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Land-use change causes rapid carbon losses in Congo Basin peatlands across climate scenarios, whereas the effects of climate change alone are uncertain

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One of Earth's most extensive tropical peatland complexes is in the central Congo Basin. Past climatic drying caused the widespread loss of a large proportion of the peat carbon stock, indicating its vulnerability to climate change. However, the additional effect caused by the interaction of climate change with land-use change—particularly drainage—on peat carbon stores has not been assessed. Here, we simulate the effects of climate and land-use change on Congo Basin peatlands. Our model is driven by an ensemble of 10 climate models to assess changes in peat carbon stocks at global warming levels 1.5, 2, 3 and 4°C. We find that the fate of the peatland carbon store is highly uncertain when we simulate climate change alone (warming level 3°C gives a median change in peat thickness of 0.04 m; range of

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approx. −5.0 to +0.3 m). By contrast, simulations that couple land-use change with twenty-first-century climate change are unequivocal: the Congo Basin peatlands will become significant emitters of carbon. When the warming level is 3°C, the change in peat thickness of a drained peatland is projected to be –2.6 m; a range of approximately –5.0 to –2.1 m. Our results emphasize the need to protect Congo Basin peatlands from widespread land-use change. A French translation of this abstract is available in the supplementary material.

This article is part of the discussion meeting issue 'African tropical peatlands: function, value and vulnerability'.

1. Introduction

Carbon-rich peat has accumulated in tropical swamp forests since well before the Last Glacial Maximum [1,2]. Tropical peatlands have previously cooled the global climate over multi-millennial timescales by drawing carbon down slowly but persistently from the atmosphere [3]. However, they can also lose carbon rapidly, through decomposition and fire, when water tables fall below the peat surface for an extended period owing to land-use change [4] or climatic drying [5]. These impacts have already been observed in the large-scale emission of peat carbon from the tropical peatlands of SE Asia [6,7].

One of the world's largest tropical peatland complexes is in the central Congo Basin [8,9] (figure 1*a*). The complex spans 167 600 km^2 and stores approximately 29 Pg of carbon in both interfluvial (rain-fed) and river-influenced peatlands [10]. Net carbon gain or loss in these peatlands depends primarily on peat surface wetness [11]. Although litter production in Congo Basin swamp forests appears to be insensitive to surface wetness [11], the rate of peat decomposition and its products (including the greenhouse gases, carbon dioxide (CO_2) and methane) depend on water table position. The peat carbon pool, comprising leaves, wood and roots, contains a large proportion of recalcitrant material that decays very slowly when waterlogged, mainly producing methane emissions that are relatively short-lived in the atmosphere; however, it decays much more quickly when exposed to oxic conditions above the water table [12–14], generating significant amounts of CO_2 [15].

In the Congo Basin, interfluvial (rain-fed) peatlands account for approximately 9.3 Pg of the total peat complex carbon stock [10], occupying a characteristic hydrogeomorphic setting. They form in broad, shallow basins that commonly stretch for tens of kilometres between major rivers [10,16]. Thus, peat surface wetness in this peatland type likely depends primarily on the difference between water inputs from rainfall and losses through evapotranspiration. The huge lateral extent of interfluvial peatlands and the low hydraulic gradients between the shallowly domed centre and its margins mean that subsurface drainage is likely to be a negligible component of the water budget at the scale of the entire peat dome (see supplementary material §S1 in [11] for detail). The peatlands receive less rainfall than other tropical peatlands, with a mean annual rainfall of only approximately 1700 mm, compared with approximately 3000 mm and approximately 2900 mm in Amazonian and SE Asian tropical peatlands, respectively [17]. The dependence of interfluvial peatlands upon rainfall, coupled with the relatively dry climate, appears to leave them particularly vulnerable to climatic drying [5].

The combined magnitude of the central Congo Basin's peat carbon store and its sensitivity to surface wetness means that it is important to understand how future climates and possible land-use change are likely to affect its stability. The effect of future climate change can be explored using ecosystem models driven with data from Earth system models (ESMs)—models that couple land, ocean and atmosphere with biogeochemical cycles—such as those used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report [18]. The most recent group of ESMs from the Coupled Model Intercomparison Project (CMIP6) [19] are widely used for this purpose. The ESMs are in turn driven by human climate forcing scenarios set out by the shared socioeconomic pathways (SSPs) [20]. For the Congo Basin, the CMIP6 models predict a wide range of future climates that include both wetter and drier conditions as well as changes in surface air temperature.

Compared with *terra firme* forests in the Congo Basin and with many peatlands in other parts of the tropics [21,22], the Central Congo Basin peatlands are in a relatively intact state, with very little recorded deforestation or intentional drainage. However, large-scale drainage of peatlands elsewhere in the tropics has caused severe environmental damage, particularly in SE Asia [7,23,24]. Drainage for road building, oil exploration and conversion to oil palm and wood pulp plantations [25] steepens local hydraulic gradients, leading to greatly increased subsurface water loss, drying of the peat surface and ultimately to large losses of peat carbon through aerobic decomposition and wildfire. Currently, no large-scale land-use changes are planned in the Congo Basin peat swamp forests. However, oil exploration blocks have been approved [26,27], and oil palm concessions have previously been granted [17], with the prospect of further expansion remaining an ongoing concern [28,29]. Concessions for industrial logging, mining and oil palm are estimated to include approximately 7.4 PgC (26%) of peat carbon stock (see extended data figure 10 in [10]). Any future implementation of schemes like those seen in SE Asia peatlands would likely have severe consequences for the stability of the Congolese peat carbon store and would compound the effect of any climatic drying [17].

Here, we use an ecosystem model, DigiBog_Congo [11], to explore the impact of a range of climate-change projections on peat carbon accumulation between 1950 and 2100 in an intact interfluvial peatland previously studied by others [5,8,16,30]. Our analysis is based on the four global warming levels (hereafter, warming levels) of 1.5, 2, 3 and 4°C above early-industrial (1850–1900) levels. We use rainfall, potential evapotranspiration (PET) and air temperature data from 10 of the CMIP6 climate models [19], each within SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, to drive our DigiBog_Congo simulations. We also combine the climate-change scenarios with land-use change, specifically the digging of drainage ditches and replacement of native vegetation with oil palm plantation, to simulate its additional consequences for peat carbon stocks.

