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Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100

Jens Leifeld[1]*, Chloé Wüst-Galley[1] and Susan Page[2]

Land-use change disturbs the function of peatland as a natural carbon sink and triggers high GHG emissions[1]. Nevertheless, historical trends and future trajectories of GHG budgets from soil do not explicitly include peatlands[2,3]. Here, we provide an estimate of the past and future role of global peatlands as either a source or sink of GHGs based on scenario timelines of land conversion. Between 1850 and 2015, temperate and boreal regions lost 26.7 million ha, and tropical regions 24.7 million ha, of natural peatland. By 2100, peatland conversion in tropical regions might increase to 36.3 million ha. Cumulative emissions from drained sites reached 80 ± 20 $PgCO_2e$ in 2015 and will add up to 249 ± 38 Pg by 2100. At the same time, the number of intact sites accumulating peat will decline. In 1960 the global peatland biome turned from a net sink into a net source of soil-derived GHGs. Annual back-conversion of most of the drained area would render peatlands GHG neutral, whereas emissions from peatland may comprise 12–41% of the GHG emission budget for keeping global warming below +1.5 to +2 °C without rehabilitation.

Following the Paris Agreement on the target to reduce global warming by 1.5–2.0 °C relative to pre-industrial times, substantial cuts in GHG emissions by 2050 towards net zero emissions are required[4]. The land-use sector plays a special role in this as it can act as both a source and sink for GHGs, and thus has the potential to become an element of net emission technologies[5].

Throughout the Holocene, natural peatlands were important carbon sinks and contributed to negative net radiative forcing of −0.2 to −0.5 $W m^{-2}$ (ref. [6]). Recent estimates still reveal an annual carbon sink of intact peatlands that is expected to increase slightly by the end of this century[7]. However, while large parts of the global peatland resource are supposedly still in a natural state, historical drainage for agriculture and forestry in the temperate and boreal zone, and increasingly also in the tropics, has transformed large areas from former sinks into net sources of GHGs. On the other hand, this opens up the potential for saving substantial amounts of prospected GHG emissions[8,9] via peatland rehabilitation. So that the potential of natural carbon uptake by intact peatlands and the potential for avoiding future GHG emissions from drained sites by rehabilitation can be explored, a comprehensive analysis of past and future emissions is needed, together with an estimate of the area of contemporary degraded peatlands that must be back-converted to align with net zero emissions by 2050 and thereafter. Ideally, such measures would be implemented in the short term because any delay will require bolder efforts in the future[4].

Here, we treat both intact and degrading peatlands together as the global peatland biome. We consider the global peatland area to have been peat accumulating in 1850, with ongoing conversion by drainage and land-use change since then. Although earlier peatland conversion has been demonstrated[10], the assumed onset of large-scale conversion activities is in line with a 3.7-fold higher natural wetland conversion rate in the twentieth and early twenty-first century as compared with earlier times[11].

To account for the uncertainty in historical and future transformation pathways, we use three scenario timelines for the global peatland biome area 1850–2100 applied to the boreal + temperate and the tropical zones, respectively. These scenarios align with measurements on the amount of peat carbon lost (see Methods and Supplementary Figs. 1 and 2). Whereas boreal and temperate peatlands had experienced widespread land conversions by the nineteenth century, drainage onset in the tropics commenced only from 1960 (ref. [12]). In the tropics, drainage continues to be extended to 2100 while peatland conversion in the boreal + temperate region fades out between 1991 and 2015. Within the scenario timelines, areas of intact peatlands decline from 404.5 ± 29.9 and 58.7 ± 4.3 million ha (Mha) in 1850 to 377.8 ± 28.0 and 22.5 ± 1.7 Mha in 2100 for boreal + temperate and tropical, respectively. This combined decline of 62.9 Mha corresponds to 7.0 and 62% of the initial peatland area in the respective climate zones (Supplementary Fig. 3).

