Expert assessment of future vulnerability of the global peatland carbon sink

Authors
Loisel, J.[1*], Gallego-Sala, A.V.[2*], Amesbury, M.J. [2,3], Magnan, G.[4], Anshari, G.[5], Beilman, D.[6], Benavides, J.C.[7], Blewett, J.[8], Camill, P.[9], Charman, D.J.[2], Chawchai, S.[10], Hedgpeth, A.[11], Kleinen, T.[12], Korhola, A.[3], Large, D.[13], Mansilla, C.A.[14], Müller, J.[15], van Bellen, S.[4], West, J.B.[1], Yu, Z.[16], Bubier, J.[17], Garneau, M.[4], Moore, T.[18], Sannel, A.B.K.[19], Page, S.[20], Väliranta, M.[3], Bechtold, M.[21], Brovkin, V.[12], Cole, L.E.S.[22], Chanton, J.P.[23], Christensen, T.R.[24], Davies, M.A.[25], De Vleeschouwer, F.[26], Finkelstein, S.A.[25], Frolking, S.[27], Gałka, M.[28], Gandois, L.[29], Girkin, N.[13], Harris, L.I.[18], Heinemeyer, A.[30], Hoyt, A.M.[31,32], Jones, M.C.[33], Joos, F.[15], Juutinen, S.[3], Kaiser, K.[34], Lacourse, T.[35], Lamentowicz, M.[36], Larmola, T.[37], Leifeld, J.[38], Lohila, A.[3], Milner, A.M.[39], Minkkinen, K.[3], Moss, P.[40], Naafs, B.D.A.[8], Nichols, J.[41], O'Donnell, J.[42], Payne, R.[30†], Philben, M. [43], Piilo S.[3], Quillet, A.[2], Ratnayake, A.S.[44], Roland, T.[2], Sjögersten, S.[13], Sonnentag, O.[45], Swindles, G.T.[46], Swinnen, W.[21], Talbot, J.[45], Treat, C.[27], Valach, A.C.[47], Wu, J.[48].

Affiliations
[1]Texas A&M University, USA
[2]University of Exeter, UK
[3]University of Helsinki, Finland
[4]Université of Quebec – Montreal, Canada
[5]Tanjungpura University, Indonesia
[6]University of Hawaii at Manoa, USA
[7]Pontificia Universidad Javeriana, Colombia
[8]University of Bristol, UK
[9]Bowdoin College, USA
[10]Chulalongkorn University, Thailand
[11]University of California – Los Angeles, USA
[12]Max Planck Institute for Meteorology, Germany
[13]University of Nottingham, UK
[14]Universidad de Magallanes, Chile
[15] Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[16]Lehigh University, USA
[17]Mount Holyoke College, USA
[18]McGill University, Montreal, Canada
[19]Stockholm University, Sweden
[20]University of Leicester, UK
[21]Department of Earth and Environmental Sciences, KU Leuven, Belgium
[22]University of St Andrews, UK
[23]Florida State University, USA
[24]Aarhus University, Denmark
[25]University of Toronto, Canada
[26]Instituto Franco-Argentino para el Estudio del Clima y sus Impactos (UMI IFAECI/CNRS-CONICET-UBA-IRD), Argentina
[27]University of New Hampshire, USA
[28]University of Lodz, Poland
[29]EcoLab, University of Toulouse, France
[30]Stockholm Environment Institute, University of York, UK
[31]Max Planck Institute for Biogeochemistry, Germany
[32]Lawrence Berkeley National Laboratory, USA
[33]United States Geological Survey – Reston, USA
[34]Texas A&M University – Galveston, USA

[35]University of Victoria, Canada
[36]Adam Mickiewicz University – Poznań, Poland
[37]Natural Resources Institute Finland (Luke), Finland
[38]Agroscope, Switzerland
[39]Royal Holloway University of London, UK
[40]University of Queensland, Australia
[41]Lamont-Doherty Earth Observatory, USA
[42]National Park Service, USA
[43]Hope College, USA
[44]Uva Wellassa University, Sri Lanka
[45]University of Montreal, Canada
[46]Queen's University, UK
[47]University of California – Berkeley, USA
[48]Grenfell Campus, Memorial University, Canada
[†]Submitted posthumously

Corresponding authors

Julie Loisel
Department of Geography, Texas A&M University, 3147 TAMU, O&M Building, Room 810, College Station TX-77843, USA
julieloisel@tamu.edu, +1 (979) 845-7141
ORCID: 0000-0002-8861-4618

Angela Gallego-Sala
Department of Geography, College of Life and Environmental Sciences, University of Exeter, Rennes Drive, Exeter, EX4 1RJ, UK
a.gallego-sala@exeter.ac.uk, +44 (0)1392 725873
ORCID: 000-0002-7483-7773

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.

[insert Figure 2 here; if possible, we would like this figure to be "3-column-wide"]

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.

[insert Figure 3 here; if possible, we would like this figure to be "2-column-wide"]

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.

Correspondence Statement

Correspondence and requests for materials should be addressed to Julie Loisel or Angela Gallego-Sala.

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.

References

1- Gallego-Sala A.V., Charman D.J., Brewer S., Page S.E., Prentice I.C., Friedlingstein P., Moreton S., Amesbury M.J., Beilman D.W., Björck S., Blyakharchuk T., Bochicchio C., Booth R.K., Bunbury J., Camill P., Carless D., Chimner R.A., Clifford M., Cressey E., Courtney-Mustaphi E., De Vleeschouwer F., de Jong R., Fialkiewicz-Koziel B., Finkelstein S.A., Garneau M., Githumbi E., Hribjlan J., Holmquist J., Hughes P.D.M., Jones C., Jones M.C., Karofeld E., Klein E.S., Kokfelt U., Korhola A., Lacourse T., Le Roux G., Lamentowicz M., Large D., Lavoie M., Loisel J., Mackay H., MacDonald G.M., Mäkilä M., Magnan G., Marchant R., Marcisz K., Martínez Cortizas A., Massa C., Mathijssen P., Mauquoy D., Mighall T., Mitchell F.J.G., Moss P., Nichols J., Oksanen P.O., Orme L., Packalen M.S., Robinson S., Roland T.P., Sanderson N.K., Sannel A.B.K., Silva-Sánchez N., Steinberg N., Swindles G.T., Turner T.E., Uglow J., Väliranta M., van Bellen S., van der Linden M., van Geel B., Wang G., Yu Z., Zaragoza-Castells J., Zhao Y. 2018. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change*, doi:10.1038/s41558-018-0271-1.

2- Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (Eds). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

3- Xu J., Morris P.J., Liu J., Holden J. 2018. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, 1(160):134-140.

4- Yu Z., Loisel J., Brosseau D.P., Beilman D.W., Hunt S.J. 2010. Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37, L13402, doi:10.1029/2010GL043584.

5- Pan Y., Birdsey R.A., Fang J., Houghton R., Kauppi P.E., Kurz W.A., Phillips O.L., Shvidenko A., Lewis S.L., Canadell J.G., Ciais P., Jackson R.B., Pacala S.W., McGuire D., Piao S., Rautiainen A., Sitch S., Hayes D. 2011. A large and persistent carbon sink in the world's forests. *Science*, 333(6045):988-993.

6- Frolking S., Roulet N., Fuglestvedt S. 2006. How northern peatlands influence the Earth's radiative budget: sustained methane emission versus sustained carbon sequestration. *Journal of Geophysical Research* 111, G01008, doi:10.1029/2005JG000091.

7- IPCC. 2013. In: Stocker T.F., Qin D., Plattner G.-K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V., Midgley P.M. (Eds.). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, p. 1535.

8- Frolking S., Talbot J., Jones M.C., Treat C.C., Kauffman J.B., Tuittila E.-S., Roulet N. 2011. Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, 19:371-396.

9- Kleinen T., Brovkin V., Schuldt R.J. 2012. A dynamic model of wetland extent and peat accumulation: Results for the Holocene, *Biogeosciences*, 9, 235–248, doi:10.5194/bg-9-235-2012.

10- Müller J. Joos, F. 2020. Peatland area and carbon over the past 21 000 years – a global process based model investigation, *Biogeosciences Discuss*., doi:10.5194/bg-2020-110.

11- Todd-Brown K.E., Randerson J.T., Post W.M., Hoffman F.M., Tarnocai C., Schuur E.A., Allison S.D. 2013. Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. *Biogeosciences*, 10(3), 1717-1736, doi.org/10.5194/bg-10-1717-2013.

12- Hugelius G., Loisel J., Chadburn S., Jackson R., MacDonald G., Marushchak M., Packalen M., Siewert M., Treat C., Turetsky M., Voigt C., Yu Z. 2020. Northern peatlands and permafrost thaw: effects on carbon and nitrogen stocks and fluxes. *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.1916387117.

13- Turetsky M.R., Benscoter B., Page S., Rein G., van der Werf, G.R., Watts A. 2015. Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, 8, 11-14. doi:10.1038/ngeo2325

14- Miettinen J., Shi C., Liew S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, 6, 67-78, doi.org/10.1016/j.gecco.2016.02.004.

15- Dommain R., Frolking S., Jeltsch-Thommes A., Joos F., Couwenberg J., Glaser P.H. 2018. A radiative forcing analysis of tropical peatlands before and after their conversion to agricultural plantations. *Global Change Biology*, 24(11), doi: 10.1111/gcb.14400.

16- Page S.E., Baird A.J. 2016. Peatlands and global change: response and resilience. *Annual Review of Environment and Resources*, 20.

17- Warren M., Frolking S., Zhaohua D., Kurnianto S. 2017. Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation. *Mitig. Adapt. Strateg. Glob. Change*, https://doi.org/10.1007/s11027-016-9712-1.

18- Parish F., Sirin A., Charman D., Joosten H., Minayeva T., Silvius M., Stringer L. (Eds.) 2008. *Assessment on Peatlands, Biodiversity and Climate Change: Main Report.* Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

19- Leifeld J., Menichetti L. 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communication*, 9, 1071. https://doi.org/10.1038/s41467-018-03406-6.

20- Nugent K.A., Strachan I.B., Roulet N.T., Strack M., Frolking S., Helbig M. 2019. Prompt active restoration of peatlands substantially reduces climate impact. *Environmental Research Letters*, 2019 14(12):124030.

21- Günther A., Barthelmes A., Huth V., Joosten H., Jurasinski G., Koebsch F., Couwenberg J. 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature communications*, 11(1):1-5.

22- Bossio D.A., Cook-Patton S.C., Ellis P.W., Fargione J., Sanderman J., Smith P., Wood S., Zomer R.J., von Unger M., Emmer I.M., Griscom B.W. 2020. The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3(5):391-398.

23- Joosten H., Couwenberg J., von Unger M. 2016. International carbon policies as a new driver for peatland restoration, pp. 291-313. In: Bonn, A. et al. (Eds.) *Peatland Restoration and Ecosystems: Science, Policy, and Practice*, Ecological Reviews, Cambridge University Press.

24- Seppälä M. 2003. Surface abrasion of palsas by wind action in Finnish Lapland. *Geomorphology*, 52, 141-148. doi:10.1016/S0169-555X(02)00254-4.

25- Treat C., Kleinen T., Broothaerts N., Dalton A.S., Dommain R., Douglas T.A., Drexler J.Z., Finkelstein S.A., Grosse G., Hope G., Hutchings J., Jones M.C., Kuhry P., Lacourse T., Lähteenoja O., Loisel J., Notebaert B., Payne R.J., Peteet D.M., Sannel A.B.K., Stelling J.M., Strauss J., Swindles G.T., Talbot J., Tarnocai C., Verstraeten G., Williams C.J., Xia Z., Yu Z., Väliranta M., Hättestrand M., Alexanderson H., Brovkin V. 2019. Widespread global peatland establishment and persistence over the last 130,000 y. *Proceedings of the National Academy of Sciences USA*, 116 (11) 4822-4827, doi:10.1073/pnas.1813305116.

26- Beilman D.W., MacDonald G.M., Smith L.C., Reimer P.J. 2009. Carbon accumulation in peatlands of West Siberia over the last 2000 years. *Global Biogeochemical Cycles 23*, GB1012. doi: 10.1029/2007GB003112.

27- Loisel J., Gallego-Sala A.V., Yu Z. 2012. Global-scale pattern of peatland *Sphagnum* growth driven by photosynthetically active radiation and growing season length. *Biogeosciences*, 9, 2737–2746, doi:10.5194/bg-9-2737-2012.

28- Charman D., Beilman D., Blaauw M., Booth R.K., Brewer S., Chambers F., Christen J.A., Gallego-Sala A.V., Harrison S.P., Hughes P.D.M., Jackson S., Korhola A., Mauquoy D., Mitchell F., Prentice I.C., van der Linden M., De Vleeschouwer F., Yu Z., Alm J., Bauer I.E., McCorish Y., Garneau M., Hohl V., Huang Y., Karofeld E., Le Roux G., Loisel J., Moschen R., Nichols J.E., Nieminen T.M., MacDonald G.M., Phadtare N.R., Rausch N., Sillasoo Ü., Swindles G.T., Tuittila E.-S., Ukonmaanaho L., Väliranta M., van Bellen S., van Geel B., Vitt D., Zhao Y. 2013. Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences* 10: 929-944. doi: 10.5194/bg-10-929-2013.

29- Jauhiainen J., Kerojoki O., Silvennoinen H., Limin S. Vasander H. 2014. Heterotrophic respiration in drained tropical peat is greatly affected by temperature – a passive ecosystem cooling experiment. *Environmental Research Letters*, 9, doi:10.1088/1748-9326/9/10/105013.

30- Wang S., Zhuang Q., Lähteenoja O., Draper F.C., Cadillo-Quiroz H. 2018. Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. *Proceedings of the National Academy of Sciences*, 115, 12407-12412.

31- Sjögersten S., Aplin P., Gauci V., Peacock M., Siegenthaler A., Turner B.L. 2018. Temperature response of ex-situ greenhouse gas emissions from tropical peatlands: interactions between forest type and peat moisture conditions. *Geoderma*, 324, 47-55.

32- Couwenberg J., Dommain R., Joosten H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, 16, 1715-1732, doi: 10.1111/j.1365-2486.2009.02016.x

33- Carlson K.M., Goodman L.K., May-Tobin C.C. 2015. Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. *Environmental Research Letters*, 10, 074006, doi:10.1088/1748-9326/10/7/074006.

34- Hoyt A.M., Gandois L., Eri J., Kai F.M., Harvey C.F., Cobb A.R. 2019. CO_2 emissions from an undrained tropical peatland: Interacting influences of temperature, shading and water table depth. *Global Change Biology*, 25, 2885–2899, doi: 10.1111/gcb.14702.

35- Freeman C., Ostle N.J., Kang H. 2001 An enzymatic 'latch' on a global carbon store. *Nature*, 409, 149.

36- Lund M., Christensen T.R., Lindroth A., Schubert P. 2012. Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. *Environmental Research Letters*, 7, 045704.

37- Cobb A.R., Hoyt A.M., Gandois L., Eri J., Dommain R., Salim K.A., Kai F.M., Su'ut N.S.H., Harvey C.F. 2017. How temporal patterns in rainfall determine the geomorphology and carbon fluxes of tropical peatlands. *Proc. Natl. Acad. Sci.,* E5187-E5196.

38- Dargie G.C., Lewis, S.L., Lawson I.T., Mitchard E.T.A., Page S.E., Bocko Y.E., Ifo S.A. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*, 542, 86-90.

39- Henman J., Poulter B. 2008. Inundation of freshwater peatlands by sea level rise: uncertainty and potential carbon cycle feedbacks. *Journal of Geophysical Research* 113 G01011.

40- Rogers K., Kelleway J.J., Saintillan N., Megonigal P., Adams J.B., Holmquist J.R., Lu M., Schile-Beers L., Zawadzki A., Mazumder D., Woodroffe C.D. 2019. Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, 567, 91-96.

41- Dommain R., Couwenberg J., Joosten H. 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, 30, 999–1010.

42- Packalen M.S., Finkelstein S.A. 2014. Quantifying Holocene variability in carbon uptake and release since peat initiation in the Hudson Bay Lowlands, Canada. *The Holocene*, 24, 1063-1074.

43- Grundling P. 2004. The role of sea-level rise in the formation of peatlands in Maputaland. *In: Boletim Geológico* 43, Ministerio dos Recursos Minerais e Energia, Direccao Geral de Geologia Mozambique, 58–67.

44- Kirwan M.L., Mudd S.M. 2012. Response of salt-marsh carbon accumulation to climate change. *Nature*, 489, 550-553.

45- Briggs J., Large D.J., Snape C., Drage T., Whittles D., Cooper M., Macquaker J.H.S., Spiro B.F. 2007. Influence of climate and hydrology on carbon in an early Miocene peatland. *Earth and Planetary Science Letters*, 253, 445-454.

46- Lähteenoja O., Reátegu Y.R., Räsänen M., Torres D.D.C., Oinonen M., Page. S. 2011. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. *Global Change Biology*, 18, 164-178, doi: 10.1111/j.1365-2486.2011.02504.x

47- Hooijer A., Page, S., Jauhiainen J., Lee W.A., Lu X.X., Idris A., Anshari G. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*, 9, 1053-1071.

48- Whittle A., Gallego-Sala A. 2016. Vulnerability of the peatland carbon sink to sea-level rise. *Scientific Reports* 6, 28758, doi.org/10.1038/srep28758.

49- Blankespoor B., Dasgupta S., Laplante B. 2014. Sea-level rise and coastal wetlands. *Ambio*, 43, 996-1005.

50- Spencer, T., Schürch, M., Nicholls, R. J., Hinkel, J., Vafeidis, A., Reef, R., McFadden, L., & et al. 2016. Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Global and Planetary Change,* 139 15-30. https://doi.org/10.1016/j.gloplacha.2015.12.018

51- Zuidhoff F.S., Kolstrup E. 2000. Changes in palsa distribution in relation to climate change in Laivadalen, northern Sweden, especially 1960-1997. *Permafrost and Periglacial Processes*, 11, 55-69.

52- Payette S., Delwaide A., Caccianiga M., Beauchemin M. 2004. Accelerated thawing of subarctic peatland permafrost over the last 50 years. *Geophysical Research Letters*, 31(18), L18208, doi:10.1029/2004GL020358.

53- Borge A.F., Westermann S., Solheim I., Etzelmüller B. 2017. Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years. *The Cryosphere*, 11, 1-16, doi:10.5194/tc-11-1-2017.

54- Cooper M.D.A., Estop-Aragones C., Fisher J.P., Thierry A., Garnett M.H., Charman D.J., Murton J.B., Phoenix G.K., Treharne R., Kokelj S.V., et al. 2017. Limited contribution of permafrost carbon to methane release from thawing peatlands. *Nature Climate Change*, 7, 507-511.

55- Bubier J., Moore T., Bellisario L., Comer N.T., Crill P.M. 1995. Ecological controls on methane emissions from a northern peatland complex in the zone of discontinuous permafrost, Manitoba, Canada. *Global Biogeochemical Cycles,* 9, 455-470.

56- Christensen T.R., Johansson T., Åkerman H.J., Mastepanov M., Malmer N., Friborg T., Crill P., Svensson B.H. 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters*, 31, L04501, doi:10.1029/2003GLO18680.

57- Olefeldt D., Turetsky M.R., Crill P.M., McGuire A.D. 2013. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. *Global Change Biology*, 19, 589-603, doi: 10.1111/gcb.12071.

58- O'Donnell J.A., Jorgenson M.T., Harden J.W., McGuire A.D., Kanevskiy M., Wickland K.P. 2012. The effects of permafrost thaw on soil hydrologic, thermal, and carbon dynamics in an Alaskan peatland. *Ecosystems*, 15: 213-229. doi: 10.1007/s10021-011-9504-0.

59- Jones M.C., Harden J., O'Donnell J., Manies K., Jorgenson T., Treat C., Ewing, S. 2017. Rapid carbon loss and slow recovery following permafrost thaw in boreal peatlands. *Global Change Biology*, 23, 1109-1127.

60- Turetsky M.R., Abbott B.W., Jones M.C., Walter Anthony K., Olefeldt D., Schuur E.A.G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D.M., Gibson C., Sannel A.B.K., McGuire A.D. 2020. Carbon release through abrupt permafrost thaw. *Nature Geoscience*, 13, 138-143, doi : 10.1038/s41561-019-0526-0.

61- Jones M.C., Grosse G., Jones B.M., Walter Anthony K. 2012. Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. *Journal of Geophysical Research – Biogeosciences*, 117, G00M07, doi:10.1029/2011JG001766.

62- Walter Anthony K.M., Zimov S.A., Grosse G., Jones M.C., Anthony P.M., Chapin III F.S., Finlay J.C., Mack M.C., Davydov S., Frenzel P., Frolking S. 2014. A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature*, 511, 452-456, doi:10.1038/nature13560.

63- Turetsky M.R., Wieder R.K., Vitt D.H., Evans R.J., Scott K.D. 2007. The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. *Global Change Biology*, 13(9), 1922-1934, doi:10.1111/j.1365-2486.2007.01381.x.

64- Rossi S., Tubiello F.N., Prosperi P., Salvatore M., Jacobs H., Biancali R., House J.I., Boschetti L. 2016. FAOSTAT estimates of greenhouse gas emissions from biomass and peat fires. *Climatic Change*, 135(3-4): 699,711.

65- Page S., Siegert F., Rieley J. *et al.* 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420, 61–65, doi:10.1038/nature01131.

66- Field R.D., van der Werf G.R., Fanin T., Fetzer E.J., Fuller R., Jethva H., Levy R., Livesey N.J., Luo M., Torres O., Worden H.M. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proceedings of the National Academy of Sciences*, 113(33): 9204-9209.

67- Gaveau D.L.A., Salim, M.A., Hergoualc'h K., Locatelli B., Sloan S., Wooster M., Marlier M.E., Molidena E., Yaen H., DeFries R., Verchot L., Murdiyarso D., Nasi R., Holmgren P., Sheil D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Scientific Reports,* 4, 6112.

68- Lyu Z., Genet H., He Y., Zhuang Q., McGuire D., Bennett A., Breen A., Clein J., Euskirshen E.S., Johnson K., Kurkowski T., Pastick N.J., Rupp S., Wylie B.K., Zhu Z. 2019. The role of environmental driving factors in historical and projected carbon dynamics of wetland ecosystems in Alaska. *Ecological Applications*, 28(6), 1377-1395.

69- Gibson C.M., Chasmer L.E., Thompson D.K., Quinton W.L., Flannigan M.D., Olefeldt D. 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications*, 9, 3041.

70- Dadap N.C., Cobb A.R., Hoyt A.M., Harvey C.F., Konings A.G. 2019. Satellite soil moisture observations predict burned area in Southeast Asian peatlands. *Environmental Research Letters*, 14, 094014, doi.org/10.1088/1748-9326/ab3891

71- Zaccone C., Guillermo R., D'Orazio V., Hadden R.M., Belcher C.M., Miano T.M. 2014. Smouldering fire signatures in peat and their implications for palaeoenvironmental reconstructions. *Geochimica Cosmochimica Acta*, 137, 134-146.

72- Kettridge N., Humphrey R.E., Smith J.E., Lukenbach M.C., Devito K.J., Petrone R.M., Waddington J.W. 2014. Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire. *Journal of Hydrology*, 513, 335-341.

73- Koh L.P., Miettinen J., Liew S.C., Ghazoul J. 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. *Proc. Natl. Acad. Sci.*, 201018776, doi.org/10.1073/pnas.1018776108.

74- Rooney R.C., Bayley S.E., Schindler D.W. 2012. Oil sands mining and reclamation cause massive loss of peatland and stored carbon. *Proceedings of the National Academies of Sciences of the USA*, 109(13), 4933-4937, doi.org/10.1073/pnas.1117693108.

