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Expert assessment of future vulnerability of the global peatland carbon sink

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Abstract

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 that are used for future climate change projections, and they are not considered in integrated assessment models that are used in impact and mitigation studies. By 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 in the far future. We also identify uncertainties and knowledge gaps in the scientific community and provide insight towards better integration of peatlands into modelling frameworks. Given the importance of the contribution by peatlands 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.

Main text

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) (ref. 1) is equivalent to ~1% of human fossil fuel emissions, or 3–10% of the current net sink of natural terrestrial ecosystems2. However, and despite occupying only 3% of the global land area3, peatlands contain about 25% (600 GtC) of the global soil C stock4, which is equivalent to twice the amount in the world's forests5. 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 landscapes4. 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 Holocene6,7. 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 regions8.

Peatland C stocks and fluxes have yet to be incorporated into Earth system models (ESMs), although they are beginning to be implemented in global terrestrial models9,10. 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 (Fig. 1a). For example, the omission of organically rich soils was a key contributor to the inaccurate estimates of organic soil mass, heterotrophic respiration and methane (CH4) emissions in recent Climate Model Intercomparison Project Phase 5 (CMIP5) simulations11. 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 stocks12, of which a sizable fraction is susceptible to wildfire13. LULCC scenarios must also account for temperate and tropical peatland degradation to derive better estimates of C fluxes14 and associated impacts on radiative forcing15. 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 worldwide16,17. Atmospheric carbon dioxide (CO2) emissions associated with degraded peatlands account for 5–10% (0.5–1 GtC) of the global annual anthropogenic CO2 emissions18,19, despite their small geographic footprint (Fig. 1b). Although the preservation of pristine peat deposits would be ideal, the restoration of degraded sites, particularly through rewetting, could prevent additional CO2 release to the atmosphere and reduce the risk of peat fires20,21. Even if restoration leads to C neutrality (that is, sites stop losing C but do not start gaining it), their GHG-saving potential would be similar to that of the most optimistic sequestration from biochar and cover cropping from all agricultural soils combined19,22. 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 arena23. In turn, the socio-economic scenarios developed in IAMs could help inform the role of management interventions in future peatland use and could 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.

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 (LUC), and permafrost thaw) and gradual drivers that can lead to rapid, nonlinear responses in peatland ecosystems (temperature increase, water table drawdown, sea-level rise, and nutrient addition) (Fig. 2). We use an expert elicitation to assess the perceived importance of these agents of change on C stocks, and ask one question: ‘What is the relative role of each agent of change in shifting the peatland C balance in the past, present and future?’ Estimates are based on responses from 44 peat experts (see Supplementary Information for details). Four time periods are studied: post-LGM (21,000 yr bp to 1750 CE), Anthropocene (1750–2020 CE), remainder 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 (Supplementary Tables S6 and S9), along with the sources that guided their estimates (Supplementary Information Appendix 4). Arithmetic means and 80% central ranges (10th to 90th percentiles) are presented (below and in Fig. 3), as well as other measures of central tendencies (Supplementary Tables S4 and S5). Central values provide order-of-magnitude estimates that may be useful to the reader, but the strength of this elicitation is in its ability to identify where experts agree and disagree, and to recognize ranges of responses across experts. Therefore, the elicitation findings can inform how integrating peatlands into modelling frameworks such as ESMs and IAMs could advance peatland process understanding and further test hypotheses that emerge from different schools of thought.

