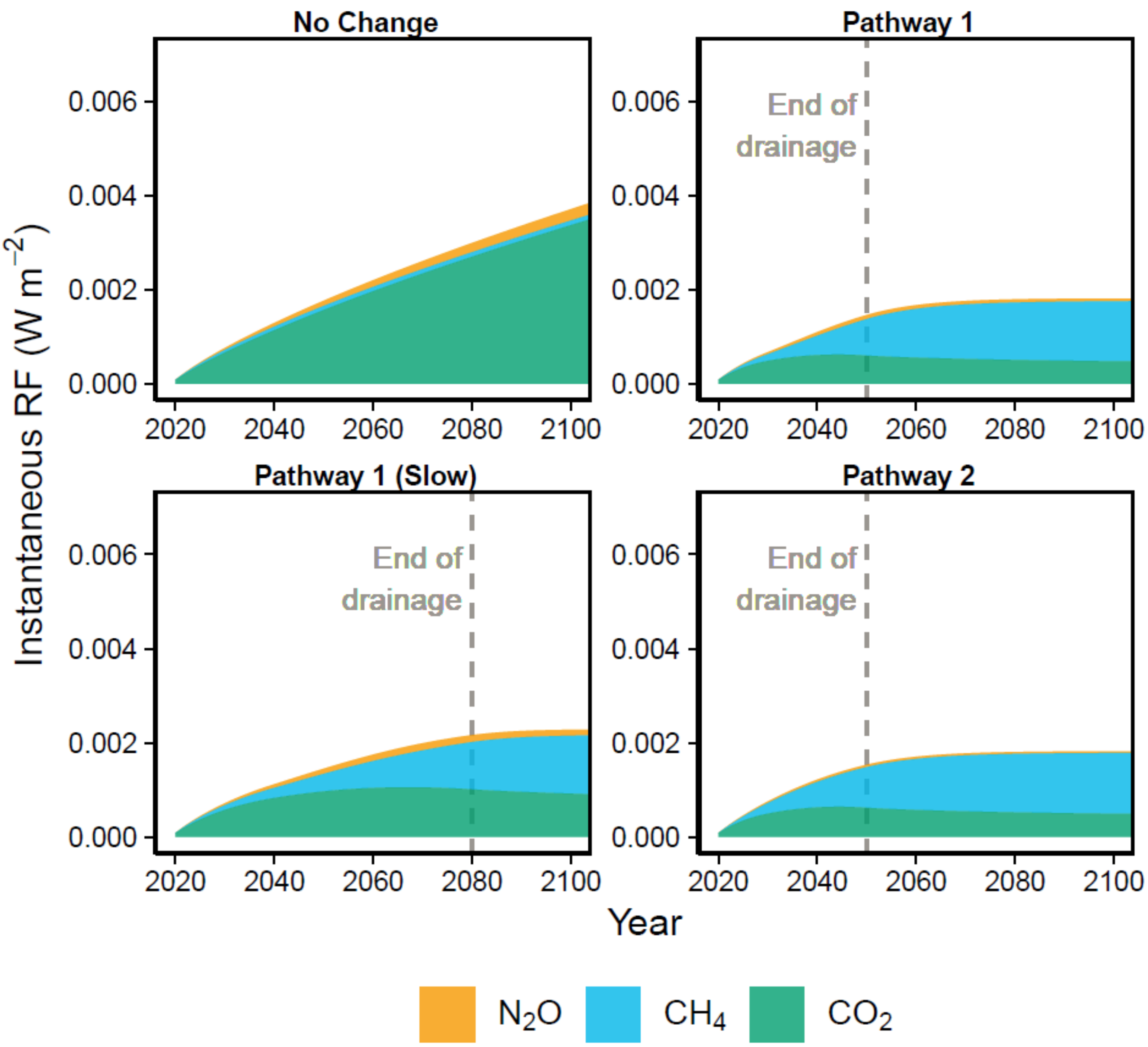

Figure 4. Climatic effects of peatland scenarios for Germany by greenhouse gas in the period until 2100. Contributions of the different greenhouse gases (nitrous oxide N_2O, methane CH_4, and carbon dioxide CO_2) to total radiative forcing (RF) are shown with estimated warming effects in the modelled pathways. 'Pathway 1' = all rewetted by 2050 including a 'moist' stage, iii) 'pathway 1(slow)' = all rewetted by 2080 including a 'moist' stage, and iv) 'pathway 2' = all rewetted by 2050 omitting a 'moist' stage.

(Sphagnum farming; Gaudig *et al*. 2018, Wichmann *et al*. 2020). Whereas most areas currently under peat extraction are required by law to be rewetted for nature conservation, it could be considered to initiate *Sphagnum* farming on half of the area currently under extraction (100 km^2) as *Sphagnum* farming areas have high nature-conservation value (Muster *et al*. 2015, 2020; Gaudig & Krebs 2016). Another 250 km^2 *Sphagnum* farming could be established on rewetted bog grassland until 2030. The remaining demand is for lower quality growing media, which can be covered by alternative renewable resources (Amberger-Ochsenbauer & Meinken 2020).

Cropland on organic soil has the highest emissions per hectare (Table A1). The envisaged conversion of all that Cropland to Grassland by 2030 will be a challenge. The regional (socio-) economic importance of cropland on organic soils varies strongly, from low output cereal and maize farming in Northeast-Germany (Hirschelmann *et al*. 2020) to highly profitable vegetable farming (potatoes, carrots) in other regions like the South-German Donaumoos (Buschmann *et al*. 2020). The total share of organic soils under Cropland in Germany is, however, only 2 % (Nordt *et al*. 2020) and as societal climate damage costs widely surpass business profits