75- Turunen J. 2008. Development of Finnish peatland area and carbon storage 1950-2000. *Boreal Environmental Research*, 13, 319-334.

76- Wild B., Andersson A., Bröder L., Vonk J., Hugelius G., McClellan J.W., Song W., Raymond P.A., Gustafsson Ö. 2019. Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. *Proc. Nat. Aca. Sci..*,116(21), 10280-10285.

77- Hoyt A.M., Chaussard E., Seppalainen S.S., Harvey C.F. 2020. Widespread subsidence and carbon emissions across Southeast Asian peatlands. *Nature Geoscience*, 13, 435-440.

78- Tuittila E.-S., Komulainen V.-M., Vasander H., Nykänen H., Martikainen P.J., Laine J. 2000. Methane dynamics of a restored cut-away peatland. *Global Change Biology*, 6, 569-581.

79- Waddington J.M., Day S.M. 2007. Methane emissions from a peatland following restoration. *Journal of Geophysical Research*, 112, G03018, doi:10.1029/2007JG000400.

80- Vet, R., Artz, R. S., Carou, S., Shaw, M., Ro, C. U., Aas, W., and Hou, A. 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*, 93, 3-100.

81- Dentener F., Drevet J., Lamarque J.F., Bey I., Eickhout B., Fiore A.M., Hauglustaine D., Horowitz W.W., Krol M., Kulshrestha U.C., Lawrence M., Galy-Lacaux C., Rast S., Shindell D., Stevenson D., Van Noije T., Atherton C., Bell N., Bergman D., Butler T., Cofala J., Collins B., Doherty R., Ellingsen K., Galloway J., Gausee M., Montanaro V., Müller J.F., Pitari G., Rodriguez J., Sanderson M., Solmon F., Strahan S., Schultz M., Sudo K., Szopa S., Wild O. 2006. Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation. *Global Biogeochem. Cycles*, GB4003, http://dx.doi.org/10.1029/ 2005GB002672.

82- Bubier J., Moore T., Bledzki L. 2007. Effects of nutrient addition on vegetation and carbon cycling in an ombrotrophic bog. *Global Change Biology*, 13: 1168-1186, doi: 10.1111/j.1365-2486.2007.01346.x.

83- Juutinen S., Moore T.R., Laine A., Bubier J.L., Tuittila E., De Young A., Chong M. 2016. Responses of mosses *Sphagnum capillifolium* and *Polytrichum strictum* to nitrogen deposition in a bog: height growth, ground cover, and CO_2 exchange. *Botany* 94, 127-138, dx.doi.org/10.1139/cjb-2015-0183.

84- Wieder R.K., Vitt D.H., Vile M.A., Graham J.A., Hartsock J.A., Fillingim H., House M., Quinn J.C., Scott K.D., Petix K.D., McMillen K.J. 2019. Experimental nitrogen addition alters structure and function of a boreal bog: critical load and thresholds revealed. *Ecological Monographs*, 89(3):e01371, doi:10.1002/ecm.1371.

85- Limpens J., Granath G., Gunnarson U., Aerts R., Bayley S., Bragazza L., Bubier J., Buttler A., van den Berg L., Francez A.-J., Gerdol R., Grosvernier P., Heijmans M.M.P.D., Hoosbeek M.R., Hotes S., Ilomets M., Leith I., Mitchell E.A.D., Moore T., Nilsson M.B., Nordbakken J.-F., Rochefort L., Rydin H., Sheppard L.J., Thormann M., Wiedermann M.M.Williams B., Xu B. 2011. Climatic modifiers of the response to N deposition in peat-forming Sphagnum mosses: a meta-analysis. *New Phytologist*, 191, 496-507, doi: 10.1111/j.1469-8137.2011.03680.x.

86- Larmola T., Bubier J.L., Kobyljanec C., Basiliko N., Juutinen S., Humphreys E., Preston M., Moore T.R. 2013. Vegetation feedbacks of nutrient deposition lead to a weaker carbon sink in an ombrotrophic bog. *Global Change Biology*, 19, 3729-3739.

87- Pinsonneault, A.J., Moore T.R., Roulet N.T. 2016. Effects of long-term fertilization on belowground stoichiometry and microbial enzyme activity in an ombrotrophic bog. *Biogeochemistry*, 129, 149-164. doi: 10.1007/s10533-016-0224-6.

88- Bragazza L., Freeman C., Jones T., Rydin H., Limpens J., Fenner N., Ellis T., Gerdol R., Hájek M., Hájek T., Iacumin P., Kutnar L., Tahvanainen T., Toberman H. 2006. Atmospheric nitrogen deposition promotes carbon loss from peat bogs. *Proceedings of the National Academy of Sciences*, 103, 19386–19389.

89- Juutinen S., Moore T.R., Bubier J.L., Arnkil S., Humphreys W., Marincak B., Roy C., Larmola T. 2018. Long-term nutrient addition increased CH_4 emission from a bog through direct and indirect effects. *Scientific Reports*, 8:3838, doi:10.1038/s41598-018-22210-2.

90- Olid, C., Nilsson M.B., Eriksson T.,Klaminder J. 2014. The effects of temperature and nitrogen and sulfur additions on carbon accumulation in a nutrient-poor boreal mire: Decadal effects assessed using ^{210}Pb peat chronologies. *J. Geophys. Res. Biogeosci.*, 119, doi:10.1002/2013JG002365.

91- Alexandrov G.A., Brovkin V.A., Kleinen T., Yu Z. 2019. The limits to northern peatland carbon stocks. *Biogeosciences Discussions*. doi:10.5194/bg-2019-76.

92- Griscom B.W., Adams J., Ellis P.W., Houghton R.A., Lomax G., Miteva D.A., Schlesinger W.H., Shoch D., Siikamäki J.V., Smith P., Woodbury P., Zganjar C., Blackman A., Campari J., Conant R.T., Delgado C., Elias P., Gopalakrishna T., Hamsik M.R., Herrero M., Kiesecker J., Landis E., Laestadius L., Leavitt S.M., Minnemeyer S., Polasky S., Potapov P., Putz F.E., Sanderman J., Silvius M., Wollenberg E., Fargione J. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44): 11645-11650.

93- Christensen T.R., Arora V.K., Gauss M., Höglund-Isaksson L., Parmentier F.-J.W. 2019. Tracing the climate signal: mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. *Scientific Reports*, 9, 1146.

94- Mach K.J., Mastrandrea M.D., Freeman P.T., Field C.B. 2017. Unleashing expert judgment in assessment. *Global Environmental Change*, 44, 1-14.

95- Schuur E.A.G., Abbott B.W., Bowden W.B., Brovkin V., Camill P., Canadell J.G., Chanton J.P., Chapin III f.S., Christensen t.R., Ciais P., Crosby B.T., Czimczik C.I., Grosse G., Harden J., Hayes D.J., Hugelius G., Jastrow J.D., Jones J.B., Kleinen T., Koven C.D., Krinner G., Kuhry P., Lawrence D.M., McGuire A.D., Natali S.M., O'Donnell J.A., Ping C.L., Riley W.J., Rinke A., Romanovsky V.E., Sannel A.B.K., C., Schaefer K., Sky J., Subin Z.M., C., Turetsky M.R., Waldrop M.P., Walter Anthony K.M., Wickland K.P., Wilson C.J., Zimov S.A. 2013. Expert assessment of vulnerability of permafrost carbon to climate change. *Climatic Change*, doi:10.1007/s10584-013-0730-7.

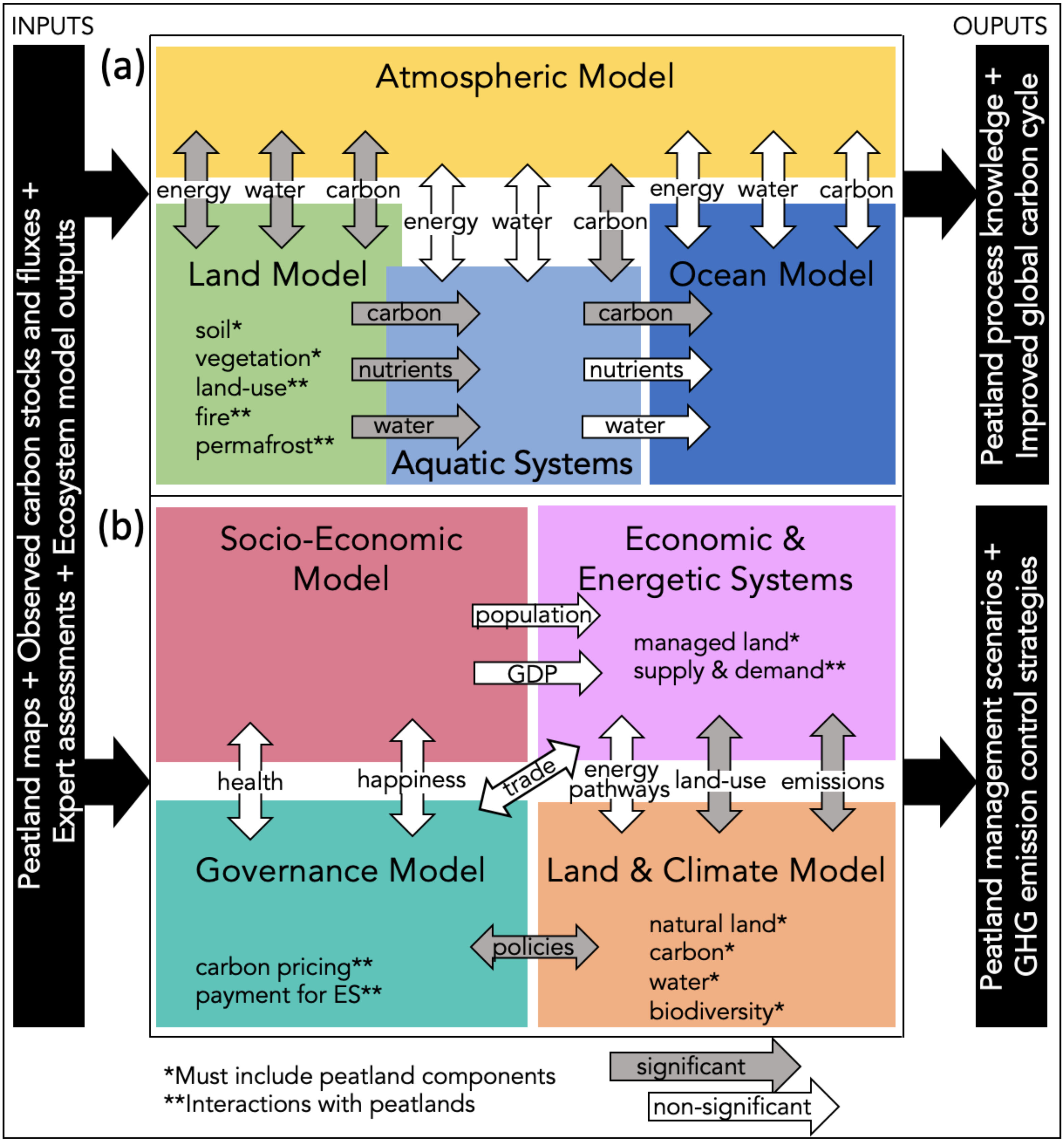
96- Bamber J.L., Oppenheimer M., Kopp R.E., Aspinall W.P., Cooke R.M. 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences of the USA*, doi/10.1073/pnas.1817205116.

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.


INPUTS
OUPUTS
Peatland maps + Observed carbon stocks and fluxes + Expert assessments + Ecosystem model outputs
(a)
Atmospheric Model
energy
water
carbon
energy
water
carbon
energy
water
carbon
Land Model
Ocean Model
carbon
nutrients
water
carbon
nutrients
water
soil*
vegetation*
land-use**
fire**
permafrost**
Aquatic Systems
Peatland process knowledge + Improved global carbon cycle
(b)
Socio-Economic Model
Economic & Energetic Systems
population
GDP
managed land*
supply & demand**
health
happiness
trade
energy pathways
land-use
emissions
Governance Model
Land & Climate Model
policies
carbon pricing**
payment for ES**
natural land*
carbon*
water*
biodiversity*
Peatland management scenarios + GHG emission control strategies
*Must include peatland components
**Interactions with peatlands
significant
non-significant

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

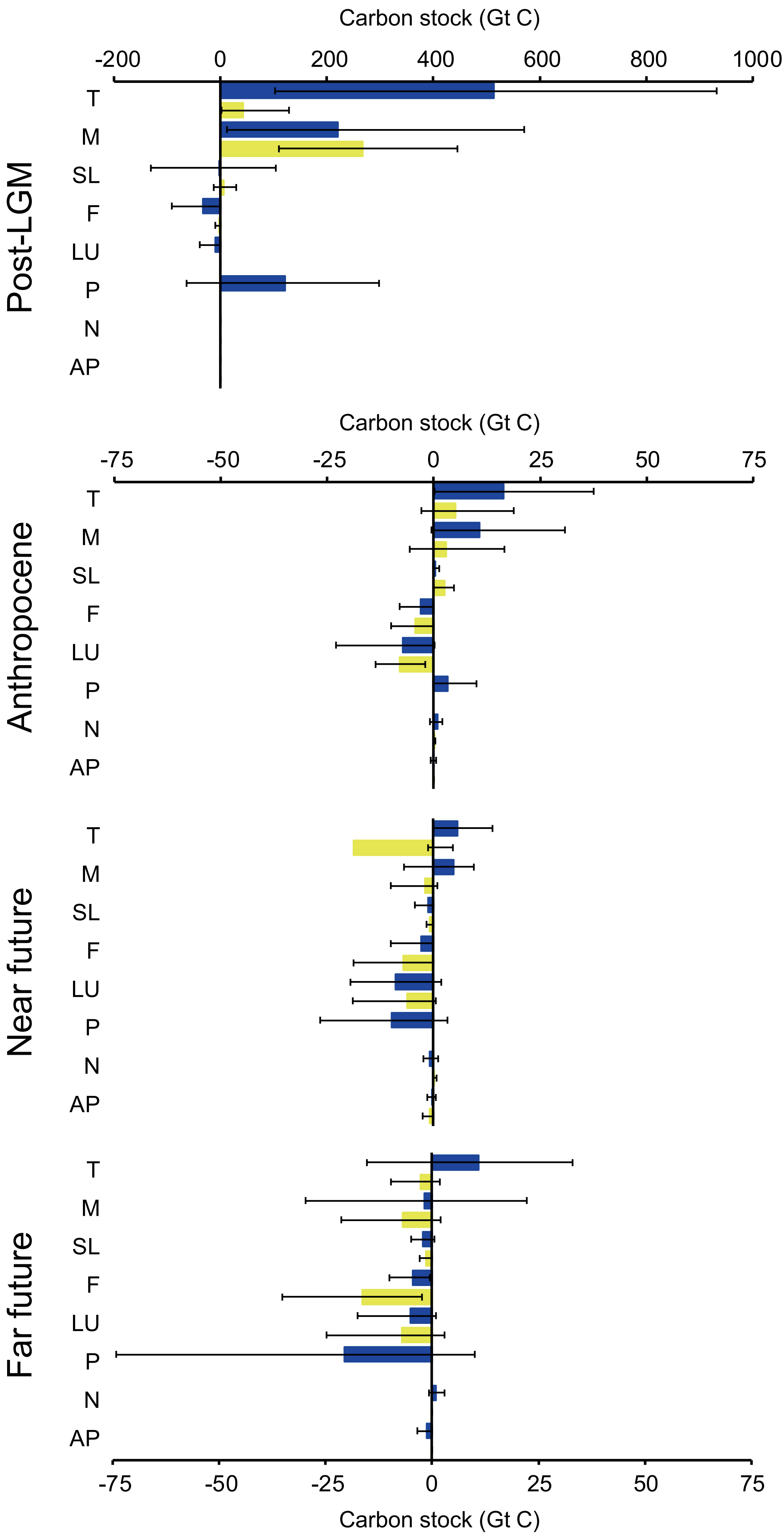
A necessary condition for peat development that also plays a key role in regulating peat carbon accumulation rates and atmospheric flux exchange. Surface wetness and moisture balance also control plant communities, which in turn impact the ratio of CO2 vs CH4 emitted to the atmosphere. Moisture balance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

PEATLANDS

Agents of Change

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.


Carbon stock (Gt C)
-200
0
200
400
600
800
1000
Post-LGM
T
M
SL
F
LU
P
N
AP
Carbon stock (Gt C)
-75
-50
-25
0
25
50
75
Anthropocene
T
M
SL
F
LU
P
N
AP
Near future
T
M
SL
F
LU
P
N
AP
Far future
T
M
SL
F
LU
P
N
AP
-75
-50
-25
0
25
50
75
Carbon stock (Gt C)

Expert assessment of future vulnerability of the global peatland carbon sink

Authors Loisel, J.[1*], Gallego-Sala, A.V.[2*], Amesbury, M.J. [2,3], Magnan, G.[4], Anshari, G.[5], Beilman, D.[6], Benavides, J.C.[7], Blewett, J.[8], Camill, P.[9], Charman, D.J.[2], Chawchai, S.[10], Hedgpeth, A.[11], Kleinen, T.[12], Korhola, A.[3], Large, D.[13], Mansilla, C.A.[14], Müller, J.[15], van Bellen, S.[4], West, J.B.[1], Yu, Z.[16], Bubier, J.[17], Garneau, M.[4], Moore, T.[18], Sannel, A.B.K.[19], Page, S.[20], Väliranta, M.[3], Bechtold, M.[21], Brovkin, V.[12], Cole, L.E.S.[22], Chanton, J.P.[23], Christensen, T.R.[24], Davies, M.A.[25], De Vleeschouwer, F.[26], Finkelstein, S.A.[25], Frolking, S.[27], Gałka, M.[28], Gandois, L.[29], Girkin, N.[13], Harris, L.I.[18], Heinemeyer, A.[30], Hoyt, A.M.[31,32], Jones, M.C.[33], Joos, F.[15], Juutinen, S.[3], Kaiser, K.[34], Lacourse, T.[35], Lamentowicz, M.[36], Larmola, T.[37], Leifeld, J.[38], Lohila, A.[3], Milner, A.M.[39], Minkkinen, K.[3], Moss, P.[40], Naafs, B.D.A.[8], Nichols, J.[41], O'Donnell, J.[42], Payne, R.[30†], Philben, M. [43], Piilo S.[3], Quillet, A.[2], Ratnayake, A.S.[44], Roland, T.[2], Sjögersten, S.[13], Sonnentag, O.[45], Swindles, G.T.[46], Swinnen, W.[21], Talbot, J.[45], Treat, C.[27], Valach, A.C.[47], Wu, J.[48].

Affiliations [1]Texas A&M University, USA, [2]University of Exeter, UK, [3]University of Helsinki, Finland, [4]Université of Quebec – Montreal, Canada, [5]Tanjungpura University, Indonesia, [6]University of Hawaii at Manoa, USA, [7]Pontificia Universidad Javeriana, Colombia, [8]University of Bristol, UK, [9]Bowdoin College, USA, [10]Chulalongkorn University, Thailand , [11]University of California – Los Angeles, USA, [12]Max Planck Institute for Meteorology, Germany, [13]University of Nottingham, UK, [14]Universidad de Magallanes, Chile, [15]Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Switzerland, [16]Lehigh University, USA, [17]Mount Holyoke College, USA, [18]McGill University, Montreal, Canada, [19]Stockholm University, Sweden, [20]University of Leicester, UK, [21]Department of Earth and Environmental Sciences, KU Leuven, Belgium, [22]University of St Andrews, UK, [23]Florida State University, USA, [24]Aarhus University, Denmark, [25]University of Toronto, Canada, [26]Instituto Franco-Argentino para el Estudio del Clima y sus Impactos, Argentina, [27]University of New Hampshire, USA, [28]University of Lodz, Poland, [29]EcoLab, University of Toulouse, France, [30]Stockholm Environment Institute, University of York, UK, [31]Max Planck Institute for Biogeochemistry, Germany, [32]Lawrence Berkeley National Laboratory, USA, [33]United States Geological Survey – Reston, USA, [34]Texas A&M University – Galveston, USA, [35]University of Victoria, Canada, [36]Adam Mickiewicz University – Poznań, Poland, [37]Natural Resources Institute Finland (Luke), Finland, [38]Agroscope, Switzerland, [39]Royal Holloway University of London, UK, [40]University of Queensland, Australia, [41]Lamont-Doherty Earth Observatory, USA, [42]National Park Service, USA, [43]Hope College, USA, [44]Uva Wellassa University, Sri Lanka, [45]University of Montreal, Canada, [46]Queen's University, UK, [47]University of California – Berkeley, USA, [48]Grenfell Campus, Memorial University, Canada, [†]Submitted posthumously.

Main section

The main section of this Supplementary Information (SI) file contains details that pertain to: (1) survey development and justification, (2) survey implementation and responses, (3) survey results, and (4) self-assessment of confidence and expertise. It also includes the Tables and Figures listed below:

*Figures S1, S2, and S3 are also presented as Extended Data.

Appendices

1. Survey development and justification

Members of the IGBP-PAGES C-PEAT working group met at Texas A&M University in May 2018 to discuss the future scientific targets of this community. During this meeting, the participants worked towards identifying the main knowledge gaps in peat science, with an emphasis on tipping points under a changing climate and increasing land-use change. It was determined that, to address these gaps, an assessment of the relative role of each agent of change on the peatland C stock was needed. The key agents of change in peatlands (temperature, moisture balance, sea-level, fire, land-use, permafrost, N deposition and atmospheric pollution) were identified by meeting participants. The main components of this manuscript were also designed during the discussions held at the meeting in Texas, where the participants developed the idea of an expert survey and literature review to fill in identified gaps that were considered important, and that would allow to build Figure 3 (see main text). The survey (Appendix 1) was developed in May 2018 through consultation with a subset of peatland experts and administered online using Qualtrics; it was inspired by a survey that was developed by the Permafrost Carbon Network[1]. The survey was accompanied by three census questions to assess each respondent's career stage (Table S1); 38 out of the 44 survey respondents provided answers to the census questions. The lead authors submitted the survey to Texas A&M University's Institutional Review Board (IRB), who determined that the proposed activity was not research involving human subjects as defined by DHHS and FDA regulations, and that further IRB review and approval was not required.

Census questions	Census answers	
What is your career stage?	graduate student: 4	post-doc: 12
	faculty/lecturer: 16	research scientist: 6
Received your PhD within the past 5 years?	yes: 9	no: 29
Received your PhD more than 20 years ago?	yes: 4	no: 34

Table S1: Census questions asked to the survey respondents.

The survey asked one general question: "What is the relative role of each agent of change for shifting the peatland C balance in the past, present, and future?" Experts were asked to provide quantitative estimates of C gain or loss for northern high-latitude and tropical peatlands. They were also asked to break down their estimates into the following four periods: post-LGM (21 ka – 1750 AD), Anthropocene (1750-2020 AD), near future / the rest of this century (2020-2100 AD), and far future (2100-2300 AD). To identify areas of consensus and uncertainty, we requested that respondents use self-assessed confidence and expertise scores to weight their answers accordingly. The five-point scale goes from 1 ("very low") to 5 ("very high"); see Appendix 1 for details. We also asked the experts to provide comments pertaining to their deductive approach on how they estimated the magnitudes of the carbon budget and/or to provide key literature references in support of their view. In many cases, experts used these "comments box" to provide semi-quantitative estimates rather than quantitative ones. We computed two sets of results: one that includes all answers, and one that only includes results from self-rated expertise of 3-4-5 (Figure S3). In the analysis presented in the main paper, we chose to include all answers, even those with a self-rated expertise of 1 and 2, as those answers did not affect the statistical distribution of the responses or skew the measures of centrality one way or another, in most cases (but see Figure S3 and associated text).

