Expert assessment of future vulnerability of the global peatland carbon sink

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Running title

The future of peatland carbon stocks

Revised manuscript submitted to *Nature Climate Change* as an *Analysis*
Today's date: 16 September 2020

The carbon balance of peatlands is predicted to shift from a sink to a source this century. However, peatland ecosystems are still omitted from the main Earth System Models used for future climate change projections and they are not considered in Integrated Assessment Models used in impact and mitigation studies. Using evidence synthesized from the literature and an expert elicitation, we define and quantify the leading drivers of change that have impacted peatland carbon stocks during the Holocene and predict their effect during this century and the far future. We also identify uncertainties and knowledge gaps among the scientific community and provide insight towards better integration of peatlands into modeling frameworks. Given the importance of peatlands' contribution to the global carbon cycle, this study shows that peatland science is a critical research area and that we still have a long way to go to fully understand the peatland-carbon-climate nexus.

Peatlands are often regarded as stable systems, with limited influence on annual carbon (C) cycling dynamics at the global scale. To some extent, this is true: their net C exchange with the atmosphere (a sink of ~0.14 Gt yr^{-1})[1] is equivalent to ~ 1% of human fossil fuel emissions, or 3-10% of the current net sink of natural terrestrial ecosystems[2]. However, and despite only occupying 3% of the global land area[3], peatlands contain about 25% (600 GtC) of the global soil C stock[4], equivalent to twice the amount in the world's forests[5]. This large and dense C store is the result of the slow process of belowground peat accumulation under saturated conditions that has been taking place over millennia, particularly following the Last Glacial Maximum (LGM), as peatlands spread across northern ice-free landscapes[4]. Given their ability to sequester C over long periods of time, peatlands acted as a cooling mechanism for Earth's climate throughout most of the Holocene[6-7]. Should these old peat C stores rejoin today's active C cycle, they would create a positive feedback on warming. However, the fate of the global peat-C store remains disputed, mainly because of uncertainties that pertain to permafrost dynamics in the high latitudes as well as land-use and land-cover changes (LULCC) in the boreal, temperate, and tropical regions[8].

Peatland C stocks and fluxes have yet to be incorporated into Earth System Models (ESMs), though they are beginning to be implemented in global terrestrial models[9-10]. As these models are moving towards the integration of permafrost dynamics, LULCC, and other disturbances such as fire, the absence of peatland C dynamics could lead to many problems in the next generation of models (Figure 1a). For example, the omission of organic-rich soils was a key contributor to the inaccurate estimates of organic soil mass, heterotrophic respiration, and methane (CH_4) emissions in recent Climate Model Intercomparison Project (CMIP5) simulations[11]. Likewise, the successful integration of permafrost dynamics into land surface models necessitates the inclusion of peatlands, as the latter occupy approximately 10% of the northern permafrost area and account for at least 20% of the permafrost C stocks[12], of which a sizable fraction is susceptible to wildfire[13]. LULCC scenarios must also account for temperate and tropical peatland degradation to derive better estimates of C fluxes[14] and associated impacts on radiative forcing[15]. The inclusion of peatlands in ESMs should help address the complexity of the interacting, cross-scale drivers of change that control peat-C dynamics and quantify their contribution to a positive C cycle feedback now and in the future.

Peatland conversion and restoration are also not considered in Integrated Assessment Models (IAMs), although there is growing anthropogenic pressure on peatland ecosystems worldwide[16-17]. Atmospheric carbon dioxide (CO_2) emissions associated with degraded peatlands account for 5-10% (0.5-1 GtC) of the global annual anthropogenic CO_2 emissions[18-19], despite their small geographic footprint (Figure 1b). While the preservation of pristine peat deposits would be ideal, the restoration of degraded sites, particularly through rewetting, could prevent additional CO_2 release to the atmosphere and reduce the risk of peat fires[20-21]. Even if restoration leads to C neutrality (i.e., sites stop losing C but do not start gaining it), their global greenhouse gas (GHG) saving potential would be similar to the most optimistic sequestration potential from biochar and cover cropping from all agricultural soils combined[19,22]. As IAMs move towards the integration of nature-based climate solutions to limit global temperature rise, peatland restoration and conservation are poised to gain in importance in those models, as well as in the international political arena[23]. In turn, the socio-economic scenarios developed in IAMs could help inform the role of management interventions on future peatland use and guide policy options to best inform the implementation of GHG emission control strategies for decision makers. Ultimately, these model outputs will help predict the effect of peatland management on the global C cycle.