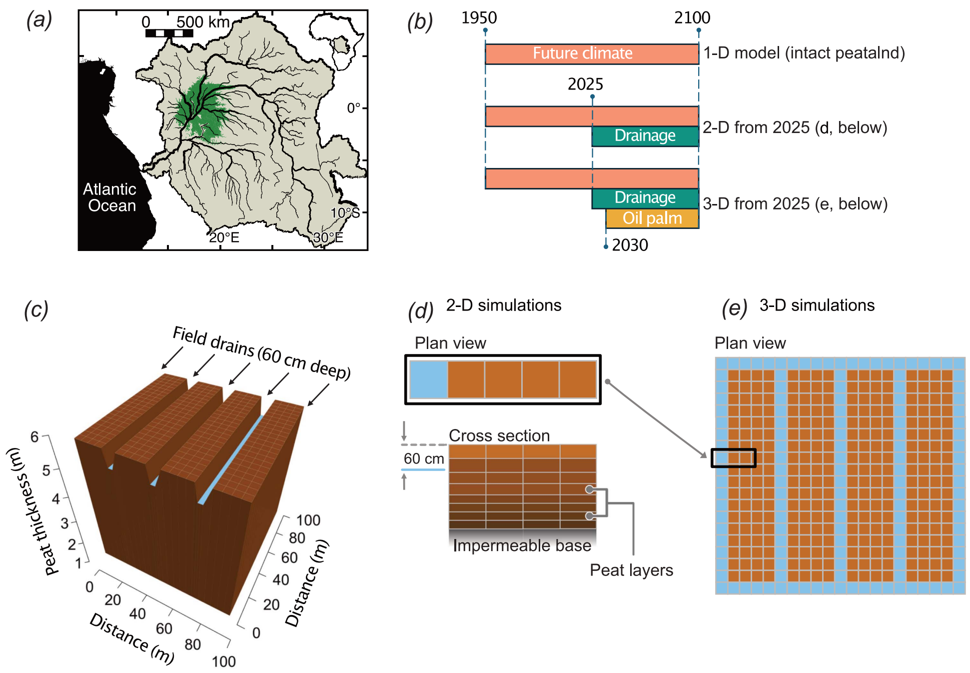

Figure 1. Model set-up. (*a*) Location of the Congo Basin peatland complex. (*b*) Simulated timelines for the three types of future peatland impacts reported here and the associated climate inputs and land uses. (*c*) Cartoon of a 100×100 m^2 block of peat for three-dimensional simulations divided into four parcels, each measuring 20×90 m^2, with ditch drains in between parcels. (*d*) Two-dimensional simulations, which use a transect of peat (brown squares) from the centre of one of the field parcels to a ditch (blue square) at the block margin. The ditch water level is maintained at 60 cm below the peat surface. Subsurface flow occurs in the direction of the central point of the parcel to the bounding ditch, outlined in black in panel (*e*). The cross section shows peat columns made up of layers. (*e*) Parcels of peat forming the three-dimensional block shown in panel (*c*): the colour of the squares are the same as panel (*d*). The ditch water levels are again set 60 cm below the peat surface. Water within the peat can flow between abutting peat columns and the bounding ditches. The map shown in panel (*a*) is from Garcin *et al.* [5].

2. Methods

(a) A model of peat accumulation in the Congo Basin

DigiBog_Congo was developed as a model of interfluvial (rain-fed) peatlands in the Congo Basin and has successfully simulated long-term trends in peatland net carbon balance (NCB) over 20 000 years [11]. The model was structured and primarily parametrized using two years of empirical data (litterfall, decomposition and water table depth) collected from two sites within an interfluvial peatland. Here, we use the model in one-, two- and three-dimensional spatial configurations (figure 1): in all cases, the peatland is represented as columns of peat. In one dimension, there is a single square-sectioned column representing the centre of the interfluvial shallow-domed peatland, whereas in two or three dimensions, multiple contiguous columns are used to represent part of a peatland so that we can simulate subsurface water flow between ditches and canals [31,32] (figure 1).

Columns of peat are made up of layers. A simulation starts with a single layer in each column: a new layer is added to each column during each year of a simulation. In the model, columns of peat gain mass from the annual addition of litter from hardwood and palm plant functional types (PFTs). At the surface, an above-ground litter layer is added that comprises leaf and wood fractions from each PFT. A third fraction, roots, is added to previously accumulated layers below the surface of the peat column. Columns lose mass because of peat decay. Each litter fraction is subdivided into two pools of material—labile and recalcitrant—that can decay at different rates depending on whether the layer (or part of it) is above or below the water table. Peat decay also depends on air temperature and the decay parameters for each pool of material (supplementary material, table S1). Therefore, a column accumulates (gains height) or loses peat (thins) depending on the difference between litter inputs and losses from the decay of all layers. These processes allow peat accumulation to vary vertically within (one dimension) and horizontally between columns (two or three dimensions). The model calculates just peat decay; it does not partition decay into soluble and gaseous products. This partitioning can be important when considering radiative forcing because the global warming potential of the carbon gases CO_2 and methane, for example, are very different.

In all configurations, water is added as positive net rainfall (precipitation − evapotranspiration > 0) or removed as negative net rainfall (precipitation − evapotranspiration < 0) from the simulated peat. In previous versions of DigiBog, the peatland is recharged with an input time series of net rainfall. In the version of the model used here, we now input separate time series for rainfall and PET and calculate net rainfall as rainfall minus actual evapotranspiration (AET), with AET depending on PET and the water table depth in each peat column [33]. As the water table becomes deeper, AET decreases according to equation (2.1), where WTD is the water table depth in cm (positive values are below the peat surface), extinct is the extinction depth in cm where AET = 0, and n is a parameter controlling the shape of the curve. This function does not affect the results presented in Young *et al.* [11] or the simulations shown here when water tables are shallow or reside above the ground surface. However, it is necessary for situations where the water table is very deep, as can be the case with ditch drainage. The parameters used in our simulations are shown in tables S1–S3 in the supplementary material.

$$\mathrm{AET} = \mathrm{PET} \cdot \begin{cases} 1 & \text{if WTD} \leq 0, \\ 1 - \left(\frac{\mathrm{WTD}}{\mathrm{extinct}}\right)^n & \text{if } 0 < \text{WTD} < \text{extinct}, \\ 0 & \text{if WTD} \geq \text{extinct}. \end{cases} \tag{2.1}$$

The one-dimensional model also loses water because of overland flow (depending on the depth of surface water and height of the peatland). Where steeper hydraulic gradients are created near bounding ditches or other structures, subsurface flow and losses become an important component of the peatland's water budget [34,35] and need to be simulated. A key property of peat that affects subsurface flow is saturated hydraulic conductivity (K_{sat}) [36–38]. In the one- and three-dimensional simulations of land-use change, K_{sat} depends on the amount of decay the peat within a layer has undergone [39]. K_{sat} is therefore a dynamic property of peat that can vary within and between columns. In all two- and three-dimensional implementations of DigiBog, subsurface flow between two columns is calculated according to the K_{sat} of the columns and the water table gradient between them [31,32]. The rise or fall of the water table in response to water flow depends on drainable porosity, which in our model remains constant. Thus, the height of water within a column can vary over time.

We used currently unpublished observations of K_{sat} from Congo Basin peatlands to parametrize the function in our model, which gave a range of K_{sat} of 0.1 cm s^{-1} for freshly added plant litter to approximately 9×10^{-5} cm s^{-1} for highly decomposed peat.

(b) Climate projections

We simulated changes in peat thickness from 1950 to 2100 using a cohort of 10 CMIP6 ESMs under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios. To assess warming impacts, we identified when each ESM reached warming levels of 1.5, 2, 3 and 4°C above pre-industrial (1850–1900) levels. Owing to inter-model differences in climate sensitivity and forcing [40–42], ESMs reached these thresholds at different times. Therefore, models that did not reach higher warming levels were excluded from those analyses. Figures 2 and 3 reflect these scenario- and model-specific time frames.

Nine of the 10 models were selected to approximately reproduce the spread of long-term global temperature increase that takes place following a doubling of atmospheric CO_2 concentration (known as the equilibrium climate sensitivity (ECS)) assessed in the IPCC Sixth Assessment Report (very likely range 2−5°C) [43,44]. We also sought to maintain a degree of independence by selecting models that did not share too many system components [45]. A similar approach was taken by Fewster *et al.* [46], who selected 12 models. However, three of the models used in Fewster *et al.* [46] did not provide the output data needed to calculate PET and could not, therefore, be used in our study. To create our 10-model ensemble, we added the ESM UKESM-1.0-LL. Although known as a 'hot model' (ECS > 5°C) that may overestimate climate impacts [47,48], they argue that excluding such models from impact analyses is not justified because important regional impacts that policymakers need to be aware of are not correlated with ECS.

