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

Philosophical Transactions B

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Abstract

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 ~-5.0 m to +0.3 m). By contrast, simulations that couple land-use change with 21st 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; range of ~-5.0 m to -2.1m. Our results emphasize the need to protect Congo Basin peatlands from widespread land-use change.

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 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 due 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 complex is in the central Congo Basin (8,9) (Figure 1a). The complex spans 167,600 km^2 and stores ~29 Pg of carbon in both interfluvial (rain-fed) and river-influenced peatlands (10). Net carbon gain or loss in these peatlands depend 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 gasses 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, but 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 ~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 km 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 Section S1 in 11 for detail). The peatlands receive less rainfall than other tropical peatlands, with mean annual rainfall of only ~1,700 mm, compared with ~3,000 mm and ~2,900 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 ~7.4 Pg C (26%) of peat carbon stock (10, Extended Data Fig. 10). Any future implementation of schemes like those seen in SE Asia peatlands would likely have severe consequences for the stability of 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°C, 2°C, 3°C and 4°C above early-industrial (1850–1900) levels. We use rainfall, potential evapotranspiration 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.

2. Methods

2.1 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 over 20,000 years (11). The model was structured and primarily parameterised 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 1-, 2- and 3-D spatial configurations (Figure 1): in all cases the peatland is represented as columns of peat. In 1-D there is a single square-sectioned column representing the centre of the interfluvial shallow-domed peatland, whereas in 2- or 3-D multiple contiguous columns are used to represent part of a peatland so that we can simulate subsurface water flow between ditches or 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 aboveground 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 (1-D) and horizontally between columns (2- or 3-D). 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 potential evapotranspiration (PET) and calculate net rainfall as rainfall minus AET (actual evapotranspiration), 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 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 (11) or the simulations shown here when water tables are shallow or reside above the ground surface. However, it is needed for situations where the water table is very deep as can be the case with ditch drainage. The parameters used in our simulations are in the Supplementary Material (Tables S1-S3).

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

The 1-D 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 2- and 3-D 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 2- and 3-D 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 (See 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 parameterise the function in our model, which gave a range of K_{sat} of 0.1 cm s^{-1} for freshly added plant litter to ~9 x 10^{-5} cm s^{-1} for highly decomposed peat.

2.2 Climate projections

We simulated changes in peat thickness from 1950 to 2100 using a cohort of 10 CMIP6 Earth System Models (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°C, 2°C, 3°C, and 4°C above pre-industrial (1850-1900) levels. Due 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 timeframes.

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 (46) who selected 12 models. However, three of the models used in (46) did not provide the output data needed to calculate potential evapotranspiration and could not, therefore, be used in our study. To create our 10-model ensemble, we added the Earth system model UKESM-1.0-LL. Although known as a "hot model" (ECS > 5°C) that may overestimate climate impacts (47), (48) 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 global mean surface temperature change and the change in the local air temperature, precipitation and potential evapotranspiration for the Congo Basin. This is commonly called pattern scaling and assumes that the change in the local meteorology is linear with 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 (50) to create simulated hourly meteorological time series. We used these outputs to create monthly time series for rainfall and potential evapotranspiration (we use annual air temperature inputs in DigiBog_Congo) for our simulations. Intra-annual noise was added following the method outlined in the supplementary material (Section S4).

CO_2 concentrations were obtained from (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).

2.3 Simulations and model parameters

We used the parameters reported in (11) to reproduce a 1-D 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 the Supplementary Material (Tables S1-S3). These tables specify those parameters that are well constrained by observations and those that were obtained by sensitivity testing. The results reported in Section 3 show the range of uncertainty due to climate model projections. They do not include uncertainty caused by the configuration or parameterisation of our peatland model, which we currently cannot quantify. We discuss the implications of these choices in Section 4.3.

We ran three sets of simulations (Figure 1b). We first simulated in 1-D the effect of climate change alone for each member of our model ensemble in each SSP (40 simulations). As in Young et al. (2023), the 1-D 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 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 (see Section 2.1). We chose to simulate this lateral subsurface water movement in 2-D. 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 2-D 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 m x 20 m series of columns Figure 1b,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 2-D simulations were from 2025 to 2100 CE for each SSP (40 simulations).

Thirdly, we simulated an oil palm plantation field in 3-D starting from 2030. For these simulations, our model was set up as a 100 m x 100 m 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 m x 20 m (Figure 1b,c,e). Although we could have also simulated the effect of oil palm on peat thickness as a 2-D transect, we chose to run our model in 3-D for visualisation 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.

