Towards net zero CO₂ in 2050: 
An emission reduction pathway for organic soils in Germany

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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 (CO₂) 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 (CO₂) 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 CO₂e 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 km²), 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 km² 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 CO₂ - and often also of nitrous oxide (N₂O). 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 CO₂ 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 CO₂ emissions (43 Gt CO₂; Friedlingstein et al. 2019). The European Union (EU) is, after Indonesia, the second largest emitter of CO₂ 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 km² (5 % of the area under land use), of which more than 98 % is drained (Trepel et al. 2017) and responsible for 47 Mt CO₂e (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 CH₄ and N₂O emissions mainly under the UNFCCC reporting sector ‘Agriculture’, and CO₂ 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 CO₂
emissions are reduced to net zero around the year 2050 (and become negative afterwards), whereas methane (CH$_4$) emissions must be halved, and N$_2$O 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$_2$O and CH$_4$ as well. Whereas CO$_2$ and N$_2$O 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$_2$O, 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$_2$e 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 the 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 2050 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$_2$O 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$_2$O 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 CO₂ 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 CO₂ emission trajectories with net zero in 2050 (in Gt yr⁻¹; IPCC 2018). Inset: CO₂ 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).

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

* = 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).

<table>
<thead>
<tr>
<th>CO(_2) (Mt)</th>
<th>Pathway 1</th>
<th>Pathway 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use category</td>
<td>2020</td>
<td>2030</td>
</tr>
<tr>
<td>Grassland</td>
<td>24.4</td>
<td>18.86</td>
</tr>
<tr>
<td>Cropland</td>
<td>11.4</td>
<td>0</td>
</tr>
<tr>
<td>Forest land</td>
<td>1.2</td>
<td>0.61</td>
</tr>
<tr>
<td>Settlements</td>
<td>2.1</td>
<td>2.00</td>
</tr>
<tr>
<td>Wetlands</td>
<td>3.9</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>43.0</td>
<td>21.47</td>
</tr>
</tbody>
</table>

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 CO₂ emissions (Figure 4). Due to the long-lived nature of CO₂ 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 CH₄ rather than CO₂ emissions. Over time the limited atmospheric lifetime of CH₄ 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 km² (UBA 2019) from which ~4 Mm³ 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 Mm³ recently mainly imported) by 2030 will require a net area of ~350 km² 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 N₂O, methane CH₄, and carbon dioxide CO₂) 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.](image-url)
(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 km²) as Sphagnum farming areas have high nature-conservation value (Muster et al. 2015, 2020; Gaudig & Krebs 2016). Another 250 km² 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.
Tables must be raised to the surface (zero CO₂ emissions) on 2,000 km² (~15% of the total area) and to ~30 cm on the remaining Grassland area to fit the IPCC (2018) CO₂ emission trajectory for 2030. The latter seems a pragmatic intermediate stage, as it allows conventional grassland use to continue, be it 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 CO₂ emissions) on 2,000 km² (~15% of the total area) and to ~30 cm on the remaining Grassland area to fit the IPCC (2018) CO₂ 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, Wichmann 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 CO₂ 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 (Wichmann 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.

(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).

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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 CO₂ emissions down to net zero in 2050. The relatively small climate effect of CH₄ compared to persistent CO₂ emissions when not rewetting (Günther et al. 2020) and the partial compensation of increased CH₄ emissions by reduced N₂O emissions (Tables A2 and A3) further justify this approach. Essentially, peatland management must choose between CO₂ emissions from drained or CH₄ 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 CO₂e y⁻¹ from agriculturally used organic soils), and also Ireland, France, the Netherlands, and Sweden (all >5 Mt CO₂e 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 CO₂ 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 CO₂ 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...
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 CO2 emissions already by 2035, i.e. in reducing emissions with double speed. Achieving net zero CO2 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.

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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.

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Appendix

Table A1. Implied CO₂, CH₄ and N₂O emission factors used in this study (after UBA 2019).

<table>
<thead>
<tr>
<th>Land use category</th>
<th>CO₂ (t ha⁻¹)</th>
<th>CH₄ (kg ha⁻¹)</th>
<th>N₂O (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland, deep-drained</td>
<td>22.669*</td>
<td>18.910</td>
<td>3.916</td>
</tr>
<tr>
<td>Grassland, shallow-drained</td>
<td>15**</td>
<td>18.910</td>
<td>7.832***</td>
</tr>
<tr>
<td>Cropland</td>
<td>29.700</td>
<td>26.000</td>
<td>16.814</td>
</tr>
<tr>
<td>Forest land</td>
<td>8.227</td>
<td>4.631</td>
<td>2.183</td>
</tr>
<tr>
<td>Settlements</td>
<td>26.360</td>
<td>22.345</td>
<td>4.122</td>
</tr>
<tr>
<td>Wetlands****</td>
<td>28.315</td>
<td>11.192</td>
<td>1.339</td>
</tr>
<tr>
<td>Rewetted*****</td>
<td>0</td>
<td>250</td>
<td>0</td>
</tr>
</tbody>
</table>

* 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 N₂O 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. CH₄ emissions (in kt) from land use on organic soil in Germany under the proposed emission reduction pathways 1 and 2 (for details, see text).

<table>
<thead>
<tr>
<th>Land use category</th>
<th>Pathway 1</th>
<th>Pathway 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td>2030</td>
</tr>
<tr>
<td>Grassland</td>
<td>20.3</td>
<td>73.9</td>
</tr>
<tr>
<td>Cropland</td>
<td>10.0</td>
<td>-</td>
</tr>
<tr>
<td>Forest land</td>
<td>0.7</td>
<td>18.9</td>
</tr>
<tr>
<td>Settlements</td>
<td>1.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Wetlands</td>
<td>1.6</td>
<td>34.8</td>
</tr>
<tr>
<td>Total</td>
<td>34.4</td>
<td>130.2</td>
</tr>
</tbody>
</table>

Table A3. N₂O emissions (in kt) from land use on organic soil in Germany under the proposed emission reduction pathways 1 and 2 (for details, see text).

<table>
<thead>
<tr>
<th>Land use category</th>
<th>Pathway 1</th>
<th>Pathway 2</th>
<th>Pathway 2</th>
<th>Pathway 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td>2030</td>
<td>2040</td>
<td>2050</td>
</tr>
<tr>
<td>Grassland</td>
<td>4.2</td>
<td>9.8</td>
<td>4.8</td>
<td>0</td>
</tr>
<tr>
<td>Cropland</td>
<td>6.4</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Forest land</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>Settlements</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Wetlands</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>7.2</td>
<td>10.3</td>
<td>5.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>