Drivers of peatland carbon stocks since the Last Glacial Maximum

For the post-LGM time period, experts consider temperature to be the most important long-term driver of peat accumulation in extra-tropical peatlands (arithmetic mean = 524 GtC; 10th to 90th percentiles = 60 GtC to 890 GtC) (Fig. 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 roles of these two agents of change (Supplementary Information Appendix 3). This exemplifies the need to integrate peatlands in ESMs, as cross-scale interactions between agents of change on peatland C dynamics could then be evaluated further. Permafrost is also thought to be of importance owing to its capacity to inhibit peat decay in northern high-latitude peatlands (218 (−14 to +531) GtC). That said, experts note that permafrost also probably contributes to lower 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 surfaces24. The large range of values for permafrost (Extended Data Fig. 1) stems from the fact that some respondents attribute the entire permafrost peatland C pool to the presence of permafrost itself, whereas others attribute the C pool mainly to temperature and moisture, with permafrost aggradation playing the secondary role of protecting C stocks. Experts suggest that, in the tropics, long-term peat C sequestration is driven mainly by moisture availability (268 (24 to 360) GtC), with wetter conditions slowing down peat decomposition. Temperature (43 (0 to 128) GtC) and sea level (7 (−13 to +52) GtC) are identified as secondary agents promoting peat formation and growth. Estimates for the net role of sea level on tropical C stocks are near zero because some of the high C accumulation rates following sea-level rise in certain regions are counterbalanced by C losses owing to continental shelf flooding and associated peat erosion or burial in other regions25 (Fig. 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 LGM4. 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 regions26–28, but can contribute to enhanced decomposition and carbon loss in the tropics29,30 where the growing season length and temperature are not limiting factors for photosynthesis1,31. Indeed, water saturation is a key control on oxygen availability in peat and on plant community composition, and therefore an important determinant for CO2 and CH4 emissions and for net ecosystem C balance in both intact and drained peatlands worldwide32–34. Soil moisture excess is a necessary condition for long-term peat development; surface wetness must remain sufficient to minimize aerobic respiration losses and to provide conditions that inhibit the activity of phenol oxidase35. In the tropical and mid-latitude regions, water table depth is recognized as the main agent driving long-term peat accumulation36–38. The literature review tells us that, at the regional scale, sea-level rise may lead to either net C losses39 or net C gains40. For example, sea-level decline in the tropics41 and land uplift following deglaciation in the North42 contributed to peat expansion over the past 5,000 years. Conversely, in the (sub-)tropics, sea-level rise can drive up groundwater levels regionally, which allows coastal peatlands to expand and accrete at greater rates43,44. This process, which took place during the previous interglacial25 and other past warm climates, is likely to be most pronounced in the large coastal peatlands of the (sub-)tropics. Tectonic subsidence can lead to vast accumulations of lignite over millions of years45,46, but its conjunction with rapid sea-level rise, rapid subsidence or peat surface collapse due to water abstraction or LUC can lead to peatland loss47,48. In general, sea-level rise has been suggested to be a threat for coastal peatlands49,50, as these systems have limited capacity to move inland because of topography or human development.

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 (Fig. 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 (Supplementary Information 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 (Fig. 3). The loss of peat C to human activity must have been considerable during the pre-industrial time and the start of the industrial era across Europe, but historical reports are too few to provide a reliable estimate18. In this case, LULCC simulations from IAMs could reduce this uncertainty or provide several scenarios. The loss of C 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 attribute the net C gain across the northern high latitudes primarily to greater peat accumulation rates that are 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 that leads to C gain in the Arctic, although 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. Finally, 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 revealed in the expert elicitation is 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 greater than 50% reduction in palsa or peat plateau area since the late 1950s51–53, although this varies by region54. 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 CH4 emissions55–57; mass-balance accounting for C stocks indicates as much as 25–60% of ‘old’ permafrost C is lost in the years to decades that follow thaw58–60. Over time, increased C sequestration and renewed peat accumulation occur in drained thermokarst lake basins61,62 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 forcing59,63. Moreover, the combustion of peat layers has led to direct losses of plant and peat C. Fire-derived emissions can be substantial, exceeding biological emissions from peat decomposition in some years64. The highest emissions are observed from drained tropical peatlands in extremely dry years such as the 1997 El Niño period (810–2570 TgC yr−1) (ref. 65) and the 2015 fire season (380 TgC yr−1) (ref. 66) in Indonesia. However, as a result of drainage, peat fires are observed even in wet years67. Although peat C losses from northern peat fires are smaller than those from tropical peat fires (for example, 5 TgC yr−1 from Alaskan wetlands)68, there is a need to consider wildfires in permafrost thaw dynamics because of their effects on soil temperature regime69. Peatland surface drying, as a result of both droughts and human activity, has been shown to increase the frequency and extent of peat fires13,70, which could lead to deeper burns and hindered recovery71 as well as peat water repellency72. In terms of LUC, it is well accepted that widespread peatland conversion, drainage and mining across the temperate and tropical regions have led to large C losses73–76, in addition to immediate ecosystem damage and land subsidence47,77. Most peatland management practices result in decreased CH4 emissions owing to drainage32, but peatland inundation or rewetting can lead to episodic CH4 releases78,79. Finally, the structure and function of peatlands are now threatened by increased N availability and atmospheric phosphorus (P) deposition80 from anthropogenic emissions81. For example, Sphagnum moss cover dies off after a few years of sustained N loading82–84, and changes in climate can exacerbate these negative effects85. Changes in microbial communities and litter quality associated with N deposition can also contribute to increased decomposition86,87 by lowering the peatland surface88 and causing a rise in the water table and CH4 emission89. Conversely, a study reported a net C gain with modest N deposition in a Swedish peatland, which was driven by a greater increase in plant production than in decomposition90; this illustrates differences, and perhaps a threshold response, in C balance response to N deposition.

