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# The role of peatland degradation, protection and restoration for climate change mitigation in the SSP scenarios

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## Abstract

Peatlands only cover a small fraction of the global land surface (∼3%) but store large amounts of carbon (∼600 GtC). Drainage of peatlands for agriculture results in the decomposition of organic matter, leading to greenhouse gas (GHG) emissions. As a result, degraded peatlands are currently responsible for 2%–3% of global anthropogenic emissions. Preventing further degradation of peatlands and restoration (i.e. rewetting) are therefore important for climate change mitigation. In this study, we show that land-use change in three SSP scenarios with optimistic, recent trends, and pessimistic assumptions leads to peatland degradation between 2020 and 2100 ranging from −7 to +10 Mha (−23% to +32%), and a continuation or even an increase in annual GHG emissions (−0.1 to +0.4 $GtCO_2$-eq $yr^{-1}$). In default mitigation scenarios without a specific focus on peatlands, peatland degradation is reduced due to synergies with forest protection and afforestation policies. However, this still leaves large amounts of GHG emissions from degraded peatlands unabated, causing cumulative $CO_2$ emissions from 2020 to 2100 in an SSP2-1.5 °C scenario of 73 $GtCO_2$. In a mitigation scenario with dedicated peatland restoration policy, GHG emissions from degraded peatlands can be reduced to nearly zero without major effects on projected land-use dynamics. This underlines the opportunity of peatland protection and restoration for climate change mitigation and the need to synergistically combine different land-based mitigation measures. Peatland location and extent estimates vary widely in the literature; a sensitivity analysis implementing various spatial estimates shows that especially in tropical regions degraded peatland area and peatland emissions are highly uncertain. The required protection and mitigation efforts are geographically unequally distributed, with large concentrations of peatlands in Russia, Europe, North America and Indonesia (33% of emission reductions are located in Indonesia). This indicates an important role for only a few countries that have the opportunity to protect and restore peatlands with global benefits for climate change mitigation.

## 1. Introduction

Peatlands only cover a small fraction of the global land surface (∼3%) but have a disproportionally large contribution to several of the current global sustainability issues (Page *et al* 2011, Loisel *et al* 2014, Scharlemann *et al* 2014, Dargie *et al* 2017). They are important for the global climate (Leifeld and Menichetti 2018), provide unique habitat to species of conservation concern (Posa *et al* 2011, Saarimaa *et al* 2019) and are important for water and nutrient regulation (Grand-Clement *et al* 2013, Loisel *et al* 2014, Ritson *et al* 2016). Total carbon stocks in peatland soils are estimated at around 600 GtC (2200 $GtCO_2$) (Yu *et al* 2010), which is four to five times the remaining carbon budget to limit global warming to 1.5° (IPCC 2021). This underscores the importance of keeping carbon stored in peatlands to achieve the goals of the Paris climate agreement (UNFCCC 2015). Recent studies in the Congo basin found peatland areas with formerly unknown large carbon stocks that are at risk of degradation, highlighting that peatlands could play an even larger role in climate change than previously thought (Dargie *et al* 2017, Crezee *et al* 2022).

Drainage of peatlands for agriculture, forestry or peat extraction results in large emissions of carbon dioxide ($CO_2$) as well as smaller amounts of other greenhouse gasses (GHGs) such as nitrous oxide ($N_2O$) and methane ($CH_4$). Several studies have estimated the contribution of degraded peatlands to GHG emissions. Global estimates currently range between 1.3 Gt $CO_2$-eq $yr^{-1}$ to 1.9 Gt $CO_2$-eq $yr^{-1}$ (Joosten 2010, Leifeld and Menichetti 2018), which is 2.3%–3.4% of annual global anthropogenic GHG emissions (56 $GtCO_2$-eq $yr^{-1}$ in 2010–2019, IPCC 2022). Halting the expansion of peatland drainage would stop the increase of contemporary peatland emissions but would not reduce them because the complete decomposition of peat soils may take centuries. Restoration of high water levels in degraded peatlands could reverse this process, halting the decomposition of organic matter and keeping carbon stored in the soil (Jaenicke *et al* 2010, Wilson *et al* 2016). Rewetting of peatland could even result in sequestration of $CO_2$ over longer time horizons (decades to centuries) but at the same time leads to higher methane emissions (Abdalla *et al* 2016). Compared to peatland degradation, however, rewetting of peatlands has major net climate benefits (Günther *et al* 2020).

Peatland degradation is tightly linked to agricultural activity, for example, with expansion of palm oil plantations on peatlands in Indonesia (Miettinen *et al* 2012) and intensively managed pasture lands on peat soils in the Netherlands (van den Born *et al* 2016). Assessing how future changes in agricultural land use may affect peatlands is key to understand how the status of peatlands and their role in climate change may develop in the future. Reducing peatland emissions can also contribute significantly to climate change mitigation (Leifeld *et al* 2019, Humpenöder *et al* 2020). In this study, we investigate how different land-use scenarios affect peatlands, what the impacts are on GHG emissions, what the role of peatland restoration is in achieving climate change mitigation targets, and how large uncertainties are. To this purpose, we use the IMAGE 3.2 integrated assessment model framework (Stehfest *et al* 2014, van Vuuren *et al* 2021). Specifically, we assess three different shared socioeconomic pathway scenarios (SSPs): the optimistic SSP1, the middle-of-the-road SSP2, and the pessimistic SSP3. In addition, we assess how much protection of non-degraded peatlands and restoration of degraded peatlands can contribute to mitigating climate change in deep mitigation pathways under these three different socio-economic futures. Finally, we look into a key uncertainty of peatland emission projections regarding estimates of the location and extent of peatland area that vary considerably in the literature. Compared to existing literature, this study provides a more detailed analysis of peatland degradation under multiple socio-economic futures using baseline as well as mitigation assumptions. Assessments are presented both at the global and the regional scale. In addition, we address model uncertainty by operationalizing these scenarios in a different integrated assessment model and for the first time we quantify the uncertainty arising from varying estimates of peatland extent.