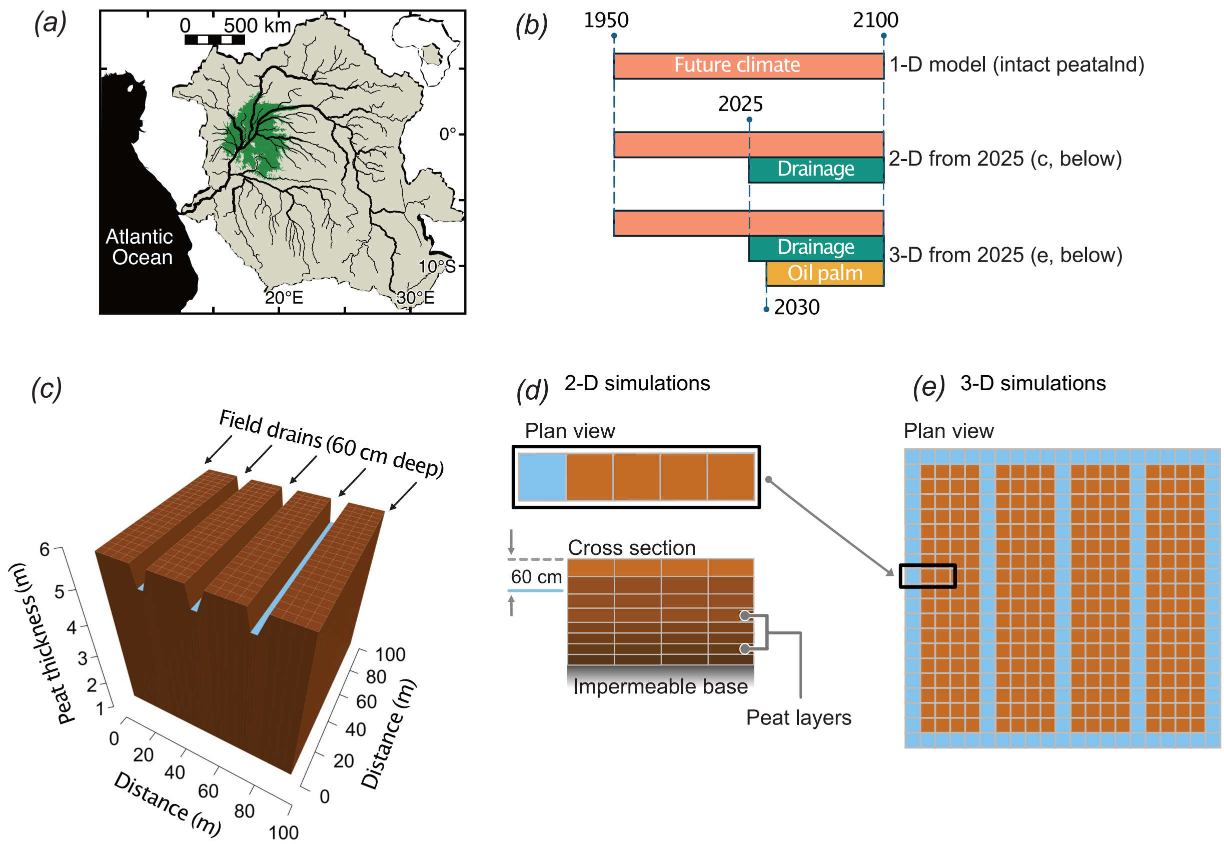