Quantification of future peatland stocks

Experts anticipate that, during the remainder of this century (2020– 2100 CE) and in the far future (2100–2300 CE), the C loss mechanisms presented above will be amplified (Fig. 3). In the northern high latitudes, whereas 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, are expected to cause substantial peatland C losses, although many experts anticipate the rate to decrease with increasing conservation and restoration efforts. Regional drought-induced C losses are also suggested for the mid-latitude regions. For the tropics, experts generally agree that every agent of change will negatively impact C stocks. Net peat C losses are predicted owing to higher temperatures (−22 (−14 to +4) GtC; the mean is 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.

The confidence of experts in their predictions declines for the far future (Supplementary Tables S6 and S7, and Extended Data Fig. 2), in part because of 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. In this area, 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 (Supplementary Information 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 CO2 concentration if cumulative anthropogenic emissions are kept below 1,000 GtC (refs. 91,92). Mitigation is therefore highly important in counterbalancing the climate impact of peatland C loss93.

Insights from the expert elicitation and their limits

Expert assessment is critical for informing decisions that require judgements that go beyond established knowledge and model simulations94. For this reason, expert opinion is often used in environmental assessments, either as a means to assess confidence levels or rank potential outputs7 or as data points that offer estimates that could not be provided otherwise95,96. This expert assessment also highlights key knowledge gaps and uncertainties, for example in the impact of permafrost aggradation and degradation on the future peatland C balance (see Supplementary Information and Extended Data Fig. 1). Our dataset reflects two main schools of thought that are anchored in conflicting evidence from the literature: rapid C loss from deep peats and slow recovery of the peatlands following permafrost thaw59,60, and net C gain from rapidly recovering plant production owing to warm and moist conditions following thaw1,28.

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 among the survey respondents, and in part because of compounded uncertainties that pertain to future levels of GHG emissions from the energy and land systems, patterns of LUC and so on, as these emissions are affected by social, economic, political and policy drivers (Supplementary Information Appendix 3). The overall confidence level for the post-LGM and Anthropocene is medium (a value of 3 on a scale of 1 to 5); even respondents who rate themselves highly as experts (score of 4 or 5) give low to medium confidence to some of their answers, which could suggest great uncertainty based on current literature (Supplementary Tables S6 and S7, and Extended Data Figs. 2 and 3). For the remainder of this century and the far future, confidence drops to low (a value of 2), which probably reflects the low confidence in our projection of human-based decisions (Supplementary Information Appendix 3 and Extended Data Fig. 2). Areas of research for which expertise is lowest include LUC, N deposition and atmospheric pollution (Supplementary Tables S8 and S9, and Extended Data Fig. 2), 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.

Although the present assessment may be used as a bridge towards policy (as 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; we anticipate this will improve understanding of the peat C process and press the community to add organic soils and peatland plant functional types in ESMs and IAMs (see Supplementary Information for further discussion).

Overall, results from the expert elicitation can help determine which ecosystem mechanisms and properties should be prioritized and 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 in peatland C dynamics, would help increase confidence in C flux predictions. Modelling 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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Data availability

Data supporting the findings of this study, as well as references used to generate the maps, are available within the supplementary information files. All anonymized survey data generated and analysed during this study are available from the corresponding authors upon request.

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Author contributions

J. Loisel, A.V.G.-S., M.J.A. and G.M. performed most of the analyses and wrote most of the manuscript. D.B., J.C.B., J. Blewett, P.C., D.J.C., S.C., A.V.G.-S., A. Hedgpeth, T.K., A.K., D.L., J. Loisel, C.A.M., J.M., S.v.B., J.B.W. and Z.Y. formulated the research goals

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Competing interests

The authors declare no competing interests.