Past, present and future land conversions change the global GHG balance of the peatland biome over time (Fig. 1a). Along with an increase in the drained area, a proportional decline in the annual GHG uptake rate of intact peatlands, from 0.31 ± 0.06 and 0.10 ± 0.06 to 0.29 ± 0.05 and 0.04 ± 0.01 $PgCO_2e$, (boreal + temperate and tropical, respectively), is observed for the period 1850–2100. In 2015 and 2100, intact peatlands still act as a sink of 0.36 ± 0.16 and 0.33 ± 0.12 $PgCO_2e$, respectively. These results are in close agreement with a recent estimate of the global peatland carbon sink of 0.14 PgC (0.51 ± 0.02 $PgCO_2$)[7]. The larger error in our estimate derives from the explicit accounting for area uncertainties. The apparent difference of around 0.16 $PgCO_2$ between the two estimates is due to the calculation principle employed in ref. [7], where ongoing decomposition of deep peat, which is included in the IPCC emission factors used herein, was not accounted for but would reduce the 0.51 $PgCO_2$ by around one-third[7].

Whereas the change in uptake is considered moderate in the context of the anthropogenic global GHG budget, increases in drainage-induced biological emissions (Supplementary Figs. 4 and 5, for emissions from fire and peat extraction see Methods) from peat decomposition are far more pronounced and indicate an almost steady increase over 250 years. For 2015, scenario timelines imply GHG release from drained peatlands of 1.53 ± 0.80 $PgCO_2e$, with 1.26 ± 0.77 of that total emitted in the tropics (Supplementary Table 1). About half of these tropical emissions from peat oxidation stem from South-East Asia[13]. Emissions from temperate and boreal systems dominated the overall picture until around 1980, when annual emissions from the tropics began to exceed 0.39 $PgCO_2e$.

[1]Agroscope, Climate and Agriculture Group, Zurich, Switzerland. [2]School of Geography, Geology and the Environment, University of Leicester, Leicester, UK. *e-mail: jens.leifeld@agroscope.admin.ch

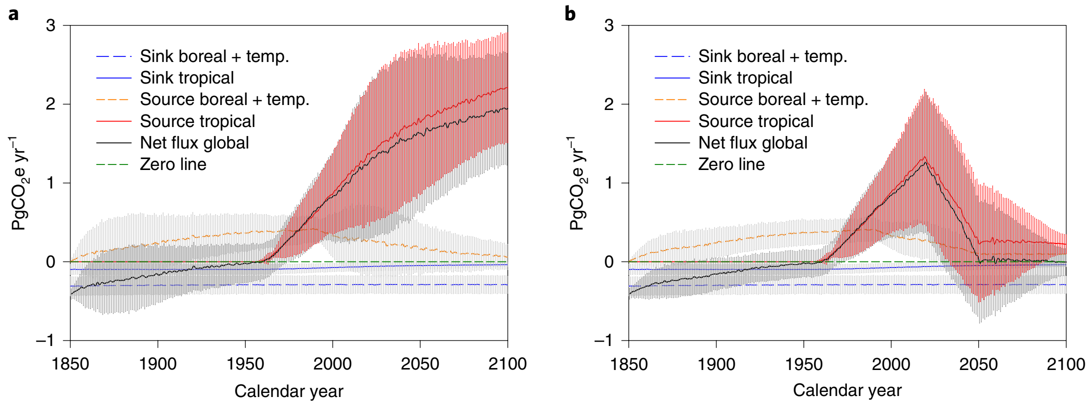

Fig. 1 | Annual GHG fluxes from biological peat oxidation and peat formation from drained and intact organic soils 1850–2100 without and including peatland rehabilitation. Both boreal + temperate (temp.) and the tropical sink (negative) decline over time owing to drainage extension. Emissions overrode uptakes in 1960 and turned the peatland biome into a net GHG source. **a**, Without rehabilitation, net flux will reach 1.96 ± 0.73 $PgCO_2e$, dominated by the tropical source of 2.21 ± 0.70 $PgCO_2e$. **b**, With rehabilitation, emissions drop sharply after 2020 and, by middle of the century, net fluxes from the boreal + temperate and tropical biomes become −0.20 ± 0.18 and 0.20 ± 0.79 $PgCO_2e$, respectively. The 95% confidence intervals combine uncertainties in both annual rates and area.

By 2100, and without counteracting measures having been taken, the annual emissions rate will reach 2.23 ± 0.69 $PgCO_2e$ in the tropics whereas that of boreal and temperate systems, owing to the exhaustion of many peat deposits by oxidation, will approximate neutrality (0.07 ± 0.16 $PgCO_2e$). Beyond 2100, emissions from the tropics will also start to decline in response to the increasing loss of peat deposits (data not shown). The delayed exhaustion of drained tropical peatlands, despite their substantially higher carbon loss rate, is caused by much later drainage onset and a larger stock of carbon per hectare[14].