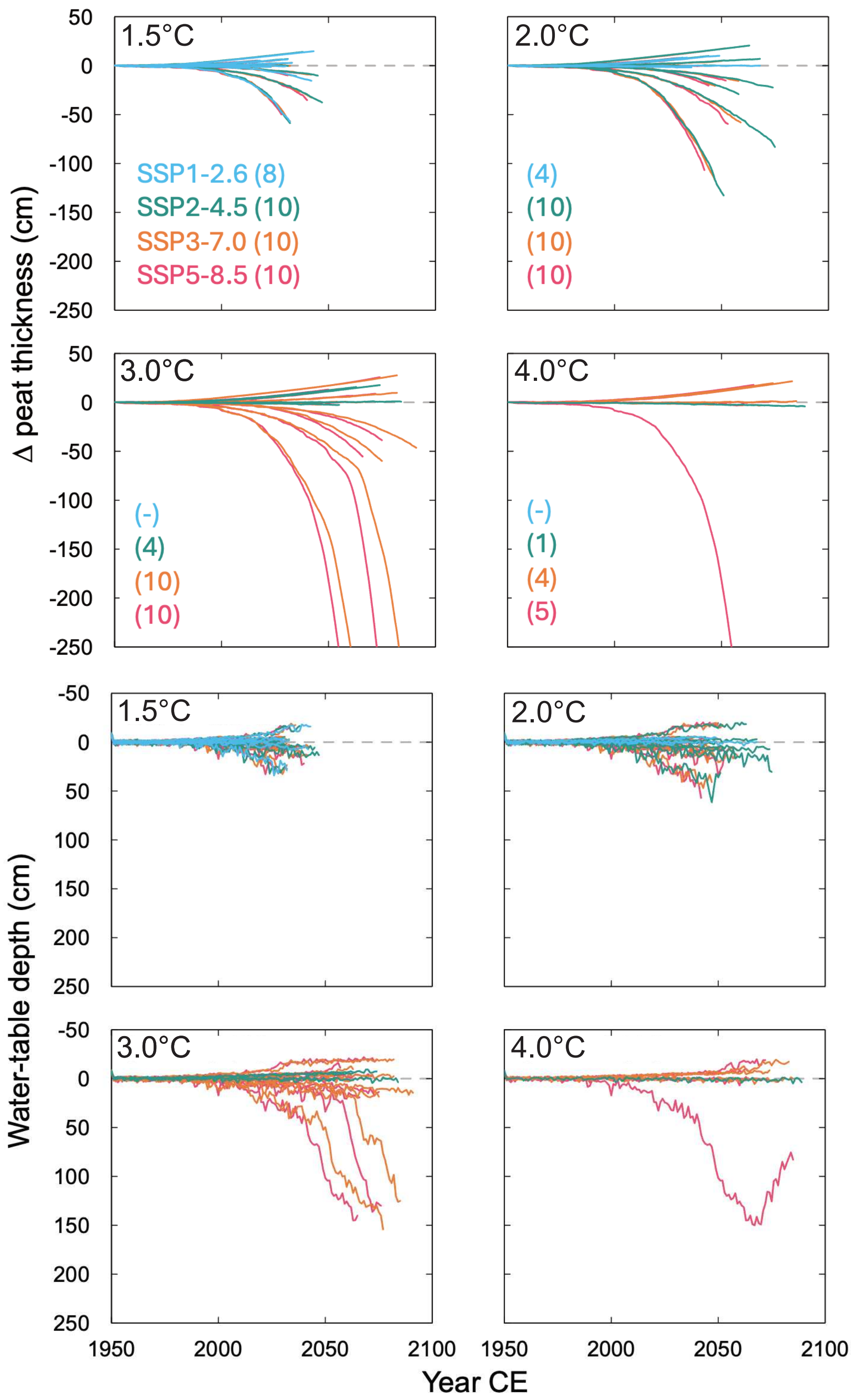