[insert Figure 1 here; if possible, we would like this figure to be "2-column-wide"]

Here, we review the main agents of change of peatland C stocks and fluxes, including drivers that can induce rapid peatland C losses (peat fire, land-use change, and permafrost thaw) and gradual drivers that can lead to rapid, nonlinear responses in peatland ecosystems (temperature increases, water table drawdowns, sea-level rise, and nutrient addition) (Figure 2). We use an expert elicitation to assess the perceived importance of these agents of change on C stocks, asking one question: "What is the relative role of each agent of change for shifting the peatland C balance in the past, present, and future?" Estimates are based on responses from 44 peat experts (see SI for details). Four time periods are studied: post-LGM (21,000 yr BP – 1750 CE), Anthropocene (1750-2020 CE), rest of this century (2020-2100 CE), and far future (2100-2300 CE). The confidence and expertise levels are tallied for each of the experts' responses (Tables S6 to S9; Figure S2), along with the sources that guided their estimates (Appendix 4). Arithmetic means and 80% central ranges (10th to 90th percentiles) are presented in the text and in Figure 3; other measures of central tendencies can be found in Tables S4 and S5. While central values provide order-of-magnitude estimates that may be useful to the reader, the strength of this elicitation is in its ability to identify where experts agree and disagree, and to recognize ranges of responses across experts. Thus, the elicitation findings can inform how integrating peatlands into modeling frameworks such as ESMs and IAMs could advance peatland process understanding and further test hypotheses that emerge from different schools of thought.

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Drivers of Peatland Carbon Stocks since the Last Glacial Maximum

During the post-LGM time period, experts consider temperature the most important long-term driver of peat accumulation in extra-tropical peatlands (arithmetic mean = 524 (10th – 90th percentiles = 60 to 890) GtC; Figure 3). A positive moisture balance is deemed a necessary condition for peatland development, maintenance, and C preservation (238 (10 to 570) GtC). Several respondents comment that it is difficult, if not impossible, to separate the respective role of these two agents of change (Appendix 3). This exemplifies the need to integrate peatlands in ESMs, as cross-scale interactions between agents of change on peatland C dynamics could be further evaluated. Permafrost is also thought to be of importance due to its capacity to inhibit peat decay in northern high-latitude peatlands (218 (-14 to +531) GtC). That said, experts note that permafrost also likely contributes to slower C accumulation rates (when compared to non-permafrost sites); permafrost also possibly contributes to peat erosion in regions where wind-drifted snow and ice crystals can abrade dry peat surfaces[24]. The large range of values for permafrost (Figure S1) stems from the fact that some respondents attribute the entire permafrost peatland C pool to the presence of permafrost itself, while others attribute the C pool mainly to temperature and moisture, with permafrost aggradation playing the secondary role of protecting C stocks. In the tropics, experts suggest that long-term peat C sequestration is mainly driven by moisture availability (268 (24 to 360) GtC), with wetter conditions slowing down peat decomposition. Temperature and sea-level are identified as secondary agents promoting peat formation and growth (43 (0 to 128) GtC and 7 GtC (-13 to +52), respectively). Estimates for the net role of sea-level on tropical C stocks is near zero because some of the rapid C accumulation rates following sea-level rise in certain regions are counterbalanced by C losses due to continental shelf flooding and associated peat erosion or burial in other regions[25] (Figure 3).