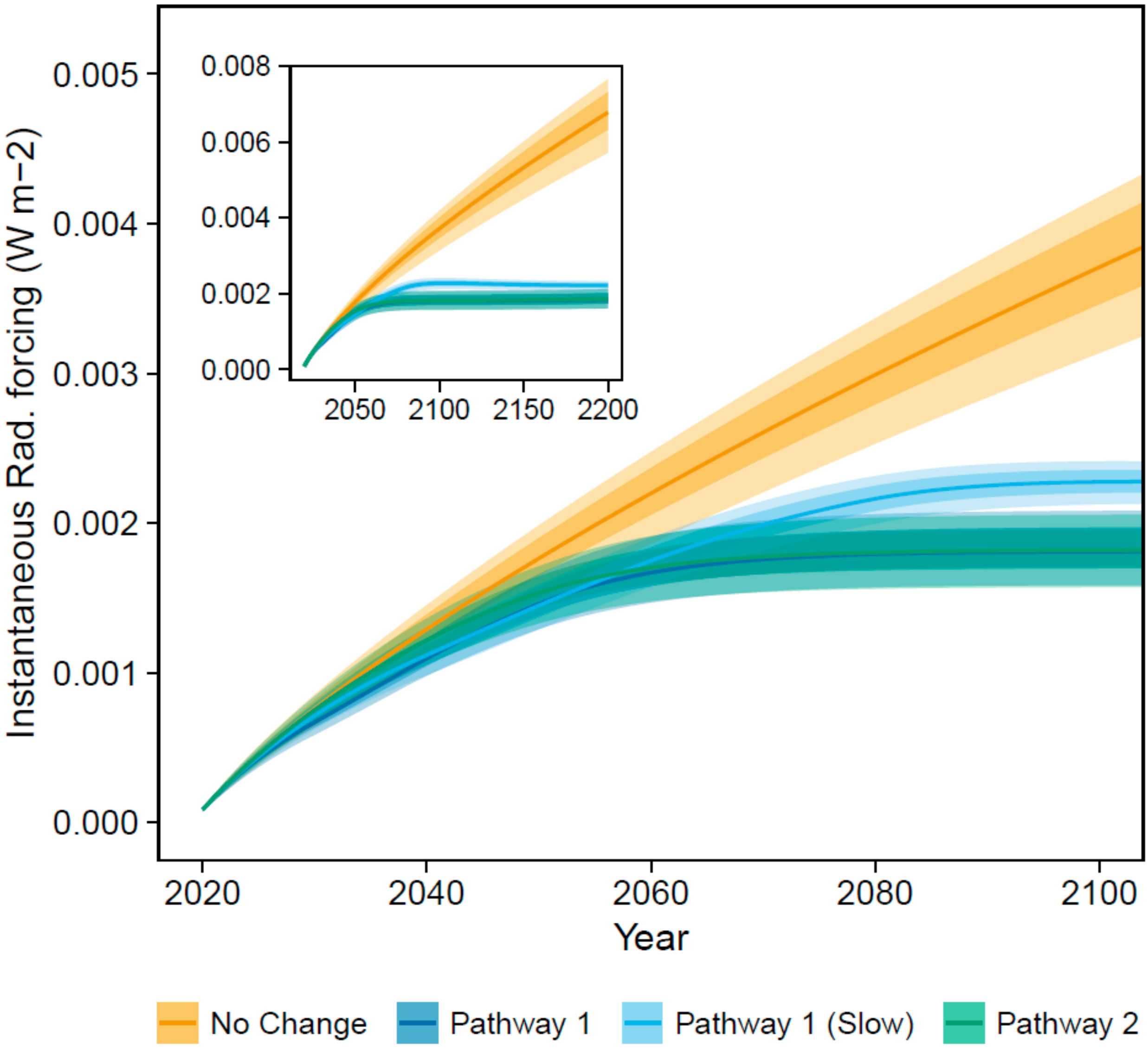

Figure 5. Combined climatic effects of peatland scenarios for Germany in the period until 2100 and 2200 (inset). Error ranges represent the range (minimum to maximum) of radiative forcing (RF) resulting from 10 and 20 % uncertainty of emission factor, represented by shading intensity. ‘Pathway 1’ = all rewetted by 2050 including a ‘moist’ stage, iii) ‘pathway 1 (slow)’ = all rewetted by 2080 including a ‘moist’ stage, and iv) ‘pathway 2’ = all rewetted by 2050 omitting a ‘moist’ stage.

(cf. Bonn *et al*. 2015), at national scale cropland use can be abandoned without much economic harm by reshuffling land use between mineral and organic soils.

The land use category Wetlands on organic soil refers - next to (also former) peat extraction sites - to areas without regular productive land use ('wild nature'). Given the absence of land use interest and the fact that high water tables best support nature conservation objectives on the long term, a rewetting of 100 % of the Wetlands by 2030 seems feasible.

For Forest land on drained organic soil, we assume water tables to be raised to surface on 50 % of the land by 2030, on 75 % by 2040, and on 100 % by 2050. For Forest land under re-wetted conditions a comprehensive cultivation and utilisation concept is already available (Röhe & Schröder 2017). Markets for Alder products exist (Abel *et al*. 2013), drained Forest land is not as heavily subsidised as drained agricultural land, and existing investments into timber processing facilities may continue to be profitable also after rewetting. Forest plots can be rewetted successively after current dry stands are harvested, and an intermediate 'moist' stage will not be necessary. Part of the current Forest land on drained peat soil will after rewetting no longer be suitable for forestry and may move to the land use category Wetlands (for simplicity, such land use shift is not included in our pathways).

Rewetting of organic soils within Settlements will generally be difficult and costly (but it should be noted that this land use category includes non-built up areas within urban/rural settlements). On the other hand, up to a million houses in the Netherlands are at risk of foundation damage with costs possibly amounting to 80 billion euros by 2050 (KCAF 2020), streets and sewage infrastructure are subsiding and dikes shifting as a result of ongoing peat subsidence (Meijer 2020). Counteractions from the 'users' side are thus required and doing nothing in the urban area is no longer an option. Therefore, we assume that two-thirds can be rewetted by 2050, as not rewetting will also incur high costs (van den Born *et al*. 2016, van Asselen *et al*. 2018).

Grassland is the land use category on drained organic soils with the largest share in area and total emissions. Next to the reductions in the other land use categories (see previous steps), mean annual water tables must be raised to the surface (= zero CO_2 emissions) on 2,000 km^2 (~15 % of the total area) and to -30 cm on the remaining Grassland area to fit the IPCC (2018) CO_2 emission trajectory for 2030. The latter seems a pragmatic intermediate stage, as it allows conventional grassland use to continue, be it with lower productivity and workability. As part of broader climate action, a shift to plant-based diets (Springmann *et al*. 2018, Poore & Nemecek 2018, Hayek *et al*. 2020) is expected. The need for grassland fodder will diminish and the gradual establishment of wet production alternatives seems feasible (paludicultures, mainly for non-meat products, Wichtmann *et al*. 2016, Wichmann 2017; cf. Buschmann *et al*. 2020). However, there are also strong arguments supporting a pathway without an intermediate stage of 'moist' conditions (pathway 2). Particularly for high intensity dairy farms, grassland managed with lower intensity does not necessarily offer a perspective, and willingness to accept immediate rewetting may be higher if appropriate compensation or alternatives are in place.