For each of the CMIP6 models and the SSP5-8.5 scenario, we derived the relationship between the global mean surface temperature change and the change in the local air temperature, precipitation and PET for the Congo Basin. This is commonly called pattern scaling, and it assumes that the change in the local meteorology is linear with the global mean temperature change [49]. This relationship was created independently for each month of the year. The regional changes were superimposed on the local climatology and temporally downscaled using the weather generator of Huntingford *et al.* [50] to create simulated hourly meteorological time series. We used these outputs to create monthly time series for rainfall and PET (we use annual air temperature inputs in DigiBog_Congo) for our simulations. Intra-annual noise was added following the method outlined in §S4 in the supplementary material.

CO_2 concentrations were obtained from Meinshausen *et al.* [51] for 1950–2014, and for 2015–2100, we used the CO_2 concentrations from the underlying SSP scenario [52] in each model. This provides some time diversity in the driving data that we use since each model reaches the warming levels at different times in the future (supplementary material, table S4).

(c) Simulations and model parameters

We used the parameters reported in Young *et al.* [11] to reproduce a one-dimensional spin-up of the virtual peatland from 19 600 to 0 cal. yr BP (1950 CE). To simulate future changes in peat accumulation from 1950 to 2100, we ran our spun-up peatland forward in time. The parameters for the simulations reported here are given in tables S1–S3 in the supplementary material. These tables specify those parameters that are well constrained by observations and those that were obtained by sensitivity testing. The results reported in §3 show the range of uncertainty owing to climate model projections. They do not include uncertainty caused by the configuration or parametrization of our peatland model, which we currently cannot quantify. We discuss the implications of these choices in §4c.

We ran three sets of simulations (figure 1*b*). We first simulated in one dimension the effect of climate change alone for each member of our model ensemble in each SSP (40 simulations). As in Young *et al.* [11], the one-dimensional simulations represent the centre of the intact peatland dome, and it is not necessary to simulate subsurface flow [11]. Next, we simulated the effect of

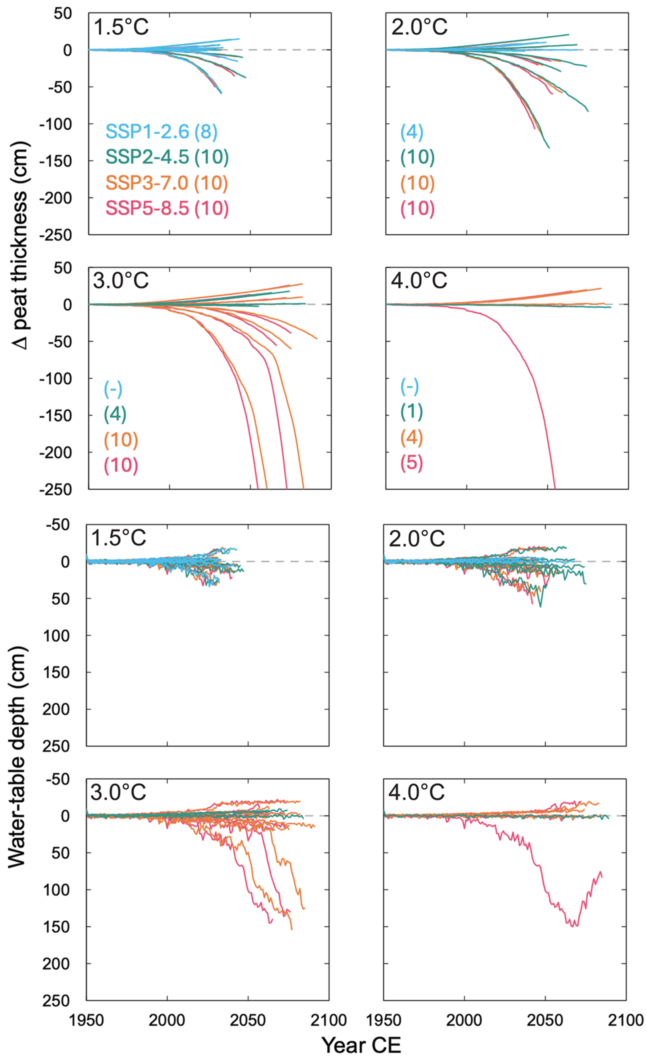

Figure 2. Modelled effects of future climate on change of peat thickness relative to the 1950 simulation (top four panels) and corresponding water table depth (bottom four panels). Each panel shows the simulations of each SSP for four warming levels. Each line is a DigiBog_Congo simulation driven by the climate projections from a single CMIP6 model; the colours correspond to the SSP (shown in the panel legend of warming level 1.5°C). Numbers in parentheses show the total number of model runs (out of 10) that reach the respective warming level for each SSP. Only model runs that reach the warming level are shown in the panels.

drainage and climate change. Land-use change on tropical peatlands usually includes drainage [4], where a peatland is divided into a grid of fields bounded by ditches (figure 1), which makes it essential to simulate subsurface flow (§2a). We chose to simulate this lateral subsurface water movement in two dimensions. In this scenario, a simulation of one field is a simulation of all the others; hence, it is not necessary to simulate a whole peatland. For the two-dimensional simulations, we simulated a transect between parallel ditches from the central point of the transect to the ditch at the edge; for this, we used a 2×20 m^2 series of columns (figure 1*b*,*d*). We set the ditch water level to a constant value of 60 cm below the ground surface [53,54]; this setting also allows water to flow from the ditch into adjacent peat if the within-peat water table falls below that of the ditch. The two-dimensional simulations were from 2025 to 2100 CE for each SSP (40 simulations).

Thirdly, we simulated an oil palm plantation field in three dimensions starting from 2030. For these simulations, our model was set up as a 100×100 m^2 field divided into four areas separated by ditch drains with constant water levels of 60 cm below the ground surface. Each of the four smaller parcels measured 90×20 m^2 (figure 1*b*,*c*,*e*). Although we could have also simulated the effect of oil palm on peat thickness as a two-dimensional transect, we chose to run our model in three dimensions for visualization purposes. For this group of model runs, we simulated SSP2-4.5 and SSP3-7.0 (20 model runs). We chose SSP2-4.5 (described by the IPCC as 'Middle of the Road') because it is the pathway that most closely resembles the policies of today's societies [55], which suggests that global mean surface temperature will be > 2.5°C above the pre-industrial average by 2100. SSP3-7.0 represents our high emissions scenario, known as 'A Rocky Road', meaning it will be difficult for societies to mitigate and adapt to climate change as Earth's surface temperature approaches +4°C above the pre-industrial level by 2100.