## 2. Methods

### 2.1. The IMAGE 3.2 model framework

The IMAGE 3.2 integrated assessment model framework[3] is designed to explore future global environmental change due to socio-economic developments and to assess potential response strategies (Stehfest *et al* 2014, van Vuuren *et al* 2021). It includes the human system with detailed descriptions of the energy and land-use systems and the natural system with representations of natural vegetation dynamics, the hydrological cycle and the climate system. This study focuses on an application in the land system models of the framework. Land is represented in the IMAGE-LandManagement model at 5 arc-minutes resolution with crop production, livestock systems, bioenergy production, forestry and natural land. Agro-economic trends are determined through coupling to the computable general equilibrium model MAGNET (Woltjer *et al* 2014) that uses information on land availability, changes in crop and livestock efficiency and impacts on crop yields of climate change and water shortages from IMAGE to calculate developments in the food system. Projections are made at the level of 26 world regions (SI figure 1). IMAGE uses food system data from MAGNET, such as demand for crop and livestock production and trends in intensification or extensification to project gridded land use in the future. Expansion of agricultural land is allocated at the grid level using empirically based statistical suitability layers derived from remote-sensing based land-use change data (Cengic *et al* 2023). Gridded land use and climate change are implemented in the dynamic global vegetation model LPJmL which represents the carbon and hydrological cycles as well as crop growth for rainfed and irrigated agriculture (Müller *et al* 2016, Schaphoff *et al* 2018).

[3] For more information on the IMAGE model visit the online documentation: http://models.pbl.nl/image.

### 2.2. Peatland implementation

A gridded map with fractional coverage of peatland at 5 arc-minutes resolution has been created to include peatland dynamics in the IMAGE model. The map is based on the S-world global soil map (Stoorvogel 2016), which is a high-resolution soil map (30 arc-seconds) combining data from the Harmonized World Soil Database (HWSD) (Nachtergaele *et al* 2012) with multiple other auxiliary data sources. Specifically, all histosols (Folic, Terric, Fibric, Thionic and Gelic Histosols) were classified as peatland, whereas all other soils were assumed not to contain peatlands. This binary classification at 30 arc-seconds is then aggregated to fractions at 5 arc-minutes.

The peatland map is combined with gridded agricultural land use in the IMAGE-LandManagement model. It is assumed that at the 5 arc-minutes level each share of agricultural land use (including 16 food crop types, 5 bioenergy crop types and grazing land) is proportionally located on peatland and non-peatland area present in each grid cell, implying that each agricultural land-use fraction is multiplied by the peatland fraction. The resulting peatland fractions with agricultural land use are assumed to be degraded. All other peatland fractions are assumed to be non-degraded. This is a simplification that may lead to over or underestimation of the degraded peatland fractions. If agriculture on peatland is abandoned during the scenario period (i.e. after the year 2015) it is assumed to be restored (i.e. rewetted). This is an optimistic assumption as restoration can be costly, but in the context of this study we consider it appropriate as the goal is to assess the maximum potential role of peatland restoration for climate change mitigation. We define restoration as halting the decomposition process typically by raising the water table, i.e. this does not imply full hydro-ecological restoration which is more difficult and costly to achieve. Aboveground carbon dynamics for deforestation due to land-use change or forest regrowth after abandonment are calculated using default vegetation dynamics of the LPJmL model. Due to data limitations historical peatland restoration is not included.

The degraded and rewetted peatland fractions are multiplied by land area and annual peatland emissions factors based on the IPCC guidelines (IPCC 2014, Wilson *et al* 2016). Emission factors for $CO_2$, $CH_4$, $N_2O$, and dissolved organic carbon (eventually also emitted as $CO_2$), are specified per biome (boreal, temperate and tropical) based on the IMAGE biome classification and per degraded land-use type (SI tables 2–5) differentiating between croplands, grasslands and plantations. This results in total anthropogenic emissions from peatland degradation and restoration. Natural peatlands are also sources of GHG emissions, but these are non-anthropogenic and, therefore, not addressed in this study.

### 2.3. Scenario description

Three SSP scenarios are implemented in this study covering a substantial range of possible land-use futures (Doelman *et al* 2018, van Vuuren *et al* 2021). The core of these scenarios is formed by economic and population projections (Dellink *et al* 2017, KC and Lutz 2017), which, together with narrative-based assumptions, shape the scenarios (SI table 1). SSP2 is characterized as a world where historical developments continue, with population growth levelling of slowly, continued economic growth, no major changes to current levels of globalized trade, continued technological development, increases in meat consumption in line with growth in welfare and no major improvements in environmental regulation such as nature protection (O'Neill *et al* 2017). SSP1 has a more optimistic outlook where the population starts to decrease by 2050, and people continue to become wealthier but are also more environmentally aware with relatively lower meat consumption and better protection of ecosystems. SSP3 has the most pessimistic outlook. Here, the global population grows strongly to more than 12 billion by the end of the century. Moreover, due to a lack of cooperation, international trade and technology development stagnate, leading to less economic growth and slow improvement of food security. In the scenario, nature protection is unsuccessful, and strong resource demand increases pose major environmental risks.

The three SSP baseline scenarios (i.e. without climate policy) are combined with ambitious climate mitigation targets to investigate the potential and impacts of climate policies required to achieve stringent targets (table 1). For SSP1 and SSP2, the 1.9 W $m^{-2}$ target is implemented which is in line with the 1.5 °C temperature goal. In SSP3, the 2.6 W $m^{-2}$ target is used (in line with 2 °C) because the 1.9 W $m^{-2}$ goal is infeasible due to the high challenges to mitigation. In the default setting (denoted by the suffix D) all standard, cost-optimal climate policies are included, such as upscaling of renewables, higher energy efficiencies in the energy use in end-use sectors and production, as well as forest protection, afforestation and non-$CO_2$ mitigation in the land-use sectors (van Vuuren *et al* 2017, 2021, Doelman *et al* 2018, 2020). Peatland protection and restoration are not included in the default scenarios but are added in the peatland scenarios (denoted by the suffix P) to assess the effects of peatland policy on climate change mitigation and land-use dynamics. Peatland protection is implemented as strict protection after 2020 of all grid cells with more than 10% peatland area share. Peatland restoration is implemented as forced abandonment of all agricultural lands between 2020 and 2030 (linearly) in grid cells with more than 10% peatland area share.

**Table 1.** Overview of scenarios and their key differences implemented in this study.

| Scenario name | Radiative forcing in 2100 (W $m^{-2}$) | Climate change mitigation policy (energy, industry and land use) | Peatland protection and restoration |
|---|---|---|---|
| SSP1 | 5.0 | | |
| SSP2 | 6.2 | | |
| SSP3 | 6.7 | | |
| SSP1-1.9-D | 1.9 | X | |
| SSP2-1.9-D | 1.9 | X | |
| SSP3-2.6-D | 2.6 | X | |
| SSP1-1.9-P | 1.9 | X | X |
| SSP2-1.9-P | 1.9 | X | X |
| SSP3-2.6-P | 2.6 | X | X |

These protection and restoration measures are highly ambitious and optimistic. This is in line with the stringent goals of 1.5 °C and 2 °C, but it is important to note that these are maximal potential estimates of peatland mitigation that do not take feasibility concerns into account.