Loss of produce, activity shifting and integration of broader sustainability objectives

Sectoral pathways should bring down CO_2 emissions as fast as possible to reduce the need for risky and unproven negative emission technologies (van Vuuren *et al*. 2017). Interim sectoral targets should be guided by a reduction burden equally distributed between sectors and comply with national reduction targets (Abel *et al*. 2019). The feasibility, timing and speed of necessary land use change will likely differ between regions and business types, in particular as a function of agricultural income and capital commitment (Schaller *et al*. 2011, Buschmann *et al*. 2020). If a land use category is too slow to change, the consequence of a prescribed or preferred pathway is that other land use categories will have to perform better. It is upon the various land use categories to agree on how to swap and balance their efforts (e.g. by emission trading).

Land use change may cause activity shifting (leakage), for example when a stop of food production on organic soils causes intensified food production on mineral soils (but see Leclère *et al*. 2020). The cumulative goal of the Paris Agreement implies that *all* sectors have to comply to a similar reduction pathway and thus increased GHG emissions from activity shifting are not acceptable. An important option to prevent leakage resulting from peatland rewetting is paludiculture, i.e. wet agriculture/forestry (Wichtmann *et al*. 2016, Tanneberger *et al*. 2020a). It may include the shift of food production to mineral soils while activities from mineral soils (e.g. biomass harvesting for energy production or solar energy production) can be shifted towards rewetted peatlands. Large-scale implementation of paludiculture, however, requires agricultural policies to set explicit incentives (Wichmann 2018) including full eligibility for the EU's Common Agricultural Policy (CAP) payments.

EU institutions have expressed support for this position (e.g. European Parliament 2019) and call for gearing all European policy instruments, including CAP, to the climate targets of the Paris Agreement (European Parliament 2020). Stopping direct payments for cropland on drained organic soils and supporting farmers in shifting to climate-smart land use is one of the policy changes required to utilise the mitigation potential of these soils efficiently and rapidly (cf. Regina *et al*. 2016, Tanneberger *et al*. 2020b). Alternatively, or additionally, also regulatory law could be considered.

Following IPCC (2018), the proposed approach gives priority to bringing CO_2 emissions down to net zero in 2050. The relatively small climate effect of CH_4 compared to persistent CO_2 emissions when not rewetting (Günther *et al*. 2020) and the partial compensation of increased CH_4 emissions by reduced N_2O emissions (Tables A2 and A3) further justify this approach. Essentially, peatland management must choose between CO_2 emissions from drained or CH_4 emissions from rewetted peatland (Günther *et al*. 2020). A refined peatland GHG emission pathway analysis could optimise rewetting site selection for all three GHGs. Given the urgency of peatland rewetting to achieve established climate protection objectives (BMU 2016, 2019b), priority for fast rewetting is the most logical consequence. Compensating for the remaining emissions (as the EU targets require), would require net sequestration e.g. in 'Other Wetlands' or in rewetted areas under Forest land, Cropland and Grassland (paludiculture).

Looking beyond climate protection, sectoral pathways can also integrate other sustainability targets (Gao & Bryan 2017). Our German pathways could, for example, be modified to integrate biodiversity objectives. This would probably result in a larger area of Grassland/Cropland shifted to Wetlands after rewetting, as such areas would have a high 'wilderness' value and would support threatened biodiversity not dependent on regular land use.

Transfer to other European countries

Apart from Germany, other European Union countries with massive GHG emissions from drained peatlands are Poland, Romania and Finland (all with emissions of >20 Mt CO_2e y^{-1} from agriculturally used organic soils), and also Ireland, France, the Netherlands, and Sweden (all >5 Mt CO_2e y^{-1}; GMC 2019). As presented above, identifying and applying a dataset for the pathway analysis was simple for Germany. The German reporting to UNFCCC contains the best available quantitative data on land use of organic soils. Also in most other countries, the best data source will be the national reporting to UNFCCC. This reporting is based on internationally agreed IPCC methodologies and contains nationally approved data, which are independently reviewed, regularly updated and improved, and publicly available at the UNFCCC website. However, it is important to be aware of UNFCCC reporting deficiencies. Data on organic soils are typically incomplete for non-annex I parties (Tubiello *et al*. 2015) and often insufficient for annex I parties (Barthelmes *et al*. 2015, Barthelmes 2018). UNFCCC reporting deficiencies for organic soils relate in particular to incomplete activity data and inappropriate and poor-quality emission factors (Barthelmes 2018).

For a 'peatland-based' 1.5 °C pathway, we also have to keep in mind that there are no IPCC definitions of 'peat' and 'peatland'. In UNFCCC reporting, peatlands are included within 'organic soils' and we have therefore included all organic soils *sensu* IPCC (2006, 2014) in our pathway analysis. According to IPCC (2006, 2014) an 'organic soil' is a soil with (dependent on the clay content) at least 12–18 % (by weight) of organic carbon. From a climate point of view, the boundary between organic and mineral soils would better be drawn at 3 % of organic carbon (calculated on a dry mass basis). Soils with a higher percentage commonly have a higher carbon density than pure organic soils (with 55 % of organic carbon) and consequently often higher CO_2 emissions in a drained state (Barthelmes 2018, Vernimmen *et al*. 2020). The problem of low percentage - high density carbon soils has already been recognised by Germany, Denmark and Ireland (who include in their UNFCCC reporting emissions from 'peaty soils') and will hopefully be appropriately addressed in future by other parties.

The assumptions for land use change on peatlands in Germany are largely valid also at the European scale. In Europe, public perceptions on peatland use have changed during the past decades: Peatland drainage, which used to be accepted and even admired, is now widely recognised as a cause of severe degradation of the environment (Regina *et al*. 2016, Wichmann 2018). Annual emission reporting has increased the visibility of the problem (Regina *et al*. 2016). Socio-economic studies addressing management change at the farm or regional level point at increasing awareness and readiness for change (e.g. Schaller *et al*. 2011, Graves & Morris 2013, Wichtmann *et al*. 2016, Ferré *et al*. 2019, Buschmann *et al*. 2020). Negative emissions technologies such as CCS and BECCS may remain technologically or economically unfeasible at the scale required for the 1.5 °C target (Smith *et al*. 2016, Walsh *et al*. 2017, Anderson & Peters 2016, Roe *et* *al*. 2019), whereas reported potentials for sequestration of carbon in agricultural soils are overly optimistic (Batjes 2019, Schlesinger & Amundson 2019). Therefore, the need for ambition in reducing CO_2 emissions from organic soils and in restoring their carbon sequestration potential is highly likely to increase.