In these simulations, we did not add any biomass from native tree types, and we assumed oil palm would produce more biomass than the native vegetation (approx. 12 Mg ha^{-1} yr^{-1}, [11]), with plant litter inputs of 40 Mg ha^{-1} yr^{-1} [56,57]. We assumed 20 Mg ha^{-1} of biomass was removed each year as harvest, the rest being added to the above- and belowground peatland in the same way as the native palm (supplementary material, tables S1,S2). Our simulated oil palm also decays using the same parameters

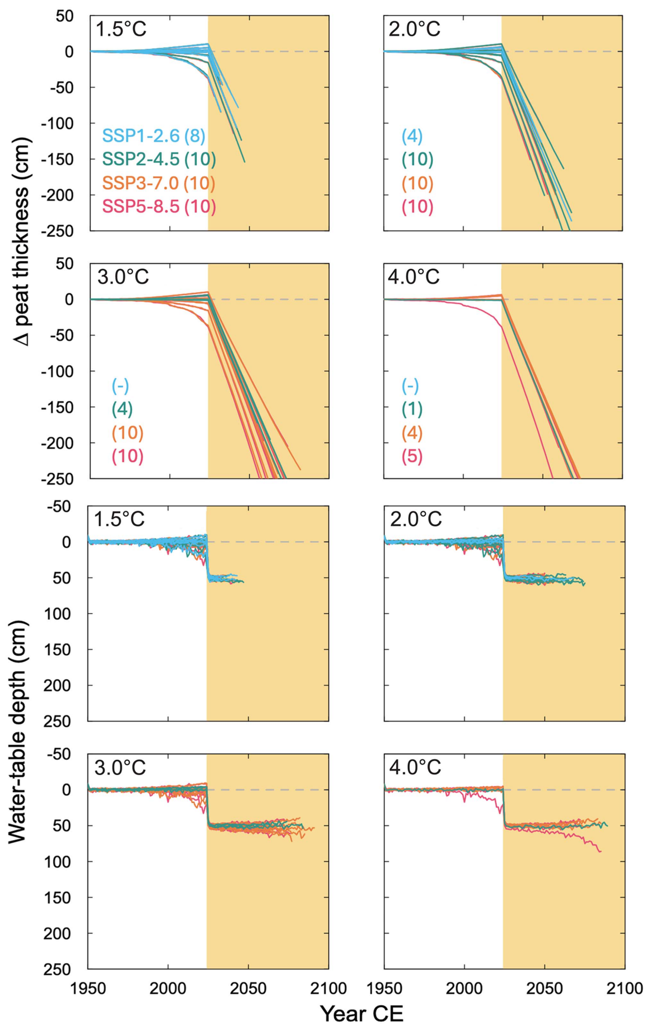

Figure 3. Effect of simulated drainage (from 2025, pale background shading) and climate change on change in peat thickness relative to the 1950 simulation (top four panels) and water table depth (bottom four panels). Each panel shows the simulations in each SSP for four warming levels. Each line is a DigiBog_Congo simulation driven by the climate projections from a single CMIP6 model; the colours correspond to the SSP (shown in the panel legend of warming level 1.5°C). Numbers in parentheses show the total number of model runs (out of 10) that reach the respective warming level for each SSP. Only model runs that reach the warming level are shown. Ditch water levels were maintained at 60 cm below the peat surface for the simulation.

as the native palm. We conservatively assumed that oil palm would reach maximum production in year one rather than several years (about five) after planting, effectively overestimating the plant litter inputs from oil palm and thereby offsetting some peat carbon losses. In practice, oil palm is replaced every 25 to 30 years, each crop taking time to reach maximum production [56,58]. However, we assumed that a single crop would last for 70 years at maximum productivity, thereby increasing litter input to the peatland in comparison with the same period with native palm inputs. As with our drainage simulation, ditches were simulated using a ditch water level maintained at 60 cm below ground level (figure 1).

3. Results

For the results of climate change only (one-dimensional simulations) and climate change with drainage (two-dimensional simulations), we report the change in peat thickness of each simulation up to and including the year when each warming level is reached (figures 2 and 3). We also calculated the overall NCB for each warming level (peat bulk density of 0.17 g cm^{-3} and carbon content of peat of 0.5). Because the year each climate model reaches a warming level can be different (supplementary material, table S4), the results shown in figures 2 and 3 end at different times. For the oil palm simulations under SSP2-4.5 and SSP3-7.0, we first report the median change in peat thickness and NCB up to 2100 for each pathway (figure 4 shows the results for SSP2-4.5). To summarize the effect of land-use change, we then report the mean change in peat thickness of all simulations under SSP2-4.5 and SSP3-7.0 (the average of the two pathways) at each warming level (figure 5).

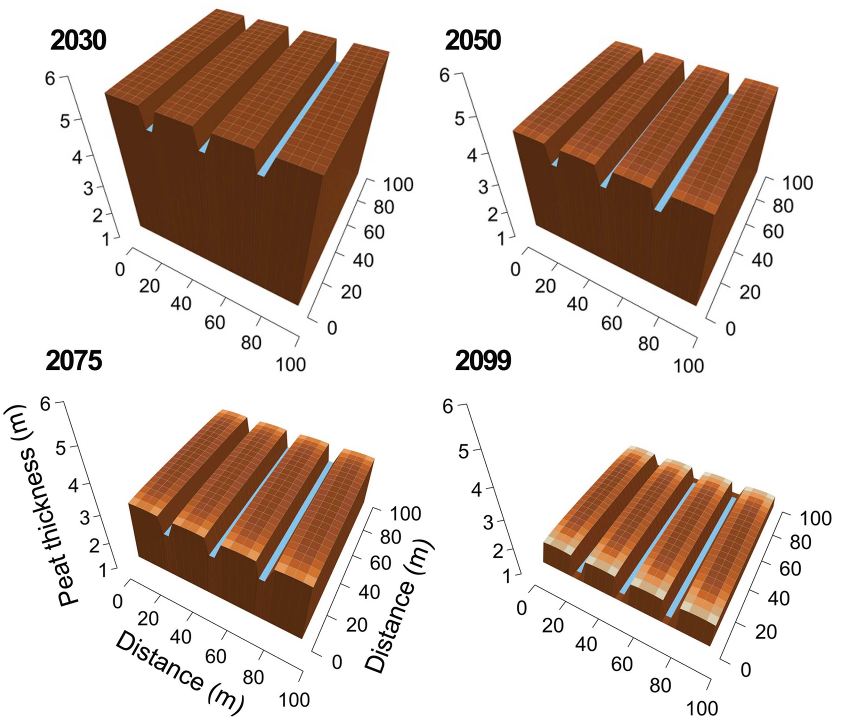

Figure 4. Simulated change in peat surface of a block of peat under oil palm from 2030 to the end of 2099 under SSP2-4.5. The surface is the mean surface from 10 simulations driven by the climate models in our CMIP6 ensemble. Lighter brown colours indicate a change in peat thickness relative to the central columns of each block (shown in dark brown)—i.e. lighter columns are thinner. Simulations ran from 2025 to the end of 2099. The peat block was drained from 2025 to the end of 2029 before the oil palm was planted. Each block is drained on all four sides. Water levels in ditches are maintained at 60 cm below the peat surface throughout the simulation.