Drained peatlands continue to degrade, often until the entire former peat deposit is fully oxidized and leached, resulting in a mineral soil after centennial drainage[10]. Correspondingly, GHG emissions from peat oxidation and excavation cumulate over decades to centuries, depending on the initial thickness of the peat layer and the loss rate. Between 1850 and 2100, drained peatlands will have released 249 ± 38 $PgCO_2e$ by biological peat oxidation (Supplementary Fig. 6). From 2015 onwards, the release will total 169 ± 44 $PgCO_2e$, dominated by tropical emissions.

What would it take for the global peatland biome to become GHG neutral by 2050 and thereafter? Despite the large area of natural peatlands still acting as CO_2 sinks, almost all drained peatlands need to be rehabilitated because rehabilitation does not fully eliminate GHG emissions[15]. Starting in 2020, annual conversion of 1.48 Mha land (0.56 Mha boreal + temperate, 0.92 Mha tropical) results in GHG neutrality by 2050 (Fig. 1b). The conversion implies full rehabilitation of all degraded boreal + temperate peatlands and large parts of degraded tropical ones (Supplementary Fig. 7). Accordingly, the area of drained peatlands would become 0.0 (boreal + temperate) and 1.6 Mha (tropical) in 2050. Thereafter, 8.0 Mha need to become GHG neutral, implying conversion of the entire tropical area still drained in 2050 plus reduction of the newly drained area after 2050 by 6.4 Mha. To maintain peatland neutrality until 2100, an annual rehabilitation rate of 0.16 Mha is needed. Peatland rehabilitation in the second half of this century must take place in the tropics only simply because, in the scenario towards net zero, no drained boreal + temperate peatland will be left after 2050. Overall, this corresponds to a reduction of 100% (boreal + temperate) and 98% (tropical) drained by 2100 as compared to the reference scenario without rehabilitation. The equivalent annual GHG savings on formerly drained areas increase from 0.06 (2020) to 1.94 (2100) $PgCO_2e\,yr^{-1}$ (average, 1.42 $PgCO_2e\,yr^{-1}$). Compared to the reference scenario, cumulative emissions over 250 years will be only 54 and 26% (without and with consideration of the natural sink, respectively) of that without measures. The average saving is comparable to a previous estimate for a time horizon until 2030 that revealed a global mitigation potential by peatland restoration of 0.741–2.47 $PgCO_2e\,yr^{-1}$ (ref. [9]). Our estimate, however, is not static but rather is based on a steady increase in savings by 0.052 $PgCO_2e\,yr^{-1}$ for the period 2020–2050, and 0.0065 $PgCO_2e\,yr^{-1}$ thereafter. This seems plausible given that it will realistically take time for implementation of large-scale rehabilitation measures. Owing to higher water tables and higher peat moisture, peatland rehabilitation will presumably also reduce the likelihood and impact of peat fires[16,17]. However, the magnitude of this and other positive and negative feedbacks between global change, CH_4 release and CO_2 uptake is highly uncertain[18] and was therefore not accounted for in our calculations.

Prevention of global mean air temperatures exceeding thresholds of +1.5 to +2.0 °C relative to pre-industrial times implies that remaining budgets of future CO_2 emissions must not be exceeded[19,20]. Although there is pronounced uncertainty in the magnitude of these budgets, they enable us to put cumulative peatland-derived GHG emissions into context. For a period starting in 1870, the IPCC[21] estimated a budget of 2,550–3,150 $PgCO_2e$ that would allow global mean air temperatures to remain below +2 °C. Without counteracting measures, GHG emissions from drained peatlands will consume 7.9 ± 1.1 to 9.8 ± 1.4% of the available balance (Supplementary Fig. 8). Because of the already high anthropogenic emissions accumulated since 1870, the available budget for 2020–2100 is substantially smaller. Here, we operate with a budget range of 400–1,600 $PgCO_2$, covering estimates in refs. [4,20,22,23] for both +1.5 and +2.0 °C. Without measures and with continued land conversion in the tropics, between 10 and 41% of the remaining budget will be exhausted (Fig. 2). Considering the compensatory effect of extant intact peatlands, these numbers fall to 8–34%. Widespread rehabilitation of formerly drained peatlands as introduced above would substantially reduce these values to 3–12% of the budget, or 1–5% when the CO_2 sink of extant peatlands is included in the overall calculation.