### 2.4. Sensitivity analysis

Mapping peatlands at the global scale is a difficult task, given differences in how peatlands are defined, and inconsistencies in data availability and quality, resulting in a wide range of estimates for peatland area and carbon stocks (Minasny *et al* 2019). In this study, we choose to use the S-world global soil map (Stoorvogel *et al* 2017), which is a reclassification of the HWSD soil map (Nachtergaele *et al* 2012), as our default peatland extent estimate. This map has relatively conservative estimates in the tropical regions which are shown to be highly uncertain (section 3.3). Therefore it is used as default out of a precautionary principle. There are various other approaches available in the literature, including (1) soil map reclassification methods similar to the default approach used in this study (Hiederer and Köchy 2011), (2) assessments based on inventories (Tanneberger *et al* 2017, Humpenöder *et al* 2020), (3) expert-based modeling (Gumbricht *et al* 2017) and (4) machine-learning algorithms (Melton *et al* 2022). In addition to our default map, we select five global spatial-explicit estimates of peatland area that are integrated in the IMAGE model to analyze the related uncertainty and its effect on GHG emissions estimates. These are the meta-studies by (1) Leifeld and Manichetti (2018) and (2) Xu *et al* (2018) that both combine multiple data sources to compile peatland maps; the inventory-based approach by (3) Humpenöder *et al* (2020) who downscale inventory data from Joosten (2010) to the grid level; the machine-learning based approach from (4) Melton *et al* (2022); and the expert-based model approach by (5) Gumbricht *et al* (2017), which is complemented by the default S-world data for the temperate and boreal zones because the data is only available for the tropical zones.

## 3. Results

### 3.1. Land-use dynamics

The SSP scenarios show very different land-use futures under baseline assumptions (figure 1). SSP2 and SSP3 show strong increases in agricultural land of 680 Mha and 1090 Mha (2020–2100 period) due to population growth and increased welfare resulting in growing food demand. SSP1 shows a strong reduction in grazing land (−850 Mha) due to increased welfare coupled with lower demand for meat as well as increased efficiency. Cropland does still increase slightly on the global level (+110 Mha), mainly due to expansion in Sub-Saharan Africa while in other regions such as the USA and China cropland decreases (SI figure 2). Agricultural expansion typically comes at the cost of natural land which decreases strongly in SSP2 and SSP3 (−730 and −1130 Mha, respectively) while it increases in SSP1 (+700 Mha). Built-up area also plays a role with relatively modest increases in all SSPs (+39 to +45 Mha). Land-use change in the baseline scenarios leads to additional peatland degradation in SSP2 and SSP3 of 7 and 10 Mha, respectively, in the 2020–2100 period (figure 2(b)). This corresponds to a 21% and 32% increase in degraded peatlands, respectively, compared to 31 Mha degraded peatlands in 2020. The increases are very geographically focused, with 67% of the expansion in SSP2 taking place in only two regions: Indonesia and Rest of South America (figures 2(c) and SI 3). This specifically implies continued conversion and drainage of the tropical peatland forests of Indonesia (Sumatra, Borneo and New Guinea) as well as losses in the Peruvian Amazon and the coastal areas of British Guyana and Surinam (SI figure 4). In SSP1 the global reduction in agricultural land leads to a reduction in degraded peatland of 7 Mha. Especially in the first half of the century in some regions still some non-degraded peatland (i.e. natural) is lost because reductions in agricultural land mainly take place later in the century, resulting in about 9 Mha of restored peatland (rewetted) by 2100.