These results are largely corroborated by the literature review. On the basis of extensive paleo records, we know that peatlands have spread across vast landscapes following the LGM[4]. As long as sufficient moisture conditions are maintained, warmer and longer growing seasons can contribute to increases in plant productivity and peat burial in many extra-tropical regions[26-28], but to enhanced decomposition and carbon loss in the tropics[29-30], where growing season length and temperature are not limiting factors for photosynthesis[1,31]. Indeed, water saturation is a key control on oxygen availability in peat and on plant community composition, and thus an important determinant for CO_2 and CH_4 emissions and on net ecosystem C balance in both intact and drained peatlands[32-34]. Soil moisture excess is a necessary condition for long-term peat development; surface wetness must remain sufficient to minimize aerobic respiration losses and provide conditions inhibiting the activity of phenol oxidase[35]. In the tropical and mid-latitude regions, water table depth is recognized as the main agent driving long-term peat accumulation[36-38]. At the regional scale, the literature review tells us that sea-level rise may either lead to net C losses[39] or net C gains[40]. For example, sea-level decline in the tropics[41] and land uplift following deglaciation in the north[42] contributed to peat expansion over the past 5000 years. Conversely, in the (sub-) tropics, sea-level rise can drive groundwater levels up regionally, which allows coastal peatlands to expand and accrete at greater rates[43-44]. This process, which took place during the previous interglacial[25] and other past warm climates, is likely to be most pronounced in the large coastal peatlands of the (sub-)tropics. While tectonic subsidence can lead to vast accumulations of lignite over millions of years[45-46], its conjunction with rapid sea-level rise, rapid subsidence, or peat surface collapse due to water abstraction or LUC can lead to peatland loss[47-48]. In general, sea-level rise has been suggested to be a threat for coastal peatlands[49-50], as these systems have limited capacity to move inland because of topography or human development.

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Drivers of Peatland Carbon Stocks during the Anthropocene

During the Anthropocene, short-term peat C losses across the northern high latitudes are linked to LUC (-7 (-23 to 0) GtC) and fire (-3 (-8 to 0) GtC) by the experts (Figure 3). As for permafrost dynamics, small C gains (2 (0 to 10) GtC) are suggested, though many experts warn that large and rapid losses of old C have only recently begun and are expected to increase in the future (Appendix 3). Peat drainage for agriculture, forestry, industrial-scale peat extraction, and grazing were identified as the main sources of anthropogenic pressure on these peatlands (Figure 3). While peat C lost to human activity must have been considerable during the pre-Industrial time and the start of the Industrial era across Europe, historical reports are too few to provide a reliable estimate[18]. In this case, LULCC simulations from IAMs could reduce this uncertainty, or provide several scenarios. The C loss to fire is attributed to an increase in both natural and anthropogenic burning. Similarly, the main suggested causes of peat C losses in the tropics are LUC (-8 (-14 to -2) GtC) and fire (-4 (-10 to 0) GtC). Despite these losses, the trend suggests that northern high-latitude peatlands have persisted as C sinks throughout the Anthropocene. Experts primarily attribute the net C gain across the northern high latitudes to faster accumulation rates induced by longer and warmer growing conditions from climate warming (16 (0 to 38) GtC). An increase in moisture from greater precipitation is suggested as an additional agent leading to C gain in the Arctic, though several experts mention C losses due to drought across the boreal and mid-latitude regions; an overall increase of 11 (-1 to +31) GtC from moisture is suggested by the survey respondents. Lastly, nitrogen (N) deposition and other atmospheric pollution are thought to have a negligible impact (<1 (-1 to +1) GtC) on the peatland C sink capacity worldwide.