In common with many other studies, this expert elicitation is based on individual literature review and does not yield new scientific data *per se*. Instead, it produces new scientific evidence and insights that are greater than the sum of the collective inputs from each individual expert[2]. Experts also draw from their harder-to-pin-down comprehensive mental maps that come from their experience, observations, fieldwork, etc. The publication of expert opinions makes the views of scientists transparent to a wider public, highlights key uncertainties and levels of agreement, and communicates any potential positive feedbacks or tipping points to stakeholders[3]. Building a bridge between scientists and other stakeholders is important, particularly in situations where policy decisions must be made based on limited or conflicting data[4]. Overall, we argue that the elicitation of expert opinion is an objective way to synthesize a range of individually biased assessments (e.g., over- and under-confidence, anchoring)[5]. This "balance-of-bias approach"[6] allows us to compare and contrast individual views, in addition to providing a broad understanding of those diverging and converging opinions via synthesis. In other words, the voice of each expert is a "spot" in a diagram (Figure S1) that integrates and relates different types of knowledge. But the sum of these spots provides more than a simple collection of individual responses: it articulates the state of knowledge and elaborates the uncertainties facing our scientific community.

2. Survey implementation and responses

To gain a full picture of the state of scientific knowledge, we purposefully sought responses from researchers across a range of disciplines (e.g. paleoecology, flux data, modelling) and career stages. The survey was distributed using the C-PEAT and FLUXNET mailing lists in October 2018. There was a total of 44 respondents. The majority were based in the UK (16) and North America (USA and Canada, 15), with other respondents from elsewhere in Europe (Belgium, France, Germany, Switzerland, Sweden, 8) and the rest of the world (Argentina, Australia, Colombia, Sri Lanka, Thailand, 5). From a career stage perspective, our respondents included at least the following demographics (38 out of 44 respondents answered the census questions): 4 graduate students, 12 post-docs, 16 faculty/lecturers, and 6 research scientists. Of this sample, 9 have received their PhDs within 5 years, 4 got theirs over 20 years ago, and 25 were in between (Table S1). Of the 44 respondents, 12 participated in the C-PEAT meeting in Texas. Note that there were no discussions about the survey, beyond that it should be conducted, at the Texas workshop.

On average, there was a slightly higher proportion of responses for northern high-latitude peatlands (overall mean across all time periods and drivers was 13.3 respondents) compared to tropical peatlands (11.2 respondents). Likewise, responses were not evenly distributed within the survey structure. For high-latitude peatlands, temperature was the driver with the most responses, with other drivers being relatively evenly distributed, and N deposition and atmospheric pollution receiving the fewest answers (Table S2). For tropical peatlands, responses were mostly evenly distributed across drivers, again with the exception of N deposition and atmospheric pollution that received fewer answers (Table S3). The distribution of responses across time periods was relatively even, with generally fewer responses for the far future (Tables S2 and S3).

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future	Mean for drivers
Temperature	26	24	19	15	21.0
Moisture balance	10	13	18	12	13.2
Sea level	16	10	13	11	12.5
Fire	15	13	15	13	14.0
Land use	15	22	19	15	17.8
Permafrost	16	13	15	10	13.5
N deposition	10	9	8	7	8.5
Atmospheric pollution	9	6	6	4	6.5
Mean for time periods	14.6	13.8	14.1	10.9	13.3

Table S2: Number of respondents for each time period and driver for high-latitude peatlands.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future	Mean for drivers
Temperature	16	17	18	16	16.8
Moisture balance	16	15	14	9	13.5
Sea level	14	9	7	8	9.5
Fire	11	12	13	9	11.3
Land use	10	16	14	11	12.8
N deposition	9	8	7	7	7.8
Atmospheric pollution	9	6	6	6	6.8
Mean for time periods	12.1	11.9	11.3	9.4	11.2

Table S3: Number of respondents for each time period and driver for the tropical peatlands.

3. Survey results

The anonymous individual survey results are presented in Figure S1. The mean, median, geometric mean (log transformation), weighted averages (see below for details), and the 10th – 90th percentiles are shown in Table S4 for the high latitudes and in Table S5 for the tropics. While results tended to be clustered for most questions, a few low- or high-end estimates often skewed the distribution of values to the right or to the left of that cluster (Figure S1). This skewness influenced the mean values, which were always farther out than the medians. While the medians were not affected by those extreme values, they didn't quite capture what was revealed by the spread of data for that same reason; ignoring extreme results is not our intention (Tables S4 and S5). Therefore, we also calculated the geometric means to represent the central tendency of each distribution. A geometric mean normalizes differently-ranged values by multiplying all values of a given sample and taking the nth root, similar to a log transformation. It is therefore an appropriate measure when values change exponentially and in case of skewed distribution[7-8]. Since the geometric mean cannot be computed if any of the values are zero or negative, we added 1000 to each value to make all values positive prior to executing the statistical analysis. Weighted means were also computed by multiplying each C flux by the expertise level of the respondent to further assess the importance of expertise on our results. For example, a C stock of 45 Gt estimated by an expert with a self-assessed expertise of 3 was turned into a value of 45 * 3 = 135. Then, for each driver and time period, the sum of the multiplied responses was divided by the sum of the expertise scores to give the weighted mean result. Those results are presented along the means, medians, and geometric means in Tables S4 and S5.

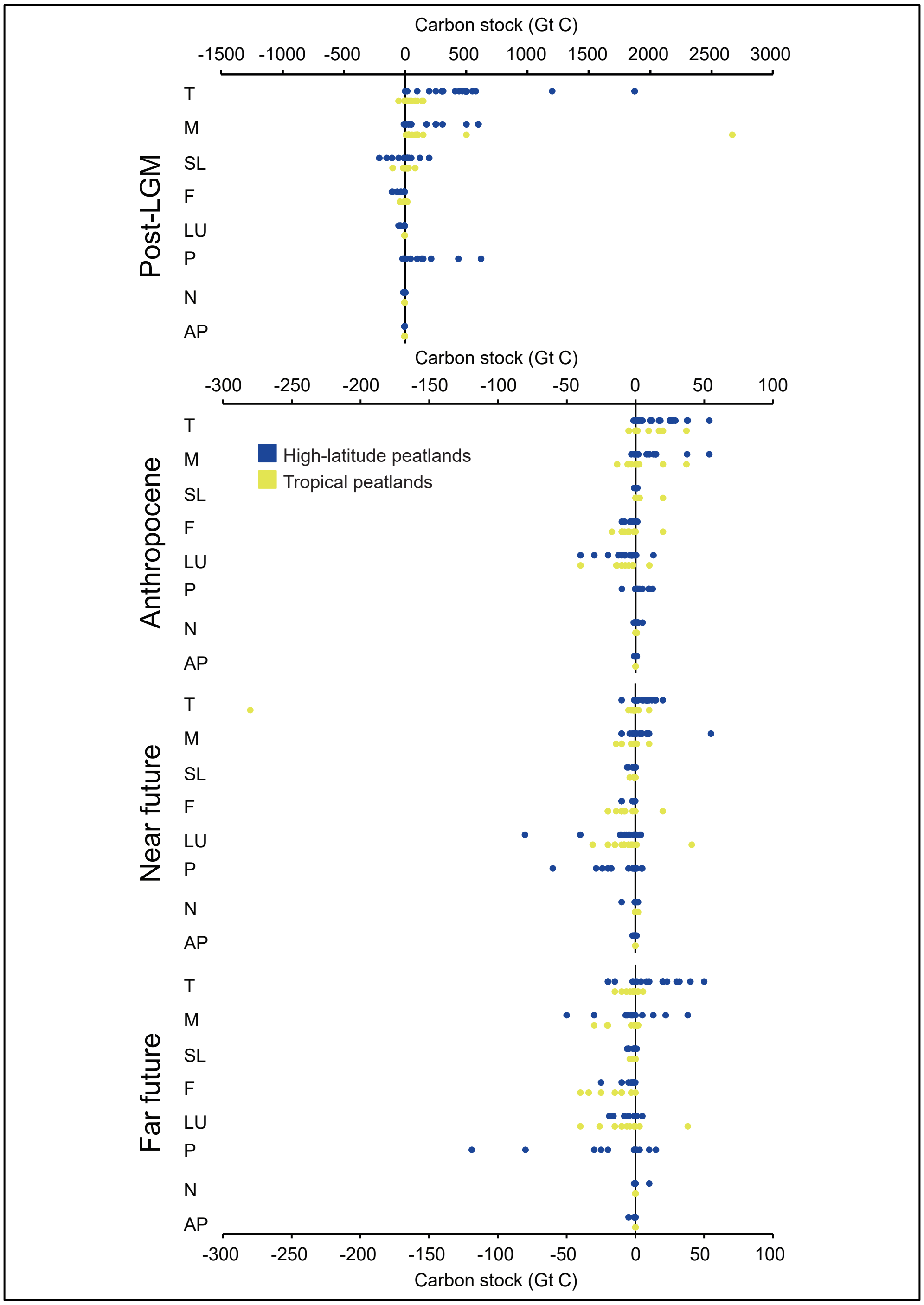
Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	514(mean) / 492(med) / 461(geo) / 565(WA) 60 – 890(10th – 90th percentiles)	16 / 15 / 16 / 18 0 – 38	6 / 7 / 6 / 6 0 – 14	11 / 9 / 11 / 13 -16 – 33
Moisture balance	220 / 215 / 203 / 184 10 – 570	11 / 5 / 11 / 9 -1 – 31	5 / 2 / 5 / 4 -7 – 10	-2 / -2 / -2 / -1 -30 – 22
Sea level	-2 / 19 / -7 / 3 -136 – 99	0 / 0 / 0 / 0 0 – 1	-1 / 0 / -1 / -1 -4 – 0	-2 / -1 / -2 / -2 -5 – 1
Fire	-33 / -10 / -33 / -34 -92 – 0	-3 / -3 / -3 / -4 -8 – 0	-3 / -1 / -3 / -3 -10 – 0	-5 / -1 / -5 / -4 -10 – 1
Land use	-11 / -1 / -11 / -12 -39 – 0	-7 / -3 / -7 / -7 -23 – 0	-9 / -1 / -9 / -7 -20 – 2	-5 / -1 / -5 / -4 -18 – 1
Permafrost	121 / 45 / 109 / 99 -14 – 349	3 / 2 / 3 / 3 0 – 10	-10 / -1 / -10 / -7 -27 – 3	-21 / -1 / -21 / -15 -75 – 9
N deposition	-1 / 0 / -1 / -1 0 – 1	1 / 1 / 1 / 1 -1 – 2	-1 / 0 / -1 / -2 -2 – 1	1 / 0 / 1 / 0 1 – 3
Atmospheric pollution	0 / 0 / 0 / 0 0 – 0	0 / 0 / 0 / 0 -1 – 1	0 / 0 / 0 / 0 -2 – 1	-1 / 0 / 1 / -1 -3 – 0

Table S4: Summary survey results for high-latitude peatlands. The mean, median (med), geometric mean (geo), weighted averaging (WA), and 10th and 90th percentiles are shown. Units in GtC. Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	43(mean) / 25(med) / 41(geo) / 49(WA) 0 – 128(10th – 90th percentiles)	5 / 1 / 5 / 7 -3 – 19	-19 / 0 / -22 / -27 -4 – 2	-3 / -1 / -3 / -5 -10 – 2
Moisture balance	268 / 85 / 183 / 339 24 – 360	3 / 0 / 3 / 4 -6 – 17	-2 / 0 / -2 / -2 -10 – 1	-7 / 0 / -7 / -9 -21 – 2
Sea level	7 / 6 / 6 / 6 -13 – 52	3 / 0 / 2 / 4 0 – 12	-1 / 1 / -1 / -1 -2 – 0	-1 / -1 / -1 / -2 -3 – 0

Fire	-3 / 0 / -3 / 0 -10 – 0	-4 / -5 / -4 / -4 -10 – 0	-7 / -10 / -7 / -6 -19 – 0	-16 / -10 / -16 / -18 -35 – -2
Land use	0 / 0 / 0 / 0 -1 – 0	-8 / -6 / -8 / -7 -14 – -2	-6 / -8 / -6 / -3 -19 – 0	-7 / -8 / -7 / -5 -25 – 3
N deposition	0 / 0 / 0 / 0 0 – 0	0 / 0 / 0 / 0 0 – 0	0 / 0 / 0 / 0 0 – 1	0 / 0 / 0 / 0 0 – 0
Atmospheric pollution	0 / 0 / 0 / 0 0 – 0	0 / 0 / 0 / 0 0 – 0	-1 / 0 / -1 / -1 -3 – 0	0 / 0 / 0 / 0 0 – 0

Table S5: Summary survey results for tropical peatlands (30°N - 30°S). The mean, median (med), geometric mean (geo), weighted averaging (WA), and 10th and 90th percentiles are shown. Units in GtC. Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere.



The survey specifically asked experts to quantify the relative contribution of each agent of change to the peatland C stock, rather than total C inventories. Therefore, summing the values presented in Tables S4 and S5 in an attempt to calculate an expert-derived total C stock is not recommended, as it would likely imply some amount of double counting and it is possible that the answer for the total C stock would be different than that for the individual drivers. The post-LGM C stocks estimated via expert elicitation (Tables S4 and S5) add up to 808 GtC and 315 GtC for high-latitude and tropical peatlands, respectively (based on arithmetic mean values). These values are much larger than most previous peat C estimates, which tend to be in the order of 500 GtC and 100 GtC for northern and tropical peatlands, respectively[9]. Our expert-derived estimates are also approximately twice as large as suggested by simulation efforts that aim at balancing the post-LGM C cycle[10-11]. While peatland C stock estimates in the order of 1000Gt have been suggested before[12], mechanisms for additional post-LGM CO_2 release (likely from the ocean) would be needed to conceive such a large land sink[13]. This discussion is well beyond the scope of this study.

Figure S1: Full survey results. Each individual response is shown as a spot. Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere. Where a range of values was given, the midpoint is used. Codes for drivers: T = temperature, M = moisture balance, SL = sea level, F = fire, LU = land use, P = permafrost, N = nitrogen deposition, AP = atmospheric pollution.

4. Self-assessment of confidence and expertise

Our results indicate low to medium confidence in our projections (Tables S6 and S7; Figure S2). Confidence levels were highest for the post-LGM and Anthropocene time periods, in part reflecting the large fraction of paleo experts, but also because of the compounding uncertainties pertaining to world economy, politics, and policy making trajectories going forward.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	3.1	3.1	2.9	2.7
Moisture balance	3.1	3.1	2.4	2.4
Sea level	2.2	2.6	2.2	2.2
Fire	2.4	2.4	1.9	1.9
Land use	1.8	2.4	2.1	1.9
Permafrost	2.8	3.2	2.7	2.7
N deposition	1.8	2	1.5	1.6
Atmospheric pollution	1.9	2.3	2	1.5

Table S6: Mean confidence values for high-latitude peatland C flux estimates. Confidence values specified in the survey were 1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high. Shading represents 1 – 1.99, 2 – 2.99 and ≥3, with darker shading representing higher confidence.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	2.7	2.5	2.5	2.1
Moisture balance	2.6	2.7	2.4	2.1
Sea level	2.3	2.6	1.7	1.9
Fire	2.7	2.8	2.4	2.3
Land use	2.1	2.4	2.6	1.9
N deposition	1.6	1.8	1.7	1.7
Atmospheric pollution	1.6	1.8	1.8	1.5

Table S7: Mean confidence values for tropical peatland C flux estimates. Confidence values specified in the survey were 1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high. Shading represents 1 – 1.99 and 2 – 2.99, with darker shading representing higher confidence.

Expertise ratings were used to test the effect of low self-assessed expertise on the overall dataset. For this, all answers with self-assessed expertise of 1 and 2 were removed and the summary data for the survey recalculated (Tables S8 and S9; Figure S2). On average, the number of respondents with self-assessed expertise of 3, 4, or 5 (from here, E>2) represented about 40% of the total dataset. Results were consistent across time periods, but varied between drivers. For example, for high-latitude peatlands, 69% of respondents were E>2 for temperature and permafrost (as high as 77% in the Anthropocene time period), whereas only 20% respondents were E>2 for atmospheric pollution. For tropical peatlands, E>2 represented over half of all responses for fire (51%), and near half for temperature (46%) and moisture (44%). Overall, for a few drivers, the n for E>2 data is low and results must be viewed with respective caution. Results from the E>2 survey respondents vs. those from the entire group were compared using the arithmetic means as central measures and the 10th – 90th percentiles to represent the spread of data (Figure S3); see Tables S10 and S11 for medians and geometric means.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future	Mean (drivers)
Temperature	18 (69%)	18 (75%)	13 (68%)	9 (60%)	14.5 (69%)
Moisture balance	6 (60%)	9 (69%)	8 (44%)	6 (50%)	7.3 (55%)
Sea level	3 (19%)	4 (40%)	2 (15%)	2 (18%)	2.8 (22%)
Fire	4 (27%)	4 (31%)	2 (13%)	2 (15%)	3 (21%)

Land use	3 (20%)	7 (32%)	5 (26%)	4 (27%)	4.8 (27%)
Permafrost	11 (69%)	10 (77%)	9 (60%)	7 (70%)	9.3 (69%)
N deposition	3 (30%)	2 (22%)	1 (13%)	1 (14%)	1.8 (21%)
Atmosph pollution	2 (22%)	2 (33%)	1 (17%)	0 (0%)	1.3 (20%)
Mean (time periods)	6.3 (43%)	7 (51%)	5.2 (46%)	3.9 (36%)	5.6 (42%)

Table S8: Number of respondents with self-assessed expertise rating of 3, 4, or 5 for each time period and driver for high-latitude peatland estimates. Values in parentheses represent the percentage of the total number of respondents for each category (from Table S2).

Agents of change	**Post-LGM**	**Anthropocene**	**Near Future**	**Far Future**	**Mean (drivers)**
Temperature	8 (50%)	8 (47%)	9 (50%)	6 (38%)	7.8 (46%)
Moisture balance	7 (44%)	9 (60%)	5 (36%)	3 (33%)	6 (44%)
Sea level	5 (36%)	5 (56%)	1 (14%)	2 (25%)	3.3 (34%)
Fire	6 (55%)	6 (50%)	6 (46%)	5 (56%)	5.8 (51%)
Land use	4 (40%)	7 (44%)	6 (43%)	3 (28%)	5 (39%)
N deposition	2 (22%)	2 (25%)	2 (29%)	2 (29%)	2 (26%)
Atmosph pollution	1 (11%)	1 (17%)	1 (17%)	1 (17%)	1 (15%)
Mean (time periods)	4.7 (39%)	5.4 (46%)	4.3 (38%)	3.1 (33%)	4.4 (39%)

Table S9: Number of respondents with self-assessed expertise rating of 3, 4, or 5 for each time period and driver for the tropical peatland estimates. Values in parentheses represent the percentage of the total number of respondents for each category (from Table S3).

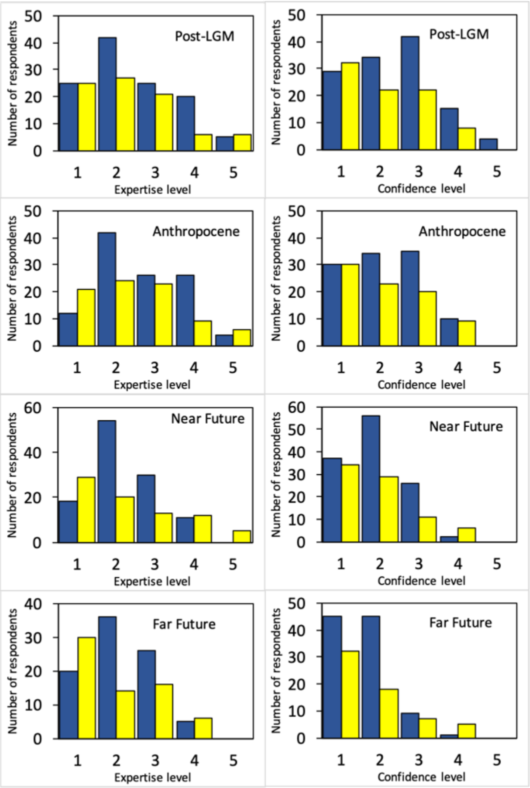


Figure S2: Distribution of survey respondents' self-rated expertise (left column) and confidence (right column) reported by time period. Blue (yellow) bars represent high-latitude (tropical) peatlands. Confidence and expertise values specified in the survey were 1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	627(mean) / 500(med) / 565(geo) 216 – 1402(10th – 90th percentiles)	19 / 22 / 20 1 – 38	8 / 8 / 8 0 – 15	16 / 20 / 16 -4 – 41
Moisture balance	268 / 255 / 240 0 – 550	11 / 8 / 17 0 – 23	1 / 1 / 1 -5 – 8	1 / 5 / 1 -19 – 18
Sea level	-2 / -8 / -9 -42 – 26	0 / 0 / 0 -1 – 0	-1 / 0 / -1 0 – 0	-2 / -1 / -1 -1 – 0
Fire	-27 / -10 / -27 -50 – -10	-5 / -4 / -5 -8 – -2	-1 / -1 / -1 -2 – -1	-4 / -4 / -4 -5 – -2
Land use	-2 / 0 / -3 -4 – 0	-4 / -4 / -4 -15 – 8	1 / 1 / 1 0 – 4	0 / 0 / 0 0 – 1
Permafrost	136 / 10/ 116 -15 – 624	4 / 3 / 5 0 – 10	-2 / 0 / -2 -8 – 5	-2 / 0 / -2 -21 – 11
N deposition	0 / 0 / - 0 – 0	2 / 1 / 2 -1 – 4	-5 / -5 / -5 -9 – -1	0 / 0 / -1 -1 – 0
Atmospheric pollution	0 / 0 / - 0 – 0	0 / 0 / 0 0 – 1	0 / 0 / 0 0 – 0	0 / 0 / 0 0 – 0

Table S10: Summary survey results for high-latitude peatlands for survey respondents who self-rated their expertise as 3, 4, or 5. The mean, median (med), geometric mean (geo), and 10th and 90th percentiles are shown. Units in GtC. Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere.

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	57(mean) / 25(med) / 63(geo) 4 – 143(10th – 90th percentiles)	10 / 5 / 13 -2 – 25	-31 / -2 / -36 -60 – 2	-6 / -4 / -6 -13 – -1
Moisture balance	482 / 30 / 313 26 – 1368	8 / 2 / 8 -5 – 29	-2 / 0 / -2 -10 – 6	-9 / -9 / -9 -20 – 2
Sea level	15 / 23 / 15 -5 – 29	4 / 1 / 8 0 – 11	-1 / -1 / -1 -1 – -1	-3 / -3 / -3 -4 – -2
Fire	3 / 0 / 4 -1 – 10	-5 / -8 / -5 -14 – 8	-7 / -10 / -7 -17 – 6	-20 / -15 / -21 -38 – -6
Land use	0 / 0 / 0 0 – 0	-3 / -4 / -3 -9 – 4	3 / -5 / 2 -11 – 23	1 / -4 / 1 -20 – 26
N deposition	0 / 0 / - 0 – 0	0 / 0 / - 0 – 0	0 / 0 / - 0 – 0	0 / 0 / - 0 – 0
Atmospheric pollution	0 / 0 / - 0 – 0	0 / 0 / - 0 – 0	-5 / -5 / -5 -5 – -5	0 / 0 / - 0 – 0

Table S11: Summary survey results for tropical peatlands (30°N - 30°S) for survey respondents who self-rated their expertise as 3, 4, or 5. The mean, median (med), geometric mean (geo), and 10th and 90th percentiles are shown. Units in Gt C. Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere.