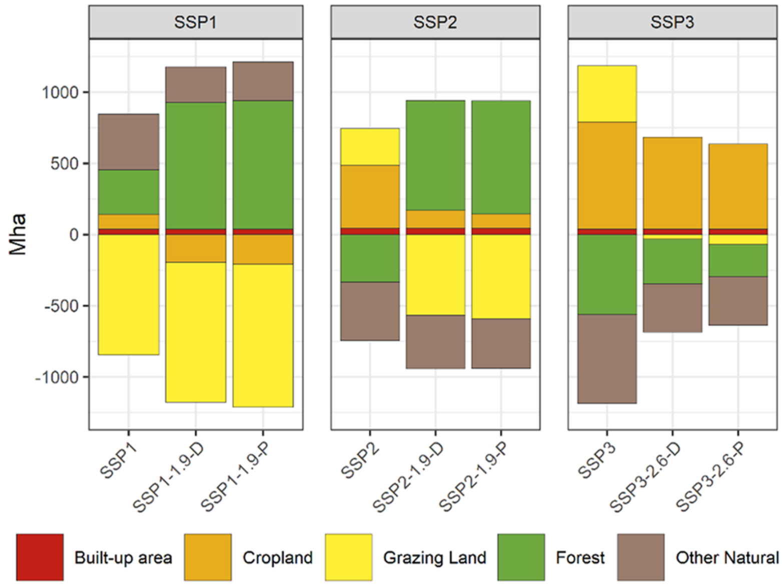


**Figure 1.** Global land-use change for five main land-use categories in the 2020–2100 period.

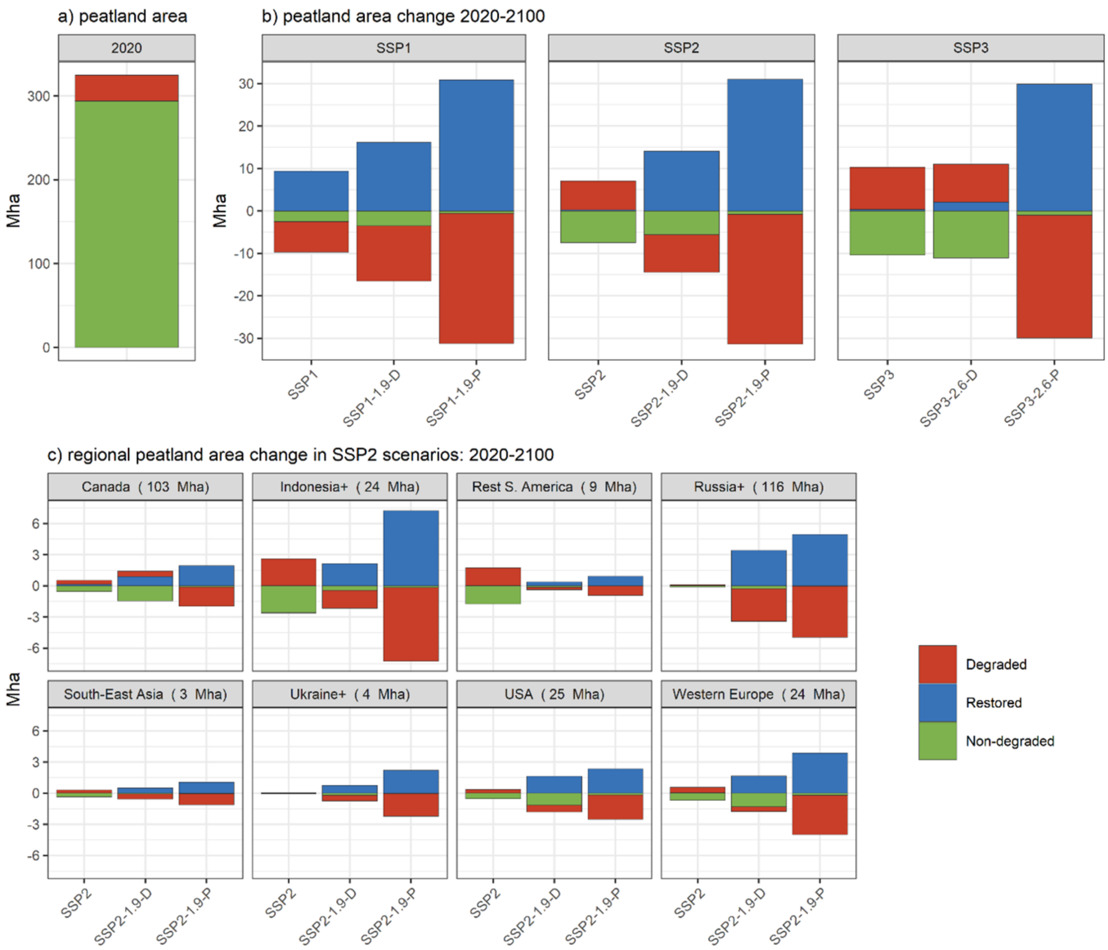


**Figure 2.** (a) Peatland area in 2020, (b) changes in global peatland area in all scenarios in the 2020–2100 period, and (c) changes in peatland area in the SSP2 scenarios in eight selected regions representing 80% of historical degraded peatland area and 88% of peatland conversion in the SSP2 baseline scenario. Between brackets the total peatland area in each region is shown.

In the default mitigation scenarios aiming for a maximum warming of 1.5 °C or 2 °C, land-based mitigation policies are implemented leading to major changes in land-use dynamics. In all scenarios forest protection is implemented to reduce deforestation emissions. These measures limit increases in agricultural land as expansion into forested areas is prohibited. Additionally, cropland area is dedicated to the production of crops or biomass for bioenergy in order to replace fossil fuels as well as to capture and store carbon. In SSP1 and SSP2, also large-scale reforestation is implemented resulting in reductions of agricultural land use. In SSP3 no afforestation takes place as land-based mitigation is assumed to be less successful. These policies result in strong increases in forest area in SSP1 and SSP2 (+890 and +770 Mha, respectively, in 2020–2100), and reduced deforestation in SSP3 (−250 Mha) mostly from reductions in grazing land (figure 1). Although not specifically targeted in the default mitigation scenarios, forest protection and afforestation partly overlap with peatland resulting in restoration of peatlands. Especially in SSP1-1.9-D and SSP2-1.9-D, this results in substantial restoration of 16 and 14 Mha of peatland, respectively (figure 2(b)). Again, the dynamics are very unevenly spread between world regions, with most of the restoration taking place in regions with historically large degraded peatland areas, notably Russia+ (25%), Indonesia+ (15%), USA (12%) and Western Europe (12%) (figure 2(c)). Canada on the other hand observes a small increase in degraded peatland due to expansion of bioenergy. In SSP3-2.6-D a modest decrease in degraded peatland is found (1 Mha). In some regions in SSP2-1.9-D still a reduction in non-degraded peatland area occurs (figure 2(c)), even though there also is a substantial increase in peatland restoration. This notably occurs in Western Europe and USA due to changes in agricultural land distribution (e.g. due to productivity changes from climate change) and highlights the importance of peatland protection which is not included in SSP2-1.9-D. Despite the co-benefits between some mitigation policies and peatland restoration, still a large area of degraded peatland remains by the end of the century in the default mitigation scenarios, ranging from 18 Mha in SSP1-1.9-D to 40 Mha in SSP3-2.6-D.

To fully make use of the mitigation potential of peatland, we assume additional policy in the mitigation scenarios to protect and restore peatlands. Consequently, nearly all degraded peatlands are restored in the 2020–2030 period (30–31 Mha) requiring small additional reductions in cropland and grazing land in the peatland mitigation scenarios compared to the default mitigation scenarios. Logically, most of the changes take place in the regions with historically large degraded peatland areas (Indonesia, Russia, Ukraine, Europe and North America). Additionally, also regions where expansion of agriculture on peatland occurred see changes in land-use distribution to non-peatland locations. Most notably in the Rest South America region, agricultural expansion is located to non-peatland areas and also slightly more agricultural expansion takes place in this region because of trade effects from peatland protection and restoration in other world regions. The changes to global land-use dynamics due to peatland policy are modest, which is also reflected by small effects on global food security indicators: food prices in 2100 increase by 0.3%–5.1% and food demand decreases by 0.8%–1.3% in the peatland mitigation scenarios compared to the default mitigation scenarios (SI figures 10–11). However, regional differences are stark, with most notably much stronger increases in Indonesia where prices increase by 44%–48% and food demand decreases by 4.6%–5.2% (SI figures 12–13).