Additional information

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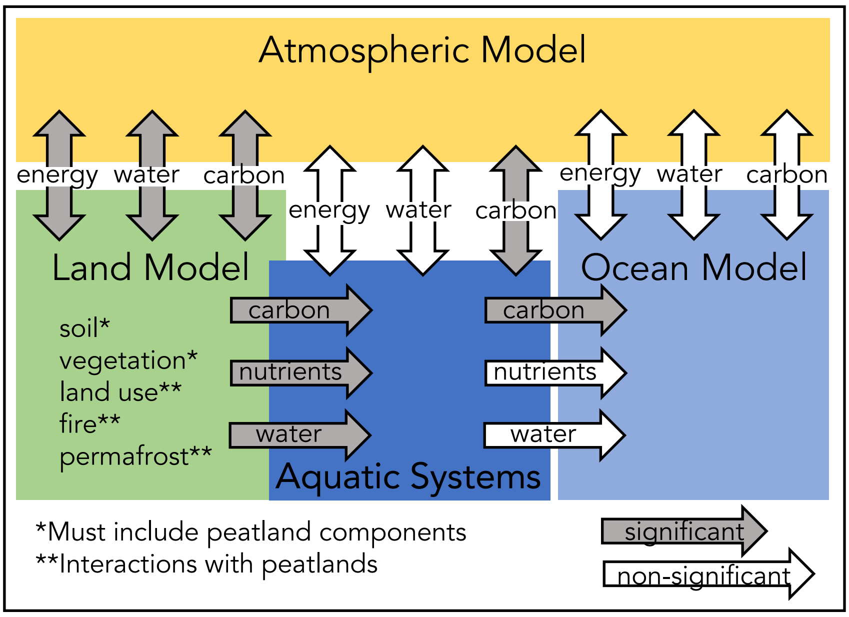
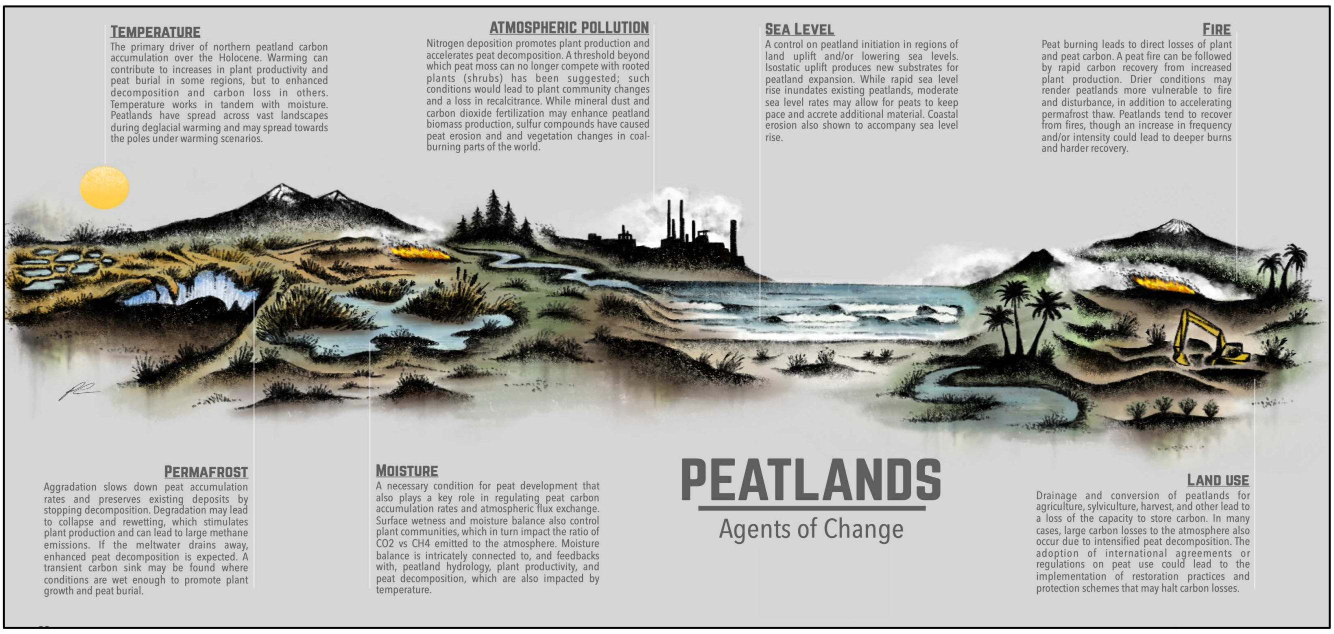