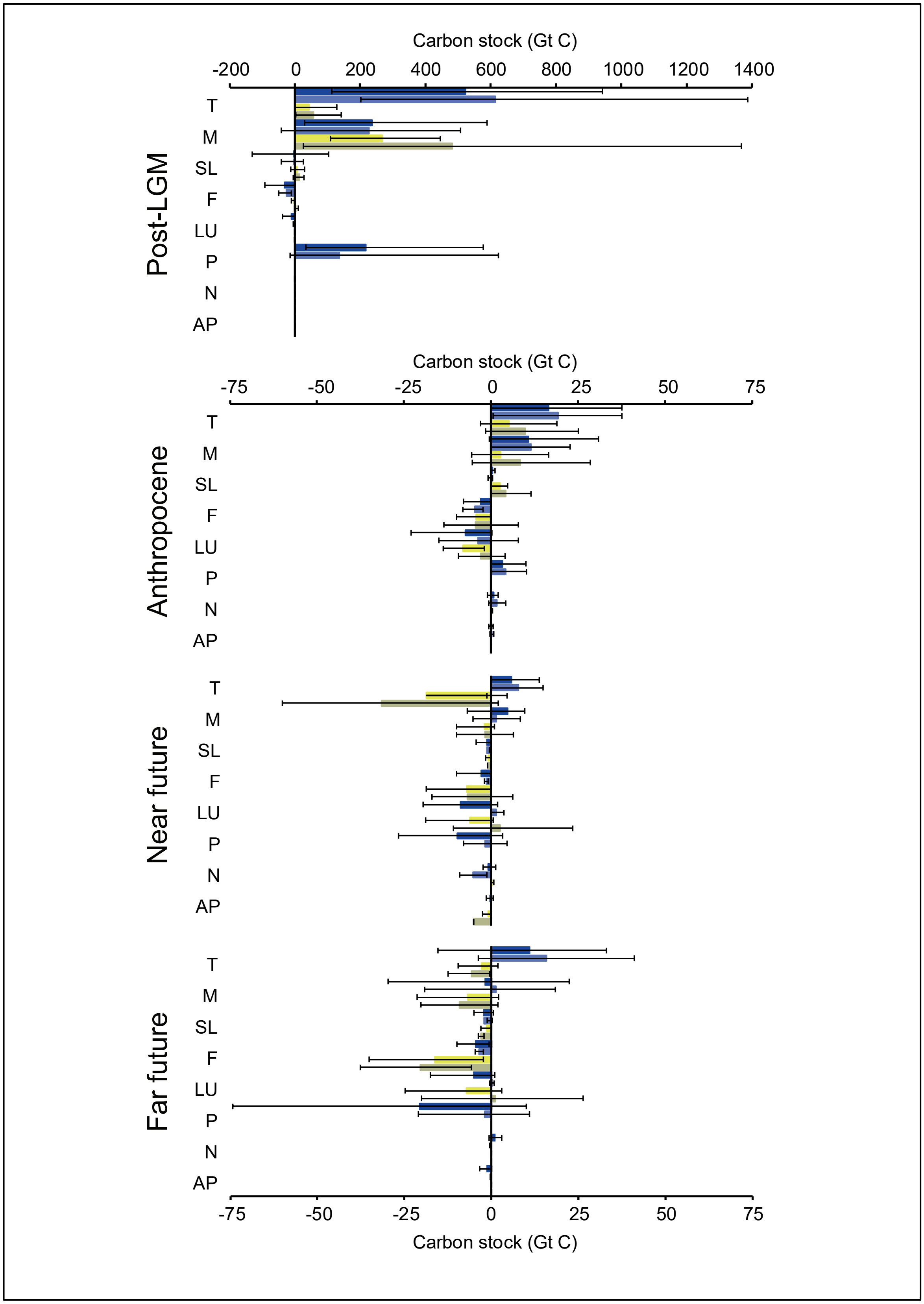


Figure S3: Comparison of full survey vs. E>2 respondents. Data shown as mean and 10th – 90th percentiles. High-latitude peatland results shown in blue (dark = all data, light = E>2). Tropical peatland data shown in yellow (dark yellow = all data, light beige = E>2). Positive values represent peatland sinks, negative values represent peatland sources to the atmosphere. Codes for drivers: T = temperature, M = moisture balance, SL = sea level, F = fire, LU = land use, P = permafrost, N = nitrogen deposition, AP = atmospheric pollution.

Overall, this expert assessment revealed key knowledge gaps and uncertainties; it also highlighted the need for fundamental research on several aspects of the peatland C sink capacity. For example, the role of sea-level since the post-LGM warming received a wide range of opinions, likely caused by the respondents' regional expertise. The impact of permafrost aggradation and degradation on peat C similarly received a wide range of responses, both in magnitude and even in sign (Figure S1). For instance, some experts perceived the presence of permafrost as the dominant cause for C stock preservation across the northern high latitudes. More work is needed to distinguish which peatlands grew in syngenetic permafrost (i.e., peat accumulation and permafrost aggradation take place concurrently) vs. those that became frozen much later during their development. In terms of future permafrost degradation, our dataset reflects two main schools of thought that are anchored in conflicting evidence from the literature. The first group expects rapid C loss from deep peats in the form of CH_4 (and CO_2 following CH_4 oxidation) and a slow recovery of the peatlands following permafrost thaw, land subsidence, and soil saturation; the second group expects a net C gain from rapidly recovering plant production due to warm and moist conditions following thaw. Lastly, we did not separate different peatland types (e.g., bogs, fens) but their individual responses to agents of change could vary. Also, the following understudied regions still limit our understanding of global peatland C dynamics: (1) tropics, (2) Far-East Russia, (3) southern hemisphere (particularly Australia and New Zealand), and (4) high-elevation and mountain regions.

5. References cited

1- Schuur E.A.G., Abbott B.W., Bowden W.B., Brovkin V., Camill P., Canadell J.G., Chanton J.P., Chapin III F.S., Christensen T.R., Ciais P., Crosby B.T., Czimczik C.I., Grosse G., Harden J., Hayes D.J., Hugelius G., Jastrow J.D., Jones J.B., Kleinen T., Koven C.D., Krinner G., Kuhry P., Lawrence D.M., McGuire A.D., Natali S.M., O'Donnell J.A., Ping C.L., Riley W.J., Rinke A., Romanovsky V.E., Sannel A.B.K., C., Schaefer K., Sky J., Subin Z.M., C., Turetsky M.R., Waldrop M.P., Walter Anthony K.M., Wickland K.P., Wilson C.J., Zimov S.A. 2013. Expert assessment of vulnerability of permafrost carbon to climate change. *Climatic Change*, doi:10.1007/s10584-013-0730-7.

2- Oppenheimer M., Oreskes N., Jamieson D., Brysse K., O'Reilly J., Shindell M., Wazeck M. 2019. *Discerning Experts: the practices of scientific assessment for environmental policy*. University of Chicago Press, 281p.

3- Socolow R.H. 2011. High-consequence outcomes and internal disagreements: tell us more, please. *Climatic Change*, 108, 775-790.

4- Horton B.P., Rahmstorf S., Engelhart S.E., Kempe A.C. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews*, 84, 1-6.

5- Baron J. 2007. Thinking and deciding (4th ed.). Cambridge University Press.

6- Oppenheimer M., Oreskes N., Jamieson D., Brysse K., O'Reilly J., Shindell M., Wazeck M. 2019. Discerning Experts: the practices of scientific assessment for environmental policy. University of Chicago Press, 281p.

7- Crawley M.J. 2005. *Statistics: An Introduction using R*. John Wiley & Sons Ltd.

8- Manikandan S. 2011. Measures of central tendency: The mean. *Journal of Pharmacol Pharmacother.*, 2(2), 140-142.

9- Yu Z., Loisel J., Brosseau D.P., Beilman D.W., Hunt S.J. 2010. Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37, L13402, doi:10.1029/ 2010GL043584.

10- Ciais P., Tagliabue A., Cuntz M., Bopp L., Scholze M., Hoffmann G., Lourantou A., Harrison S.P., Prentice I.C., Kelley D.I., Koven C., Piao S.L. 2011. Large inert carbon pool in the terrestrial biosphere during the Last Glacial Maximum. *Nature Geoscience*, 5, 74-79, doi:10.1038/ngeo1324.

11- Stocker B.D., Yu Z., Massa C., Joos F. 2017. Holocene peatland and ice-core data constraints on the timing and magnitude of CO2 emissions from past land use. *Proceedings of the National Academy of Sciences*, 114: 1492-1497, doi:10.1073/pnas.1613889114.

12- Nichols J., Peteet D. 2019. Rapid expansion of northern peatlands and doubled estimate of carbon storage, *Nature Geoscience*, doi:10.1038/s41561-019-0454-z.

13- Jeltsch-Thömmes A., Battaglia G., Cartapanis O., Jaccard S.L., Joos F. 2019. Low terrestrial carbon storage at the Last Glacial Maximum: constraints from multi-proxy data. *Climate of the Past*, 15, 849-879.

Appendix 1: Expert opinion survey

Vulnerability of Peatland Carbon Stocks:
Expert Assessment Survey

Introduction

The goal of this survey is to use an expert assessment approach to determine the magnitude of changes in the peat carbon budget during: (a) the post-LGM (21000 BP-1750 AD), (b) the Anthropocene (1750-present), (c) the near future (present-2100 AD), and (d) the far future (2100-2300 AD). We are particularly interested in expert opinion regarding the relationship between a series of drivers and the peatland carbon budget that could lead to 'surprises' (i.e., possible thresholds and tipping points), since such non-linearity is difficult to predict on the basis of models. You will be asked to provide separate estimates of the peatland carbon budget for (a) tropical and (b) high-latitude peatlands. We request that you fill in both, whatever your expertise level, as we wish to identify where there is consensus of opinion and where there is greater uncertainty. You will be provided with the opportunity to let us know how confident you are for each one of your answers; if you have little or no expertise concerning a particular question, skip it and indicate your expertise level as 1 (see below).

We recognize that all the different components of peatland carbon dynamics are difficult to quantify and are not, and cannot be, precisely and definitively modeled or measured. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. By administering this survey to scientists with the most relevant expertise, we want to identify and evaluate the possible and probable magnitude of peatland fluxes.

Instructions

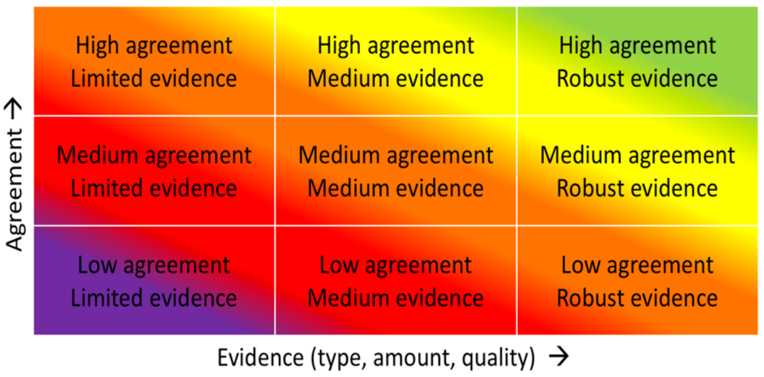
Please answer each question below for tropical and high-latitude peatlands. Immediately next to your answer, indicate your level of confidence and your expertise concerning your answer. Additionally, we ask you to provide comments pertaining to your approach on how you estimated the magnitudes of the carbon budget and/or key literature references in support of your view; this will allow us to compare responses from multiple experts. If the answer to a particular question is currently unknown, but there is a particular research direction that you think could resolve some of that uncertainty, please provide details in the "comments" space. If you have little or no expertise concerning a particular question, skip it and indicate your expertise level as 1.

The five-point "**Confidence level**" scale is defined as follows (see **Figure 1**):

1 I have very low confidence in my answer; it is my best guess but it could easily be far off the mark. Scientific uncertainty on this issue is very large due to limited evidence AND low agreement.

2 I have low confidence in my answer; it is as good as anyone can offer at this time. Scientific uncertainty on this issue is large due to limited evidence OR low agreement.

3 I have medium confidence in my answer; it is as good as anyone can offer at this time. Scientific uncertainty on this issue is moderate. The true value is likely to be different from my answer.



High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Figure 1. Evidence and agreement statements and their relationship to confidence, which increases towards the top-right corner. Redrawn and modified from IPCC AR5's Guidance Note for Lead Authors.

4 I have high confidence in my answer; it is the best anyone can offer at this time. Scientific uncertainty on this issue is low due to robust evidence OR high agreement.

5 I have very high confidence in my answer and would be surprised if it was far off from the true value. Scientific uncertainty on this issue is very low due to robust evidence AND high agreement.

The five-point “**Expertise level**” scale is defined as follows:

1 I have no familiarity with the literature and I do not actively work on this particular question.

2 I have some familiarity with the literature and have worked on related questions but I haven't contributed to the literature on this issue; and I am not an expert on this question.

3 I am familiar with, and have contributed to, the literature in related topics, but I do not consider this issue to be central to my expertise; I have worked on related issues.

4 I have contributed to the relevant literature and have worked on this specific issue, but do not consider myself one of the foremost experts on this particular issue.

5 I contribute actively to the literature directly concerned with this issue, and I consider myself one of the foremost experts on it.

Feel free to share this survey with other peatland scientists who may not be C-PEAT or FLUXNET members.

1. For high-latitude northern peatlands only (> 45N). How much cumulative peatland carbon release or uptake from the atmosphere is due to the different drivers during the different time periods (Gt Carbon absorbed or emitted as either CO_2, CH_4 or DOC). If you wish to comment on southern peatlands (> 45S), please do so using the space provided in Question 3. If you can't quite isolate the role of each driver of change (e.g., temperature vs. moisture balance), please explain your answer in the "comments" space provided. Note that the average apparent carbon sink for the last millennium is ~ 0.14 Gt C per year for global peatlands (Gallego-Sala et al. 2018).

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Northern peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Temperature	*Sink =?Gt due to ?* *Source= ?Gt due to?* *Overall net sink =?Gt*			*Sink =?Gt due to ?* *Source =?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*		
Comments:												
Key Literature:												
Moisture balance												
Comments:												
Key Literature:												
Sea level												
Comments:												

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Northern peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Key Literature:												
Fire	*Sink =?Gt due to ?* *Source= ?Gt due to?* *Overall net sink =?Gt*			*Sink =?Gt due to ?* *Source =?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =Gt*		
Comments:												
Key Literature:												
Land-use												
Comments:												
Key Literature:												
Permafrost												
Comments:												
Key Literature:												
N deposition												

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Northern peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Northern peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Comments:												
Key Literature:												
Atmospheric Pollution												
Comments:												
Key Literature:												

2. For lowland (sub-)tropical peatlands only (from 30N to 30S). How much cumulative peatland carbon release or uptake from the atmosphere is due to the different drivers during the different time periods (GT Carbon absorbed or emitted as either CO_2, CH_4 or DOC). If you wish to comment on montane peatlands, please do so using the space provided in Question 3. If you can't quite isolate the role of each driver of change (e.g., temperature vs. moisture balance), please explain your answer in the "comments" space provided. Note that the average apparent carbon sink for the last millennium is ~ 0.14 Gt C per year for global peatlands (Gallego-Sala et al. 2018).

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Tropical peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Temperature	*Sink =?Gt due to ?* *Source= ?Gt due to?* *Overall net sink =?Gt*			*Sink =?Gt due to ?* *Source =?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*		
Comments:												
Key Literature:												
Moisture balance												
Comments:												
Key Literature:												
Sea-level												
Comments:												

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Tropical peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Key Literature:												
Fire	*Sink =?Gt due to ?* *Source= ?Gt due to?* *Overall net sink =?Gt*			*Sink =?Gt due to ?* *Source =?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =?Gt*			*Sink=?Gt due to ?* *Source=?Gt due to?* *Overall net sink =Gt*		
Comments:												
Key Literature:												
Land-use												
Comments:												
Key Literature:												
N deposition												
Comments:												
Key Literature:												
Atmospheric												

Driver	**Post-LGM** (21000 BP – 1750 AD) **peatland flux** (sink/source)			**Anthropocene** (1750 – present) **peatland flux** (sink/source)			**Near Future** (present – 2100) **peatland flux** (sink/source)			**Far Future** (2100 – 2300) **peatland flux** (sink/source)		
	Tropical peatlands	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**	**Tropical peatlands**	**Confidence Level (1-5)**	**Expertise Level (1-5)**
Pollution												
Comments:												
Key Literature:												

3. Other comments. If you wish to provide additional comments on southern high-latitude peatlands, tropical montane peatlands, or peatland areas that were excluded above, or if you have any other comments, please do so here:

On behalf of the C-PEAT steering committee, we thank you for your answers. We will contact you in December with updated information.
Don’t forget to provide your name and email address in the online survey.

Appendix 2: Maps and case studies

Survey respondents provided examples from the peer-reviewed literature to document the effect of each agent of change on peatland C budget (Tables A2.1 and A2.2, below). The maps presented below (Figure A2.1) show the location of a subset of these case studies (Tables A2.3 and A2.4). References cited in Tables A2.1 through A2.4 can be found in Appendix 4.

Agents of change	**Peatland processes**	**Regions**	**References**
Deglacial climate warming	.Rapid peat initiation .Rapid lateral expansion .Rapid vertical accumulation	northern high-latitudes, south Patagonia	.Synthesis work: Smith et al. 2004; MacDonald et al. 2006; Yu et al. 2009, 2010; Jones and Yu 2010; Loisel et al. 2014 .Individual sites: Lacourse et al. 2019; Weckström et al. 2010; Mathijssen et al. 2019; Ratcliffe et al. 2018; Swinnen et al., 2019
Neoglacial climate cooling	.Slow vertical accumulation	northern high-latitudes	Synthesis work: Yu et al. 2009; Loisel et al. 2014 ; Garneau et al. 2014 .Individual sites: Yu 2006
MCA climate warming	.Rapid vertical accumulation	northern high-latitudes	Synthesis work: Charman et al. 2013
LIA climate cooling	.Slow vertical accumulation	northern high-latitudes, south Patagonia	.Synthesis work: Charman et al. 2013 .Individual sites: Mauquoy et al. 2002, 2004; Galka et al. 2014; Chambers et al. 2014
Lower surface moisture	.Lake-to-peat transition .Fen-to-bog transition	south Patagonia; east Canada	.Synthesis work: Loisel & Yu 2013; Väliranta et al. 2017 .Individual sites: Heusser 1993; Markgraf & Huber 2010; van Bellen et al. 2013; De Vleeschouwer et al. 2014; Mansilla et al. 2018
Higher surface moisture	.Rapid lateral expansion .Pool inception .Bog-to-fen transition .Rapid vertical accumulation	northern high-latitudes; NE China; Congo Basin	.Synthesis work: Korhola et al. 2010; Ruppel et al. 2013; Xing et al. 2015; Treat et al. 2016 .Individual sites: Foster et al. 1988; Foster & Wright 1990; Dargie et al. 2017; Garneau et al. 2018
Multi-decadal droughts	.Slow vertical accumulation .Rapid vertical accumulation	continental North America, Amazon	.Synthesis work: Booth et al. 2005 .Individual sites: Swindles et al. 2018
Early-Holocene high fire frequency	.Peat loss (burnt)	south Patagonia, Canada	.Synthesis work: Huber & Markgraf 2003 .Individual sites: Kuhry 1994; Camill et al. 2009
Sea level rise / Marine incursion	.Peat loss (eroded) .Peat flooding and burial	SE Asia, south Africa, south Patagonia	.Synthesis work: Dommain et al. 2011 .Individual sites: McCulloch & Davies 2001; Unkel et al. 2010; Gabriel et al. 2017
Sea level fall / Isostatic rebound	.Peat initiation	Southeast Asia, Hudson Bay lowlands	.Synthesis work: Dommain et al. 2014; Packalen et al. 2014; Packalen & Finkelstein 2014 .Individual sites: Glaser et al. 2004; Rieley et al. 2008
Neoglacial permafrost aggradation	.Slow vertical accumulation	pan-boreal and subarctic	.Synthesis work: Vitt et al. 2000; Treat & Jones 2018 .Individual sites: Robinson & Moore 1999; Vardy et al. 2000; Oksanen et al. 2001; Oksanen 2006; Kuhry 2008; Sannel & Kuhry 2008; Kokfelt et al. 2010; Pelletier et al. 2017; Kiellman et al. 2018; Sannel et al. 2018; Beilman et al. 2009
Peat initiation in thermokarsts	.Rapid vertical accumulation	Alaska	.Individual sites: Jones et al. 2013
LIA permafrost aggradation	.Slow vertical accumulation	eastern Canada	.Individual sites: Lamarre et al. 2012
Atmospheric dust / tephra deposition	.Rapid vertical accumulation .Slow vertical accumulation	south Patagonia, Japan, eastern Europe	.Synthesis work: Fontjin et al.2014; Smith et al., 2019 .Individual sites: Hughes et al. 2013 ; Vanneste et al. 2016; Fialkiewicz-Koziel et al. 2016; Mansilla et al. 2018

Table A2.1: Post-LGM case studies.

Agents of change	**Peatland processes**	**Regions**	**Period / duration**	**Effect on C sink**	**References**
Climate warming	.Fen-to-bog transition .Rich-to-Poor fen transition .Rapid vertical accumulation .Shrub expansion	Alaska, Scandinavia, Zoige Plateau	Last 100 yr	Gain	Synthesis work: Individual sites: Loisel & Yu 2013 ; Wang et al. 2015 ; Gałka et al. 2018; Taylor et al. 2019; Klein et al. 2013; Gałka et al. 2017; Lamentowicz et al. 2008, 2009, 2011
Lower surface moisture	.*Sphagnum* expansion .Rapid vertical accumulation .Peat loss (decay)	western Canada, Finnish Lapland, European Russia, south Patagonia, Poland	Last 200 yr	Unk.	Synthesis work: Individual sites: Magnan et al. 2018; van Bellen et al. 2018; Zhang et al. 2018; van Bellen et al. 2016; Gałka et al. 2014; Piilo et al. 2019; Marcisz et al. 2015; van der Knaap 2011
Permafrost degradation	.Rapid vertical accumulation .Peat loss (decay)	High boreal and subarctic	Last ~250 yr	Unk.	Synthesis work: Treat & Jones 2018 Individual sites: Payette et al. 2004; Turetsky et al. 2000, 2002, 2007; Camill et al. 2001; Camill 1999; Estop-Aragonès et al. 2018; Pelletier et al. 2017; Sannel & Kuhry 2011; Swindles et al. 2015; Jorgenson et al. 2001; O'Donnell et al. 2012
High fire frequency and intensity	.Peat loss (burnt and smoldering)	boreal region, Indonesia, southern Patagonia	Last 200 yr	Unk.	Synthesis work: Turetsky et al. 2004, 2011; Kasischke & Bruhwiler 2002; van der Werf et al. 2010 Individual sites: Lavoie & Pellerin 2007; Hope et al. 2005; Cole et al. 2015; Huber & Markgraf 2003; Page et al. 2002; Gaveau et al. 2014; Lamentowicz et al. 2020
Land-use change: clear-cutting, agriculture, forestry, pasture, peat mining, flooding	.Peat loss (decay) .Peat flooding and burial	Finland, Europe, Canada, Congo, Indonesia, south Africa, Poland, New Zealand, south Patagonia	Last 200 yr	Loss	Synthesis work: Houghton 2012; Carlson et al. 2013; Leifeld et al. 2018; Wijedasa et al. 2018; Byun et al. 2018 Individual sites: Nieminen 2004; Rooney et al. 2012; Krüger et al. 2016; Gałka et al. 2015, 2017b; Hooijer et al., 2012; Moore et al. 2013; Miettinen et al. 2017; Schipper & McLeod, 2002; Balze et al. 2004; Lamentowicz and Obremska 2010; Gabriel et al. 2017; Hansen et al. 2008; Lamentovicz et al. 2015; Słowiński et al. 2019; Kołaczek et al. 2018; Teodoru et al. 2012; Dargie et al. 2017; Henn et al. 2016; Grootjans et al. 2014
Atmospheric pollution	.*Sphagnum* changes	Germany, Poland, Russia, south Patagonia	Last 200 yr	Unk.	Individual sites: Gałka et al. 2019; De Vleeschouwer et al. 2014; Fialkiewicz-Koziel et al. 2016
Nitrogen deposition	.Peat loss (decay) .Rapid vertical accumulation .Vegetation change	eastern Canada, western Canada, Sweden, UK, Europe, south Patagonia	Last ~150 yr	Gain/Loss	Synthesis work: Turunen et al. 2004; Limpens et al. 2011; Kleinbecker et al. 2008 Individual sites: Vitt et al. 2003; Gunnarsson et al. 2008; Wieder et al. 2019; Bubier et al. 2007; Larmola et al. 2013; Juutinen et al. 2016; Pinsonneault et al. 2016; Bragazza et al. 2006; Kivimäki et al. 2013; Olid et al. 2014; Bragazza et al. 2012, Fritz et al. 2012

Table A2.2: Anthropocene case studies.