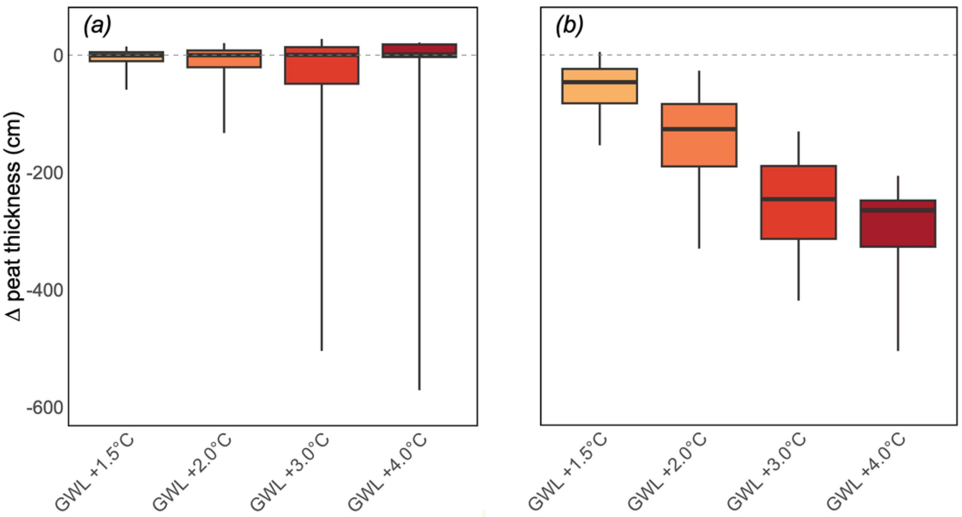

Figure 5. Comparison of the effect of (*a*) climate change on peat thickness with (*b*) the combined effect of climate change and drainage on peat thickness for four warming levels. Box plots show the median and interquartile range (whiskers represent the full range of results). Data for each box and whiskers are from the CMIP6 model ensemble used to simulate the effect of SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 on peat accumulation.

(a) Simulated effect of climate change on peat accumulation

Change in peat thickness under individual simulations of twenty-first-century climate change is highly uncertain (figure 2). However, the median change in simulated peat thickness (where negative values are a reduction in peat thickness) from 1950 (peat thickness of 590 cm) is always indistinguishable from no change. For warming level 1.5°C, it is –0.5 cm (range –58.8 to 14.7 cm); for warming level 2°C, it is –0.1 cm (range –132.6 to 20.5 cm); for warming level 3°C, it is +0.4 cm (range –503.9 to 27.6 cm) and for warming level 4°C, it is +1.0 cm (range –570.8 to 21.6 cm). The median NCB for warming levels 1.5, 2, 3 and 4°C are –5.2, –1.2, +2.9 and +6.1 g m^{-2} yr^{-1}, respectively.

Irrespective of the emission pathway, four of the 10 CMIP6 models predicted an increase in peat thickness at warming level 1.5°C, five predicted an increase at warming level 2°C and warming level 3°C, and three of the five CMIP6 models to reach warming level 4°C predicted an increase in peat thickness. When emission pathways are considered, four of the 10 models show an increase in peat thickness for SSP1-2.6 (at warming levels 1.5 and 2°C). Five models show an increase in peat thickness for SSP2-4.5 (at warming levels 1.5, 2 and 3°C). Five models show an increase in peat thickness for SSP3.70 and SSP5-8.5 (at warming levels 1.5, 2, 3 and 4°C).

(b) Simulated effect of climate and land-use change on peat thickness

The result of peat drainage is unequivocal (figure 3). Simulations of ditch drainage using the two-dimensional version of Digi-Bog_Congo (driven by all climate models reaching 1.5, 2, 3 and 4°C of warming in all SSPs) rapidly lost peat. The loss of peat increased substantially with increased warming. The median change in peat thickness from 1950 (590 cm) was –46.5 cm (range –154.0 to 5.2 cm) for warming level 1.5°C, –126.6 cm (range –330.3 to –26.9 cm) for warming level 2°C, –246.1 cm (range –419.0 to –130.6 cm) for warming level 3°C and –264.9 cm (range –504.9 to –206.2 cm) for warming level 4°C. The median NCBs for warming levels 1.5, 2, 3 and 4°C are –469, –1087, –1730 and –1835 g m^{-2} yr^{-1}, respectively.

Our three-dimensional simulations of oil palm production, including ditch drainage, for SSP2-4.5 and SSP3-7.0 showed a median change in peat thickness of –397.5 cm (range –407.6 to –391.4 cm) and –408.4 cm (range –417.6 to –403.2 cm) by 2100, respectively. The median NCB for both pathways over the same period is –2252.5 and –2314.2 g m^{-2} yr^{-1}, respectively. Figure 4 shows the change in peat surface for four years (2030, 2050, 2075 and 2099) of the SSP2-4.5 simulation. As time progresses, the peat surface next to the ditches (light brown) thins more quickly than the surface at the centre of the blocks (dark brown), producing a slightly domed shape. The mean change in peat thickness across both SSP2-4.5 and SSP3-7.0 (the average of these two pathways) is –57.8 cm for warming level +1.5°C, –148.7 cm for warming level +2°C, –251.7 cm for warming level +3°C and –315.3 cm for warming level +4°C.

4. Discussion

(a) Effect of global warming on peatlands protected from land-use change

Our palaeo simulations (approx. 20 000 to 0 BP) of the same location as used here [11] showed that Congo Basin peatlands are highly sensitive to surface wetness. Therefore, we expect drier futures to increase peat losses. We also expect the opposite in wet conditions: peat thickness increases when the annual average water table is above or close to the peat surface and plant inputs outweigh peat decay. The results reported here match these broad expectations, but simulated losses of peat take place over a very short timescale (decades) compared with a previous dry phase that extended over millennia [5,11,30].

Overall, our results show that the effect of future climate change alone is highly uncertain. The median result for all pathways is close to no change in peat thickness, and therefore no change in NCB. Some simulations driven by climate models that predict an increase in rainfall show gains in peat thickness of up to approximately 0.3 m, while others driven by drier climates show large losses of peat (> 5 m) as Earth's climate warms (figures 2 and 5*a*). These losses can account for most of the peat accumulated prior to 1950. Since DigiBog_Congo is deterministic, these uncertainties are driven by the different rainfall regimes predicted by the climate models we use for producing the driving data, making it imperative to improve the understanding of future rainfall in the Congo Basin.

Of the climate-only simulations where there is a reduction in peat thickness, losses increase as the mean global surface temperature rises (shown as warming levels; figure 5*a*), suggesting that under a drying future in equatorial Africa, peat decay will outweigh increases in plant productivity owing to rises in atmospheric CO_2 concentration. Conversely, simulated peat tends to thicken during wetter, warmer futures. This is because although increases in temperature drive increases in peat decomposition, the peat surface is largely saturated, and decay takes place slowly under anoxic conditions. Our simulations of the palaeoclimate are validated with observations from peat cores and from field experiments [11] and strongly suggest that reductions in the Congo Basin peat carbon stock will occur much more slowly, if at all, if the peatland water table is close to or above the peat surface for prolonged periods of time.

(b) Effect of global warming and land-use change on peatland carbon stores

Our results indicate that combining land use with twenty-first-century climate change will cause a rapid, catastrophic loss of peat (figures 3 and 5*b*). Congo Basin interfluvial (rain-fed) peatlands store approximately 9.3 PgC in peat [10]. Assuming the proportional change in peat thickness can be applied uniformly across this store, the median change in carbon stocks of our simulations of climate change combined with ditch drainage for warming levels 1.5, 2, 3 and 4°C are –1.1 (–11.8%), –3.1 (–33.3%), –6.1 (–65.6%) and –6.5 PgC (–69.9%), respectively. From the perspective of Earth's current warming pathway (SSP2-4.5) [55], our results suggest a first-order estimate of the impact of land use could cause the loss of approximately 6.2 PgC by 2100.