The EU climate policy framework is slowly but steadily offering more support for climate change mitigation measures related to land use on organic soils: Accounting for Forest Management and Afforestation, Reforestation, Deforestation is already mandatory under UNFCCC rules, whereas accounting for Cropland and managed Grassland will become mandatory for all EU Member States from 2021 onwards. Accounting for managed Wetlands will become mandatory in the EU in 2026 (European Parliament and Council 2013, Barthelmes 2018). Reductions in land-based emissions can be included in a country's Nationally Determined Contribution (NDCs) under the Paris Agreement. The EU's Common Agricultural Policy (CAP) is becoming more open and supportive for 'wet' land use options on organic soils (see above).

In addition to those presented already for the German situation, we see several other supporting conditions for rapid land use transition in the various land use categories on drained organic soils in Europe:

- Cropland: Cropland on drained peatland concentrated in Europe and Indonesia accounts for 32 % of global cropland emissions despite peatlands producing just 1.1 % of total crop kilocalories. It is highly likely that emission reduction policies will be directed to locations where cropland produces both high emissions and low nutritional value (Carlson *et al*. 2017).
- Cropland and Grassland: Paludiculture has been applauded in recent reports published by the Food and Agriculture Organization of the United Nations (Joosten *et al*. 2012, Biancalani & Avagyan 2014) and IPCC (IPCC 2014) as a GHG mitigation option and peat conserving action with emission factors similar to those of traditional wetland restoration (Wilson *et al*. 2016). When the value of land is low, willingness to change land use to paludiculture proves to be high (e.g. Buschmann *et al*. 2020). In addition, in drained sites continuing soil subsidence will lead to increasing drainage costs, flood risks, salt intrusion and exposure of acid sulphate and low-fertility quartz soils, which may become strong drivers for land use change.
- Settlements: Subsiding organic soils are seen as a substantial risk and cost factor in land planning, in particular in coastal regions (van den Born *et al*. 2016).

At the same time, there are constraining conditions, especially on Cropland and Grassland:

- In regions with highly profitable vegetable farming on drained peatland, e.g. vegetables such as carrots and potatoes in Switzerland (Ferré *et al*. 2019), Norway, South-Germany (Buschmann *et al*. 2020) and Denmark, there are high opportunity costs of adopting sustainable practices on these soils. The same applies to regions with intensive dairy farming e.g. in the Netherlands, NW-Germany and Finland, where the 'value' of drained peatland - often determined by public payments - is high and the farmers' willingness to change land use is low (Buschmann *et al*. 2020). High value, 'intensive' paludicultures are not yet widely known and - although likely (Wichmann 2017) - profitability has not yet been proven beyond pilot scale.
- High heterogeneity in land use intensity, i.e. heterogeneity in water table requirements, leads to a low willingness to change land use. Increasing expenses for the drainage system, increasing drought damage and decreasing soil fertility are not yet considered a problem by most farmers (Buschmann *et al*. 2020).
- Although more nature and climate friendly farming was already targeted in the current CAP funding period, environmental protection goals were largely insufficiently addressed (Pe'er *et al*. 2019), and this may repeat itself in the upcoming period.

Linking peatland rewetting and climate policies

Whereas international and national climate policies call for peat soil conservation, various issues (e.g. the profitability of conventional land use, the difficult economic environment of farmers, and cultural backgrounds) still constrain the wide-scaled implementation of emission reduction measures (Regina *et al*. 2016, Wichmann 2018, Abel *et al*. 2019, Ferré *et al*. 2019). The mitigation potential of peatlands could be better utilised when decisions on agricultural land management would be more systematically informed by soil type and societal costs (Regina *et al*. 2016) and better linked to policies relating to ground and surface water quality and biodiversity (Bonn *et al*. 2016, Wüstemann *et al*. 2017). Peatland rewetting could be a prime example to demonstrate the benefits of pursuing the delivery of multiple ecosystem services, such as biodiversity, soil enrichment, water and air quality, and sustainability goals along with GHG emission reduction (van Vuuren *et al*. 2017, Griscom *et al*. 2017).

The land use transition proposed in our 'peatland pathway' may look highly challenging and radical. But our pathway is far from compliant with more ambitious climate policy targets such as the 'equity pathways', which reflect equality, historical responsibility, capability, and future development opportunities at a global scale (Messner *et al*. 2010, Gignac & Matthews 2015, Wang *et al*. 2015). Equity considerations would for Germany and Europe likely result in a pathway targeting net zero CO_2 emissions already by 2035, i.e. in reducing emissions with double speed. Achieving net zero CO_2 emissions by 2050 may, furthermore, not be sufficient to meet the warming target spelled out in the Paris Agreement (Rogelj *et al*. 2019). The proposed pathway may thus seem radical - but *not* preparing for and implementing such a pathway is, in the current situation, at least as radical.

ACKNOWLEDGEMENTS

We gratefully acknowledge the input of stakeholders from all peatland-rich German regions during several workshops in 2016–2018 with the 'MoorDialog' project and the funding of the German Federal Environment Ministry (BMU) for this project. Part of this study is also funded by the European Social Fund (ESF) and the Ministry of Education, Science and Culture of Mecklenburg-Western Pomerania within the scope of the project WETSCAPES (ESF/14-BM-A55-0027/16 to ESF/14-BM-A55-0035/16). We are also grateful for comments from Alexandra Barthelmes, Sophie Hirschelmann, Anke Nordt, Felix Reichelt, Michael Trepel and Sabine Wichmann.

AUTHOR CONTRIBUTIONS

SA, JC, GG, JPe, HJ and FT developed the peatland pathway for Germany. TD, JK, AG and JPo provided additional data and text. FT wrote the draft and finalised the manuscript with the support of all authors.

REFERENCES

Abel, S., Couwenberg, J., Dahms, T., Joosten, H. (2013) The database of potential paludiculture plants (DPPP) and results for Western Pomerania. *Plant Diversity and Evolution*, 130, 219–228.