Vector of change on the map	Arrow #	Region	Key reference(s)
Temperature (Early Holocene explosive peat growth)	1	Alaska, USA	Jones & Yu, 2010
	2	Pacific Canada	Lacourse et al. 2019
	3	Scotland	Ratcliffe et al. 2018; Swinnen et al. 2019
	4	Fennoscandia	Weckström et al. 2010
	5	West Siberia, Russia	Smith et al. 2004
	6	South Patagonia	Yu et al. 2010; Mathijssen et al. 2019
	7	Congo	Dargie et al. 2017
	8	Indonesia	Page et al. 2004
Moisture (Mid/late Holocene peat expansion)	1	Alaska, USA	Jones et al. 2012
	2	Hudson Bay Lowlands, Canada	Glaser et al. 2004; Packalen et al. 2014; Packalen & Finkelstein 2014
	3	Fennoscandia	Korhola et al. 2010; Weckstrom et al. 2010; Ruppel et al. 2013
	4	Central Europe	Gałka et al. 2015
	5	China	Xing et al. 2015
	6	Southeast Asia	Rieley et al. 2008; Dommain et al. 2014
Moisture (Mid/late Holocene fen-bog shifts)	1	Fennoscandia	Väliranta et al. 2017
	2	South Patagonia	Loisel & Yu, 2013; De Vleeschouwer et al. 2014
Moisture (Late Holocene wetting & pool inception)	1	Eastern Canada	Foster et al. 1988; van Bellen et al. 2013; Garneau et al. 2018
	2	Fennoscandia	Foster & Wright 1990
Moisture (Early Holocene flooding)	1	Indonesia	Dommain et al. 2011
Moisture (Mid-Holocene droughts)	1	Mid-continental USA	Booth et al. 2005
	2	Amazon	Swindles et al. 2018
Atmospheric pollution (Tephra loading)	1	South Patagonia	Vanneste et al. 2016; Mansilla et al. 2018
	2	Colombia	Liu et al. 2019
	3	Japan	Hughes et al. 2013
	4	Kamchatka, Russia	Klimaschewski et al. 2015
Permafrost (Late Holocene & LIA aggradation)	1	Northwestern Canada	Vardy et al. 2000
	2	Western Canada	Robinson & Moore 1999; Vitt et al. 2000; Pelletier et al. 2017
	3	West-central Canada	Kuhry 2008; Sannel & Kuhry, 2008
	4	Eastern Canada	Lamarre et al. 2012
	5	Fennoscandia	Oksanen 2006; Kokfelt et al. 2010; Kjellman et al. 2018; Sannel et al. 2018
	6	European Russia	Oksanen et al. 2001, 2003
	7	West Siberia	Beilman et al. 2009
Fire (Early Holocene high frequency & severity)	1	Western Canada	Kuhry 1994; Camill et al. 2009
	2	South Patagonia	Huber & Markgraf, 2003

Table A2.3. Post-LGM case studies used for the map (Figure A2.1).

Vector of change on the map	Arrow #	Region	Reference(s)
Permafrost (Degradation, thaw)	1	Alaska, USA	Jorgenson et al. 2001; O'Donnell et al. 2012
	2	Northwestern Canada	Pelletier et al. 2017; Estop-Aragonès et al. 2018
	3	Western Canada	Turetsky et al. 2000, 2002, 2007
	4	West-central Canada	Camill et al. 2001; Camill 1999
	5	Northwestern Québec	Payette et al. 2004; Lamarre et al. 2012
	6	Fennoscandia	Sannel & Kuhry 2011; Swindles et al. 2015
	7	European Russia	Sannel & Kuhry 2011
Fire (Increased intensity, frequency)	1	Alaska, USA	Turetsky et al. 2011
	2	Western Canada	Turetsky et al. 2004
	3	Eastern Canada	Lavoie & Pellerin 2007
	4	Poland	Lamentowicz et al. 2020
	5	Indonesia	Page et al. 2002; van der Werf et al. 2010; Gaveau et al. 2014
Land use (Deforestation, drainage)	1	Western Canada	Rooney et al. 2012
	2	California, USA	Drexler et al. 2018
	3	Central Europe	Lamentowicz et al. 2015; Gałka et al. 2015, 2017b; Słowiński et al. 2019
	4	Fennoscandia	Nieminen 2004; Krüger et al. 2016
	5	Amazon	Aragao et al. 2007; Wang et al. 2018
	6	South Patagonia	Balze et al. 2004
	7	Congo	Hansen et al. 2008
	8	Indonesia & Malaysia	Hooijer et al., 2012; Wijedasa et al. 2018; Miettinen et al. 2017
	9	Indonesia	Carlson et al. 2013; Moore et al. 2013
	10	New Zealand	Schipper & McLeod 2002
Temperature (Ecosystem state shifts)	1	Alaska, USA	Klein et al. 2013; Loisel & Yu 2013b; Gałka et al. 2018; Taylor et al. 2019
	2	Western Canada	Magnan et al. 2018; van Bellen et al. 2018
	3	Fennoscandia	Gałka et al. 2017a
	4	Finnish Lapland & European Russia	Zhang et al. 2018
	5	Central Europe	Lamentowicz et al. 2008, 2009; Gałka et al. 2015; Marcisz et al. 2015; Gałka et al. 2019
	6	South Patagonia	Van Bellen et al. 2016
Nitrogen deposition	1	Western Canada	Vitt et al. 2003; Wieder et al. 2016
	2	Eastern Canada	Turunen et al. 2004; Bubier et al. 2007; Larmola et al. 2013; Juutinen et al. 2016; Pinnsonault et al. 2016
	3	United Kingdom	Kivimäki et al. 2013
	4	Fennoscandia	Gunnarsson et al. 2008; Olid et al. 2014
	5	Northern Italy	Bragazza et al. 2012
Moisture (Reservoir flooding)	1	Eastern Canada	Teodoru et al. 2012
	2	Poland	Lamentowicz and Obremska 2010

Table A2.4. Anthropocene case studies used for the map (Figure A2.1).

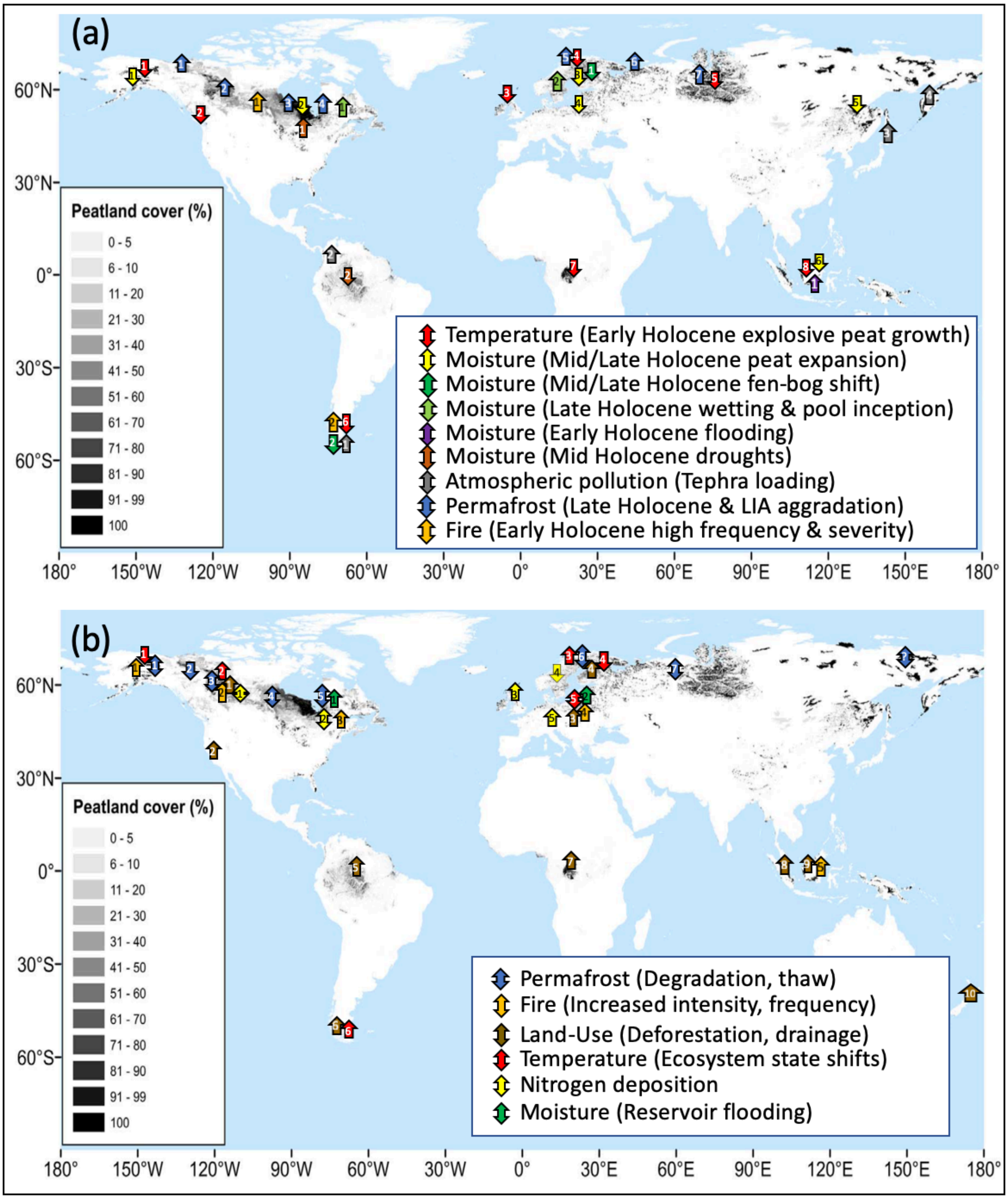


Figure A2.1. The main agents of change responsible for increased (arrows pointing up) or diminished C gains (arrows pointing down) (a) since the post-LGM warming (21ka – 1750 CE), and (b) during the Anthropocene (1750 – 2020 CE). Upward arrows indicate C losses; downward arrows indicate C gains. LIA: Little Ice Age. Numbers refer to individual studies that document the case studies (Tables A2.3, A2.4).

Appendix 3: Key comments from survey respondents

A. General comments
01. We neglected/omitted mountain and alpine peatlands (both tropics and high latitudes) but they are very important from an ecosystem service perspective and may be at risk from particular threats

02. We neglected/omitted southern hemisphere high-latitude and (sub-)Antarctic peatlands but they are very important from an ecosystem service perspective and may be at risk from particular threats

03. Lack of globally-scaled data made this exercise difficult

04. Evidence in the literature for the impact of particular drivers is conflicting, making quantitative predictions difficult.

05. What are the main known unknowns? e.g., land-use has data gaps (e.g. Australasia, South America, Africa)

06. Many experts do not feel able to, or think it is currently possible to, reliably quantify the role of each driver; these experts reported the relative trajectory of change (e.g. ‘will fire lead to more carbon loss in the future?’) and the relative significance of different factors

07. We didn't provide a RCP scenario for near and far future

08. Potential expert bias: ‘modern’ peatland people often believe that net carbon loss is the most likely future outcome whereas paleo people often believe the reverse

09. Our approach does not integrate methane fluxes, only focuses on carbon stocks

10. Personality may come out: some feel "overly careful" and "not confident" vs. “too confident”

11. Interactions between the drivers of change is important and many people found it difficult to separate these, particularly temperature and moisture.

B. Comments for high-latitude peatlands
12. Interactions between the drivers of change are important (temperature and moisture, temperature and permafrost, moisture and fire, moisture and permafrost, fire and permafrost, fire and land-use, N deposition and atmospheric pollution) but not considered in the survey

13. Temperature may be the key driver of northern peatland accumulation rates, but it’s impossible to tease it apart from the "necessary" moisture conditions

14. Warmer conditions in the northern hemisphere lead to more C sequestration, as long as there is an adequate moisture supply. That said, many people see this trend change for the near and far future, such that warming is expected to lead to C loss because warmer temperatures eventually benefit decomposition over NPP

15. People disagree about the future of moisture: projections suggest increases in precipitation the high latitudes, but droughts can still occur. Difficult to compare the relative impact of these competing effects. Critically low moisture levels might be reached at the regional scale during droughts, leading to C loss

16. Sea level: we could model that

17. Land-use: agriculture, sylviculture, peat extraction/mining, but also restoration and protection

18. Pollution: includes CO_2 fertilization, sulphur deposition, dust, tropospheric ozone. While mineral dust and carbon dioxide fertilization may enhance peatland biomass production, sulphur compounds have caused peat erosion and vegetation changes in coal-burning parts of the world.

19. Not just absolute temperature, but also seasonality and growing season length, for example, are important drivers

20. Moisture balance is intricately connected to, and feedbacks with, peatland hydrology, plant productivity and peat decomposition, which are also impacted by temperature

21. Following permafrost thaw, 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

22. A peat fire can be followed by rapid carbon recovery from increased plant production, though an increase in frequency and/or intensity could lead to deeper burns and harder recovery.

C. Comments for tropical peatlands

23. Poor peatland mapping

24. High uncertainty in total carbon pool

25. Sampling bias and under-representation of many tropical peatland regions in databases

26. Climatic, cultural, and topographic settings are drastically different across the tropics (including tectonics – subsiding foreland basins, for example)

27. Interactions between the drivers of change is important (temperature and land-use (drainage), temperature and moisture, moisture and land-use, moisture and fire (ENSO, but also drainage), moisture and sea level, land-use and fire, land-use and sea level)

28. Temperature is probably not a limiting growth factor. Why does peat grow under warm temperatures anyway? Lower carbohydrates and higher aromatics than in high-latitude peats; anything else?

29. Some papers say that moisture is the primary driver of the majority of lowland tropical peat growth. BUT others say that sea level is the major controlling driver of peat accumulation in lowland tropics (coastal/aquatic regions)! Sea level vs moisture: not sure which is the main driver based on responses. Rising sea level initiates peat growth but also kills shelf peat (inundation). Future sea level rise may accelerate peat carbon accumulation and initiate new peatlands, but also flood lowland sites (especially drained sites that are subsiding): no agreement here either! Also: saltwater intrusion in coastal peatlands

30. Fire management and suppression have not been investigated in the tropics

31. Will the need to conserve outweigh the pressure to develop? Also, what is happening in SE Asia might happen in Congo and the Amazon in the future... population growth could lead to drainage of these peatlands as well, unless protection schemes are developed based on lessons learned

32. Not much scientific work done on nitrogen deposition and atmospheric pollution in tropical peats

33. Haze and particulate matter from peat fires are very important research topics from a social, economic, and health perspective

Appendix 4: References cited by survey respondents

Ali, M., Taylor, D. and Inubushi, K. 2006. Effects of environmental variations on CO_2 efflux from a tropical peatland in eastern Sumatra. Wetlands 26, 612–618.

Anshari, G., Kershaw, A.P. and van der Kaars, S. 2001. A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum Wildlife Reserve, West Kalimantan, Indonesia. Palaeogeography Palaeoclimatology Palaeoecology 171, 213-228.

Aragao, L.E.O.C., Mahli, Y., Roman-Cuesta, R.M., Saatchi, S., Anderson, L.O. and Shimabukaro, Y.E. 2007. Spatial patterns and fire response of recent Amazonian droughts. Geophysical Research Letters, 34 L07701.

Balze, V. M., Blanco, D. E. & Loekemeyer, N. (2004) Aspectos sobre usos y conservacion de los turbales patagónicos. In: Los Turbales de la Patagonia: Bases para su inventario y la conservación de su biodiversidad. ISBN 905882019X. Wetlands International. p 129-140.

Ballhorn, U., Siegert, F., Mason, M. and Limin, S. 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. PNAS 106, 21213–21218.

Bechtold, M., De Lannoy, G.J.M., Koster, R.D., Reiche, R.H., Mahanama, S.P., Bleuten, W., Bourgault, M.A., Brümmer, C., Burdun, I., Desai, A.R., Devito, K., Grünwalkd, T., Grygoruk, M., Humphreys, E.R., Klatt, J., Kurbatova, J., Lohila, A., Munir, T.M., Nilsson, M.B., Price, J.S., Röhl, M., Scheider, A. amd Tiemeyer, B. 2019. PEAT-CLSM: A Specific Treatment of Peatland Hydrology in the NASA Catchment Land Surface Model. Journal of Advances in Modeling Earth Systems. DOI: 10.1029/2018MS001574.

Beck, I., Ludwig, R., Bernier, M., Lévesque, E. and Boike, J. 2015. Assessing permafrost degradation and land cover changes (1986–2009) using remote sensing data over Umiujaq, sub-Arctic Québec. Permafrost and Periglacial Processes 26, 129-141.

Beilman, D.W., MacDonald, G.M., Smith, L.C. and Reimer, P.J. Carbon accumulation in peatlands of West Siberia over the last 2000 years. Global Biogeochemical Cycles 23, GB1012.

Benscoter, B.W. and Wieder, R.K. 2003. Variability in organic matter lost by combustion in a boreal bog during the 2001 Chisholm fire. Canadian Journal of Forest Research 33, 2509-2513.

Blain D, Row C, Alm J, Byrne K, Parish F (2006) Wetlands. Peatland section. In: Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K (eds) 2006 IPCC guidelines for National Greenhouse gas Inventories, Volume 4. Africultureal, Forestry and Other Land Use: Intergovernmental Panel on Climate Change

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L. and De Vries, W. 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. Ecological Applications 20, 30–59.

Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E. et al. (2005). A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages. The Holocene, 15(3), 321-328.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., Antonio, C.M.D., Defries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E. and Krawchuk, M.A. 2009. Fire in the Earth System. Science 324, 481–484.

Bragazza, L., Buttler, A., Habermacher, J., Brancaleoni, L., Gerdoi, R., Fritze, H., Hanajik, P., Laiho, R. and Johnson, D. 2012. High nitrogen deposition alters the decomposition of bog plant litter and reduces carbon accumulation. Global Change Biology 18, 1163-1172.

Bragazza, L., Freeman, C., Jones, T., Rydin, H., Limpens, J., Fenner, N., Ellis, T., Gerdola, R., Hájek, M., Hájek, T., Iacumin, P., Kutnar, L., Tahvanainen, T. and Toberman, H. 2006. Atmospheric nitrogen deposition promotes carbon loss from peat bogs. PNAS 103, 19386-19389.

Bridgham, S.D., Pastor, J., Dewey, B., Weltzin, J.F. and Updegraff, K. 2008. Rapid carbon response of peatlands to climate change. Ecology 89, 3041–3048.

Bubier, J.L., Moore, T.R. and Bledzki, L. A. 2007. Effects of nutrient addition on vegetation and carbon cycling in an ombrotrophic bog. Global Change Biology 13, 1168-1186.

Byun, E., Finkelstein, S., Cowling, S.A. and Badiou, P. 2018. Potential carbon loss associated with post-settlement wetland conversion in southern Ontario, Canada. Carbon Balance and Management 13, 6.

Camill, P. (1999). Peat accumulation and succession following permafrost thaw in the boreal peatlands of Manitoba, Canada. Ecoscience, 6(4), 592-602.

Camill, P. 2005. Permafrost thaw accelerates in Boreal peatlands during late-20th century climate warming. Climatic Change 68, 135-152.

Camill, P., Barry, A., Williams, E., Andreassi, C., Limmer, J. and Solick, D. 2009. Climate-vegetation-fire interactions and their impact on long-term carbon dynamics in a boreal peatland landscape in northern Manitoba, Canada. Journal of Geophysical Research: Biogeosciences 114, G04017.

Camill, P., Lynch, J.A., Clark, J.S., Adams, B. and Jordan, B. 2001. Changes in biomass, aboveground net primary production, and peat accumulation following permafrost thaw in the boreal peatlands of Manitoba, Canada. Ecosystems 4, 461-478.

Carlson, K. M., Curran, L. M., Asner, G. P., Pittman, A. M. et al. (2013). Carbon emissions from forest conversion by Kalimantan oil palm plantations. Nature Climate Change, 3(3), 283.

Carlson, K.M., Goodman, L.K. and May-Tobin, C.C. 2015. Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. Environmental Research Letters 10, 074006.

Chambers, F. M., Mauquoy, D., Brain, A., Blaauw, M. et al. (2007) Globally synchronous climate change 2800 years ago: Proxy data from peat in South America. Earth and Planetary Science Letters, 253, 439-444.

Chambers, F.M., Brain, S.A., Mauquoy, D., McCarroll, J., Daley, T. 2014. The ‘Little Ice Age’ in the Southern Hemisphere in the context of the last 3000 years: Peat-based proxy-climate data from Tierra del Fuego. The Holocene. 24 (12), 1649-1656.

Charman, D.J., Amesbury, M.J., Hinchcliffe, W., Hughes, P.D.M., Mallon, G., Blake, W.H., Gallego-Sala, A. V. and Mauquoy, D. 2015. Drivers of Holocene peatland carbon accumulation across a climate gradient. Quaternary Science Reviews 121, 110-119.

Charman, D.J., Beilman, D.W., Blaauw, M., Booth, R.K., Brewer, S., Chambers, F.M., Christen, J. A., Gallego-Sala, A., Harrison, S.P., Hughes, P.D.M., Jackson, S.T., Korhola, A., Mauquoy, D., Mitchell, F.J.G., Prentice, I. C., van der Linden, M., De Vleeschouwer, F., Yu, Z.C., Alm, J., Bauer, I.E., Corish, Y.M.C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols, J.E., Nieminen, T.M., MacDonald, G.M., Phadtare, N.R., Rausch, N., Sillasoo, U., Swindles, G.T., Tuittila, E-S., Ukonmaanaho, L., Väliranta, M., van Bellen, S., Van Geel, B., Vitt, D.H., Zhao, Y. 2013. Climate-related changes in peatland carbon accumulation during the last millennium. Biogeosciences, 10, 929-944.

Chen, H., Yang, G., Peng, C., Zhang, Y., Zhu, D., Zhu, Q., Hu, J., Wang, M., Zhan, W., Zhu, E., Bai, Z., Li, W., Wu, N., Wang, Y., Gao, Y., Tian, J., Kang, X., Zhao, X. and Wu, J. 2014. The carbon stock of alpine peatlands on the Qinghai-Tibetan Plateau during the Holocene and their future fate. Quaternary Science Reviews, 95: 151-158.

Chimner, R.A. and Ewel, K.C. 2005. A tropical freshwater wetland: II. Production, decomposition and peat formation. Wetlands Ecology and Management 13, 671-684.

Cole, L.E.S., Bhagwat, S.A. and Willis, K.J. 2015. Long-term disturbance dynamics and resilience of tropical peat swamp forests. Journal of Ecology, 103, 16–30.