The importance of permafrost and fire seen in the expert elicitation are reflected in the main findings from the literature review. For instance, across the northern high-latitude regions, increasing air temperatures and winter precipitation have been linked to a >50% reduction in palsa or peat plateau area since the late 1950s[51-53], although this is variable by region[54]. In general, thermokarst landforms such as ponds or collapse-scar wetlands with saturated soils form when ice-rich peat thaws and collapses. These mainly anaerobic environments are characterized by high CH_4 emissions[55-57]; mass-balance accounting for C stocks indicates as much as 25-60% of “old” permafrost C is lost in the years to decades following thaw[58-60]. Over time, increased C sequestration and renewed peat accumulation occurs in drained thermokarst lake basins[61-62] and collapse-scar wetlands, but it can take decades to centuries and sometimes millennia for collapse-scar wetlands to transition from having a positive (warming) to a negative (cooling) net radiative forcing[59,63]. Moreover, the combustion of peat layers has led to direct losses of plant and peat C (Figure 3). Fire-derived emissions can be substantial, exceeding biological emissions from peat decomposition in some years[64]. The highest emissions are observed from drained tropical peatlands in extreme dry years such as the 1997 El Niño (810-2570 TgC yr^{-1})[65] and the 2015 fire season (380 Tg C yr^{-1})[66] in Indonesia. However, as a result of drainage, peat fires are even observed in wet years[67]. Although peat C losses from northern peat fires are smaller (e.g., 5 TgC yr^{-1} from Alaskan wetlands)[68], there is a need to consider wildfires in permafrost thaw dynamics due to their effects on soil temperature regime[69]. Peatland surface drying, both as a result of droughts and human activity, has been shown to increase the frequency and extent of peat fires[13,70], which could lead to deeper burns and hindered recovery[71] as well as peat water repellency[72]. In terms of LUC, it is well accepted that widespread peatland conversion, drainage, and mining across the temperate and tropical regions has led to large C losses[73-76], in addition to immediate ecosystem damage and land subsidence[47,77]. While most peatland management practices result in decreased CH_4 emissions due to drainage[32], peatland inundation or rewetting can lead to episodic CH_4 releases[78-79]. Lastly, the structure and function of peatlands are now threatened by increased N availability and atmospheric phosphorus (P) deposition[80] from anthropogenic emissions[81]. For example, *Sphagnum* moss cover dies off after a few years of sustained N loading[82-84]; changes in climate can exacerbate these negative effects[85]. Changes in microbial communities and litter quality associated with N deposition can also contribute to increased decomposition[86-87] by lowering the peatland surface[88] and causing a rise in the water table and CH_4 emission[89]. Conversely, a study reported C gain with modest N deposition in a Swedish peatland, driven by a greater increase in plant production than in decomposition[90], illustrating differences, and perhaps a threshold response, in C balance response to N deposition.

Quantification of Future Peatland Stocks

During the rest of this century (2020 – 2100 CE) and the far future (2100 – 2300 CE), experts expect the C loss mechanisms presented above to be amplified (Figure 3). In the northern high latitudes, while C gains are still linked to shifts in temperature and precipitation (17 (-16 to +47) and 3 (-37 to +32) GtC, respectively), C losses to fire are expected (-7 (-10 to 0) GtC). Many respondents suggest that better fire management could mitigate this. These losses are predicted to be accompanied by additional ones from permafrost degradation (-30 (-102 to +12) GtC), sea-level rise that would inundate coastal peatlands (-3 (-9 to +1) GtC), and LUC (-14 (-38 to +3) GtC). The latter, and primarily drainage for agriculture, is expected to cause significant peatland C losses, though many experts expect the rate to slow with increasing conservation and restoration efforts. Regional drought-induced C losses are also suggested for the mid-latitude regions. In the tropics, experts generally agree that every agent of change will negatively impact C stocks. Net peat C losses are predicted due to warmer temperatures (-22 (-14 to +4) GtC; mean skewed outside 10th – 90th percentile range by an outlier), fires (-23 (-54 to -2) GtC), negative moisture balance (-9 (-31 to +3) GtC), and sea-level rise (-3 (-5 to 0) GtC). Of particular importance is the evolution of the El Niño Southern Oscillation, as El Niño droughts may lead to substantial C losses to the atmosphere. LUC (-13 (-44 to +3) GtC) is also predicted to play a key role in the future, as it could lead to the drainage of large peat basins, such as the Amazon and Congo.