Abel, S., Barthelmes, A., Gaudig, G., Joosten, H., Nordt, A., Peters, J. (2019) *Klimaschutz auf Moorböden - Lösungsansätze und Best-Practice-Beispiele. (Climate Protection on Peat Soils - Solutions and Best Practice Examples)*. Proceedings of the Greifswald Mire Centre 03/2019 (self-published, ISSN 2627-910X), 84 pp. (in German). Online at: https://greifswaldmoor.de/files/images/pdfs/201908_Broschuere_Klimaschutz%20auf%20Moorböden_2019.pdf, accessed 01 Feb 2020

Amberger-Ochsenbauer, S., Meinken, E. (2020) *Torf und alternative Substratausgangsstoffe. (Peat and Alternative Raw Materials for Growing Media)*. Bundesanstalt für Landwirtschaft und Ernährung (BLE), Bonn, 52 pp. (in German). Online at: https://www.blemedienservice.de/frontend/esddownload/index/id/1345/on/0129_DL/act/dl, accessed 13 Sep 2020.

Anderson, K., Peters, G. (2016) The trouble with negative emissions. *Science*, 354(6309), 182–183.

Barthelmes, A. (ed.) (2018) *Reporting Greenhouse Gas Emissions from Organic Soils in the European Union: Challenges and Opportunities*. Policy brief, Proceedings of the Greifswald Mire Centre 02/2018 (self-published, ISSN 2627-910X), 16 pp. Online at: https://greifswaldmoor.de/files/dokumente/GMC%20Schriften/18-02_Barthelmes_GMC.pdf, accessed 01 Feb 2020.

Barthelmes, A., Couwenberg, J., Risager, M., Tegetmeyer, C., Joosten, H. (2015) *Peatlands and Climate in a Ramsar Context - a Nordic-Baltic Perspective.* TemaNord 544, Nordic Council of Ministers, Rosendahls-Schultz Grafisk, Albertslund, 247 pp. Online at: http://norden.diva-portal.org/smash/get/diva2:814147/FULLTEXT02.pdf, accessed 01 Feb 2020.

Batjes, N. (2019) Technologically achievable soil organic carbon sequestration in world croplands and grasslands. *Land Degradation and Development*, 30, 25–32.

Biancalani, R., Avagyan, A. (eds.) (2014) *Towards Climate-Responsible Peatlands Management*. Food and Agriculture Organization of the United Nations (FAO), Rome, 117 pp. Online at: http://www.fao.org/3/a-i4029e.pdf, accessed 01 Feb 2020.

BMEL (2020) Gärtnern ohne Torf - schütze das Klima! (Gardening without peat - protect the climate!). Web page, Bundesministerium für Ernährung und Landwirtschaft, Berlin (in German). Online at: https://www.torffrei.info/, accessed 12 Oct 2020.

BMU (2016) *Klimaschutzplan 2050: Klimaschutzpolitische Grundsätze und Ziele der*

Bundesregierung (*Climate Protection Plan 2050: Foundation and Targets of the Federal Government's Climate Policy*). Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), Berlin, 92 pp. (in German). Online at: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf, accessed 01 Feb 2020.

BMU (2019a) *Projektionsbericht der Bundesregierung 2019* (*Projection Report of the Federal Government*). Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), Berlin, 232 pp. (in German). Online at: https://www.bmu.de/download/projektionsbericht-der-bundesregierung-2019/, accessed 01 Feb 2020.

BMU (2019b) *Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050* (*Climate Protection Programme 2030 of the Federal Government to Implement the Climate Protection Plan 2050*). Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), 173 pp. (in German). Online at: https://www.bundesregierung.de/resource/blob/975226/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019-10-09-klima-massnahmen-data.pdf?download=1, accessed 08 Sep 2020.

Bonn, A., Berghöfer, A., Couwenberg, J., Drösler, M., Jensen, R., Kantelhardt, J., Luthardt, V., Permien, T., Röder, N., Schaller, L., Schweppe-Kraft, B., Tanneberger, F., Trepel, M., Wichmann, S. (2015) Klimaschutz durch Wiedervernässung von kohlenstoffreichen Böden (Climate protection through rewetting of carbon-rich soils). In: Hartje, V., Wüstemann, H., Bonn, A. (eds.) *Naturkapital und Klimapolitik. Synergien und Konflikte* (*Natural Capital and Climate Policy*. *Synergies and Conflicts*). TEEB-DE, Berlin, Leipzig, 124–147 (in German). Online at: https://www.ufz.de/export/data/global/190502_TEEB_DE_Bericht1_Klima_Langfassung.pdf, accessed 01 Feb 2020.

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (2016) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*. Cambridge University Press, 493 pp.

Buschmann, C., Röder, N., Berglund, K., Berglund, Ö., Lærke, P.E., Maddison, M., Mander, Ü., Myllyse, M., Osterburg, B., van den Akker, J.H.J. (2020) Perspectives on agriculturally used drained peat soils: Comparison of the socioeconomic and ecological business environments of six European regions. *Land Use Policy*, 90, 104181, 13 pp.

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., Havlik, P., O'Connell, C.S., Johnson, J.A., Saatchi, S., West, P.C. (2017) Greenhouse gas emissions intensity of global croplands. *Nature Climate Change*, 7(1), 63–67.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A., Joosten, H. (2011) Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, 674, 67–89.

European Commission (2020) *Proposal for a Regulation of the European Parliament and of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law) COM/2020/80 Final*. Online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588581905912&uri=CELEX:52020PC0080, accessed 25 Aug 2020.

European Parliament (2019) *Report on the proposal for a regulation of the European Parliament and of the Council establishing rules on support for strategic plans to be drawn up by Member States under the Common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulation (EU) No 1305/2013 of the European Parliament and of the Council and Regulation (EU) No 1307/2013 of the European Parliament and of the Council (COM(2018)0392 - C8-0248/2018 - 2018/0216(COD))*. Committee on Agriculture and Rural Development. A8-0200/2019. Online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A392%3AFIN, accessed 01 Feb 2020.

European Parliament (2020) *The European Green Deal*. *European Parliament Resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP))*. Online at: https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html, accessed 01 Feb 2020

European Parliament and Council (2013) *Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and on information concerning actions relating to those activities*, 18 pp. Online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32013D0529, accessed 01 Feb 2020.

Ferré, M., Muller, A., Leifeld, J., Bader, C., Müller, M., Engel, S., Wichmann, S. (2019) Sustainable management of cultivated peatlands in Switzerland: Insights, challenges, and opportunities. *Land Use Policy*, 87, 104019, 14 pp.