Figure 1: A conceptual structure of an Earth System Model schematic showing carbon, energy, water, and nutrient pools and transfers across the fast (non-deep time) model components. In addition to their key role in the global C cycle (CO_2, CH_4, DOC), peatlands actively contribute to energy, water, and nutrient exchanges with the atmosphere, the hydrosphere, and the world's oceans. Peatland-related stocks and fluxes across these pools are important, particularly when considering land-use change and other landscape processes such as permafrost dynamics and fire disturbance. Grey arrows represent fluxes with a significant contribution from peatlands; white arrows represent non-significant peatland fluxes.



PEATLANDS

Agents of Change

TEMPERATURE

The primary driver of northern peatland carbon accumulation over the Holocene. Warming can contribute to increases in plant productivity and peat burial in some regions, but to enhanced decomposition and carbon loss in others. Temperature works in tandem with moisture. Peatlands have spread across vast landscapes during deglacial warming and may spread towards the poles under warming scenarios.

ATMOSPHERIC POLLUTION

Nitrogen deposition promotes plant production and accelerates peat decomposition. A threshold beyond which peat moss can no longer compete with rooted plants (shrubs) has been suggested; such conditions would lead to plant community changes and a loss in recalcitrance. While mineral dust and carbon dioxide fertilization may enhance peatland biomass production, sulfur compounds have caused peat erosion and and vegetation changes in coal-burning parts of the world.

SEA LEVEL

A control on peatland initiation in regions of land uplift and/or lowering sea levels. Isostatic uplift produces new substrates for peatland expansion. While rapid sea level rise inundates existing peatlands, moderate sea level rates may allow for peats to keep pace and accrete additional material. Coastal erosion also shown to accompany sea level rise.

FIRE

Peat burning leads to direct losses of plant and peat carbon. A peat fire can be followed by rapid carbon recovery from increased plant production. Drier conditions may render peatlands more vulnerable to fire and disturbance, in addition to accelerating permafrost thaw. Peatlands tend to recover from fires, though an increase in frequency and/or intensity could lead to deeper burns and harder recovery.

PERMAFROST

Aggradation slows down peat accumulation rates and preserves existing deposits by stopping decomposition. Degradation may lead to collapse and rewetting, which stimulates plant production and can lead to large methane emissions. If the meltwater drains away, enhanced peat decomposition is expected. A transient carbon sink may be found where conditions are wet enough to promote plant growth and peat burial.

MOISTURE

A necessary condition for peat development that also plays a key role in regulating peat carbon accumulation rates and atmospheric flux exchange. Surface wetness and moisture balance also control plant communities, which in turn impact the ratio of CO2 vs CH4 emitted to the atmosphere. Moisture balance is intricately connected to, and feedbacks with, peatland hydrology, plant productivity, and peat decomposition, which are also impacted by temperature.

LAND USE

Drainage and conversion of peatlands for agriculture, sylviculture, harvest, and other lead to a loss of the capacity to store carbon. In many cases, large carbon losses to the atmosphere also occur due to intensified peat decomposition. The adoption of international agreements or regulations on peat use could lead to the implementation of restoration practices and protection schemes that may halt carbon losses.

<u>Figure 2</u>: The main agents of change impacting peatlands globally. Infographic created by Patrick Campbell.