### 3.2. GHG emissions dynamics

The SSP scenarios show a substantial range in GHG emissions from the agriculture, forestry and land-use (AFOLU) sector by the end of the century. With strong increases in SSP3 from 10.8 $GtCO_2$-eq $yr^{-1}$ in 2020 up to 16.9 $GtCO_2$-eq $yr^{-1}$ in 2100 (figure 3(a), $CO_2$-equivalents of $CH_4$ and $N_2O$ are calculated using 100 year time horizon global warming potentials (GWP100, Forster *et al* 2007)). In SSP1 on the other hand, emissions are reduced to 6.0 $GtCO_2$-eq $yr^{-1}$ by 2100. Deforestation continues in the baseline SSP2 and SSP3 scenarios throughout the century resulting in substantial AFOLU $CO_2$ emissions, while in SSP1 a small negative net $CO_2$ flux occurs due to abandonment of agricultural land. Non-$CO_2$ emissions in SSP2 and SSP3 show substantial increases due to growth of the agricultural sector, while in SSP1 a modest decrease takes place. Emissions from peatland form 10% of annual AFOLU emissions in 2020 (1.1 $GtCO_2$-eq $yr^{-1}$), which in turn is comprised of 90% $CO_2$ emissions as almost all emissions result from degrading peatlands. The remaining share is predominantly $N_2O$ (figure 3(b)). By the end of the century emissions from peatlands have increased substantially in SSP2 (1.4 $GtCO_2$-eq $yr^{-1}$) and SSP3 (1.6 $GtCO_2$-eq $yr^{-1}$) while a modest decrease occurs in SSP1 (1.0 $GtCO_2$-eq $yr^{-1}$). The relative importance has changed however, with peatlands representing 15% of total remaining positive AFOLU emissions in SSP1 compared to 9% of total AFOLU emissions in SSP3. The emissions are very unevenly distributed, with 30% of 2020 emissions originating from Indonesia which increases further to 33% in SSP2 by 2100 (figure 3(c)). The boreal and temperate regions also have substantial emission shares, with 12% and 10% from Russia and Western Europe, respectively, but these are not projected to increase much when recent trends are assumed to continue (SSP2). The strongest relative increase takes place in the Rest South America region, with 185% increase in emissions.

The default mitigation scenarios show strong decreases in AFOLU emissions: in all scenarios non-$CO_2$ emissions are reduced by 39% to 50% compared to baseline levels, due to technical mitigation measures as well as reductions in food consumption. $CO_2$ emissions go strongly negative in SSP1-1.9-D and SSP2-1.9-D as afforestation is applied at scale. In SSP3-2.6-D $CO_2$ emissions are reduced by 47%, but remain positive as

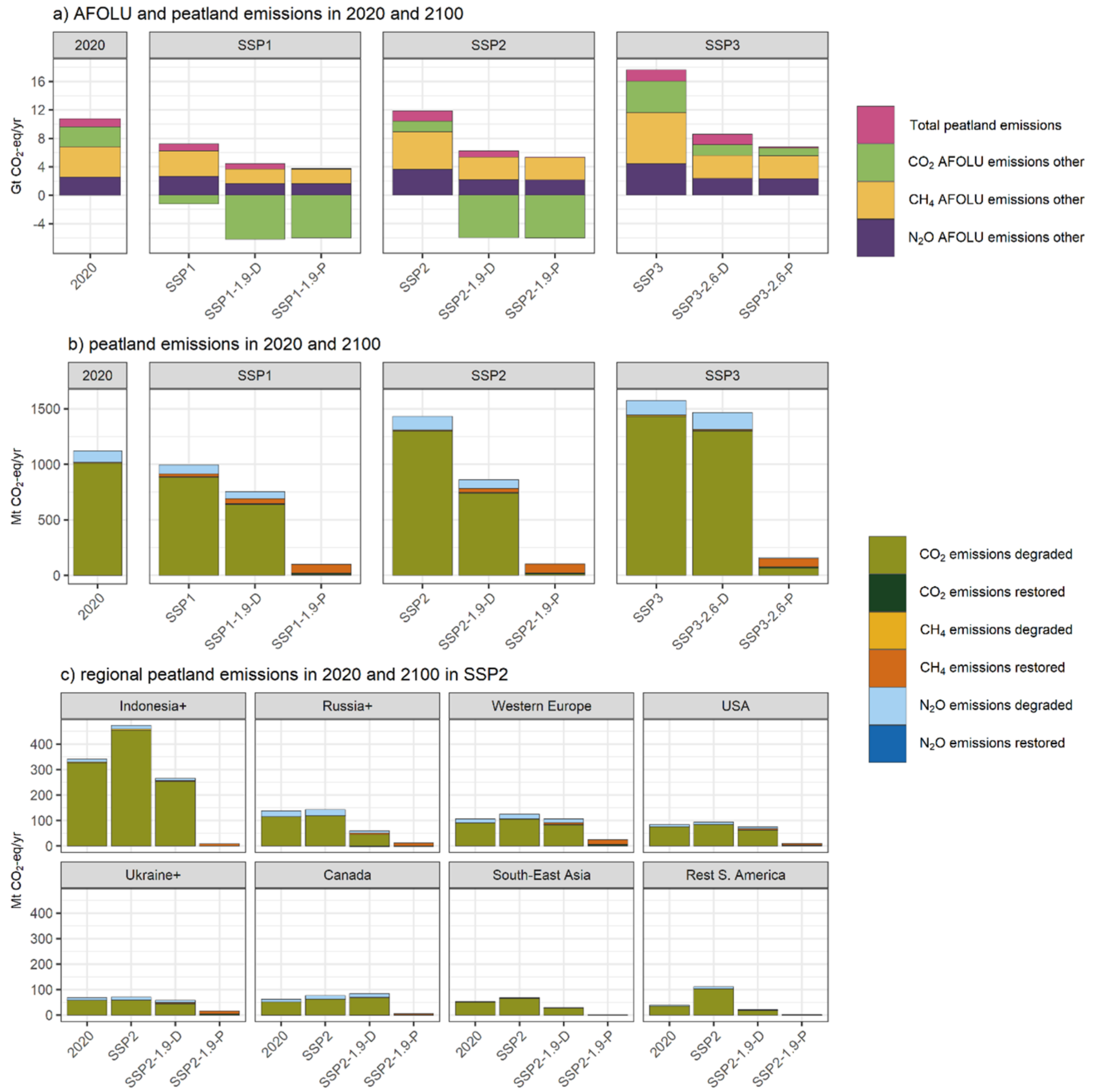


**Figure 3.** (a) Global GHG emissions from the AFOLU sector (excluding peatland) for $CO_2$, $N_2O$ an $CH_4$ and total GHG emissions from peatlands, (b) global peatland GHG emissions distinguished by source from degraded or rewetted peatlands and by GHG and (c) selected regional GHG emissions distinguished by source from degraded or rewetted peatlands and by GHG. Emissions are defined in terms of $CO_2$-equivalents calculated using 100 year time horizon global warming potentials (GWP100, Forster *et al* (2007)).

afforestation is assumed to be infeasible in line with the scenario narrative. Peatland emissions decrease slightly in SSP3-2.6-D (−6% compared to baseline in 2100) as not all peatland degradation is prevented by forest protection measures. In fact in Russia an increase in peatland degradation occurs as cropland expansion is prevented in the tropics due to forest protection measures leading to displacement of crop production to Russia, among others (SI figure 2). On the other hand, in SSP2-1.9-D a strong reduction in peatland emissions takes place (−39%) as agricultural land diminishes compared to the baseline due to forest protection and afforestation resulting in restoration of peatlands. The emission reduction in SSP1-1.9-D is relatively smaller (−24%) than in SSP2-1.9-D because already in the SSP1 baseline a substantial reduction in agricultural land occurs resulting in less relative improvement in the mitigation scenario.