Figure 1. Model set-up. (a) Location of Congo Basin peatland complex. (b) Simulated timelines for the three types of future peatland impacts reported here and the associated climate inputs and land uses. (c) Cartoon of 100 m x 100 m block of peat for 3-D simulations divided into four parcels each measuring 20 m x 90 m with ditch drains in between parcels. (d) 2-D simulations, which uses 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 (e). The cross section shows peat columns made up of layers. (e) Parcels of peat forming the 3-D block shown in (c): colour of squares are the same as (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. Map shown in (a) is from (5).

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 (~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 and S2). Our simulated oil palm also decays using the same parameters as 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 (1-D simulations) and climate change with drainage (2-D 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 net carbon balance (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 summarise 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).



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287 **Figure 2.** Modelled effects of future climate on change of peat thickness relative to the 1950
288 simulation (top four panels) and corresponding water-table depth (bottom four panels). Each
289 panel shows the simulations of each SSP for four warming levels. Each line is a DigiBog_Congo
290 simulation driven by the climate projections from a single CMIP6 model; the colours correspond
291 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 ten) that reach the respective warming level for each SSP. Only model runs that reach the warming level are shown in the panels.

3.1 Simulated effect of climate change on peat accumulation

Change in peat thickness under individual simulations of 21st 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 (-503.9 to 27.6 cm), and for warming level 4°C it is +1.0 cm (-570.8 to 21.6 cm). The median NCB for warming levels 1.5°C, 2°C, 3°C, 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 of the CMIP6 models to reach warming level 4°C predicted an increase in peat thickness. When emission pathways are considered, four of the ten models show an increase peat thickness for SSP1-2.6 (at warming levels 1.5°C and 2°C). Five models show an increase in peat thickness for SSP2-4.5 (at warming levels 1.5°C, 2°C and 3°C). Five models show an increase in peat thickness for SSP3.70 and SSP5-8.5 (at warming levels 1.5°C, 2°C, 3°C, and 4°C).

3.2 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 2-D version of DigiBog_Congo (driven by all climate models reaching 1.5°C, 2°C, 3°C 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 cm 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°C, 2°C, 3°C, and 4°C , are -469, -1087, -1730, and -1835 g m^{-2} yr^{-1} respectively.

Our 3-D 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, 2099) of the SSP2-4.5 simulation. As time progresses the peat surface next to the ditches (light brown) thins quicker 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.

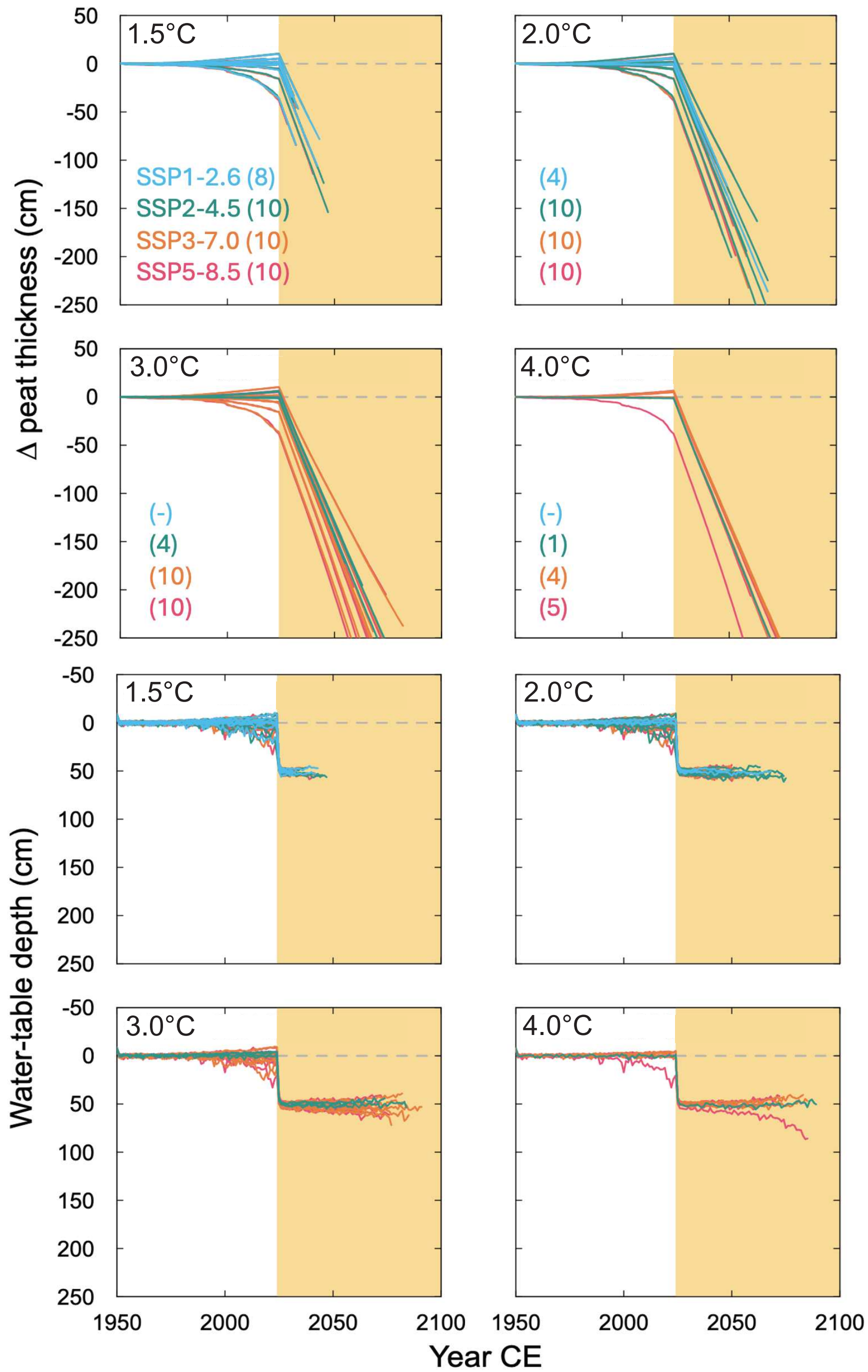

Figure 3. Effect of simulated drainage (from 2025, pale background shading) and climate change on change in peat thickness relative to the 1950 simulation (top four panels) and water-table depth (bottom four panels). Each panel shows the simulations in each SSP for four warming levels. Each line is a 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 ten) 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.