Experts' confidence in their predictions declines for the far future (Tables S6 and S7; Figure S2), in part due to the lack of models capable of simulating the effect of agents of change on peatland C stocks, but also because policy and land management decisions will influence the future of peatlands. This is an area where the integration of peatlands into IAMs would allow the generation of pertinent scenarios to help inform the science, as well as policy options and land management decisions. A growing world population may put additional pressure on peatlands, as farming becomes possible at higher latitudes, and further deforestation may occur in the tropics, but the need to conserve peat resources may eventually outweigh these pressures. In this case, the adoption of policies designed to protect peatlands would greatly limit C losses. Likewise, the pricing of C could change the way peatlands are perceived, valued, and managed. These diverging opinions are all included in our assessment (Appendix 3), but explicit IAM simulations would allow exploration of different policies and socio-economic scenarios. Noteworthy is that extra-tropical peatlands could play an important role, second only to the oceans, in reducing the global atmospheric CO_2 concentration if cumulative anthropogenic emissions are kept below 1000 GtC[91-92]. Mitigation is therefore highly important in counterbalancing the climate impact of peatland C loss[93].

Insights from the Expert Elicitation and their Limits

Expert assessment is critical to inform decisions that require judgements that go beyond established knowledge and model simulations[94]. For this reason, expert opinion is often used in environmental assessments either as a means to assess confidence levels or rank potential outputs[7], or as data points that offer estimates that could not be provided otherwise[95,96]. This expert assessment also highlights key knowledge gaps and uncertainties such as, for example, the impact of permafrost aggradation and degradation on the future peatland C balance (see SI and Figure S1). Our dataset reflects two main schools of thought that are anchored in conflicting evidence from the literature: (1) rapid C loss from deep peats and a slow recovery of the peatlands following permafrost thaw[59-60], and (2) net C gain from rapidly recovering plant production due to warm and moist conditions following thaw[1,28]. Overall, results from the expert elicitation can be used to help prioritize which ecosystem mechanisms and properties should be integrated into ESMs; in turn, those model outputs will help constrain the peat-carbon-climate feedback and inform future data collection strategies.

Our results indicate low to medium confidence in future C flux estimates. Confidence levels are highest for the post-LGM and Anthropocene time periods, in part reflecting the majority of paleo researchers in the survey respondents, but also because of compounding uncertainties pertaining to future levels of GHG emissions from the energy and land systems, patterns of land-use change, etc., which are affected by social, economic, political, and policy drivers (Appendix 3). The overall confidence levels for the post-LGM and Anthropocene is medium (a value of 3 on a scale of 1 to 5); even highly self-rated experts (4-5) give low to medium confidence to some of their answers, which could suggest great uncertainty based on current literature (Tables S6 and S7, Figures S2, S3). For the rest of this century and the far future, confidence drops to low (a value of 2), likely reflecting the low confidence in our projection of human-based decisions (Figure S2, Appendix 3). Areas of research for which expertise is lowest include LUC, N deposition, and atmospheric pollution (Tables S8 and S9, Figure S2), which may have contributed to some of the low confidence levels mentioned above. Here again, results from the expert elicitation provide a unique opportunity to generate pertinent socio-economic scenarios that will help inform our science, policy options, and land management decisions.

While this present assessment may be used as a bridge towards policy –decisions need to be made even when uncertainty is high and confidence is low – we are not interested in offering “consensus statements” on peatland C storage. Rather, our intent is to contribute a novel perspective that identifies the central tendencies, communicates uncertainties, and highlights contradictions to improve peat-C process understanding and press the community to add organic soils and peatland plant functional types in ESMs and IAMs (see SI for further discussion). Overall, results from the expert elicitation can help prioritize which ecosystem mechanisms and properties should be integrated into ESMs; in turn, those model outputs will help constrain the peat-carbon-climate feedback, inform future data collection strategies, and advance understanding by further testing different hypotheses. As such, the inclusion of peatland process understanding in models, and particularly better attribution of the role of each agent of change on peatland C dynamics, would help increase confidence in C flux predictions. Modeling efforts that include peatland dynamics would improve ESM and IAM outputs and benefit the peatland and climate research communities, in a positive feedback loop.