Dedicated peatland restoration policies result in major reductions in peatland emissions in all peatland scenarios (figure 3(b)). $CO_2$ emissions and $N_2O$ emissions go down quickly, and even modest $CO_2$ sequestration is assumed in boreal regions as reported by Wilson *et al* (2016) (SI tables 2–5). Methane emissions increase from the large area of restored peatlands, up to 78–81 $MtCO_2$-eq $yr^{-1}$ by 2100. However, these emissions are negligible compared to $CO_2$ and $N_2O$ emissions from degrading peatlands. Mirroring the fact that the bulk of peatlands emissions comes from certain regions, also the emissions reductions are focused in a few geographic locations, most notably again Indonesia, but also Russia and Western Europe. Even though Indonesia only has slightly more restored peatland area than Russia and Western Europe, it does

**Table 2.** Cumulative $CO_2$ emissions from energy and industry, AFOLU, peat degradation and total in the 2020–2100 period.

| Cumulative $CO_2$ emissions ($GtCO_2$) in the 2020–2100 period | Energy and industry emissions | AFOLU emissions (excl. peatlands) | Peatland emissions | Total |
|---|---|---|---|---|
| SSP1 | 2767 | 50 | 78 | 2895 |
| SSP1-1.9-D | 486 | −285 | 65 | 266 |
| SSP1-1.9-P | 486 | −291 | 6 | 201 |
| SSP2 | 3904 | 308 | 96 | 4309 |
| SSP2-1.9-D | 259 | −183 | 73 | 149 |
| SSP2-1.9-P | 259 | −193 | 6 | 73 |
| SSP3 | 4323 | 452 | 103 | 4879 |
| SSP3-2.6-D | 114 | 257 | 96 | 467 |
| SSP3-2.6-P | 114 | 212 | 10 | 336 |

have a much larger share of emissions reduction because peatland emissions per area in the tropics are much higher than in the temperate and boreal zones.

Comparing cumulative $CO_2$ emissions from peatland in the 2020–2100 period to cumulative emissions in the energy and industry sector and the AFOLU sector emphasizes the importance of including peatland protection and restoration in climate change mitigation policy (table 2). In the default mitigation scenarios, peatland $CO_2$ emissions make up large shares of the $CO_2$ budgets as projected in the scenarios: 21% in the SSP3-2.6-D scenario, 25% in the SSP1-1.9-D scenario and 49% of the SSP2-1.9-D scenario. Including peatland policies greatly reduces these shares to 2%–3%. As the effect of these policies on land-use dynamics and, therefore, on the food and agricultural system are fairly limited at the global scale, including peatland protection and restoration is a critical component of a policy package making stringent mitigation targets feasible without major negative impacts on food security. However, the possibility, or responsibility, to implement these policies is very unequally divided between world regions, highlighting a key challenge.

### 3.3. Sensitivity to varying peatland estimates

Spatial-explicit estimates of peatland area extent vary greatly in the literature. The integration of five additional estimates of peatland area in IMAGE provides the opportunity to assess the sensitivity of our degraded peatland area and emissions projections to these estimates. Table 3 shows the total peatland area, degraded peatland area in 2020 and 2100, and cumulative peatland $CO_2$ emissions from this sensitivity at the global scale and disaggregated to tropical and temperate and boreal regions. Degraded peatland areas vary widely, from 31 to 96 Mha in 2020 and from 38 to 123 Mha in 2100. This is also reflected in the cumulative $CO_2$ emissions that range from 87 $GtCO_2$ to 344 $GtCO_2$. The approach based on Stoorvogel *et al* (2016), which is the default method in this study, yields results that are in line with other studies. However, the sensitivity analysis shows various higher estimates of degraded peatlands and GHG emissions indicating that we may underestimate peatland degradation in some locations. The highest estimate is found using the map from Leifeld and Menichetti (2018). As this map is considered an 'upper estimate of the possible global peatland area extent', it is to be expected that this is the highest estimate both in degraded peatland area and GHG emissions. The largest variation in the projections is found in the tropical regions, most notably in South America and Sub-Saharan Africa: emissions in the Rest South America region range from 34 $MtCO_2$-eq $yr^{-1}$ to 1.5 $GtCO_2$-eq $yr^{-1}$ in 2100, and emissions in Western Africa range from 25 to 800 $MtCO_2$-eq $yr^{-1}$. This is mainly due to the higher estimates of current peatland extent in the tropics in Gumbricht *et al* (2017) and Leifeld and Menichetti (2018) highlighting the uncertainty of peatland extent in the tropical regions of the world (table 3). The importance of tropical peatlands in South America and Sub-Saharan Africa is in line with Gumbricht *et al* (2017) that highlighted the underestimation of peatland in the Amazon basin, as well as with recent publications on the extent of peatland stocks in the Congo basin (Dargie *et al* 2017, Crezee *et al* 2022) (figure 4).

## 4. Discussion

Here we show the important role that peatland protection and restoration plays in global climate mitigation. Various other studies have investigated the role of peatland degradation in climate change. A comparison with these other studies shows that our estimates are on the lower end of the range in terms of degraded peatland area and GHG emissions in the historical period. For total degraded peatland area on the global scale we estimate 31 Mha in 2020, where other studies report 43 Mha in 2008 (Joosten 2010), and 51 Mha (Leifeld and Menichetti 2018) and 46 Mha in 2015 (Humpenöder *et al* 2020). For GHG emissions we report

**Table 3.** Peatland area estimates in 2020 and cumulative $CO_2$ emission estimates for the 2020–2100 period in the SSP2 baseline scenario using different peatland area maps. Results are shown at the global level and disaggregated in predominantly tropical regions and temperate and boreal regions.