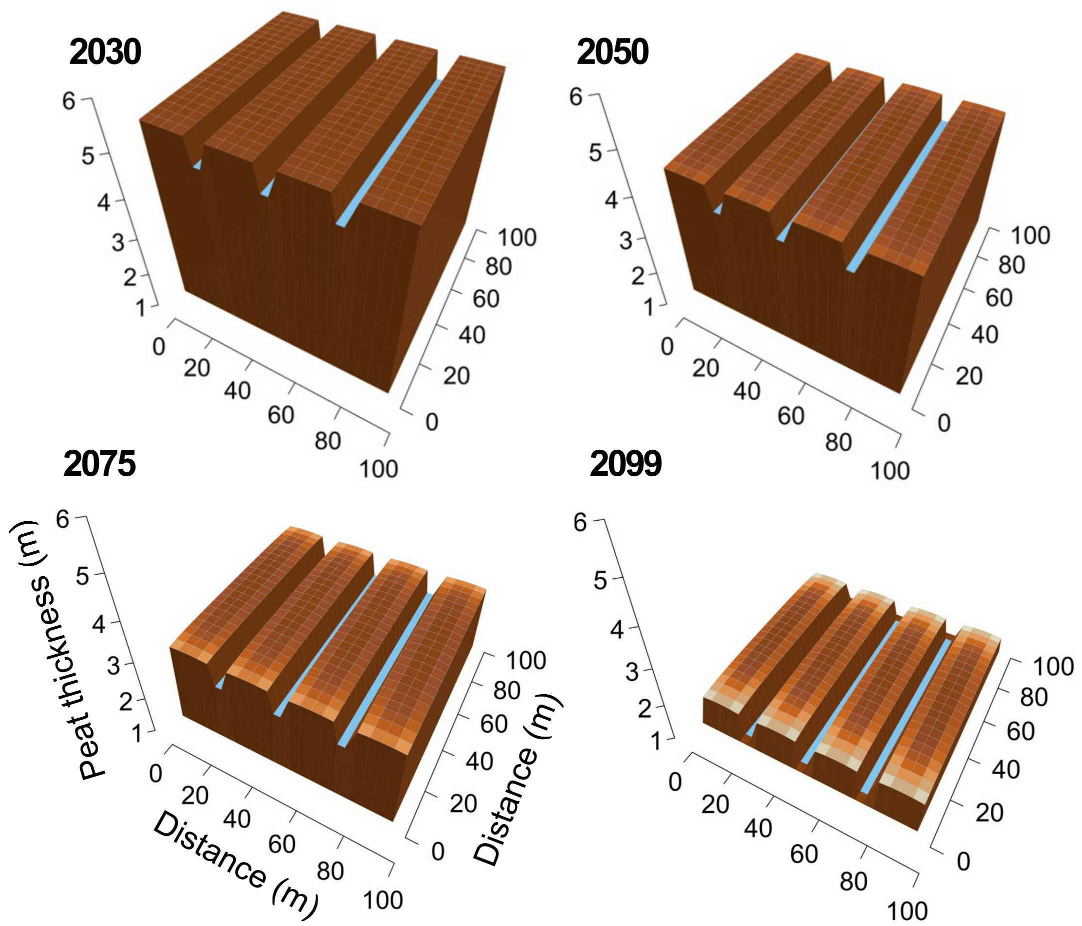

Figure 4. Simulated change in peat surface of a block of peat under oil palm from 2030 to the end of 2099 under SSP2-4.5. The surface is the mean surface from 10 simulations driven by the climate models in our CMIP6 ensemble. Lighter brown colours indicate a change in peat thickness relative to the central 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 oil palm was simulated. Each block is drained on all four

sides. Water levels in ditches are maintained at 60 cm below the peat surface throughout the simulation.

4. Discussion

4.1 Effect of global warming on peatlands protected from land-use change

Our palaeo simulations (~20,000 BP 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 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 ~0.3 m, whilst others driven with drier climates show large losses of peat (>5 m) as Earth's climate warms (Figures 2 and 5a). 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 5a), suggesting that under a drying future in equatorial Africa, peat decay will outweigh increases in plant productivity due 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.