Friedlingstein, P., Jones, M.W., O`Sullivan, M., Andrew, R.M. and 69 others (2019) Global Carbon budget 2019. *Earth System Science Data*, 11, 1783–1838.

Gao, L., Bryan, A.B. (2017) Finding pathways to national-scale land-sector sustainability. *Nature*, 544, 217–222.

Gaudig, G., Krebs, M. (2016) Torfmooskulturen als Ersatzlebensraum - Nachhaltige Moornutzung trägt zum Artenschutz bei (Sphagnum farming sites as surrogate habitat - sustainable peatland utilisation supports species conservation). *Biologie in unserer Zeit*, 46(4), 251–257 (in German).

Gaudig, G., Krebs, M., Prager, A., Wichmann, S. and 30 others (2018) Sphagnum farming from species selection to the production of growing media: a review. *Mires and Peat*, 20, 13, 30 pp.

Geurts, J.J.M, van Duinen, G.-J.A., van Belle, J., Wichmann, S., Wichtmann, W., Fritz, C. (2019) Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change. *Journal of Sustainable and Organic Agricultural Systems*, 69(1), 5–8.

Gignac, R., Matthews, H.D. (2015) Allocating a 2 °C cumulative carbon budget to countries. *Environmental Research Letters*, 10(7), 075004, 9 pp.

GMC (Greifswald Mire Centre) (2019) *Briefing Paper on the Role of Peatlands in the New European Union's Common Agriculture Policy (CAP)*, 6 pp. Online at: https://greifswaldmoor.de/files/dokumente/Infopapiere_Briefings/GMC-briefing%20paper_CAP_final.pdf, accessed 01 Feb 2020.

Graves, A.R., Morris, J. (2013) *Restoration of Fen Peatland Under Climate Change*. Report to the Adaptation Sub-committee of the Committee on Climate Change, Cranfield University, Bedford, 61 pp. Online at: https://www.theccc.org.uk/wp-content/uploads/2013/07/Report-for-ASC-project_FINAL-9-July.pdf, accessed 01 Feb 2020.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A. and 28 others (2017) Natural climate solutions. *PNAS*, 114(44), 11645–11650.

Günther, A., Huth, V., Jurasinski, G., Glatzel, S. (2015) The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. *Global Change Biology Bioenergy*, 7(5), 1092–1106.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., Couwenberg, J. (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications*, 11, 1644, 5 pp.

Hawken, P. (2017) *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*. Penguin Books, New York, 256 pp.

Hayek, M.N., Harwatt, H., Ripple, W.J., Mueller, N.D. (2020) The carbon opportunity cost of animal-sourced food production on land. *Nature Sustainability*. https://doi.org/10.1038/s41893-020-00603-4

Hirschelmann, S., Tanneberger, F., Wichmann, S., Reichelt, F., Hohlbein, M., Couwenberg, J., Busse, S., Schröder, C., Nordt, A. (2020) *Moore in Mecklenburg-Vorpommern im Kontext nationaler und internationaler Klimaschutzziele - Zustand und Entwicklungspotenzial. Faktensammlung* (*Peatlands in Mecklenburg-Vorpommern in the Light of National and International Climate Protection Targets - Condition and Potential. Compilation of Facts*.) Proceedings of the Greifswald Mire Centre 03/2020 (self-published, ISSN 2627-910X), 33 pp. Online at: https://www.greifswaldmoor.de/files/dokumente/GMC%20Schriften/2020-03_Moore%20in%20MV_Faktensammlung_%20Hirschelmann%20et%20al_final.pdf, accessed 12 Oct 2020 (in German).

Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A., Popp, A. (2020) Peatland protection and restoration are key for climate change mitigation. *Environmental Research Letters*, 15(10), 12 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K. (eds.), IGES, Japan (5 volumes). Online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (ed. by Hiraishi T., Krug T., Tanabe K., Srivastava N., Baasansuren J., Fukuda M., Troxler, T.G). IPCC, Geneva, 354 pp. Online at: https://www.ipcc-nggip.iges.or.jp/public/wetlands/

IPCC (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the* *context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (ed. by V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Mattews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T.). IPCC, Geneva. Online at: https://www.ipcc.ch/sr15/, accessed 01 Feb 2020.

IPCC (2019) *Climate Change and Land.* An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (ed. by Shukla, P.R., Skea, J., Slade, R., van Diemen, R., Haughey, E., Malley, J., Pathak, M., Portugal-Pereira, J.), IPCC, Geneva. Online at: https://www.ipcc.ch/srccl/, accessed 01 Feb 2020.

Joosten, H. (2009) *The Global Peatland CO_2 Picture. Peatland Status and Drainage Associated Emissions in all Countries of the World.* Wetlands International, Wageningen, 35 pp. Online at: https://unfccc.int/sites/default/files/draftpeatland co2report.pdf, accessed 01 Feb 2020.

Joosten, H., Tapio-Biström, M.-L., Tol, S. (eds.) (2012) *Peatlands - Guidance for Climate Change Mitigation Through Conservation, Rehabilitation and Sustainable Use.* Second edition, Food and Agriculture Organization of the United Nations and Wetlands International, 114 pp. Online at: http://www.fao.org/3/a-an762e.pdf , accessed 01 Feb 2020.

Joosten, H., Sirin, A., Couwenberg, J., Laine, J., Smith, P. (2016) The role of peatlands in climate regulation. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press, 63–76.

Jurasinski, G., Günther, A., Huth,V., Couwenberg, J., Glatzel, S. (2016) Greenhouse gas emissions. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.) *Paludiculture - Productive Use of Wet Peatlands*, Schweizerbart Science Publishers, Stuttgart, 79–93.

Kaiser, M., Tanneberger, F. (2020) Treibhausgase. (Greenhouse gases). In: Närmann, F., Birr, F., Kaiser, M., Nerger, M., Luthardt, V., Zeitz, J., Tanneberger, F. *Klimaschonende, biodiversitäts-fördernde Bewirtschaftung von Niedermoor-böden* (*Climate-Friendly, Biodiversity-Enhancing Utilisation of Fen Soils*). BfN-Skripten 572, Bundesamt für Naturschutz, Bonn-Bad Godesberg (in German).

Kandel, T.P., Karki, S., Elsgaard, L., Labouriau, R., Lærke, P.E. (2020) Methane fluxes from a rewetted agricultural fen during two initial years of paludiculture. *Science of The Total Environment*, 713, 136670, 8 pp.