Cooper, M.D.A., Estop-Aragonés, C., Fisher, J.P., Thierry, A., Garnett, M.H., Charman, D.J., Murton, J.B., Phoenix, G.K., Treharne, R., Kokelj, S. V, Wolfe, S.A., Lewkowicz, A.G., Williams, M. and Hartley, I.P. 2017. Limited contribution of permafrost carbon to methane release from thawing peatlands. Nature Climate Change 7, 507-511.

Couwenberg, J., Dommain, R.R. and Joosten, H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. Global Change Biology, 16, 1715–1732.

Crippa, P., Castruccio, S., Archer-Nichols, S., Lebron, G.B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C and Spracklen, D.V. 2016. Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia. Scientific Reports 6, 37074.

Cronin, T.M. 2012. Rapid sea level rise. Quaternary Science Reviews 56, 11-30.

Daniels, S.M., Evans, M.G., Agnew, C.T. and Allott, T.E.H. 2008. Sulphur leaching from headwater catchments in an eroded peatland, South Pennines, U.K. Science of the Total Environment 407, 481–496.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S. E., Bocko, Y.E. and Ifo, S.A. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86-90.

Davidson, E.A. and Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Davidson, N.C. 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Marine and Freshwater Research 65, 934-941.

Davies, M.G., Gray, A., Rein, G. and Legg, C.J. 2013. Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. Forest Ecology and Management 308, 169-177.

De Vleeschouwer, F., Vanneste, H., Mauquoy, D., Piotrowska, N. et al. (2014) Emissions from Pre-Hispanic Metallurgy in the South American Atmosphere. PLos ONE, 9(10)

Dommain, R., Couwenberg, J. and Joosten, H. 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. Quaternary Science Reviews 30, 999-1010.

Dommain, R., Couwenberg, J., Glaser, P.H., Joosten, H. and Suryadiputra, N.N. 2014. Carbon storage and release in Indonesian peatlands since the last deglaciation. Quaternary Science Reviews, 97, 1-32.

Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T.V. and Aerts, R. 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. Nature 460, 616-620.

Erkens, G., van der Meulen, M.J. and Middelkoop, H. 2016. Double trouble: Subsidence and CO_2 respiration due to 1000 years of Dutch coastal peatlands cultivation. Hydrogeology Journal 24, 551-568.

Estop-Aragonés, C., Cooper, M.D.A., Fisher, J.P., Thierry, A., Garnett, M.H., Charman, D.J., Murton, J.B., Phoenix, G.K., Treharne, R., Sanderson, N.K., Burn, C.R., Kokelj, S. V., Wolfe, S.A., Lewkowicz, A.G., Williams, M. and Hartley, I.P. 2018. Limited release of previously-frozen C and increased new peat formation after thaw in permafrost peatlands. Soil Biology and Biochemistry 118, 115–129.

Evans, C.D., Williamson, J.M., Kacaribu, F., Irawan, D., Suardiweianto, Y., Hidayat, M.F., Laurén, A. and Page, S.E. 2018. Rates and spatial variability of peat subsidence in an Indonesian plantation landscape. Geoderma 338, 410-421.

Fanin, T. and Van Der Werf, G.R. 2017. Precipitation–fire linkages in Indonesia (1997–2015). Biogeosciences 14, 3995–4008.

Fenner, N. and Freeman, C. 2011. Drought-induced carbon loss in peatlands. Nature Geoscience 4, 895-900.

Ferguson, P. and Lee, J.A. 1980. Some effects of bisulphate and sulphate on the growth of Sphagnum species in the field. Environmental Pollution Series A, Ecological and Biological 21, 59-71.

Ferguson, P. and Lee, J.A. 1983. Past and present sulphur pollution in the southern Pennines. Atmospheric Environment 17, 1131-1137.

Fialkiewicz-Koziel B., Smieja-Krol B., Frontasyeva M., Slowinski M., Marcisz K., Lapshina E., Gilbert D., Buttler A., Jassey V.E., Kaliszan K., Laggoun-Defarge F., Kolaczek P., Lamentowicz M. 2016. Anthropogenic- and natural sources of dust in peatland during the Anthropocene. *Scientific Reports*, 6, 38731.

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human amplification of drought-induced biomass burning in Indonesia since 1960. Nature Geoscience 2, 185-188.

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. PNAS 113, 9204-9209.

Fischer, H., Meissner, K.J., Mix, A.C., Abram, N.J., Austermann, J., Brovkin, V., Capron, E., Colombaroli, D., Daniau, A.L., Dyez, K.A., Felis, T., Finkelstein, S.A., Jaccard, S.L., McClymont, E.L., Rovere, A., Sutter, J., Wolff, E.W., Affolter, S., Bakker, P., Ballesteros-Cánovas, J.A., Barbante, C., Caley, T., Carlson, A.E., Churakova, O., Cortese, G., Cumming, B.F., Davis, B.A.S., De Vernal, A., Emile-Geay, J., Fritz, S.C., Gierz, P., Gottschalk, J., Holloway, M.D., Joos, F., Kucera, M., Loutre, M.F., Lunt, D.J., Marcisz, K., Marlon, J.R., Martinez, P., Masson-Delmotte, V., Nehrbass-Ahles, C., Otto-Bliesner, B.L., Raible, C.C., Risebrobakken, B., Sánchez Goñi, M.F., Arrigo, J.S., Sarnthein, M., Sjolte, J., Stocker, T.F., Velasquez Alvárez, P.A., Tinner, W., Valdes, P.J., Vogel, H., Wanner, H., Yan, Q., Yu, Z., Ziegler, M. and Zhou, L. 2018. Palaeoclimate constraints on the impact of 2°C anthropogenic warming and beyond. Nature Geoscience 11, 474–485.

Fontijn K., Lachowycz S.M., Rawson H., Pyle D.M., Mathera T.A., Naranjo J.A., Moreno- Roa H. 2014. Late Quaternary tephrostratigraphy of southern Chile and Argentina. *Quaternary Science Reviews*, 89, 70-84.

Foster, D. R., & Wright Jr, H. E. (1990). Role of ecosystem development and climate change in bog formation in central Sweden. Ecology, 71(2), 450-463.

Foster, D. R., Wright Jr, H. E., Thelaus, M., & King, G. A. (1988). Bog development and landform dynamics in central Sweden and south-eastern Labrador, Canada. The Journal of Ecology, 1164-1185.

Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M.D., Smith, P., van der Velde, M., Vicca, S., Babst, F., Beer, C., Buchmann, N., Canadell, J.G., Ciais, P., Cramer, W., Ibrom, A., Miglietta, F., Poulter, B., Rammig, A., Seneviratne, S.I., Walz, A., Wattenbach, M., Zavala, M.A. and Zscheischler, J. 2015. Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. Global Change Biology 21, 2861–2880.

French, H.M. and Millar, S.W.S. 2014. Permafrost at the time of the Last Glacial Maximum (LGM) in North America. Boreas 43, 667–677.

Fritz, C., van Dijk, G., Smolders, A.J.P., Pancotto, V.A., Elzenga, T.J.T.M., Roelofs, J.G.M., Grootjans, A.P. 2012. Nutrient additions in pristine Patagonian Sphagnum bog vegetation: can phosphorus addition alleviate (the effects of) increased nitrogen loads. Plant Biol. 14, 491–499.

Frolking, S. and Roulet, N.T. 2007. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. Global Change Biology 13, 1079-1088.

Frolking, S., Roulet, N.T., Tuittila, E-S., Bubier, J.L., Quillet, A., Talbot, J. and Richard, P.J.H. 2010. A new model of Holocene peatland net primary production, decomposition, water balance and peat accumulation. Earth System Dynamics 1, 1-21.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E-S. and Roulet, N. 2011. Peatlands in the Earth’s 21st century climate system. Environmental Reviews 19, 371–396.

Gałka M., Miotk-Szpiganowicz G., Marczewska M., Barabach J., van der Knaap W.O., Lamentowicz M., 2015. Palaeoenvironmental changes in Central Europe (NE Poland) during the last 6200 years reconstructed from a high resolution multi-proxy peat archive. The Holocene, 25, 421-434.

Gałka M., Tobolski K., Górska A., Milecka K., Fiałkiewicz-Kozieł B., Lamentowicz M., 2014. Disentangling the drivers of a Baltic bog development during the Little Ice Age in northern Poland. *Quaternary International* 328-329: 323-337.

Gałka, M., Szal, M., Watson, E.J., Gallego-Sala, A., Amesbury, M.J., Charman, D.J., Roland, T., Turner, T.E., Swindles, G.T., 2017. Vegetation succession, carbon accumulation and hydrological change in sub-Arctic peatlands (Abisko, northern Sweden). Permafrost and Periglacial Process 28, 589-604.

Gałka, M., Tobolski, K., Górska, A., Lamentowicz, M., 2017. Resilience of plant and testate amoeba communities after climatic and anthropogenic disturbances in a Baltic bog in Northern Poland: Implications for ecological restoration. The Holocene, 27, 130–141.

Gałka M., Swindles G., Szal M., Fulweber R., Feurdean A., 2018. Response of plant communities to climate change during the late Holocene: palaeoecological insights from peatlands in the Alaskan Arctic. Ecological Indicators 85, 525-536.

Gałka, M., Szal, M., Broder, T, Loisel, J., Knorr, K-H., 2019. Peatbog resilience to pollution and climate change over the past 2700 years in the Harz Mountains, Germany. Ecological Indicators 97, 183-193.

Gallego-Sala, A. V., Charman, D.J., Brewer, S., Page, S.E., Prentice, I.C., Friedlingstein, P., Moreton, S., Amesbury, M.J., Beilman, D.W., Björck, S., Blyakharchuk, T., Bochicchio, C., Booth, R.K., Bunbury, J., Camill, P., Carless, D., Chimner, R.A., Clifford, M., Cressey, E., Courtney-Mustaphi, C., De Vleeschouwer, F., de Jong, R., Fialkiewicz-Koziel, B., Finkelstein, S.A., Garneau, M., Githumbi, E., Hribjlan, J., Holmquist, J., Hughes, P.D.M., Jones, C., Jones, M.C., Karofeld, E., Klein, E.S., Kokfelt, U., Korhola, A., Lacourse, T., Le Roux, G., Lamentowicz, M., Large, D., Lavoie, M., Loisel, J., Mackay, H., MacDonald, G.M., Makila, M., Magnan, G., Marchant, R., Marcisz, K., Martínez Cortizas, A., Massa, C., Mathijssen, P., Mauquoy, D., Mighall, T., Mitchell, F.J.G., Moss, P., Nichols, J., Oksanen, P.O., Orme, L., Packalen, M.S., Robinson, S., Roland, T.P., Sanderson, N.K., Sannel, A.B.K., Silva-Sánchez, N., Steinberg, N., Swindles, G.T., Turner, T.E., Uglow, J., Väliranta, M., van Bellen, S., van der Linden, M., van Geel, B., Wang, G., Yu, Z., Zaragoza-Castells, J. and Zhao, Y., 2018. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. Nature Climate Change 8, 907–913.

Garneau, M., Turunen, J., Beaulieu-Audy, V., Asnong, H. Submitted. Recent and long-term carbon and nitrogen apparent accumulation rates from boreal peatlands, James Bay lowlands, northeastern Canada.

Garneau, M., Tremblay, L., & Magnan, G. (2018). Holocene pool formation in oligotrophic fens from boreal Québec in northeastern Canada. The Holocene, 28(3), 396-407.

Garneau, M., van Bellen, S., Magnan, G., Beaulieu-Audy, V., Lamarre, A. and Asnong, H. 2014. Holocene carbon dynamics of boreal and subarctic peatlands from Québec, Canada. The Holocene 24, 1043-1053.

Gauci, V., Dise, N. and Fowler, D. 2002. Controls on suppression of methane flux from a peat bog subjected to simulated acid rain sulfate deposition. Global Biogeochemical Cycles 16. DOI: 10.1029/2000GB001370.

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific Reports 4, 6112.

Gibson, C.M., Chasmer, L.E., Thompson, D.K., Quinton, W.L., Flannigan, M.D. and Olefeldt, D. 2018 Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications 9, 3041. DOI: 10.1038/s41467-018-05457-1.

Girkin, N.T., Turner, B.L., Ostle, N. and Sjo, S. 2018. Root-derived CO_2 flux from a tropical peatland. Wetland Ecology and Management 8, 985–991.

Glaser, P. H., Siegel, D. I., Reeve, A. S., Janssens, J. A., & Janecky, D. R. 2004. Tectonic drivers for vegetation patterning and landscape evolution in the Albany River region of the Hudson Bay Lowlands. *Journal of Ecology*, *92*(6), 1054-1070.

Glauber, A.J. and Gunawan, I. (eds.). 2016. The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis. Jakarta: The World Bank.

Gorham, E. 1991. Northern peatlands - role in the carbon-cycle and probable responses to climatic warming. Ecological Applications 1, 182-195.

Gorham, E. and Janssens, J.A. 1992. The paleorecord of geochemistry and hydrology in northern peatlands and its relation to global change. Suo 43, 117-126.

Grace, J., Mitchard, E. and Gloor, E. 2014. Perturbations in the carbon budget of the tropics. Global Change Biology 20, 3238–3255.

Grootjans, A., Iturraspe, R., Fritz, C. 2014. Mires and mire types of Peninsula Mitre, Tierra del Fuego, Argentina. Mires and Peat. 20, 1-20.

Gunnarsson, U., Boresjö Bronge, L., Rydin, H. and Ohlson, M. 2008. Near-zero recent carbon accumulation in a bog with high nitrogen deposition in SW Sweden. Global Change Biology 14, 2152-2165.

Haberle, S.G., Hope, G.S. and Van Der Kaars, S., 2001. Biomass burning in Indonesia and Papua New Guinea: Natural and human induced fire events in the fossil record. Palaeogeography Palaeoclimatology Palaeoecology 171, 259–268.

Halsey, L.A., Vitt, D.H. and Gignac, L.D. 2000. Sphagnum-dominated peatlands in North America since the last glacial maximum: their occurrence and extent. Bryologist 103, 334-352.

Hansen M.C., Roy D.P., Lindquist E., Adusei B., Justice C.O., Altstatt A. 2008. A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin. *Remote Sensing of Environment*, *112*(5), 2495-2513.

Hapsari, K.A., Biagioni, S., Jennerjahn, T.C., Reimer, P.M., Saad, A., Achnopha, Y., Sabiham, S. and Behling, H. 2018. Environmental dynamics and carbon accumulation rate of a tropical peatland in Central Sumatra, Indonesia. Quaternary Science Reviews 169, 173-187.

Harden, J.W., Koven, C.D., Ping, C.L., Hugelius, G., David McGuire, A., Camill, P., Jorgenson, T., Kuhry, P., Michaelson, G.J., O'Donnell, J.A., Schuur, E.A.G., Tarnocai, C., Johnson, K. and Grosse, G. 2012. Field information links permafrost carbon to physical vulnerabilities of thawing. Geophysical Research Letters 39 L15704. DOI:10.1029/2012GL051958.

Harris, N.L., Brown, S., Hagen, S.C., Saatchi, S.S., Petrova, S., Salas, W., Hansen, M.C., Potapov, P.V. and Lotsch A. 2012. Baseline map of carbon emissions from deforestation in tropical regions. Science 336, 1573-1576.

Heil, A., Langmann, B. and Aldrian, E. 2007. Indonesian peat and vegetation fire emissions: Study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model. Mitigation and Adaptation Strategies for Global Change 12, 113 – 133.

Helbig, M., Chasmer, L.E., Kljun, N., Quinton, W.L., Treat, C.C. and Sonnentag, O. 2017. The positive net radiative greenhouse gas forcing of increasing methane emissions from a thawing boreal forest-wetland landscape. Global Change Biology 23, 2413-2427.

Henman, J. and Poulter, B. 2008. Inundation of freshwater peatlands by sea level rise: uncertainty and potential carbon cycle feedbacks. Journal of Geophysical Research: Biogeosciences 113. DOI: 10.1029/2006JG000395.

Henn, J. J., Anderson, C. B., Martínez, G. 2016. Landscape-level impact and habitat factors associated with invasive beaver distribution in Tierra del Fuego. Biological Invasions. 18 (6), 1679-1688.

Hergoualc'h, K., Hendry, D.T., Murdiyarso, D., Verchot, L.V. 2017. Total and heterotrophic soil respiration in a swamp forest and oil palm plantations on peat in Central Kalimantan, Indonesia. Biogeochemistry, 135, 203–220.

Heusser, C. J. 1993. Late Quaternary forest-steppe contact zone, Isla Grande de Tierra del Fuego, subantarctic South America. Quaternary Science Reviews, 12(3), 169-177.

Hirano, T., Jauhiainen, J., Inoue, T., Takahashi, H. 2009. Controls on the carbon balance of tropical peatlands. Ecosystems 12, 873–887.

Hirano, T., Kusin, K., Limin, S. and Osaki, M. 2014. Carbon dioxide emissions through oxidative peat decomposition on a burnt tropical peatland. Global Change Biology 20, 555–565.

Hodgkins, S.B., Richardson, C.J., Dommain, R., Wang, H., Glaser, P.H., Verbeke, B., Winkler, B.R., Cobb, A.R., Rich, V.I., Missilmani, M., Flanagan, N., Ho, M., Hoyt, A.M., Harvey, C.F., Vining, S.R., Hough, M.A., Moore, T.R., Richard, P.J.H., De La Cruz, F.B., Toufaily, J., Hamdan, R., Cooper, W.T. and Chanton, J.P. 2018. Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. Nature Communications, 9, 1–13.

Holden, J., Chapman, P.J. and Labadz, J.C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Progress in Physical Geography: Earth and Environment 28, 95-123.

Holden, J., Evans, M.G., Burt, T.P. and Horton, M. 2006. Impact of land drainage on peatland hydrology. Journal of Environmental Quality 35, 1764-1778.

Holden, J., Shotbolt, L., Bonn, A., Burt, T.P., Chapman, P.J., Dougill, A.J., Fraser, E.D.G., Hubacek, K., Irvine, B.J., Kirkby, M.J., Prell, C., Reed, M.S., Stagl, S., Stringer, L.C., Turner, A.G.D. and Worall, F. 2007. Environmental change in moorland landscapes. Earth Science Reviews 82, 75-100.

Holmquist, J.R., MacDonald, G.M. and Gallego-Sala, A. 2014. Peatland initiation, carbon accumulation, and 2 ka depth in the James Bay Lowland and adjacent regions. Arctic Antarctic and Alpine Research 46, 19-39.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H. and Jauhiainen, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7, 1505-1514.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W., Lu, X., Idris, A. and Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences 9, 1053–1071.

Hooijer, A., Silvius, M., Wosten, H. and Page, S.E. 2006. Peat CO_2 assessment of CO_2 from drained peatlands in Southeast Asia. Delft: Delft Hydraulics.

Hope, G., Chokkalingam, U., & Anwar, S. (2005). The stratigraphy and fire history of the Kutai Peatlands, Kalimantan, Indonesia. Quaternary Research, 64(3), 407-417.

Horton, B.P., Rahmstorf, S., Engelhart, S.E. and Kemp, A.C. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews 84, 1–6.

Houghton, R.A. 2012. Carbon emissions and the drivers of deforestation and forest degradation in the tropics. Current Opinion in Environmental Sustainability 4, 597-603.

Householder, J.E., Janovec, J.P., Tobler, M.W., Page, S.E. and Lähteenoja, O. 2012. Peatlands of the Madre de Dios River of Peru: distribution, geomorphology and habitat diversity. Wetlands 32, 359–368.

Huber, U. M., & Markgraf, V. (2003). Holocene fire frequency and climate change at Rio Rubens Bog, southern Patagonia. In Fire and climatic change in temperate ecosystems of the western Americas (pp. 357-380). Springer, New York, NY.

Huber, U. M. & Markgraf, V. (2003) European impact on fire regimes and vegetation dynamics at the steppe-forest ecotone of southern Patagonia. The Holocene, 13 (4), 567-579.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C. and Schirrmeister, L. 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences 11, 6573–6593.

Hughes, P. D. M., Mallon, G., Brown, A., Essex, H. J. et al. (2013). The impact of high tephra loading on late-Holocene carbon accumulation and vegetation succession in peatland communities. Quaternary Science Reviews, 67, 160-175.

Hulme, P. D. 1994. A paleobotanical study of paludifying pine forest on the island of Hailuoto, northern Finland. New Phytologist 126, 153-162.

Ise, T., Dunn, A.L., Wofsy, S.C. and Moorscroft, P.R. 2008. High sensitivity of peat decomposition to climate change through water-table feedback. Nature Geoscience 1, 763-766.

Ishikura, K., Hirano, T., Okimoto, Y., Hirata, R., Kiew, F., Melling, L., Aeries, E.B., Lo, K.S., Musin, K.K., Waili, J.W., Wong, G.X. and Ishii, Y. 2018. Soil carbon dioxide emissions due to oxidative peat decomposition in an oil palm plantation on tropical peat. Agriculture, Ecosystems and Environment 254, 202–212.

Jauhiainen, J., Hooijer, A. and Page, S.E. 2012. Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia. Biogeosciences, 9, 617–630.

Jauhiainen, J., Kerojoki, O., Silvennoinen, H., Limin, S. and Vasander, H. 2014. Heterotrophic respiration in drained tropical peat is greatly affected by temperature - A passive ecosystem cooling experiment.

Environmental Research Letters 9, 1–18.

Jauhiainen, J., Silvennoinen, H., Könönen, M., Limin, S. and Vasander, H. 2016. Management driven changes in carbon mineralization dynamics of tropical peat. Biogeochemistry 129, 115–132.

Jones, B. M., Baughman, C. A., Romanovsky, V. E., Parsekian, A. D., Babcock, E. L., Stephani, E., Jones, M. C., Grosse, G., and Berg, E. E. 2016. Presence of rapidly degrading permafrost plateaus in south-central Alaska, The Cryosphere, 10, 2673-2692, https://doi.org/10.5194/tc-10-2673-2016,

Jones, M. C., & Yu, Z. 2010. Rapid deglacial and early Holocene expansion of peatlands in Alaska. Proceedings of the National Academy of Sciences, 107(16), 7347-7352.

Jones, M.C., Booth, R.K., Yu, Z. and Ferry, P. 2013. A 2200-year record of permafrost dynamics and carbon cycling in a collapse-scar bog, interior Alaska. Ecosystems 16, 1-19.

Jones, M.C., Harden, J., O'Donnell, J., Manies, K., Jorgenson, T., Treat, C. and Ewing, S. 2017. Rapid carbon loss and slow recovery following permafrost thaw in boreal peatlands. Global Change Biology 23, 1109-1127.

Joosten, H. and Clarke, D. 2002. The wise use of mires and peatlands. International Mire Conservation Group and International Peat Society. 304 pp.

Jorgenson, M.T., Racine, C.H., Walters, J.C. and Osterkamp, T.E. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48, 551-579.

Miettinen J., Aljosja, H., Ronald, V., Soo Chin, L. and Page, S.E. 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environmental Research Letters 12, 024014.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J., De Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Roupsard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S. and Zhang, K., 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature 467, 951–954.

Juutinen, S., Moore, T.R., Laine, A., Bubier, J.L., Tuittila, E., De Young, A., Chong, M. 2016. Responses of mosses *Sphagnum capillifolium* and *Polytrichum strictum* to nitrogen deposition in a bog: height growth, ground cover, and CO_2 exchange. *Botany* 94: 127–138; dx.doi.org/10.1139/cjb-2015-0183.

Kanakidou, M., Myriokefalitakis, S., Daskalakis, N., Fanourgakis, G., Nenes, A., Baker, A.R., Tsigaridis, K. and Mihalopoulos, N., 2016. Past, present and future atmospheric nitrogen deposition. Journal of Atmospheric Science 73, 2039–2047.

Kasischke, E. S., & Bruhwiler, L. P. (2002). Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. Journal of Geophysical Research: Atmospheres, 107(D1), FFR-2.