4.2 Effect of global warming and land-use change on peatland carbon stores

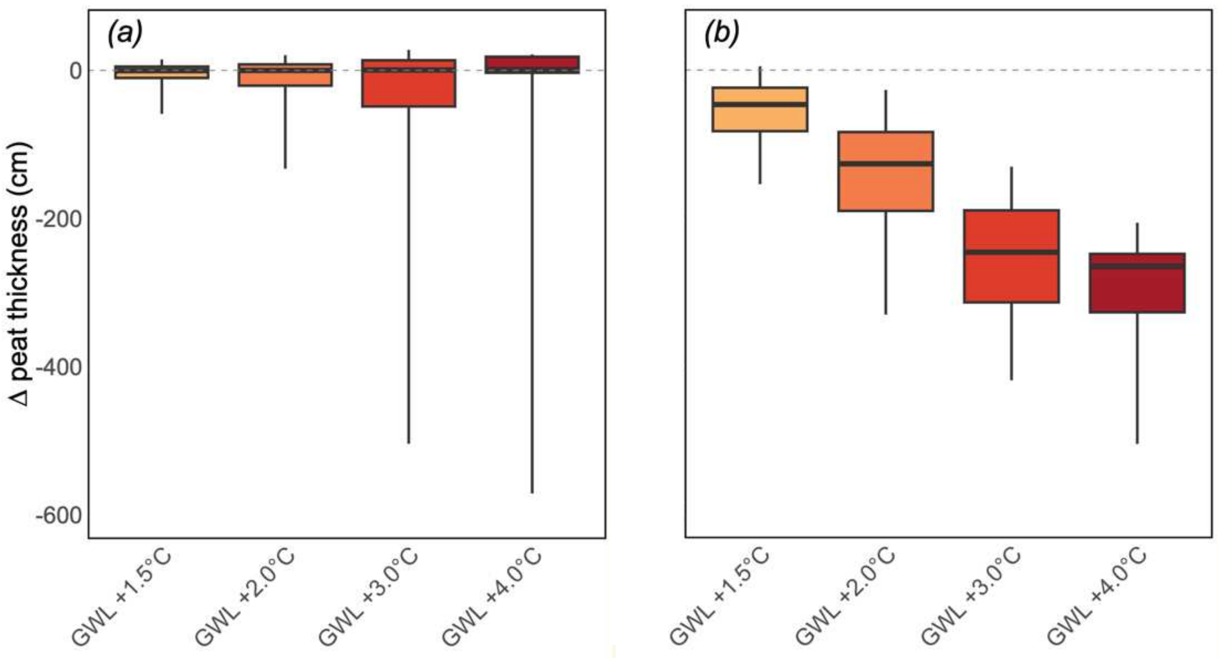

Figure 5. Comparison of the effect of (a) climate change on peat thickness with (b), the combined effect of climate change and drainage on peat thickness for four warming levels. Box plots show the median and interquartile range (whiskers represent the full range of results). Data for each box and whiskers 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.

Our results indicate that combining land use with 21st Century climate change will cause a rapid, catastrophic loss of peat (Figures 3 and 5b). Congo Basin interfluvial (rain-fed) peatlands store ~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°C, 2°C, 3°C, 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 ~6.2 PgC by 2100.

Whilst 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 subirrigation 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 toward rotation end (56). We also assumed a single crop rather than the likely two or more rotations within this timeframe. These assumptions result in conservative peat loss estimates.

Whilst modified peatlands have been shown to be vulnerable to fire (59,60), we do not explore its 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 5b) that will contribute to an increase in the rate of global mean surface temperature rise.

4.3 Model performance.

As reported in (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 paper, we note that, whilst 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 (also see Table S1). We did not alter any parameter we had field measurements for. 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 Section 4.2 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 warming level 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 ~150 cm were observed at a site in the Republic of the Congo near the Sangha River in October 2024 (Greta Dargie, pers. comm.) 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 recognise 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 impact 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. Whilst 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.

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Data, code and materials

The model code for the simulation reported here is available from: https://doi.org/10.5281/zenodo.15319266

Declaration of AI use

We used Claude by Anthropic for two purposes: 1) to find snippets of R code for the processing of outputs from DigiBog_Congo; and 2) 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.

Competing interests

We have no competing interests to declare regarding this article.