The peatland biome, almost unprecedented in the longevity and magnitude of its carbon sink, has been transformed by human activity and the sign of its GHG balance has reversed. With ongoing land-use change in the tropics alone, a substantial proportion of the remaining carbon budget for maintaining global mean air temperatures below critical thresholds is at risk by using <3% of the terrestrial surface. Through implementation of radical measures to back-convert most of the drained area now and over the next three decades, this trend

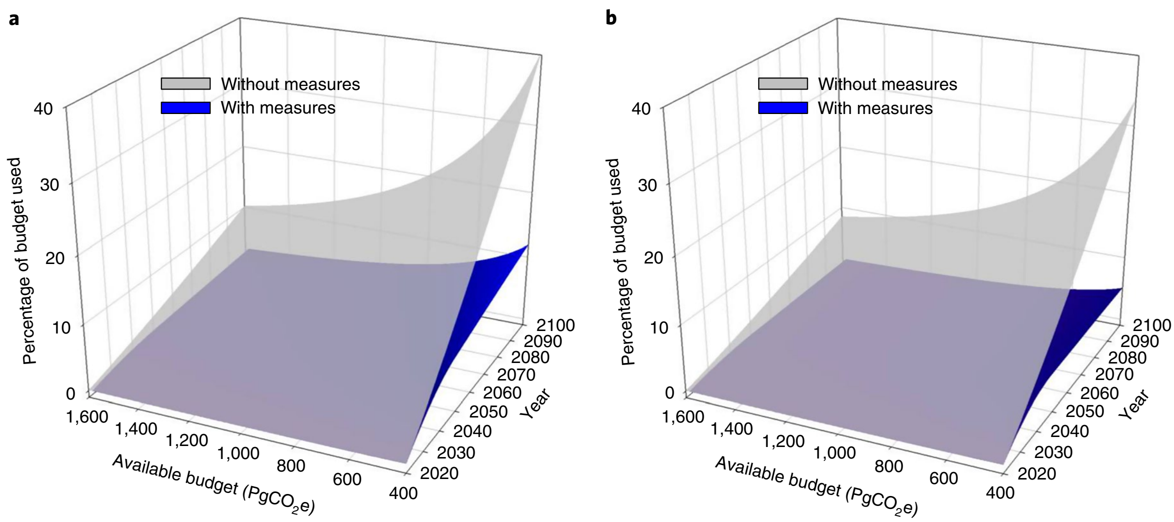

Fig. 2 | Percentage of global CO_2 budget required to maintain air temperature <1.5–2.0 °C consumed by drained peatlands 2020–2100 for a budget range of 400–1,600 $PgCO_2e$. a,**b**, Drained and rehabilitated peatlands (**a**) and drained, rehabilitated and undisturbed sites (**b**), with or without rehabilitation measures. For example, a remaining budget of 800 $PgCO_2$ converts to consumption between 6% (with measures) and 20% (without measures) by 2100 if drained peatlands only are considered, and 3% (with measures) and 17% (without measures) if undisturbed sites are also included.

can be reversed. The substantial contribution of drained peatlands to national GHG totals, and the many problems associated with subsidence of organic soils[24], have already prompted action at national and regional levels[25–28]. For example, a programme for conversion of up to 2 Mha of drained peat swamps in Indonesia has been issued[29]. This and other extensive peatland actions that also valorize the avoided emissions after rehabilitation, as well as the natural sink, urgently need to be implemented to leave the remaining budget for sectors where emission savings are more difficult to achieve.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-019-0615-5.

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Methods

Scenario timelines. We applied three different scenario timelines of peatland conversion to (1) boreal + temperate and (2) tropical peatlands. These timelines, rather than one single shape of peatland conversion over time, were selected because the true shape is unknown. The timelines were constrained by three anchors: (1) drainage onset in 1850 (boreal + temperate) and 1960 (tropical); (2) the area of drained tropical and non-tropical peatlands in 2015 taken from ref. [1]; and (3) the final area of drained peatland that was assumed to equal the 2015 value (27 Mha) for boreal + temperate peatlands, and to increase from its 2015 value (24 Mha) to a final area of 36.3 Mha of tropical peatlands based on refs. [30,12]. For the boreal + temperate region, we assume no new drainage after 2015 because there are clear indications that the fraction of drained peatlands has been constant or dropping in the period 1990–2008 in major temperate and boreal countries. For example, the area of drained peatland in 1990 was 31.3, 1.3, 0.18 and 0.80 Mha in Europe (inclusive of Russia to the Ural mountains), the United States (without Alaska), Canada and the Asian part of Russia, respectively. The corresponding numbers for 2008 were 22.0, 1.3, 0.18 and 0.90 Mha (ref. [31]).