KCAF (2020) Funderingsproblematiek neemt fors toe (Foundation problems are rapidly increasing). *KCAF Nieuwsbrief*, Oktober 2020 (in Dutch). Online at: https://mailchi.mp/kcaf/nieuwsbrief-oktober, accessed 11 Jan 2021.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M. and 54 others (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, 585, 551–556.

Meijer, R. (2020) New land subsidence map reveals the Netherlands' (in)stability. News communication dated 08 Sep 2020, Delft University of Technology, The Netherlands. Online at: https://www.tudelft.nl/en/2020/tu-delft/new-land-subsidence-map-reveals-the-netherlands-instability/, accessed 25 Sep 2020.

Messner, D., Schellnhuber, J., Rahmstorf, S., Klingenfeld, D. (2010) The budget approach: A framework for a global transformation toward a low-carbon economy. *Journal of Renewable and Sustainable Energy*, 2(3), 031003, 15 pp.

Moxey, A., Moran, D. (2014) UK peatland restoration: Some economic arithmetic. *Science of the Total Environment*, 484, 114–120.

Muster, C., Gaudig, G., Krebs, M., Joosten, H. (2015) Sphagnum farming: the promised land for peat bog species? *Biodiversity and Conservation*, 24, 1989–2009.

Muster, C., Krebs, M., Joosten, H. (2020) Seven years of spider community succession in a Sphagnum farm. *Journal of Arachnology*, 48(2), 119–131.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H. (2013) Anthropogenic and natural radiative forcing (Chapter 8). In: Stocker, T.F., Qin, S., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740.

Nordt, A., Wichmann, S., Risse, J., Peters, J., Schäfer, A. (2020) *Anreize für Paludikultur zur Umsetzung der Klimaschutzziele 2030 und 2050* (*Incentives for Paludiculture to Achieve the*

Climate Protection Goals 2030 and 2050). DUENE, Greifswald, 45 pp. (in German).

Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., Hansjürgens, B., Lomba, A., Möckel, S., Passoni, G., Schleyer, C., Schmidt, J., Lakner, S. (2019) A greener path for the EU Common Agricultural Policy. *Science*, 365(6452), 449–451.

Poore, J., Nemecek, T. (2018) Reducing food's environmental impacts through producers and consumers. *Science*, 992, 987–992.

Regina, K., Budiman, A., Greve, M.H., Grønlund, A., Kasimir, Å., Lehtonen, H., Petersen, S., Smith, P., Wösten, H. (2016) GHG mitigation of agricultural peatlands requires coherent policies. *Climate Policy*, 16(4), 522–541.

Röder, N., Henler, M., Liebersbach, H., Kreins, P., Osterburg, B. (2015) Evaluation of land use based greenhouse gas abatement measures in Germany. *Ecological Economics*, 117, 193–202.

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D. (2019) Contribution of the land sector to a 1.5 °C world. *Nature Climate Change*, 9, 817–828.

Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., Nicholls, Z., Meinshausen, M. (2019) A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, 573, 357–363.

Röhe, P., Schröder, J. (2017) Paludikultur mit Anbau der Schwarzerle (Paludiculture by Alder cultivation). *AFZ Der Wald*, 23, 49–53 (in German).

Roßkopf, N., Fell, H., Zeitz, J. (2015) Organic soils in Germany, their distribution and carbon stocks. *Catena*, 133, 157–170.

SABAFC and SABF (2016) *Climate Change Mitigation in Agriculture and Forestry and in the Downstream Sectors of Food and Timber Use: Executive Summary*. Scientific Advisory Board on Agricultural Policy, Food and Consumer Health Protection and Scientific Advisory Board on Forest Policy at the Federal Ministry of Food and Agriculture, Berlin, 24 pp. Online at: https://literatur.thuenen.de/digbib_extern/dn059534.pdf , accessed 12 Oct 2020.

Schaller, L., Kantelhardt, J., Drösler, M. (2011) Cultivating the climate: socio-economic prospects and consequences of climate-friendly peat land management in Germany. *Hydrobiologia*, 674, 91–104.

Schlesinger, W.H., Amundson, R. (2019) Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, 25, 386–389.

Smith, P., Davis, S., Creutzig, F., Fuss, S. and 36 others (2016) Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, 6, 42–50.

Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T., Rayner, M., Scarborough, P. (2018) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, 2(10), 1451–1461.

Tanneberger, F., Schröder, C., Hohlbein, M., Lenschow, U., Permien, T., Wichmann, S., Wichtmann, W. (2020a) Climate change mitigation through land use on rewetted peatlands - cross-sectoral spatial planning for paludiculture in Northeast Germany. *Wetlands*, 40, 2309–2320.

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Ó Brolcháin, N., Peters, J., Wichtmann, W. (2020b) The power of nature-based solutions: How peatlands can help us to achieve key EU sustainability objectives. *Advanced Sustainable Systems* (early view), 2000146, 10 pp. https://doi.org/10.1002/adsu.202000146

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J. and 18 others (2020) A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecological Indicators*, 109, 105838, 14 pp.

Trepel, M., Pfadenhauer, J., Zeitz, J., Jeschke, L. (2017) Germany. In: Joosten, H., Tanneberger, F., Moen, A. (eds.) *Mires and Peatlands of Europe: Status, Distribution and Conservation*. Schweizerbart Science Publishers, Stuttgart, 413–424.

Tubiello, F.N., Salvatore, M., Alessandro, F.F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R.D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M.J., Srivastava, N., Smith, P. (2015a) The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. *Global Change Biology*, 21(7), 2655–2660.

UBA (2019) *Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2019*. National Inventory Report for the German Greenhouse Gas Inventory 1990–2017, German Environment Agency, Dessau, 945 pp. Online at: https://www.

umweltbundesamt.de/publikationen/submission-under-the-united-nations-framework-4, accessed 06 Sep 2020.

UNFCCC (2015) *Adoption of the Paris Agreement: Proposal by the President, Draft decision -/CP.21*. FCCC/CP/2015/L.9/Rev.1., United Nations Framework Convention on Climate Change. Online at: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf, accessed 01 Feb 2020.

Van Asselen, S., Erkens, G., Stouthamer, E., Woolderink, H.A.G., Geeraert, R.E.E., Hefting, M.M. (2018) The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, The Netherlands. *Science of The Total Environment*, 636, 177–191.