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Acknowledgements

This work developed out of the PAGES (Past Global Changes) C-PEAT (Carbon in Peat on EArth through Time) working group; we acknowledge support from PAGES funded by the US and Swiss National Science Foundations. We also thank INQUA (International Union for Quaternary Research) and the Department of Geography at Texas A&M University for workshop support. We thank Patrick Campbell for creating the peatland infographic, as well as Dave McGuire, Katharine Mach, and three anonymous reviewers for their comments on previous versions of the manuscript. We also acknowledge Universidad Javeriana (J.C.B.) and research support from US NSF grants 1802838 (J.L.), 1019523 (J.L.B.), and 1802825 (C.T. and S.F), UK NERC grants NE/1012915 and NE/S001166/1 (A.G.-S. and D.J.C.), PAI/SIA 77180002 CONICYT and Nexer-UMag grant 7718002 (C.A.M.), US Geological Survey Land Resources R&D (M.C.J.), Natural Sciences and Engineering Research Council of Canada (S.F., T.L., and J.W.), National Science Centre of Poland grant 2015/17/B/ST10/01656 (M.L.), Academy of Finland projects 286731 and 319262 (T.L.), Fonds Wetenschappelijk Onderzoek grant 1167019N (W.S.), the Office of international affairs and global network at Chulalongkorn University (S.C.), and the Alexander von Humboldt Foundation (M.B.), World Bank AHEAD DOR grant (A.S.R.), and the Swiss National Science Foundation grant #200020_172476 (F.J. and J.M.).

Author Contributions

J.L., A.G.-S., M.A., and G.M. performed the majority of analyses and wrote the majority of the manuscript. D.B., J.C.B., J.B., P.C., D.J.C., S.C., A.G.-S., A.H., T.K., A.K., D.L., J.L., C.A.M., J.M., S.v.B., J.B.W., and Z.Y. formulated the research goals and ideas during the 2018 C-PEAT workshop in Texas. J.L.B., M.G., T.M., A.B.K.S., S.P., M.V., A.H., S.J., T.L., A.L., K.M., and C.T.

wrote parts of the Review section. Other co-authors contributed with unpublished data or completed the expert opinion survey. All co-authors contributed to data analysis and writing of the manuscript. All survey data generated and analyzed during this study are available from the corresponding author on reasonable request. The references used to generate the maps for this study are included in the supplementary information files of this article.

Data Availability

The authors declare that data supporting the findings of this study are available within the supplementary information files; anonymized survey data are available from the corresponding authors upon request.

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Figure Captions

Figure 1: Integrating peatland knowledge in climate change modeling frameworks. A conceptual structure of (a) an Earth System Model (ESM), and (b) an Integrated Assessment Model (IAM). The ESM emphasizes peatland carbon, energy, water, and nutrient pools and exchanges with the atmosphere, aquatic/freshwater systems, and the world's oceans. The IAM focuses on the importance of considering peatlands in policy options and land management decisions, as these carbon-rich ecosystems can significantly contribute to GHG emission reduction strategies. Grey arrows represent fluxes with important contribution from peatlands; white arrows represent non-peatland fluxes; ES: ecosystem services; GDP: gross domestic product; GHG: greenhouse gas.

Figure 2: The main agents of change impacting the global peatland carbon balance globally. Using an expert elicitation combined with a literature review, the importance of each agent in the past, present, and future is semi-quantitatively assessed in this study. Infographic created by Patrick Campbell. For a high-resolution image without text details and a brief review of each agent of change, see Appendix 5.

Figure 3: Expert assessment of the global peatland carbon balance over time. Changes in carbon stocks are shown for the extra-tropical northern region (blue) and the (sub-)tropical region (yellow) for the post-LGM (21,000 BP – 1750 CE), Anthropocene (1750 – 2020 CE), Near Future / Rest of this Century (2020 – 2100 CE), and Far Future (2100 – 2300 CE). Agents of change: temperature (T), moisture (M), sea-level (SL), fire (F), land use (LU), permafrost (P), nitrogen deposition (N), atmospheric pollution (AP). Columns: arithmetic means; error bars: 80% central range. Positive values represent carbon sinks to the atmosphere. Individual survey responses are shown in Figure S1.