The trajectories used were (1) linear increase, (2) exponential rise to maximum and (3) sigmoidal increase (Supplementary Fig. 1). To compute emissions we combined the three timelines by taking their mean and 95% confidence interval.

Peatland area in 1850 was 404.5 Mha (boreal + temperate) and 58.7 Mha (tropical). A 7.4% s.e.m. was taken as initial uncertainty for these areas, based on peatland areas published in refs. [1,31,32]. For 2015, the area of drained peatland estimated by this approach is 47.0 ± 10.6 Mha.

The scenario timelines provide plausible, albeit non-testable, scenarios given the time elapsed since drainage onset and the frequently poor records kept in many countries. However, the plausibility of the scenarios could be validated for boreal + temperate sites using a comparison to radiocarbon-based field estimates of percentage carbon loss[33] (Supplementary Fig. 2). The scenario timelines intentionally add uncertainty to the overall emission estimate, which is mostly visible in the annual rates rather than in the cumulative emissions.

The scenario timeline of intact peatlands is defined as the difference regarding the total area in 1850 and its gradual decline according to ongoing drainage. According to this, the area of intact peatlands declines from 404.5 ± 29.9 (boreal + temperate) and 58.7 ± 4.3 Mha (tropical) to 377.8 ± 28.0 and 22.5 ± 1.7 Mha, respectively, between 1850 and 2100 (Supplementary Fig. 3).

Emission factors and cumulative budgets. We applied a generic emission factor to drained peatlands of 16.1 ± 5.5 $tCO_2e\,ha^{-1}\,yr^{-1}$ for boreal + temperate and 61.2 ± 38.5 $tCO_2e\,ha^{-1}\,yr^{-1}$ for tropical peatlands. These emission factors (subsuming CO_2, CH_4, N_2O and dissolved organic carbon (DOC), with DOC converted to CO_2) are based on ref. [21] and emission factor uncertainties reported therein and weighted, for the two groups, by climate and land use using the spatial distribution given in ref. [1]. The IPCC Wetland Supplement[21] provides 95% confidence intervals together with emission factors for all gases and land uses. The contribution of CO_2 stemming directly from both oxidation and DOC (indirect CO_2) was estimated to account for 87% (boreal + temperate) and 94% (tropical) of all GHG emissions when weighted by climate and land use according to ref. [1]. In our calculations, we used only the relative uncertainty of CO_2 for uncertainty analysis and applied it to the total emission, because (1) it accounts for the majority of the overall emission and (2) the uncertainty for CO_2 is, on average, larger than that for DOC. Resulting emission factor uncertainties were 34% for (boreal + temperate) and 63% for the tropics (Supplementary Fig. 4). Applied to the scenario timelines, the resulting GHG emissions from drained peatlands in 2015 are 1.26 ± 0.77 (tropical) and 0.27 ± 0.23 (boreal + temperate) $PgCO_2e$.

Peat accumulation of intact peatlands follows long-term carbon accumulation rates for northern (that is, temperate + boreal) peatlands according to ref. [34], and for tropical sites following refs. [35,36]. A discount of 9.0% on measured long-term net carbon accumulation was calculated to compensate for long-term CH_4 emissions[6] and thus to convert CO_2 uptake into the long-term GHG budget of the soils. Hence, uptake rates and cumulative uptake as reported here encompass CH_4 emissions and thus are given in units of CO_2C-equivalent. The resulting annual uptake rates are 0.21 ± 0.04 and 0.45 ± 0.14 tCO_2C-equivalent ha^{-1} (95% confidence interval) for northern and tropical peatlands, respectively. The resulting net balance over time is displayed in Supplementary Fig. 5.