While our simulations are a simplification of the natural system, their results are likely to be conservative. We chose to maintain a ditch-water level of 60 cm below the peat surface throughout the land-use part of the simulations (figure 3). This assumes water is available to keep ditches topped up to this level during dry periods, when it is common for tropical peatland ditches to dry out partially or completely during the dry season(s). In effect, our simulations assume sub-irrigation of the peat in dry seasons, which reduces losses caused by high rates of oxic decay.

We assumed maximum oil palm production began immediately after plantation creation (2030), although actual production takes several years to peak and declines towards rotation end [56]. We also assumed a single crop rather than the more likely two or more rotations within this timeframe. These assumptions result in conservative peat loss estimates.

While modified peatlands have been shown to be vulnerable to fires [59,60], we do not explore their effect in our simulations. Fire in converted SE Asian peatlands has caused huge losses of peat carbon and caused thousands of deaths from air pollution [61–63]. Peatland fires in the Congo Basin should be expected where drainage occurs, but even discounting the additional loss of peat from fire and the negative impacts of air pollution on human health, the effects of land-use change on Congo Basin peatlands will cause rapid peat losses (figure 5*b*) that will contribute to an increase in the rate of global mean surface temperature rise.

(c) Model performance

As reported in Young *et al.*[11], our model skilfully simulates the past NCB of the site reported here (including the effects of increased decay caused by an extended droughty period), suggesting the mechanisms of peat accumulation and loss are represented in sufficient detail. In that article, we note that, while we were able to constrain many key model parameters using field observations (such as litter input and peat decay), empirical evidence is not available for all of them (supplementary material, table S1). We did not alter any parameter for which we had field measurements. To understand the impact of our parameter choices, we tested the sensitivity of our model by comparing simulated age-depth curves with one from a peat core taken nearby (see §4b in [11]).

We further assessed the performance of our model using the future annual average water table depth (figures 2 and 3) from our simulations of climate change alone. Water table depths of several metres below observed values would cause excessive peat decay within a short period and could not be justified. We find that water table depths for the simulations to a warming level of 1.5°C compare well with observed values [64] (figure 2), and that simulated annual average water tables do not exceed 154 cm (figure 2; warming level 3°C). Water table depths of approximately 150 cm were observed at a site in the Republic of the Congo near the Sangha River in October 2024 (Greta Dargie 2024, personal communication). The deepest monthly value is for the MRI-ESM2.0 model within SSP3-7.0 and is comparable with observations from other tropical peatlands during extended dry periods or drainage [65,66].

Nevertheless, it is important to recognize that our results do not include the range of uncertainties caused by parameter selection or how certain processes are incorporated into our model, which are currently unknown. Efforts to improve our understanding of Congo Basin peatlands began relatively recently [5,8,10,16,30,64,67,68]. The limited data to constrain some of our model parameters or processes not only reflects our current state of knowledge but also highlights where future laboratory experiments and field campaigns should be targeted. Despite these knowledge gaps, our simulations provide important insights into the different impacts of climate change and the combined impact of climate and land-use change on Congo Basin peat stocks.

5. Conclusion

Under most combinations of our 10-climate model ensemble and SSP scenarios, our simulations suggest relatively small changes in future peat accumulation in the currently intact rain-fed interfluvial peatlands of the central Congo Basin. Earth's mean surface air temperature is currently following the pathway described by SSP2-4.5, which implies 2.5 to 3°C of warming above the pre-industrial average by 2100. While our results indicate the effect of this warming is uncertain, some of our simulations, driven by wetter climate model projections for the region, indicate small increases in peat thickness, while those driven by drier climate model projections indicate significant peat losses. This underscores the urgent need for investment in understanding rainfall in the Congo Basin to ascertain if the region is more likely to become wetter or drier.

However, under any future climate scenario, large-scale land-use change that causes peatland water tables to remain below the surface for prolonged periods of time—such as drainage for agricultural conversion, oil drilling, pulp wood production or road building—will result in large, rapid losses of peat carbon, causing a positive feedback to global warming. The interactive effect of climate change and large-scale land-use change on peat accumulation is likely to have disastrous and irreversible consequences for Congolese peat carbon stocks and CO_2 emissions. As such, protecting the central Congo Basin's peatlands from large-scale drainage and other modifications should be of the highest priority for regional and international policymakers.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. The model code for the simulation reported here is available from Zenodo [69].

Supplementary material is available online [70].

Declaration of AI use. We used Claude by Anthropic for two purposes: (i) to find snippets of R code for the processing of outputs from DigiBog_Congo and (ii) for suggestions on how to transfer part of DMY's original model code into the new DigiBog_io_module.f90 (see the Zenodo repository). The new module improves the stopping and starting of simulations within a single model run.

Authors' contributions. D.M.Y.: conceptualization, data curation, formal analysis, methodology, software, visualization, writing—original draft; A.J.B.: conceptualization, funding acquisition, methodology, project administration, software, supervision, writing—original draft, writing—review and editing; P.J.M.: conceptualization, funding acquisition, methodology, software, supervision, writing—original draft, writing—review and editing; E.B.: methodology, resources, writing—original draft, writing—review and editing; C.S.: methodology, resources, writing—original draft, writing—review and editing; J.R.: resources, visualization, writing—review and editing; G.C.D.: funding acquisition, investigation, writing—review and editing; A.B.: funding acquisition, writing—review and editing; R.A.B.: funding acquisition, methodology, writing—review and editing; Y.E.B.: investigation; P.C.: resources, writing—review and editing; D.E.C.: investigation; B.C.: writing—review and editing; Y.G.: resources, writing—review and editing; S.G.: writing—review and editing; N.T.G.: writing—review and editing; P.G.: writing—review and editing; D.H.: writing—review and editing; I.T.L.: funding acquisition, writing—review and editing; S.E.P.: funding acquisition, writing—review and editing; E.S.: writing—review and editing; M.S.: writing—review and editing; S.S.: funding acquisition, writing—review and editing; S.A.I.: conceptualization, funding acquisition; S.L.L.: conceptualization, funding acquisition, project administration, resources, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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References