| *Global* | Total peatland area in 2020 (Mha) | Degraded peatland area in 2020 (Mha) | Degraded peatland area in 2100 (Mha) | Cumulative $CO_2$ emissions in the 2020–2100 period ($GtCO_2$) |
|---|---|---|---|---|
| Default (Stoorvogel *et al*) | 325 | 31 | 38 | 96 |
| Gumbricht *et al* | 440 | 66 | 86 | 241 |
| Humpenöder *et al* | 407 | 35 | 43 | 116 |
| Leifeld and Manichetti | 920 | 96 | 123 | 344 |
| Melton *et al* | 386 | 54 | 69 | 193 |
| Xu *et al* | 440 | 32 | 39 | 87 |
| *Tropical regions* | | | | |
| Default (Stoorvogel *et al*) | 46 | 13 | 18 | 57 |
| Gumbricht *et al* | 150 | 41 | 59 | 188 |
| Humpenöder *et al* | 54 | 17 | 23 | 75 |
| Leifeld and Manichetti | 197 | 66 | 91 | 279 |
| Melton *et al* | 105 | 31 | 46 | 146 |
| Xu *et al* | 42 | 5 | 11 | 33 |
| *Temperate and boreal regions* | | | | |
| Default (Stoorvogel *et al*) | 279 | 18 | 20 | 39 |
| Gumbricht *et al* | 289 | 25 | 27 | 53 |
| Humpenöder *et al* | 354 | 18 | 20 | 41 |
| Leifeld and Manichetti | 724 | 30 | 32 | 65 |
| Melton *et al* | 281 | 22 | 23 | 47 |
| Xu *et al* | 398 | 27 | 28 | 53 |

1.1 $GtCO_2$-eq $yr^{-1}$, where Leifeld and Menichetti (2018) report 1.9 $GtCO_2$-eq $yr^{-1}$ and Humpenöder *et al* (2020) 1.5 $GtCO_2$-eq $yr^{-1}$. Joosten (2010) only reports $CO_2$ emissions of 1.3 $GtCO_2$ $yr^{-1}$, which is slightly higher than the 1.0 $GtCO_2$ $yr^{-1}$ found here. A key difference is the fact that in our study only degradation due to agriculture is taken into account while peatland degradation is also caused by forestry or peat extraction, although agriculture is estimated to be responsible for 87% of degrading peatland emissions and therefore the largest source (Joosten 2010). Also, a relatively conservative peatland extent map has been implemented, as shown in the sensitivity analysis, where degraded peatland areas are shown to range between 31 and 96 Mha in 2020 depending on the map used. Nonetheless, it is found that peatland degradation plays a key role in climate change and climate change mitigation which confirms the findings from other studies.

The projections of peatland degradation presented in this study range between −7 and +10 Mha from 2020 to 2100 under baseline conditions on the global scale. The default mitigation scenarios show decreases between −1 and −16 Mha, while in the peatland mitigation scenarios by assumption nearly all peatland is restored (30–31 Mha). Leifeld *et al* (2019) made a projection of future peatland degradation based on recent historical conversion rates resulting in the loss of 11 Mha between 2015 and 2100. Humpenöder *et al* (2020) report peatland degradation of 10 Mha between 2015 and 2100 assessed with the MAgPIE model in an SSP2 mitigation scenario aiming for 2 °C (RCP 2.6). Both studies find conversion rates up to the end of the century similar to the pessimistic baseline estimate reported here (SSP3). A notable difference with Humpenöder *et al* (2020) is that their SSP2 mitigation scenario shows strong conversion of peatlands mainly due to large-scale expansion of agriculture for bioenergy production, while in this study land-based mitigation in fact results in lower peatland degradation due to reduced forest conversion and afforestation. This illustrates how different implementations or assumptions on land-based mitigation will result in very different estimates of peatland conversion without dedicated peatland policies. All studies concur however that full restoration and rewetting of peatlands is essential to optimally use the climate change mitigation potential of peatlands.

We show that on the global scale, peatland policies cause modest changes in land-use change dynamics and on food security. However, locally, impacts can be much larger. This is reflected by food security effects in Indonesia that are much stronger compared to other regions in our scenario results. The assumption that all agricultural land on peatlands is fully abandoned would have major impacts on the livelihoods of farmers in those locations. To address these impacts, follow-up research should include management options to limit