Van den Born, F., Kragt, D., Henkens, B., Rijken, B., van Bemmel, R., van der Sluis, S. (2016) *Dalende bodems, stijgende kosten. Mogelijke maatregelen tegen veenbodemdaling in het landelijk en stedelijk gebied* (*Sinking Soils, Rising Costs. Possible Measures Against Peat Subsidence in Rural and Urban Areas*) (in Dutch). PBL, Den Haag, 96 pp. Online at: https://www.pbl.nl/sites/default/files/downloads/pbl-2016-dalende-bodems-stijgende-kosten-1064.pdf, accessed 12 Oct 2020 (in Dutch).

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. (2011) The representative concentration pathways: an overview. *Climatic Change*, 109, 5–31.

Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E. (2017) Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, 8, 391–397.

Vernimmen, R., Hooijer, A., Joosten, H., Ballhorn, U., Nuutinen, M., Tata, H. (2020) Peatland mapping. In: FAO: *Peatlands Mapping and Monitoring - Recommendations and Technical Overview*, FAO, Rome, 7–18.

Walsh, B., Ciais, P., Janssens, I.A., Peñuelas, J., Riahi, K., Rydzak, F., van Vuuren, D.P., Obersteiner, M. (2017) Pathways for balancing CO_2 emissions and sinks. *Nature Communications*, 8, 14856, 12 pp.

Wang, L, Chen, W., Zhang, H., Ma, D. (2015) Dynamic equity carbon permit allocation scheme to limit global warming to two degrees. *Mitigation and Adaptation Strategies for Global Change*, 22, 609–628.

Wichmann, S. (2017) Commercial viability of paludiculture. A comparison of harvesting reeds for biogas production, direct combustion, and thatching. *Ecological Engineering*, 103, 497–505.

Wichmann, S. (2018) *Economic Incentives for Climate Smart Agriculture on Peatlands in the EU*. Proceedings of the Greifswald Mire Centre 01/2018, Greifswald, 38 pp. Online at: https://greifswaldmoor.de/files/dokumente/GMC%20Schriften/Report_Economic%20incentives_Cinderella_GMC%20Proceedings_web.pdf

Wichmann, S., Krebs, M., Kumar, S., Gaudig, G. (2020) Paludiculture on former bog grassland: Profitability of Sphagnum farming in North West Germany. *Mires and Peat*, 26, 08, 18 pp.

Wichtmann, W., Schröder, C., Joosten, H. (eds.) (2016) *Paludiculture – Productive Use of Wet Peatlands*. Schweizerbart Science Publishers, Stuttgart, 272 pp.

Wilson, D., Blain, D., Couwenberg, J., Evans, C.D., Murdiyarso, D., Page, S.E., Renou-Wilson, F., Rieley, J.O., Sirin, A., Strack, M., Tuittila, E.-S. (2016) Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 17, 04, 28 pp.

Wüstemann, H., Bonn, A., Albert, C., Bertram, C., Biber-Freudenberger, L., Dehnhardt, A., Döring, R., Elsasser, P., Hartje, V., Mehl, D., Kantelhardt, J., Rehdanz, K., Schaller, L., Scholz, M., Thrän, D., Witing, F., Hansjürgens, B. (2017) Synergies and trade-offs between nature conservation and climate policy: Insights from the "Natural Capital Germany - TEEB DE" study. *Ecosystem Services*, 24, 187–199.

Submitted 07 Feb 2020, final revision 16 Nov 2020
Editor: Stephan Glatzel

Author for correspondence: Dr Franziska Tanneberger, Institute of Botany and Landscape Ecology, Greifswald University, partner in the Greifswald Mire Centre, Soldmannstr. 15, D-17487 Greifswald, Germany.
Tel: +49 3834 4204137; Email: tanne@uni-greifswald.de

Appendix

Table A1. Implied CO_2, CH_4 and N_2O emission factors used in this study (after UBA 2019).

Land use category	CO_2 (t ha^{-1})	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})
Grassland, deep-drained	22.669*	18.910	3.916
Grassland, shallow-drained	15**	18.910	7.832***
Cropland	29.700	26.000	16.814
Forest land	8.227	4.631	2.183
Settlements	26.360	22.345	4.122
Wetlands****	28.315	11.192	1.339
Rewetted*****	0	250	0

* mixed emission factor for deep-drained, shallow-drained and woody grassland (UBA 2019);
** own emission factor for a peatland drained to −30 cm (mean annual water table) based on Couwenberg *et al*. (2011) and Jurasinski *et al*. (2016);
*** double the emission factor of deep-drained, because N_2O emissions peak around -30 cm water table depth (note that the German value is anyhow low compared with IPCC 2014 (12.9 deep-drained grassland, 6.6 for nutrient poor grassland));
**** includes also peat extraction areas (19,857 ha);
***** from Günther *et al*. (2020).

Table A2. CH_4 emissions (in kt) from land use on organic soil in Germany under the proposed emission reduction pathways 1 and 2 (for details, see text).

CH_4 (kt)	Pathway 1				Pathway 2			
Land use category	2020	2030	2040	2050	2020	2030	2040	2050
Grassland	20.3	73.9	224.0	364.4	20.3	162.3	263.4	364.4
Cropland	10.0	-	-	-	10.0	-	-	-
Forest land	0.7	18.9	28.0	37.1	0.7	18.9	28.0	37.1
Settlements	1.8	2.6	8.3	15.8	1.8	2.6	8.3	15.8
Wetlands	1.6	34.8	34.8	34.8	1.6	34.8	34.8	34.8
Total	34.4	130.2	295.1	452.1	34.4	218.6	334.5	452.1

Table A3. N_2O emissions (in kt) from land use on organic soil in Germany under the proposed emission reduction pathways 1 and 2 (for details, see text).

N_2O (kt)	Pathway 1				Pathway 2			
Land use category	2020	2030	2040	2050	2020	2030	2040	2050
Grassland	4.2	9.8	4.8	0	4.2	6.8	3.4	0
Cropland	6.4	-	-	0	6.4	-	-	0
Forest land	0.3	0.2	0.1	0	0.3	0.2	0.1	0
Settlements	0.3	0.3	0.2	0.1	0.3	0.3	0.2	0.1
Wetlands	0.2	0.0	0.0	0	0.2	0.0	0.0	0
Total	7.2	10.3	5.1	0.1	7.2	7.3	3.7	0.1