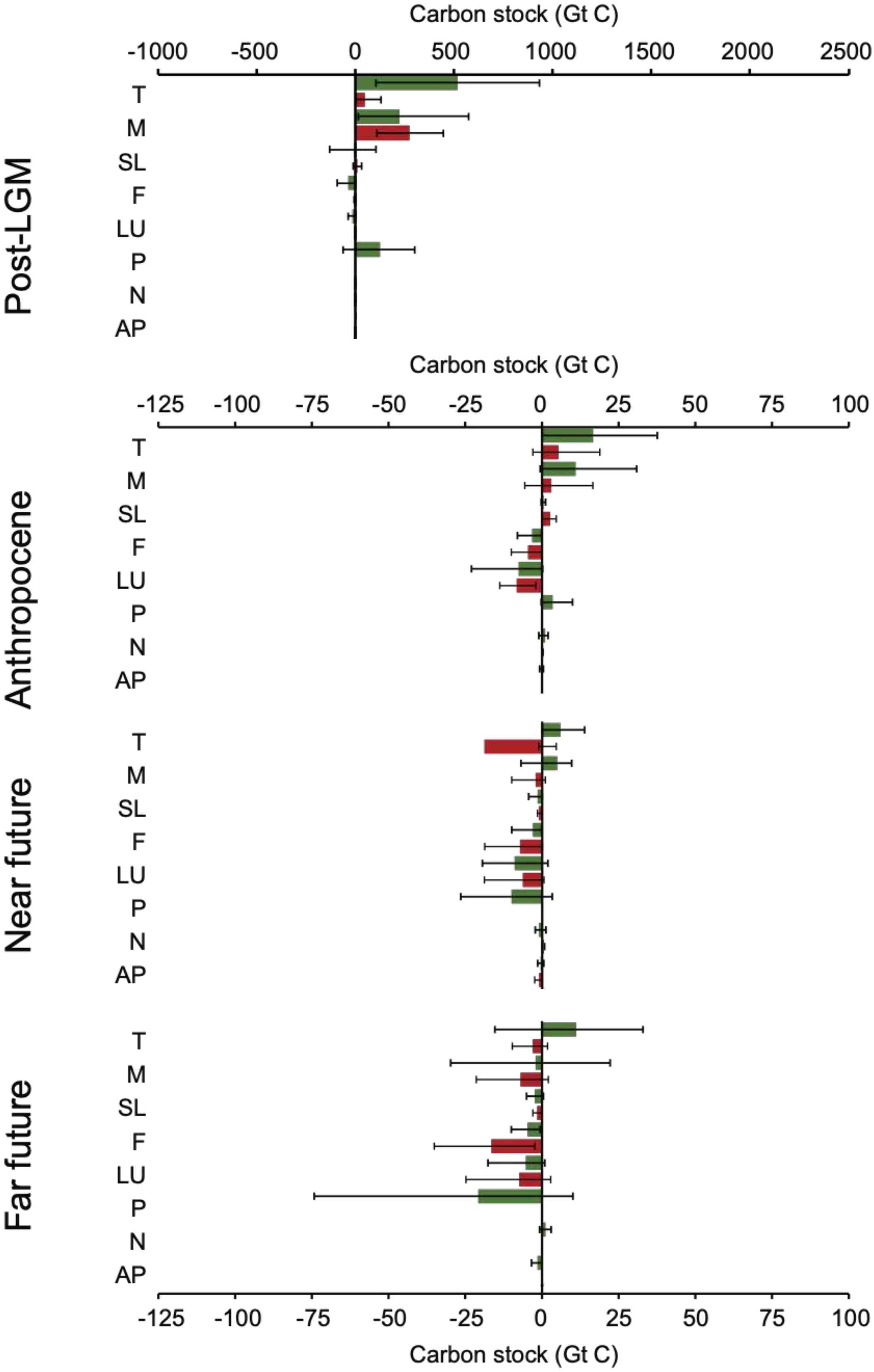


Figure 4: The global peatland carbon (C) balance over time and its main agents of change. Changes in C stocks are shown for the extra-tropical northern region (in green) and the (sub-)tropical region (in red). Changes in C stocks for the (a) post-LGM warming (21,000 – 1750 CE), (b) Anthropocene (1750 – 2020 CE), (c) Near Future (2020 – 2100 CE), and (d) Far Future (2100 – 2300 CE) are shown. The agents of change are temperature (T), moisture (M), sea-level (SL), fire (F), land-use (LU), permafrost (P), nitrogen deposition (N), and atmospheric pollution (AP). Columns represent arithmetic mean values; error bars represent the 80% central range. Positive values are considered C sinks; negative values are considered C sources to the atmosphere.