1. Cole LES *et al.* 2022 Tropical peatlands in the Anthropocene: lessons from the past. *Anthropocene* **37**, 100324. (doi:10.1016/j.ancene.2022.100324)
2. Ruwaimana M, Anshari GZ, Silva LCR, Gavin DG. 2020 The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47 000 years. *Environ. Res. Lett.* **15**, 114027. (doi:10.1088/1748-9326/abb853)
3. Keddy PA *et al.* 2009 Wet and wonderful: the world's largest wetlands are conservation priorities. *BioScience* **59**, 39–51. (doi:10.1525/bio.2009.59.1.8)
4. Page S *et al.* 2022 Anthropogenic impacts on lowland tropical peatland biogeochemistry. *Nat. Rev. Earth Environ.* **3**, 426–443. (doi:10.1038/s43017-022-00289-6)
5. Garcin Y *et al.* 2022 Hydroclimatic vulnerability of peat carbon in the central Congo Basin. *Nature* **612**, 277–282. (doi:10.1038/s41586-022-05389-3)
6. Hoyt AM, Chaussard E, Seppalainen SS, Harvey CF. 2020 Widespread subsidence and carbon emissions across Southeast Asian peatlands. *Nat. Geosci.* **13**, 435–440. (doi:10.1038/s41561-020-0575-4)
7. Gaveau DLA *et al.* 2014 Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Sci. Rep.* **4**, 6112. (doi:10.1038/srep06112)
8. Dargie GC *et al.* 2017 Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature* **542**, 86–90. (doi:10.1038/nature21048)
9. Hastie A *et al.* 2024 A new data-driven map predicts substantial undocumented peatland areas in Amazonia. *Environ. Res. Lett.* **19**, 094019. (doi:10.1088/1748-9326/ad677b)
10. Crezee B *et al.* 2022 Mapping peat thickness and carbon stocks of the central Congo Basin using field data. *Nat. Geosci.* **15**, 639–644. (doi:10.1038/s41561-022-00966-7)
11. Young DM *et al.* 2023 Simulating carbon accumulation and loss in the central Congo peatlands. *Glob. Change Biol.* **29**, 6812–6827. (doi:10.1111/gcb.16966)
12. Hoyos-Santillan J, Lomax BH, Large D, Turner BL, Boom A, Lopez OR, Sjögersten S. 2015 Getting to the root of the problem: litter decomposition and peat formation in lowland Neotropical peatlands. *Biogeochemistry* **126**, 115–129. (doi:10.1007/s10533-015-0147-7)
13. Hodgkins SB *et al.* 2018 Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. *Nat. Commun.* **9**, 3640. (doi:10.1038/s41467-018-06050-2)
14. Wright EL, Black CR, Cheesman AW, Turner BL, Sjögersten S. 2013 Impact of simulated changes in water table depth on ex situ decomposition of leaf litter from a Neotropical peatland. *Wetlands* **33**, 217–226. (doi:10.1007/s13157-012-0369-6)
15. Kalhori A, Wille C, Gottschalk P, Li Z, Hashemi J, Kemper K, Sachs T. 2024 Temporally dynamic carbon dioxide and methane emission factors for rewetted peatlands. *Commun. Earth Environ.* **5**, 62. (doi:10.1038/s43247-024-01226-9)
16. Davenport IJ *et al.* 2020 First evidence of peat domes in the Congo Basin using LiDAR from a fixed-wing drone. *Remote Sens*. **12**, 2196. (doi:10.3390/rs12142196)
17. Dargie GC, Lawson IT, Rayden TJ, Miles L, Mitchard ETA, Page SE, Bocko YE, Ifo SA, Lewis SL. 2019 Congo Basin peatlands: threats and conservation priorities. *Mitig. Adapt. Strateg. Glob. Change* **24**, 669–686. (doi:10.1007/s11027-017-9774-8)
18. IPCC. 2014 *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the 5th assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.
19. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE. 2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958. (doi:10.5194/gmd-9-1937-2016)
20. O'Neill BC *et al.* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482. (doi:10.5194/gmd-9-3461-2016)
21. Mishra S, Page SE, Cobb AR, Lee JSH, Jovani-Sancho AJ, Sjögersten S, Jaya A, Aswandi, Wardle DA. 2021 Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *J. Appl. Ecol.* **58**, 1370–1387. (doi:10.1111/1365-2664.13905)
22. UNEP. 2022 *Global Peatlands Assessment—the state of the world's peatlands: evidence for action toward the conservation, restoration, and sustainable management of peatlands*. Nairobi, Kenya: United Nations Environment Programme. (doi:10.59117/20.500.11822/41222)
23. Cooper HV, Evers S, Aplin P, Crout N, Dahalan MPB, Sjogersten S. 2020 Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. *Nat. Commun.* **11**, 407. (doi:10.1038/s41467-020-14298-w)
24. Miettinen J, Hooijer A, Vernimmen R, Liew SC, Page SE. 2017 From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. *Environ. Res. Lett.* **12**, 024014. (doi:10.1088/1748-9326/aa5b6f)
25. Miettinen J, Shi C, Liew SC. 2016 Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Glob. Ecol. Conserv.* **6**, 67–78. (doi:10.1016/j.gecco.2016.02.004)
26. Eyob Z. 2025 *New mapping analysis exposes expanded oil plans in the DRC, endangering ecosystems and communities*. https://earth-insight.org/press-release/drc-oil-expansion-plans-2025 (accessed 4 July 2025).
27. Klein AL. 2025 *DRC offers 52 new oil blocks to boost exploration*. https://energycapitalpower.com/drc-offers-52-new-oil-blocks-to-boost-exploration (accessed 4 July 2025).