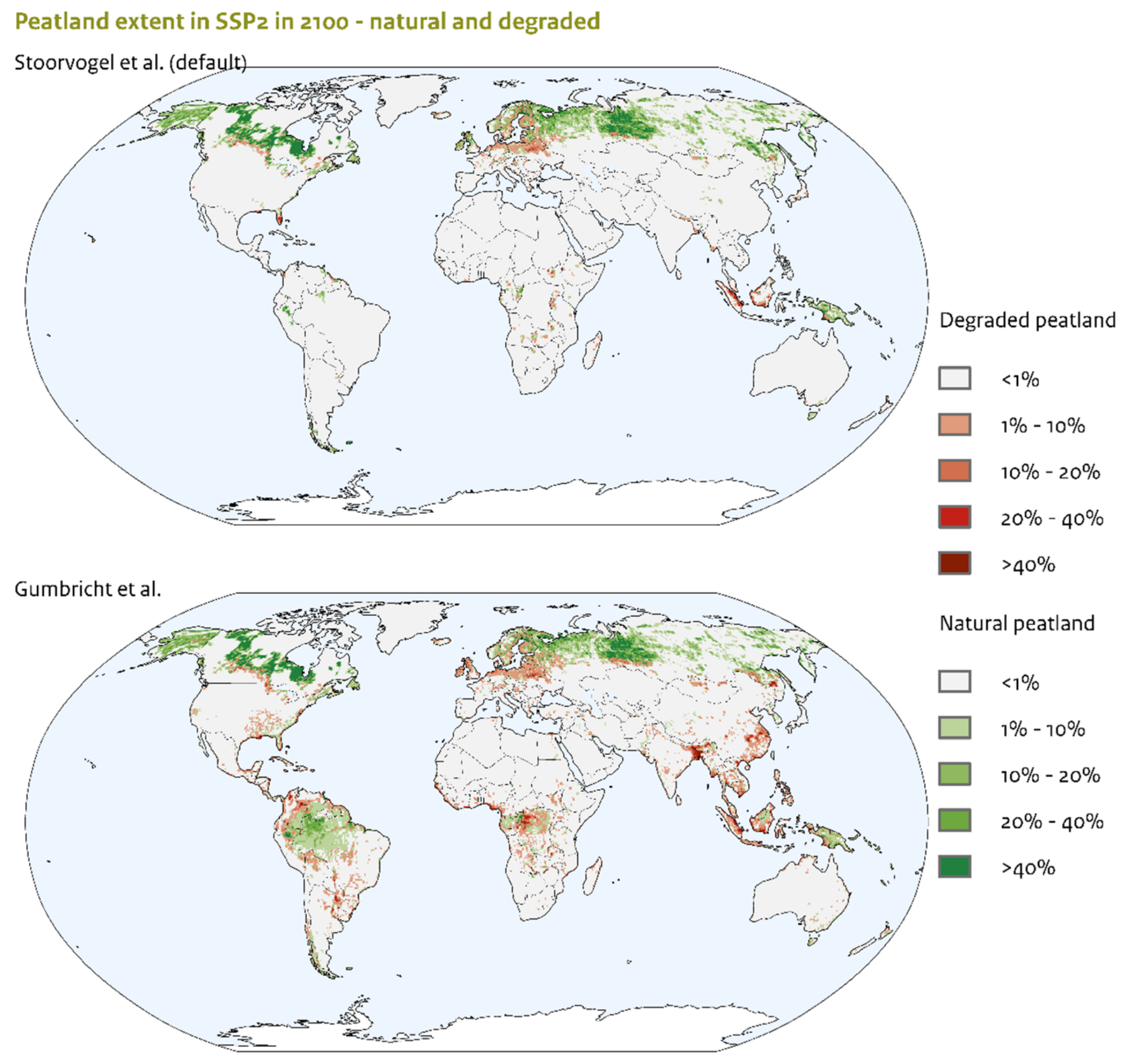


**Figure 4.** Spatial-explicit degraded and non-degraded peatland areas in 2100 in SSP2 for the default peatland map used in this study (adapted from Stoorvogel *et al* 2017. CC BY 4.0) and one sensitivity peatland map adapted from Gumbricht *et al* (2017) (CC BY 4.0) (for other sensitivity maps see SI figures 8 and 9). Data is aggregated to the percentage peatland area of total land area per half degree grid cell. When grid cells have both degraded and natural peatlands only the degraded percentage is shown.

decomposition of peat soils but also continue agricultural production. One option is paludiculture which is proposed as a farming practice where water levels are kept at near-surface to preserve peat while still using the land for agriculture using adapted management techniques (UNEP 2022).

A key uncertainty in the methodology concerns the implementation of constant emission factors as adopted from the IPCC (2014) and Wilson *et al* (2016). Emission factors may vary markedly depending on water table depths that can be different due to management regimes. Shallow peat deposits may be fully oxidized even after a few years resulting in much lower emissions factors than during the initial degradation phase (Hooijer *et al* 2012). As the analysis presented in this study is not constrained by the depth of peat deposits this implies we might overestimate emissions. Cross-checking showed that cumulative gridded emissions exceed gridded soil carbon stocks of S-world (Stoorvogel *et al* 2017) by 15%. However this stock estimate excludes carbon stocks in peatland soils deeper than 1 m, which are common but not reliably mapped at the global scale. This indicates that full oxidization of peatland soils most likely will not constrain peatland emissions substantially before the end of the century. Next to uncertainty of degraded peatland emission factors, also the factors for peatland restoration are highly uncertain. This is most notably in the tropics where 'rewetting as a management practice is still in its infancy' and emission factors are based on surrogate data (Wilson *et al* 2016). Climate change impacts on peatlands emissions are excluded even though higher temperatures and reduced rainfall could amplify the decomposition process (Leng *et al* 2019), and also emissions of peat fires are not considered. Although peat fires can cause large emission peaks they are typically temporary whereas constant emissions from drainage are, over a longer time horizon, the larger source of GHG emissions (Page and Hooijer 2016). Despite the fact that constant emission factors are a simplification, including emissions from peatland degradation is key to include in scenarios assessing the effects of land use on climate change. More dynamics related to the depth of peatland soils, peat fires and climate change impacts are beyond the scope of this study but are important directions of future research.

Another source of uncertainty regards spatial-explicit land-use allocation: as peatlands are typically concentrated in certain geographic locations, allocation of agricultural expansion in one location or another within a region can greatly affect GHG emissions. In this study only the IMAGE model is applied, but differences in land use allocation between land-use models have been shown to be substantial (Prestele *et al* 2016). Overlaying peatland maps with land-use projections from different land use models could provide a quantification of this uncertainty, but is beyond the scope of this study.

As highlighted here, the mitigation challenge of restoring peatlands is unequally distributed between world regions, with one third of projected GHG emission reductions located in Indonesia. Moreover, the sensitivity analysis showed that tropical peatland conversion may be underestimated in our study indicating risks of peatland degradation in the Amazon and Congo basins. For peatland degradation and restoration, similar to preventing deforestation and the potential of afforestation, the largest risk of impacts on climate change as well as the largest potential for climate change mitigation is located in the tropical regions of the world (Doelman *et al* 2020). At the same time these are also among the lower-income regions of the world that from an equity perspective should not have to carry most of the burden of preventing dangerous climate change (Höhne *et al* 2014, van den Berg *et al* 2020) underlining a key challenge of preventing peatland degradation and enabling peatland restoration. On the other hand, large areas of potential peatland restoration are also located in high-income regions, most notably Western Europe and the USA, that have lower GHG emissions per hectare but still considerable potential to prevent continued climate change impacts of peatland degradation.

## 5. Conclusions

In this article, we presented an analysis of peatland degradation and restoration in three SSP scenarios under baseline assumptions and with climate change mitigation targets both excluding and including specific peatland protection and restoration measures. It is shown that future peatland degradation may vary substantially depending on socio-economic assumptions, with a moderate reduction in degraded peatlands in SSP1 (−7 Mha) and substantial expansion of peatland degradation in SSP3 (+10 Mha). Default mitigation scenarios (without specific peatland policies) substantially reduce peatland emissions due to synergies with forest protection and afforestation policies, but still leave substantial amounts of GHG emissions from degraded peatlands unabated, that amount to 65–96 $GtCO_2$ cumulatively until 2100. If dedicated peatland protection and restoration policies are implemented to prevent further peatland degradation and to restore currently degraded peatlands, these emissions are reduced to less than 10 $GtCO_2$ cumulatively making ambitious mitigation targets better feasible without major changes required to land-use dynamics. This emphasizes the need to synergistically combine land-based mitigation measures such as forest and peatland protection and peatland restoration and afforestation.

The opportunity to protect and restore peatlands is unequally distributed between regions, with one-third of required GHG emissions reductions located in one country (Indonesia) where prevention of additional peatland degradation is essential as well as restoration of already degraded peatlands. A large potential for peatland restoration is found in temperate and boreal regions such as Europe, North America and Russia, while these regions do not show high risk for additional peatland degradation. In contrast, in South America peatland degradation is projected to expand substantially while its current extent of degraded peatlands if fairly limited. A sensitivity analysis shows that our study may underestimate future peatland degradation in tropical regions, notably the Amazon and Congo basin, underscoring the importance to limit peatland degradation in these regions.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.7681342 (Doelman *et al* 2023).

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