Kasischke, E.S. and Turetsky, M.R. 2006. Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 33 L09703, doi: 10.1029/2006GL025677.

Kasischke, E.S., Amiro, B.D., Barger, N.N., French, N.H.F., Goetz, S.J., Grosse, G., Harmon, M.E., Hicke, J.A., Liu, S and Masek, J.G. 2013. Impacts of disturbance on the terrestrial carbon budget of North America. Journal of Geophysical Research Biogeosciences 118, 303-316.

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R., Camilloni, I., Doblas- Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, G.A., Prather, M., Sarr, A., Sch€ar, C., Sutton, R., van Oldenborgh, G.J., Vecchi, G., Wang, H.J., 2013. Near-term climate change: projections and predictability. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 953-1028.

Kivimäki, S.K., Sheppard, L.J., Leith, I.D. and Grace, J. 2013. Long-term enhanced nitrogen deposition increases ecosystem respiration and carbon loss from a Sphagnum bog in the Scottish Borders. Environmental and Experimental Botany 90, 53–61.

Kjellman, S. E., Axelsson, P. E., Etzelmüller, B., Westermann, S. et al. (2018). Holocene development of subarctic permafrost peatlands in Finnmark, northern Norway. The Holocene, 28(12), 1855-1869.

Klein, E. S., Yu, Z., & Booth, R. K. (2013). Recent increase in peatland carbon accumulation in a thermokarst lake basin in Southwestern Alaska. Palaeogeography, Palaeoclimatology, Palaeoecology, 392, 186-195.

Kleinebecker, T., Hölzel, N., Vogel, A. 2008. South Patagonian ombrotrophic bog vegetation reflects biogeochemical gradients at the landscape level. Journal of Vegetation Science. 19,151-160.

Klimaschewski A., Barnekow L., Bennett K.D., Andreev A.A., Andrén E., Bobrov A.A., Hammarlund D. 2015. Holocene environmental changes in southern Kamchatka, Far Eastern Russia, inferred from a pollen and testate amoebae peat succession record. *Global and Planetary Change*, 134, 142-154.

Koh, L.P., Miettinen, J., Liew, S.C. and Ghazoul, J. 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. PNAS 108, 5127-5132.

Korhola, A., Ruppel, M., Seppä, H., Väliranta, M. et al. 2010. The importance of northern peatland expansion to the late-Holocene rise of atmospheric methane. Quaternary Science Reviews, 29(5-6), 611-617.

Kokfelt, U., Reuss, N., Struyf, E., Sonesson, M. et al. (2010). Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden. Journal of Paleolimnology, 44(1), 327-342.

Kołaczek P., Karpińska-Kołaczek M., Marcisz K., Gałka M., Lamentowicz M., 2018. Palaeohydrology and the human impact on one of the largest raised bogs complex in the Western Carpathians (Central Europe) during the last two millennia. *The Holocene*, 28(4), 595-608.

Koven, C.D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G. and Tarnocai, C. 2011. Permafrost carbon-climate feedbacks accelerate global warming. PNAS 108, 14769-14774.

Koven, C.D., Schuur, E.A.G., Schädel, C., Bohn, T.J., Burke, E.J., Chen, G., Chen, X., Ciais, P., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Jafarov, E.E., Krinner, G., Kuhry, P., Lawrence, D.M., MacDougall, A.H., Marchenko, S.S., McGuire, A.D., Natali, S.M., Nicolsky, D.J., Olefeldt, D., Peng, S., Romanovsky, V.E., Schaefer, K.M., Strauss, J., Treat, C.C. and Turetsky, M. 2015. A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. Philosophical Transactions of the Royal Society A 373, 20140423.

Krawchuk, M.A., Moritz, M.A., Parisien, M.A., Van Dorn, J. and Hayhoe, K. 2009. Global pyrogeography: The current and future distribution of wildfire. PLoS One 4, e5102.

Kreuzburg, M., Ibenthal, M., Janssen, M., Rehder, G., Voss, M., Naumann, M., Feldens, P., 2018. Sub-marine Continuation of Peat Deposits From a Coastal Peatland in the Southern Baltic Sea and its Holocene Development. Frontiers in Earth Science 6. DOI: 10.3389/feart.2018.00103.

Krüger, J.P., Alewell, C., Minkkinen, K., Szidat, S., Leifeld, J., 2016. Calculating carbon changes in peat soils drained for forestry with four different profile-based methods. Forest Ecology and Management, 381: 29-36.

Kuhry, P. 1994. The role of fire in the development of Sphagnum-dominated peatlands in western boreal Canada. Journal of Ecology 82, 899-910.

Kuhry, P. (2008). Palsa and peat plateau development in the Hudson Bay Lowlands, Canada: timing, pathways and causes. Boreas, 37(2), 316-327.

Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Murdiyarso, D. and Frolking, S., 2015. Carbon accumulation of tropical peatlands over millennia: A modeling approach. Global Change Biology 21, 431–444.

Kylander M.E., Martinez-Cortizas A., Bindler R., Kaal J., Sjostrom J.K., Hansson S.V., Silva-Sanchez N., Greenwood S.L., Gallagher K., Rydberg J., Morth C.M. and Rauch S. 2018. Mineral dust as a driver of carbon accumulation in northern latitudes. Scientific Reports 8, 6876.

Lacourse, T. Adeleye, M.A., & Stewart, J.R. 2019. Peatland formation, succession and carbon accumulation at a mid-elevation poor fen in Pacific Canada. The Holocene 29, 1694-1707.

Lähteenoja, O., Flores, B. and Nelson, B. 2013. Tropical peat accumulation in Central Amazonia. Wetlands 33, 495–503.

Lähteenoja, O., Reátegui, Y.R., Räsänen, M., Torres, D.D.C., Oinonen, M. and Page, S. 2012. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. Global Change Biology, 18, 164–178.

Lamarre, A., Garneau, M. and Asnong, H. 2012. Holocene paleohydrological reconstruction and carbon accumulation of a permafrost peatland using testate amoeba and macrofossil analyses, Kuujjuarapik, subarctic Québec, Canada. Review of Palaeobotany and Palynology 186, 131-141.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y. and Sambridge, M. 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. PNAS 111, 15296–15303.

Lamentowicz, M., Obremska, M., 2010. A rapid response of testate amoebae and vegetation to inundation of a kettle hole mire. Journal of Paleolimnology. 43, (3) 499–511.

Lamentowicz M., Mueller M., Gałka M., Barabach J., Milecka K., Goslar T., Binkowski M., 2015. Reconstructing human impact on peatland development during the past 200 years in CE Europe through biotic proxies and X-ray tomography. *Quaternary International*, 357, 282-294.

Lamentowicz M., Cedro A., Gałka M., Miotk-Szpiganowicz G., Mitchell E.A.D., Pawlyta J., Goslar T. 2008. Last millennium palaeoenvironmental changes from a Baltic bog (Poland) inferred from stable isotopes, pollen, plant macrofossils and testate amoebae. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 265, 93-106.

Lamentowicz M., Gałka M., Pawlyta J., Lamentowicz Ł., Goslar T., Miotk-Szpiganowicz G. 2011. Climate change and human impact in the southern Baltic during the last millennium reconstructed from an ombrotrophic bog archive. *Studia Quaternaria*, 28, 3-16.

Lamentowicz M., Milecka K., Gałka M., Cedro A., Pawlyta J., Piotrowska N., Lamentowicz Ł., van der Knaap W.O. 2009. Climate- and human-induced hydrological change since AD 800 in an ombrotrophic mire in Pomerania (N Poland) tracked by testate amoebae, macro-fossils, pollen, and tree-rings of pine. *Boreas*, 38(2), 214-229.

Lamentowicz M., Kołaczek P., Mauquoy D., Kittel P., Łokas E., Słowiński M., Jassey V.J.E., Niedziółka K., Kajukało-Drygalska K., Marcisz K. 2020. Always on the tipping point – a search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland. *Quaternary Science Reviews*. (in press)

Lamers, L.P.M., Ten Dolle, G.E., Van Den Berg, S.T.G., Van Delft, S.P.J. and Roelofs, J.G.M. 2001. Differential responses of freshwater wetland soils to sulphate pollution. Biogeochemistry 55, 87-101.

Langner A, Siegert F (2009) Spatiotemporal fire occurrence in Borneo over a period of 10 years. Global Change Biology, 15, 48–62.

Larmola, T., Bubier, J.L., Kobyljanec, C. Basiliko, N., Juutinen, S., Humphreys, E., Preston, M., and Moore, T. 2013. Vegetation feedbacks of nutrient addition lead to a weaker carbon sink in an ombrotrophic bog. Global Change Biology 19, 3729–3739.

Lavoie, C., & Pellerin, S. (2007). Fires in temperate peatlands (southern Quebec): past and recent trends. Botany, 85(3), 263-272.

Lawson, I.T., Kelly, T.J., Aplin, P., Boom, A., Dargie, G., Draper, F.C.H., Hassan, P.N.Z.B.P., Hoyos-Santillan, J., Kaduk, J., Large, D., Murphy, W., Page, S.E., Roucoux, K.H., Sjögersten, S., Tansey, K., Waldram, M., Wedeux, B.M.M. and Wheeler, J. 2015. Improving estimates of tropical peatland area, carbon storage, and greenhouse gas fluxes. Wetland Ecology and Management 23, 327–346.

Leiber-Sauhritl, K., Fuß, R., Voigt, C. and Freibauer. A. 2014. High CO_2 fluxes from grassland on histic Gleysol along soil carbon and drainage gradients. Biogeosciences 11, 749-761.

Leifeld J. and Menichetti, L. 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nature Communications 9, 1071.

Leifeld J., Wüst-Galley C., Page S., 2019. Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. Nature Climate Change 9, 945-947.

Li, W., Dickinson, R.E., Fu, R., Niu, G-Y., Yang, Z-L. and Canadell, J.G. 2007. Future precipitation changes and their implications for tropical peatlands. Geophysical Research Letters 34, L01403.

Limpens, J., G. Granath, U. Gunnarsson, R. Aerts, S. Bayley, L. Bragazza, J. Bubier, A. Buttler, L.J.L. van den Berg, A-J. Francez, R. Gerdol, P. Grosvernier, M.M.P.D. Heijmans, M.R. Hoosbeek, S. Hotes, M. Ilomets, I. Leith, E.A.D. Mitchell, T. Moore, M.B. Nilsson, J-F. Nordbakken, L. Rochefort, H. Rydin, L.J. Sheppard, M. Thormann, M.M. Wiedermann, B.L. Williams and B. Xu 2011. Climatic modifiers of the response to nitrogen deposition in peat-forming Sphagnum mosses: a meta-analysis. New Phytologist 191, 496–507.

Liu X., Wu J., Zhu D., Zhu Q., Wu N., Peng C., Li X., Froking S. and Chen H. 2016. Peat mass and carbon stock during the last 10000 years in Sanjiang Plain: a modeling approach. Chinese Journal of Applied and Environmental Biology 22, 1-12.

Liu X., Chen H., Zhu Q., Wu J., Frolking S., Zhu D., Wang M., Wu N., Peng C. and He X. 2018. Holocene peatland development and carbon stock of Zoige peatland, Tibetan Plateau: a modeling approach. Journal of Soils and Sediments 18, 2032-2043.

Liu B., Booth R.K., Escobar J., Wei Z., Bird B.W., Pardo A., …, Ouyang J. 2019. Ecology and paleoenvironmental application of testate amoebae in peatlands of the high-elevation Colombian páramo. *Quaternary Research*, 92(1), 14-32.

Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J. and Penttil, T. 2011. Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. Biogeosciences 8, 3203–3218.

Loisel, J., and Yu, Z. 2013. Recent acceleration of carbon accumulation in a boreal peatland, south central Alaska. Journal of Geophysical Research: Biogeosciences 118, 41-53.

Loisel, J., & Yu, L. (2013) Holocene peatland carbon dynamic in Patagonia. Quaternary Science Reviews, 69, 125-141.

Loisel, J., van Bellen, S., Pelletier, L., Talbot, J., Hugelius, G., Karran, D., Yu, Z., Nichols, J. and Holmquist, J. 2017. Insights and issues with estimating northern peatland carbon stocks and fluxes since the Last Glacial Maximum. Earth Science Reviews 165, 59–80.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P., Alm, J., Amesbury, M.J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K.E., Belyea, L.R., Bunbury, J., Chambers, F.M., Charman, D.J., De Vleeschouwer, F., Fiakiewicz-Kozie , B., Finkelstein, S. A., Galka, M., Garneau, M., Hammarlund, D., Hinchcliffe, W., Holmquist, J., Hughes, P., Jones, M.C., Klein, E.S., Kokfelt, U., Korhola, A., Kuhry, P., Lamarre, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G., Magnan, G., Makila, M., Mallon, G., Mathijssen, P., Mauquoy, D., McCarroll, J., Moore, T., Nichols, J., O'Reilly, B., Oksanen, P., Packalen, M., Peteet, D., Richard, P.J., Robinson, S., Ronkainen, T., Rundgren, M., Sannel, B.K., Tarnocai, C., Thom, T., Tuittila, E.-S., Turetsky, M.R., Valiranta, M., van der Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y. and Zhou, W. 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. The Holocene 24, 1028-1042.

Luan, J., Liu, S., Wu, J., Wang, M. and Yu, Z. 2018. The transient shift of driving environmental factors of carbon dioxide and methane fluxes in Tibetan peatlands before and after hydrological restoration. Agricultural and Forest Meteorology 250-251, 138-146.

MacDonald, G.M., Beilman, D., Kremenetski, K., Sheng, Y., Smith, L. and Velichko, A. 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. Science 314, 285–288.

Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., Jandt, R.R., Schuur, E.A.G., Shaver, G.R., Verbyla, D.L., 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature 475, 489–492.

Magnan, G., van Bellen, S., Davies, L. et al. (2018). Impact of the Little Ice Age cooling and 20th century climate change on peatland vegetation dynamics in central and northern Alberta using a multi-proxy approach and high-resolution peat chronologies. Quaternary Science Reviews, 185, 230-243.

Magnan, G., Stum-Boivin, L.E., Garneau, M., Grondin, P. and Fenton, N. 2019. Holocene vegetation dynamics and hydrological variability in forested peatlands of the Clay Belt, eastern Canada, reconstructed using a palaeoecological approach. Boreas 48, 131–146.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113, 65-79.

Mansilla, C. A., McCulloch, R. & Morello, F. (2018) The vulnerability of the Nothofagus forest-steppe ecotone to climate change: Palaeoecological evidence from Tierra del Fuego (~53°S). Palaeogeography, Palaeoclimatology, Palaeoecology, 508, 59-70.

Marcisz K., Tinner W., Colombaroli D., Kołaczek P., Słowiński M., Fiałkiewicz-Kozieł B., Łokas E., Lamentowicz M. 2015. Long-term hydrological dynamics and fire history during the last 2000 years in CE Europe reconstructed from a high-resolution peat archive. *Quaternary Science Reviews*, 112, 138-152.

Marion, G. M., & Oechel, W. C. (1993). Mid-to late-Holocene carbon balance in Arctic Alaska and its implications for future global warming. The Holocene, 3(3), 193-200.

Markgraf, V. & Huber, U. 2010. Late and postglacial vegetation and fire history in Southern Patagonia and Tierra del Fuego. Palaeogeography, Palaeoclimatology, Palaeoecology, 297 (2), 351-366.

Marwanto, S. and Agus, F.2014. Is CO_2 flux from oil palm plantations on peatland controlled by soil moisture and/or soil and air temperatures? Mitigation and Adaptation Strategies for Global Change 19, 809–819.

Mathijssen, P. J.H., Gałka, M., Borken, W., Knorr, K-H. 2019. Plant communities control long term carbon accumulation and biogeochemical gradients in a Patagonian bog. Science of The Total Environment, 684, 670-681.

Matson, P., McDowell, W., Townsend, A. and Vitousek, P. 1999. The globalization of N deposition: ecosystem consequences in tropical environments. Biogeochemistry 46, 67–83.

Mauquoy, D., Engelkes, T., Groot, M. H. M., Markesteijn, F. et al. (2002). High-resolution records of late-Holocene climate change and carbon accumulation in two north-west European ombrotrophic peat bogs. Palaeogeography, Palaeoclimatology, Palaeoecology, 186(3-4), 275-310.

Mauquoy, D., Van Geel, B., Blaauw, M., Speranza, A., & van der Plicht, J. (2004). Changes in solar activity and Holocene climatic shifts derived from 14C wiggle-match dated peat deposits. The Holocene, 14(1), 45-52.

McCulloch, R. & Davies, S. (2001) Late-glacial and Holocene palaeoenvironmental change in the central Strait of Magellan, southern Patagonia. Palaeogeography, Palaeoclimatology, Palaeoecology, 173, 143-173.

McGuire, A.D., Lawrence, D.M., Koven, C., Clein, J.S., Burke, E., Chen, G., Jafarov, E., MacDougall, A.H., Marchenko, S., Nicolsky, D., Peng, S., Rinke, A., Ciais, P., Gouttevin, I., Hayes, D.J., Ji, D., Krinner, G., Moore, J.C., Romanovsky, V., Schädel, C., Schaefer, K., Schuur, E.A.G. and Zhuang, Q. 2018. Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. PNAS 115, 3882-3887

McLaughlin, J.W. and Webster, K. 2013. Effects of a changing climate on peatlands in permafrost zones: a literature review and application to Ontario’s far north. Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, ON. Climate Change Research Report CCRR-34 168 pp.

Melling, L., Hatano, R. and Goh, K.J. 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus 57B, 1–11.

Melton, J.R., Wania, R., Hodson, E.L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C.A., Beerling, D.J., Chen, G., Eliseev, A. V., Denisov, S.N., Hopcroft, P.O., Lettenmaier, D.P., Riley, W.J., Singarayer, J.S., Subin, Z.M., Tian, H., Zürcher, S., Brovkin, V., Van Bodegom, P.M., Kleinen, T., Yu, Z.C. and Kaplan, J.O. 2013. Present state of global wetland extent and wetland methane modelling: Conclusions from a model inter-comparison project (WETCHIMP). Biogeosciences 10, 753–788.

Michaletz, S.T., Cheng, D., Kerkhoff, A.J. and Enquist, B.J. 2014. Convergence of terrestrial plant production across global climate gradients. Nature 512, 39–43.

Miettinen, J., Shi, C. and Liew, S.C. 2011. Deforestation rates in insular Southeast Asia between 2000 and 2010. Global Change Biology, 17, 2261–2270.

Miettinen, J., Shi, C., Liew, S.C. 2012. Two decades of destruction in Southeast Asia’s peat swamp forests. Frontiers in Ecology and the Environment, 10, 124–128.

Miettinen, J., Shi, C., Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 6, 67–78.

Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S.C. and Page, S.E. 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environmental Research Letters 12, 024014.

Mikaloff Fletcher, S.E., Tans, P.P., Bruhwiler, L.M., Miller, J.B., and Heimann, M. 2004. CH_4 sources estimated from atmospheric observations of CH_4 and its $^{13}C/^{12}C$ isotopic ratios: 1. Inverse modeling of source processes, Global Biogeochemical Cycles, 18, GB4004.

Minkkinen, K., Korhonen, R., Savolainen, I. and Laine, J. 2002. Carbon balance and radiative forcing of Finnish peatlands 1900-2100 - the impact of forestry drainage. Global Change Biology 8, 785–799.

Mitsch, W.J., Zhang, L., Stefanik, K.C., Nahlik, A.M., Anderson, C.J., Bernal, B., Hernandez, M. and Song, K., 2012. Creating Wetlands: Primary Succession, Water Quality Changes, and Self-Design over 15 Years. Bioscience 62, 237–250.

Moore, T.R. and Turunen, J. 2004. Carbon accumulation and storage in mineral subsoil beneath peat. Soil Science Society of America Journal 68, 690-696.

Moore, S., Evans, C. D., Page, S. E., Garnett, M. H. et al. (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. Nature, 493(7434), 660.

Moritz, M.A., Parisien, M.-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J. and Hayhoe, K. 2012. Climate change and disruptions to global fire activity. Ecosphere 3, Article 49.

Morris, P.J., Swindles, G.T., Valdes, P.J., Ivanovic, R.F., Gregoire, L.J., Smith, M.W., Tarasov, L., Haywood, A.M. and Bacon, K.L. 2018. Global peatland initiation driven by regionally asynchronous warming. PNAS 115, 4851-4856.

Moss, P., Tibby, J., Shapland, F., Fairfax, R., Stewart, P., Barr, C., Petherick, L., Gontz, A. and Sloss, C. 2016. Patterned fen formation and development from the Great Sandy Region, south-east Queensland, Australia. Marine and Freshwater Research 67, 816-827.

Murdiyarso, D., Hergoualc'h, K. and Verchot, L.V. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. PNAS 107, 19655-19660.

Nakatsubo, T., Uchida, M., Sasaki, A., Kondo, M., Yoshitake, S. and Kanda, H. 2015. Carbon accumulation rate of peatland in the High Arctic, Svalbard: Implications for carbon sequestration. Polar Science 9, 267-275.

Nieminen, M. (2004). Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three Norway spruce forests growing on drained peatlands in southern Finland. Silva Fennica, 38 (2), 123-132.

O'Donnell, J.A., Jorgenson, M.T., Harden, J.W., McGuire, A.D., Kanevskiy, M.Z. and Wickland, K.P. 2012. The Effects of Permafrost Thaw on Soil Hydrologic, Thermal, and Carbon Dynamics in an Alaskan Peatland. Ecosystems 15, 213–229.

Oksanen, P. O., Kuhry, P., & Alekseeva, R. N. (2001). Holocene development of the Rogovaya river peat plateau, European Russian Arctic. The Holocene, 11(1), 25-40.

Oksanen, P., Kuhry, P., & Alekseeva, R. (2003). Holocene development and permafrost history of the Usinsk mire, northeast European Russia. Géographie physique et Quaternaire, 57(2-3), 169-187.

Oksanen, P.O. (2006). Holocene development of the Vaisjeäggi palsa mire, Finnish Lapland. Boreas, 35(1), 81-95.

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., Mcguire, A.D., Romanovsky, V.E., Sannel, A.B.K., Schuur, E.A.G., Turetsky, M.R., 2016. Circumpolar distribution and carbon storage of thermokarst landscapes. Nature Communications 7, 1–11.

Olid C., Nilsson M.B., Eriksson T., Klaminder J. 2014. The effects of temperature and nitrogen and sulfur additions on carbon accumulation in a nutrient-poor boreal mire: Decadal effects assessed using 210Pb peat chronologies, J. Geophys. Res. Biogeosci., 119, doi:10.1002/2013JG002365.

Olid, C., Diego, D., Garcia-Orellana, J., Cortizas, A.M., Klaminder, J., 2016. Modeling the downward transport of ^{210}Pb in Peatlands: Initial Penetration-Constant Rate of Supply (IP-CRS) model. Science of the Total Environment 541, 1222–1231.

Packalen, M.S. and Finkelstein, S.A. 2014. Quantifying Holocene variability in carbon uptake and release since peat initiation in the Hudson Bay Lowlands, Canada. The Holocene 24, 1063-1074.

Packalen, M.S., Finkelstein, S.A. and McLaughlin, J.W. 2014. Carbon storage and potential methane production in the Hudson Bay Lowlands since mid-Holocene peat initiation. Nature Communications 5, 4078.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H-D.V., Jaya, A. and Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420, 61–65.

Page, S.E., Wűst, R.A.J., Weiss, D., Rieley, J.O., Shotyk, W. and Limin, S.H. 2004. A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. Journal of Quaternary Science, 19, 625-635.

Page, S.E., Hoscilo, A., Langner, A., Tansey, K., Siegert, F., Limin, S. and Reiley, J. 2009. Tropical peatland fires in Southeast Asia. In: Tropical Fire Ecology. Springer Praxis Books. Springer, Berlin, Heidelberg. pp. 263-187.