28. Ordway EM, Sonwa DJ, Levang P, Mboringong F, III LM, Naylor RL, Nkongho RN. 2019 Sustainable development of the palm oil sector in the Congo Basin: the need for a regional strategy involving smallholders and informal markets. *Center for International Forestry Research (CIFOR)*. (doi:10.17528/cifor/007279).
29. De Augustinis F, Kiriko JK. 2025 *DRC's plans to dramatically increase palm oil production*. https://pulitzercenter.org/stories/drcs-plans-dramatically-increase-palm-oil-production (accessed 4 July 2025).
30. Hawthorne D *et al.* 2023 Genesis and development of an interfluvial peatland in the central Congo Basin since the Late Pleistocene. *Quat. Sci. Rev.* **305**, 107992. (doi:10.1016/j.quascirev.2023.107992)
31. Baird AJ, Morris PJ, Belyea LR. 2012 The DigiBog peatland development model 1: rationale, conceptual model, and hydrological basis. *Ecohydrology* **5**, 242–255. (doi:10.1002/eco.230)
32. Young DM, Baird AJ, Morris PJ, Holden J. 2017 Simulating the long-term impacts of drainage and restoration on the ecohydrology of peatlands. *Water Resour. Res.* **53**, 6510–6522. (doi:10.1002/2016WR019898)
33. Shokri N, Salvucci GD. 2011 Evaporation from porous media in the presence of a water table. *Vadose Zone J.* **10**, 1309–1318. (doi:10.2136/vzj2011.0027)
34. Baird AJ, Low R, Young D, Swindles GT, Lopez OR, Page S. 2017 High permeability explains the vulnerability of the carbon store in drained tropical peatlands. *Geophys. Res. Lett.* **44**, 1333–1339. (doi:10.1002/2016GL072245)
35. Cobb AR, Dommain R, Tan F, Hwee En Heng N, Harvey CF. 2020 Carbon storage capacity of tropical peatlands in natural and artificial drainage networks. *Environ. Res. Lett.* **15**, 114009. (doi:10.1088/1748-9326/aba867)
36. Waddington JM, Morris PJ, Kettridge N, Granath G, Thompson DK, Moore PA. 2015 Hydrological feedbacks in northern peatlands. *Ecohydrology* **8**, 113–127. (doi:10.1002/eco.1493)
37. Morris PJ *et al.* 2022 Saturated hydraulic conductivity in northern peats inferred from other measurements. *Water Resour. Res.* **58**, e2022WR033181. (doi:10.1029/2022WR033181)
38. Baird AJ, Eades PA, Surridge BWJ. 2008 The hydraulic structure of a raised bog and its implications for ecohydrological modelling of bog development. *Ecohydrology* **1**, 289–298. (doi:10.1002/eco.33)
39. Morris PJ, Baird AJ, Young DM, Swindles GT. 2015 Untangling climate signals from autogenic changes in long-term peatland development. *Geophys. Res. Lett.* **42**,10 788–10 797. (doi:10.1002/2015GL066824)
40. Tebaldi C *et al.* 2021 Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth Syst. Dynam.* **12**, 253–293. (doi:10.5194/esd-12-253-2021)
41. Smith CJ *et al.* 2020 Effective radiative forcing and adjustments in CMIP6 models. *Atmos. Chem. Phys.* **20**, 9591–9618. (doi:10.5194/acp-20-9591-2020)
42. Chai Y *et al.* 2025 Constrained Earth system models show a stronger reduction in future Northern Hemisphere snowmelt water. *Nat. Clim. Change* **15**, 514–520. (doi:10.1038/s41558-025-02308-y)
43. Forster P *et al.* 2021 The Earth's energy budget, climate feedbacks, and climate sensitivity. In *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V Masson-Delmotte *et al.*), 923–1054. Cambridge, UK: Cambridge University Press. (doi:10.1017/9781009157896.009)
44. Rugenstein M *et al.* 2020 Equilibrium climate sensitivity estimated by equilibrating climate models. *Geophys. Res. Lett.* **47**, e2019GL083898. (doi:10.1029/2019GL083898)
45. Brunner L, Pendergrass AG, Lehner F, Merrifield AL, Lorenz R, Knutti R. 2020 Reduced global warming from CMIP6 projections when weighting models by performance and independence. *Earth Syst. Dynam.* **11**, 995–1012. (doi:10.5194/esd-11-995-2020)
46. Fewster RE, Morris PJ, Ivanovic RF, Swindles GT, Peregon AM, Smith CJ. 2022 Imminent loss of climate space for permafrost peatlands in Europe and Western Siberia. *Nat. Clim. Change* **12**, 373–379. (doi:10.1038/s41558-022-01296-7)
47. Hausfather Z, Marvel K, Schmidt GA, Nielsen-Gammon JW, Zelinka M. 2022 Climate simulations: recognize the 'hot model' problem. *Nature* **605**, 26–29. (doi:10.1038/d41586-022-01192-2)
48. Swaminathan R *et al.* 2024 Regional impacts poorly constrained by climate sensitivity. *Earth's Future* **12**, e2024EF004901. (doi:10.1029/2024EF004901)
49. Mathison C *et al.* 2025 A rapid application emissions-to-impacts tool for scenario assessment: probabilistic regional impacts from model patterns and emissions (PRIME). *Geosci. Model Dev.* **18**, 1785–1808. (doi:10.5194/gmd-18-1785-2025)
50. Huntingford C *et al.* 2010 IMOGEN: an intermediate complexity model to evaluate terrestrial impacts of a changing climate. *Geosci. Model Dev.* **3**, 679–687. (doi:10.5194/gmd-3-679-2010)
51. Ritchie H, Roser M. 2020 *CO_2 emissions*. https://archive.ourworldindata.org/20260608-233547/co2-emissions.html.
52. Meinshausen M *et al.* 2020 The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605. (doi:10.5194/gmd-13-3571-2020)
53. Parish F, Mathews J, Lew SY, Faizuddin M, Lo J (eds). 2019 *RSPO manual on best management practices (BMPs) for existing oil palm cultivation on peat*. 2nd edition. Kuala Lumpur, Malaysia: RSPO.
54. Hooijer A *et al*. 2024 Benefits of tropical peatland rewetting for subsidence reduction and forest regrowth: results from a large-scale restoration trial. *Sci. Rep.* **14**, 10721. (doi:10.1038/s41598-024-60462-3)
55. Bevacqua E, Schleussner CF, Zscheischler J. 2025 A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. *Nat. Clim. Change* **15**, 262–265. (doi:10.1038/s41558-025-02246-9)
56. Hoffmann MP *et al.* 2014 Simulating potential growth and yield of oil palm (*Elaeis guineensis*) with PALMSIM: model description, evaluation and application. *Agric. Syst.* **131**, 1–10. (doi:10.1016/j.agsy.2014.07.006)
57. Wakhid N, Hirano T. 2021 Soil CO2 emissions and net primary production of an oil palm plantation established on tropical peat. *Mires Peat* **27**, 1–11. (doi:10.19189/MAP.2021.OMB.STA.2159)
58. Wakhid N, Hirano T, Dariah A, Agus F. 2022 Net primary production of oil palm plantations on tropical peat. *Mires Peat* **28**, 1–12. (doi:10.19189/MAP.2021.SNPG.STA.2288)
59. Turetsky MR, Benscoter B, Page S, Rein G, van der Werf GR, Watts A. 2015 Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci.* **8**, 11–14. (doi:10.1038/ngeo2325)
60. Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S. 2002 The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61–65. (doi:10.1038/nature01131)
61. Prosperi P, Bloise M, Tubiello FN, Conchedda G, Rossi S, Boschetti L, Mirella S, Martial B. 2020 New estimates of greenhouse gas emissions from biomass burning and peat fires using MODIS Collection 6 burned areas. *Clim. Change* **161**, 415–32. (doi:10.1007/s10584-020-02654-0)

62. Girkin NT *et al.* 2022 Tropical peatlands in the Anthropocene: the present and the future. *Anthropocene* **40**, 100354. (doi:10.1016/j.ancene.2022.100354)
63. Grosvenor MJ, Ardiyani V, Wooster MJ, Gillott S, Green DC, Lestari P, Wiranda S. 2024 Catastrophic impact of extreme 2019 Indonesian peatland fires on urban air quality and health. *Commun. Earth Environ.* **5**, 649. (doi:10.1038/s43247-024-01813-w)
64. Georgiou S *et al.* 2023 Mapping water levels across a region of the Cuvette Centrale peatland complex. *Remote Sens.* **15**, 3099. (doi:10.3390/rs15123099)
65. Putra SS, Holden J, Baird AJ. 2021 The effects of ditch dams on water-level dynamics in tropical peatlands. *Hydrol. Process.* **35**, e14174. (doi:10.1002/hyp.14174)
66. Sundari S, Hirano T, Yamada H, Kusin K, Limin S. 2012 Effect of groundwater level on soil respiration in tropical peat swamp forests. *J. Agric. Meteorol.* **68**, 121–134. (doi:10.2480/agrmet.68.2.6)
67. Bocko YE, Panzou GJL, Dargie GC, Mampouya YEW, Mbemba M, Loumeto JJ, Lewis SL. 2023 Allometric equation for *Raphia laurentii* De Wild, the commonest palm in the central Congo peatlands. *PLoS ONE* **18**, e0273591. (doi:10.1371/journal.pone.0273591)
68. Sciumbata M, Wenina YEM, Mbemba M, Dargie GC, Baird AJ, Morris PJ, Ifo SA, Aerts R, Lewis SL. 2023 First estimates of fine root production in tropical peat swamp and terra firme forests of the central Congo Basin. *Sci. Rep.* **13**, 12315. (doi:10.1038/s41598-023-38409-x)
69. Young DM, Baird AJ, Morris PJ. 2025 DigiBog_Congo (Royal Society meeting on African Tropical peatlands). Zenodo. (doi:10.5281/zenodo.15319267)
70. Young DM *et al.* 2026 Supplementary material from: Land-use change causes rapid carbon losses in Congo Basin peatlands across climate scenarios, whereas the effects of climate change alone are uncertain. FigShare. (doi:10.6084/m9.figshare.c.8560489)