A zero net emission in 2050 was computed using the above emission factors, carbon accumulation rates and peatland areas while including GHG emissions from rehabilitated peatlands. With the onset of restoration measures in 2020, an annual conversion rate (Mha) was calculated to match GHG neutrality by 2050 including extant peatlands worldwide. The target of net zero was distributed between boreal + temperate and tropical peatlands to obtain a maximum share of the boreal + temperate region to the overall reduction. This is based on the finding that no new net drainage in the boreal + temperate region occurs (see above), and that the majority of rehabilitation measures are currently initiated in that region (see citations in main text). We did not consider rehabilitated peatlands becoming net GHG sinks or GHG neutral as argued in ref. [9], but rather applied the generic emissions factors for a 100-year global warming potential for rehabilitated peatlands, compiled in ref. [15], to be in line with our approach of estimating emissions from drainage 1850–2100 (Supplementary Fig. 4). In regard to drained sites, emissions factors for rehabilitated peatlands consider the area-weighed contribution from each land-use type. On average, rehabilitation via rewetting causes an emission reduction of 91 and 64% for tropical and boreal + temperate sites, respectively. The fraction of rehabilitated peatland is shown in Supplementary Fig. 7.

All timelines and cumulative GHG uptake and emissions were calculated using random Monte Carlo analysis, applying the uncertainties in area, emission and uptake as described above, based on the assumption of normally distributed emissions. Cumulated timelines display the 95% confidence interval.

Emissions from peat fires and peat extraction. Our centennial perspective encompasses a period of 250 years for which two other important GHG sources from peatlands, namely emissions from both peat fires and peat extraction, cannot be quantified. Results from shorter periods or single events indicate that fire-derived emissions can be substantial, in some years even exceeding biological emissions from peat decomposition. Between 1997 and 2011 emissions from tropical peat fires added around 1.00 ± 0.37 $PgCO_2e\,yr^{-1}$ to the biological GHG emissions from soil[37]. Furthermore, examples of single wildfires in the northern hemisphere revealed emissions of around 0.04 $PgCO_2$ (North Carolina in 2008 (ref. [38]) and up to 0.25 $PgCO_2$ (Western Russia in 2010 (ref. [39])), albeit the contribution of peat- versus biomass-derived CO_2 could not be separated in these studies. These emissions are high when compared to our estimated biological emissions from global peat decomposition in drained sites, averaging 1.28 $PgCO_2e\,yr^{-1}$ (1997–2011).

Peat extraction for horticulture or as fuel is another relevant GHG source, assuming that any peat excavated from the field will decompose off-site or be burned subsequently. It is estimated that around 0.5 Mha of peatlands is used for peat extraction[40], delivering around 26 Mt of peat dry matter or around 13 Mt of peat carbon per year with little change over the past 20 years (refs. [41,42]). Peat extraction almost exclusively occurs in temperate and boreal regions[42]. Under conditions of instantaneous oxidation of mined peat, around 0.05 $PgCO_2\,yr^{-1}$ will be released from it. In addition, on-site emissions from mined areas average 3.1 $tCO_2e\,ha^{-1}$ (mostly as CO_2 (ref. [21]))—that is, a global total of around 0.016 $PgCO_2e$. Together, peat extraction corresponds to around 5% of GHG emissions from biological oxidation after drainage, as reported here.

Although we have not explicitly considered emissions from fire and peat extraction in our main calculations, these would not substantially affect our results regarding cumulative emissions from degraded peatlands; biological oxidation, fire and extraction depend on the same fuel source and corresponding emissions are, hence, not additive in the long term. This means that cumulative emissions from drained sites would not have increased systematically if fire and extraction sources could have been calculated separately for 1850–2100, although scenario timelines may underestimate total emissions for certain years or periods. One exception to this is that the size of the compensatory sink of natural sites, as reported here, might be reduced if fire was explicitly accounted for: under changing climatic conditions, with higher evapotranspiration and extended periods of low rainfall, peat moisture status may decline also under undrained conditions, enhancing the risk of fires[17]. Furthermore, with increased risk of wildfire, thermokarst formation may accelerate with subsequent consequences for the carbon balance of the affected areas[43]. Nevertheless, the magnitude of the various positive and negative feedbacks between global change and the GHG balance of peatlands remains highly uncertain[18].

Data availability

All figure source data files are available at https://issues.pangaea.de/browse/PDI-21686.

Code availability

The numerical codes for the Monte Carlo simulations that support the findings of this study are available from the corresponding author on reasonable request.

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Author contributions

J.L. designed the study and prepared the manuscript with contributions from C.W.-G. and S.P.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to J.L.

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