Page, S.E., Morrison, R., Malins, C., Hooijer, A., Rieley, J.O. and Jauhiainen J. 2011. Review of Peat Surface Greenhouse Gas Emissions from Oil Palm Plantations in Southeast Asia. Washington DC: The International Council on Clean Transportation White Paper Number 15.

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology 17, 798–818.

Page, S.E. and Hooijer, A. 2016. In the line of fire: the peatlands of Southeast Asia. Philosophical Transactions of the Royal Society B 371, 20150176.

Payette, S., Delwaide, A., Caccianiga, M., Beauchemin, M., 2004. Accelerated thawing of subarctic peatland permafrost over the last 50 years. Geophysical Research Letters 31, 1–4.

Pelletier, N., Talbot, J., Olefeldt, D., Turetsky, M., Blodau, C., Sonentag, O. and Quinton, W.L. 2017. Influence of Holocene permafrost aggradation and thaw on the paleoecology and carbon storage of a peatland complex in northwestern Canada. The Holocene 27, 1391-1405

Philben, M., Kaiser, K. and Benner, R. 2014. Does oxygen exposure time control the extent of organic matter decomposition in peatlands? Journal of Geophysical Research Biogeosciences 119, 897–909.

Philben, M., Holmquist, J., Macdonald, G.M., Duan, D., Kaiser, K. Benner, R. 2015. Temperature, oxygen and vegetation controls on decomposition in a James Bay peatland. Global Biogeochemical Cycles 29, 729–743.

Pinsonneault, A.J., Moore T.R., Roulet N.T. 2016. Effects of long-term fertilization on belowground stoichiometry and microbial enzyme activity in an ombrotrophic bog. *Biogeochemistry* 129: 149-164. doi: 10.1007/s10533-016-0224-6.

Pitkänen, A., Turunen, J., Tahvanainen, T. and Simola, H. 2013. Carbon storage change in a partially forestry-drained boreal mire determined through peat column inventories. Boreal Environmental Research 18, 223–234.

Poulter, B., Bousquet P., Canadell J., Ciais P., Peregon A, Saunois M., Arora, V., Beerling D., Brovkin V., Jones C.D., Joos F., Gedney N., Ito A., Kleinen T., Koven C., MacDonald K., elton J., Peng C., Peng S., Schroder R., Prigent C., Riley B., Saito M., Spahni R., Tian H., Taylor L., Viovy N., Wilton D., Wiltshire A., Xu X., Zhang B., Zhang Z., Zhu Q. 2017. Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics, *Environmental Research Letters*,

Plunkett, G., & Swindles, G. T. (2008). Determining the Sun's influence on Lateglacial and Holocene climates: a focus on climate response to centennial-scale solar forcing at 2800 cal. BP. Quaternary Science Reviews, 27(1-2), 175-184.

Putra, E.I., Hayasaka, H., Takahashi, H. and Usup, A. 2008. Recent Peat Fire Activity in the Mega Rice Project Area, Central Kalimantan, Indonesia. Journal of Disaster Research 3, 334–335.

Putra, E.I. and Hayasaka, H. 2011. The effect of the precipitation pattern of the dry season on peat fire occurrence in the Mega Rice Project area, Central Kalimantan, Indonesia. Tropics 19, 145–156.

Ratnayake, A.S., Sampei, Y., Ratnayake, N.P. and Roser, B.P. 2017. Middle to late Holocene environmental changes in the depositional system of the tropical brackish Bolgoda Lake, coastal southwest Sri Lanka. Palaeogeography Palaeoclimatology Palaeoecology 465, 122–137.

Reay, D.S., Dentener, F., Smith, P., Grace, J. and Feely, R.A. 2008. Global nitrogen deposition and carbon sinks. Nature Geoscience 1, 430-437.

Rieley, J.O. and Page, S.E. 2005. Wise use of tropical peatlands: focus of Southeast Asia. ALTERRA – Wageningen University and Research Centre and the EU INCO – STRAPEAT and RESTORPEAT Partnership. Wageningen: The Netherlands.

Rieley, J. O., Wüst, R. A. J., Jauhiainen, J., Page, S. E. et al. (2008). Tropical peatlands: carbon stores, carbon gas emissions and contribution to climate change processes. In Peatlands and climate change (pp. 148-181). International Peat Society.

Robinson, S. D., & Moore, T. R. (1999). Carbon and peat accumulation over the past 1200 years in a landscape with discontinuous permafrost, northwestern Canada. Global Biogeochemical Cycles, 13(2), 591-601.

Robinson, S.D. and Moore, T.R. 2000. The Influence of Permafrost and Fire upon Carbon Accumulation in High Boreal Peatlands, Northwest Territories, Canada. Arctic, Antarctic and Alpine Research 32, 155-166.

Rooney, R.C., Bayley, S.E. and Schindler, D.W. 2012. Oil sands mining and reclamation cause massive loss of peatland and stored carbon. PNAS 109, 4933-4937

Roulet, N.T., Lafleur, P.M., Richard, P.J., Moore, T.R., Humphreys, E.R. and Bubier, J. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology 13, 397-411.

Ruddiman, W.F., 2007. The early anthropogenic hypothesis: Challenges and responses. Reviews of Geophysics, 45, 2006RG000207.

Ruppel, M., Väliranta, M., Virtanen, T., & Korhola, A. (2013). Postglacial spatiotemporal peatland initiation and lateral expansion dynamics in North America and northern Europe. The Holocene, 23(11), 1596-1606.

See S.W., Balasubramanian R., Wang W. 2006. A study of the physical, chemical, and optical properties of ambient aerosol particles in Southeast Asia during hazy and nonhazy days. *Journal of Geophysical Research Atmospheres*, 111, D10S08.

Sanderman J., Hengl T., Fiske G.J. 2017. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, 114(36), 9575-9580.

Sannel, A. B. K., & Kuhry, P. (2008). Long-term stability of permafrost in subarctic peat plateaus, west-central Canada. The Holocene, 18(4), 589-601.

Sannel, A. B. K. & Kuhry, P. (2011). Warming-induced destabilization of peat plateau/thermokarst lake complexes. Journal of Geophysical Research – Biogeosciences, 116, doi:10.1029/2010JG001635.

Sannel, A. B. K., Hempel, L., Kessler, A., Prėskienis, V. (2018). Holocene development and permafrost history in sub-arctic peatlands in Tavvavuoma, northern Sweden. Boreas, 47(2), 454-468.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B. and Canadell, J.G. 2016. The growing role of methane in anthropogenic climate change. Environmental Research Letters 11, 120207.
Schaefer, K., Lantuit, H., Romanovsky, V.E., Schuur, E.A.G. and Witt, R. 2014. The impact of the permafrost carbon feedback on global climate. Environmental Research Letters 9, 085003.

Schipper, L. A., & McLeod, M. (2002). Subsidence rates and carbon loss in peat soils following conversion to pasture in the Waikato Region, New Zealand. Soil Use and Management, 18(2), 91-93.

Schuldt, R. J., Brovkin, V., Kleinen, T. and Winderlich, J. 2013. Modelling Holocene carbon accumulation and methane emissions of boreal wetlands – an Earth system model approach. Biogeosciences 10, 1659-1674.

Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S. V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J.G. and Zimov, S.A. 2008. Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle. Bioscience 58, 701–714.

Schuur, E.A.G., McGuire, A.D., Schadel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D. and Kuhry, P. 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179.
Simola, H., Pitkänen, A., Turunen, J., 2012. Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. European Journal of Soil Science 63, 798–807.

Singarayer, J.S., Valdes, P.J., Friedlingstein, P., Nelson, S. and Beerling, D.J. 2011. Late Holocene methane rise caused by orbitally controlled increase in tropical sources. Nature 470, 82–85.

Sjögersten, S., Aplin, P., Gauci, V., Peacock, M., Siegenthaler, A. and Turner, B.L. 2018. Temperature response of ex-situ greenhouse gas emissions from tropical peatlands: Interactions between forest type and peat moisture conditions. Geoderma 324, 47–55.

Sjogersten, S., Black, C.R., Evers, S., Hoyos-Santillan, J., Wright, E.L. and Turner, B.L. 2014. Tropical wetlands: a missing link in the global carbon cycle? Global Biogeochemical Cycles 28, 1371–1386.

Sjögersten, S., Cheesman, A.W., Lopez, O. and Turner, B.L. 2011. Biogeochemical processes along a nutrient gradient in a tropical ombrotrophic peatland. Biogeochemistry 104, 147–163.

Słowiński M., Lamentowicz M., Łuców D., Barabach J., Brykała D., Tyszkowski S., Pieńczewska A., Śnieszko Z., Dietze E., Jażdżewski K., Obremska M., Ott F., Brauer A., Marcisz K. 2019. Paleoecological and historical data as an important tool in ecosystem management. *Journal of Environmental Management*, 236, 755-768.

Smith, L., Sheng, Y. and Macdonald, G.M. 2007. Thawing Permafrost and Thicker Active Layers in Sub-arctic Sweden. Permafrost and Periglacial Processes 18, 201–208.

Smith, L.C., MacDonald, G.M., Velichko, A.A., Beilman, D.W., Borisova, O.K., Frey, K.E., Kremenetski, K.V. and Sheng, Y. 2004. Siberian peatlands a net carbon sink and global methane source since the early Holocene. Science 303, 353–356.

Smith R, E., Smith V.C., Fontjin K., Gebhardt C., Wastegård S., Zolitschka B., Ohlendorf C., Stern C., Mayr C. 2019. Refining the Late Quaternary tephrochronology for southern South America using the Laguna Potrok Aike sedimentary record. *Quaternary Science Review*, 218, 137-156.

Spahni, R., Joos, F., Stocker, B.D., Steinacher, M. and Yu, Z.C. 2013. Transient simulations of the carbon and nitrogen dynamics in northern peatlands: from the Last Glacial Maximum to the 21st century. Climate of the Past 9, 1287-1308.

Stocker, B.D., Yu, Z., Massa, C. and Joos, F. 2017. Holocene peatland and ice-core data constraints on the timing and magnitude of CO 2 emissions from past land use. PNAS 114, 1492–1497.

Strachan, I.B., Pelletier, L. and Bonneville, M.C. 2016. Inter-annual variability in water table depth controls net ecosystem carbon dioxide exchange in a boreal bog. Biogeochemistry 127, 99–111.

Strack, M., Waddington, J.M., Rochefort, L. and Tuittila, E.S. 2006. Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown. Journal of Geophysical Research Biogeosciences 111, 1–10.

Swindles, G.T., Kelly, T.J., Roucoux, K.H. and Lawson, I.T. 2018. Response of testate amoebae to a late Holocene ecosystem shift in an Amazonian peatland. European Journal of Protistology, 64, 13–19.

Swindles, G. T., Morris, P. J., Whitney, B., Galloway, J. M. et al. (2018). Ecosystem state shifts during long-term development of an Amazonian peatland. Global Change Biology, 24(2), 738-757.

Swindles, G. T. Morris, P. J., Whitney, B., Galloway, J. M., Gałka, M., Gallego-Sala, A., Macumber, A. L., Mullan, D., Smith, M. W., Amesbury, M. J., Roland, T. P., Sanei, H., Patterson, R. T., Sanderson, N., Parry, L., Charman, D. J., Lopez, O., Valderamma, E., Watson, E. J., Ivanovic, R. F., Valdes, P. J., Turner, T. E. and Lähteenoja, O. 2017. Ecosystem state shifts during long-term development of an Amazonian peatland. Global Change Biology 24, 738-757.

Swindles, G.T., Morris, P.J., Mullan, D., Watson, E., Turner, E., Roland, T., Amesbury, M.J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D.J., Sanderson, N., Garneau, M., Carrivick, J.L., Woulds, C., Holden, J., Parry, L. and Galloway, J.M. 2015. The long-term fate of permafrost peatlands under rapid climate warming. Scientific Reports 5, 17951.

Swindles, G. T., Plunkett, G., & Roe, H. M. (2007). A delayed climatic response to solar forcing at 2800 cal. BP: multiproxy evidence from three Irish peatlands. The Holocene, 17(2), 177-182.

Swinnen W., Broothaerts N., Verstraeten G. 2019. Modelling long-term blanket peatland development in eastern Scotland. Biogeoscience, 16, 3977–3996.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mahzitova, G. and Zimov, S. 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles 23, GB2023.

Taylor, D., Yen, O.H., Sanderson, P.G. and Dodson, J., 2001. Late Quaternary peat formation and vegetation dynamics in a lowland tropical swamp; Nee Soon, Singapore. Palaeogeography Palaeoclimatology Palaeoecology 171, 269-287.

Taylor, L. S., Swindles, G. T., Morris, P. J., Gałka, M., & Green, S. M. (2019). Evidence for ecosystem state shifts in Alaskan continuous permafrost peatlands in response to recent warming. Quaternary Science Reviews, 207, 134-144.

Teodoru C.R., Bastien J., Bonneville M.-C., del Giorgio P.A., Demarty M., Garneau M., ..., Strachan I.B. 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. *Global Biogeochemical Cycles*, 26(2).

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Drösler, M., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Freibauer, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Roßkopf, N., Sommer, M. and Zeitz, J. 2016. High emissions of greenhouse gases from grasslands on peat and other organic soils. Global Change Biology 22, 4134–4149.

Tran, D.B., Dargusch, P., Herbohn, J. and Moss, P., 2013. Interventions to better manage the carbon stocks in Australian Melaleuca forests. Land Use Policy 35, 417-420.

Treat, C.C. and Jones, M.C., 2018. Near-surface permafrost aggradation in Northern Hemisphere peatlands shows regional and global trends during the past 6000 years. Holocene 28, 998–1010.

Treat, C.C., Wollheim, W.M., Varner, R.K., Grandy, A.S., Talbot, J. and Frolking, S. 2014. Temperature and peat type control CO2 and CH4 production in Alaskan permafrost peats. Global Change Biology 20, 2674–2686.

Treat, C.C., Wollheim, W.M., Varner, R.K. and Bowden, W.B. 2016. Longer thaw seasons increase nitrogen availability for leaching during fall in tundra soils. *Environmental Research Letters 11, 064013.*

Treat, C.C., Jones, M.C., Camill, P., Gallego-Sala, A., Garneau, M., Harden, J.W., Hugelius, G., Klein, E.S., Kokfelt, U., Kuhry, P., Loisel, J., Mathijssen, P.J.H., O'Donnell, J.A., Oksanen, P.O., Ronkainen, T.M., Sannel, A.B.K., Talbot, J., Tarnocai, C. and Väliranta, M. 2016. Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils. Journal of Geophysical Research Biogeosciences 121, 78–94.

Treat, C.C., Kleinen, T., Broothaerts, N., Dalton, A.S., Dommain, R., Douglas, T.A., Drexler, J.Z., Finkelstein, S.A., Grosse, G., Hope, G., Hutchings, J., Jones, M.C., Kuhry, P., Lacourse, T., Lähteenoja, O., Loisel, J., Notebaert, B., Payne, R.J., Peteet, D.M., Sannel, A.B.K., Stelling, J.M., Strauss, J., Swindles, G.T., Talbot, J., Tarnocai, C., Verstraeten, G., Williams, C.J., Xia, Z., Yu, Z., Väliranta, M., Hättestrand, M., Alexanderson, H., Brovkin, V., 2019. Widespread global peatland establishment and persistence over the last 130,000 y. PNAS 116, 4822–4827.

Tsuji, L.J.S., Gomez, N., Mitrovica, J.X. and Kendall, R. 2009. Post-Glacial Isostatic Adjustment and Global Warming in Subarctic Canada: Implications for Islands of the James Bay Region. Arctic 62, 458-467.

Tsuji, L.J.S., Daradich, A., Gomez, N., Hay, C. and Mitrovica, J.X. 2016. Sea Level Change in the Western James Bay Region of Subarctic Ontario: Emergent Land and Implications for Treaty No. 9. Arctic 69, 99-107.

Tubiello, F., Biancalani, R., Salvatore, M., Rossi, S. and Conchedda, G. 2016. A worldwide assessment of greenhouse gas emissions from drained organic soils. Sustainability 8, 371.

Turetsky, M.R. and Wieder, R.K. 2011. A direct approach to quantifying organic matter lost as a result of peatland wildfire. Canadian Journal of Forest Research 31, 363–366.

Turetsky, M. R., Wieder, R. K., Williams, C. J., & Vitt, D. H. (2000). Organic matter accumulation, peat chemistry, and permafrost melting in peatlands of boreal Alberta. Ecoscience, 7(3), 115-122.

Turetsky, M., Wieder, K., Halsey, L., and Vitt, D. 2002. Current disturbance and the diminishing peatland carbon sink. Geophysical Research Letters 29, 1526.

Turetsky, M. R., Amiro, B. D., Bosch, E., & Bhatti, J. S. (2004). Historical burn area in western Canadian peatlands and its relationship to fire weather indices. Global Biogeochemical Cycles, 18(4).

Turetsky, M.R., Weider, R.K., Vitt, D.H., Evans, R.J. and Scott, K.D. 2007. The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. Global Change Biology 13, 1922-1934.

Turetsky, M.R., Kane, E.S., Harden, J.W., Ottmar, R.D., Manies, K.L., Hoy, E. and Kasischke, E.S. 2010. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience 4: 27-31.

Turetsky, M.R., Donahue, W.F. and Benscoter, B.W. 2011. Experimental drying intensifies burning and carbon losses in a northern peatland. Nature Communications 2, 514–515.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D. et al. (2011). Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience, 4(1), 27.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., Werf, G.R. and Van Der Watts, A. 2015. Global vulnerability of peatlands to fire and carbon loss. Nature Geoscience 8, 11–14.

Turunen, J., Roulet, N.T., Moore, T.R. and Richard, P.J. 2004. Nitrogen deposition and increased carbon accumulation in ombrotrophic peatlands in eastern Canada. Global Biogeochemical Cycles, 18, GB3002.

Unkel, I., Fernandez, M., Björck, S., Ljung, K. et al. (2010) Records of environmental changes during the Holocene from Isla de los Estados (54.5°S), southeastern Tierra del Fuego. Global and Planetary Change, 74, 99-113.

Utstøl-Klein, S., Halvorsen, R. and Ohlson, M. 2015. Increase in carbon accumulation in a boreal peatland following a period of wetter climate and long-term decrease in nitrogen deposition. New Phytologist 206, 1238–1246.

Väliranta, M., Salojärvi, N., Vuorsalo, A., Juutinen, S., Korhola, A., Luoto, M. and Tuittila, E-S. 2017. Holocene fen–bog transitions, current status in Finland and future perspectives. The Holocene 27, 752-764.

van Bellen, S., Garneau, M., Ali, A.A. and Bergeron, Y. 2012. Did fires drive Holocene carbon sequestration in boreal ombrotrophic peatlands of eastern Canada? Quaternary Research 78, 50-59.

van Bellen, S. Garneau, M. and Bergeron, Y. 2010. Impact of Climate Change on Forest Fire Severity and Consequences for Carbon Stocks in Boreal Forest Stands of Quebec, Canada: a Synthesis. Fire Ecology 6, 16-44.

van Bellen, S., Garneau, M., Ali, A. A., Lamarre, A., Robert, E.C., Magnan, G., Asnong, H. and Pratte, S. 2013. Poor fen succession over ombrotrophic peat related to late Holocene increased surface wetness in subarctic Quebec, Canada. Journal of Quaternary Science 28, 748-760.

van Bellen, S., Magnan, G., Davies, L., Froese, D. et al. (2018). Testate amoeba records indicate regional 20th century lowering of water tables in ombrotrophic peatlands in central-northern Alberta, Canada. Global Change Biology, 24(7), 2758-2774.

van Bellen, S., Mauquoy, D., Hughes, P. D. M., Roland, T. P. et al. (2016) Late-Holocene climate dynamics recorded in the peat bogs of Tierra del Fuego, South America. The Holocene, 26 (3), 489-501.

van der Knaap W.O., Lamentowicz M., van Leeuwen J.F.N., Hangartner S., Leuenberger M., Mauquoy D., Goslar T., Mitchell E.A.D., Lamentowicz Ł., Kamenik C. 2011. A multi-proxy, high-resolution record of peatland development and its drivers during the last millennium from the subalpine Swiss Alps. *Quaternary Science Reviews*, 30(23-24), 3467-3480.

van der Kaars, S., Tapper, N. and Cook, E.J. 2010. Observed relationships between El Niño-Southern Oscillation, rainfall variability and vegetation and fire history on Halmahera, Maluku, Indonesia. Global Change Biology 16, 1705–1714.

van der Werf, G.R., Dempewolf, J., Trigg, S.N., Randerson, J.T., Kasibhatla, P.S., Giglio, L., Murdiyarso, D., Peters, W., Morton, D.C., Collatz, G.J., Dolman, A.J. and DeFries, R.S. 2008. Climate regulation of fire emissions and deforestation in equatorial Asia. PNAS 105, 20350–20355.

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., DeFries, R.S., Jin, Y. and van Leeuwen, T.T. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmospheric Chemistry and Physics 10, 11707-11735.

Vanneste, H., De Vleeschouwer, F., Bertrand, S., Martínez-Cortizas, A. et al. (2016). Elevated dust deposition in Tierra del Fuego (Chile) resulting from Neoglacial Darwin Cordillera glacier fluctuations. Journal of Quaternary Science, 31(7), 713-722.

Vardy, S. R., Warner, B. G., Turunen, J., & Aravena, R. (2000). Carbon accumulation in permafrost peatlands in the Northwest Territories and Nunavut, Canada. The Holocene, 10(2), 273-280.

Vasander, H., Tuittila, E-S., Lode, E., Lundin, L., Ilomets, M., Sallantaus, T., Heikkilä, R., Pitkänen, M-L. and Laine, J., 2003. Status and restoration of peatlands in Northern Europe. Wetlands Ecology and Management 11, 51-63.

Vitt, D. H., Halsey, L. A., Bauer, I. E., & Campbell, C. (2000). Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences, 37(5), 683-693.

Vitt, D.H., Wieder, K., Halsey, L. A. and Turetsky, M.R. 2003. Response of Sphagnum fuscum to Nitrogen Deposition: A Case Study of Ombrogenous Peatlands in Alberta, Canada. Bryologist 106, 235–245.

Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K. and Moore, P.A. 2015. Hydrological feedbacks in northern peatlands. Ecohydrology 8, 113–127.

Waldron, S., Flowers, H., Arlaud, C., Bryant, C. and McFarlane, S. 2008. The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance. Biogeosciences Discussions 5, 1139–1174.

Wallage, Z.E., Holden, J. and McDonald, A.T. 2006. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. Scienc of the Total Environment 367, 811–821.

Wang, M. and Moore, T.R. 2014. Carbon, nitrogen, phosphorus, and potassium stoichiometry in an ombrotrophic peatland reflects plant functional type. Ecosystems 17, 673-684.

Wang M., Chen H., Wu N., Peng C., Zhu Q., Zhu D., Yang G., Wu J., He Y., Gao Y., Tian J. and Zhao X. 2014. Carbon dynamics of peatlands in China during the Holocene. Quaternary Science Reviews 99, 34-41.

Wang M., Yang G., Gao Y., Chen H., Wu N., Peng C., Zhu Q., Zhu D., Wu J., He Y., Tian J., Zhao, X. and Zhang, Y. 2015. Higher recent peat C accumulation than that during the Holocene on the Zoige Plateau. Quaternary Science Reviews 114, 116-125.

Wang M., Wu J., Luan J., Lafleur P., Chen H. and Zhu X. 2017. Near-zero methane emission from an abandoned boreal peatland pasture based on eddy-covariance measurements. PLOS ONE, 12, e0189692.

Wang M., Wu J., Lafleur P., Luan J., Chen H. and Zhu X. 2018. Can abandoned peatland pasture sequestrate more carbon dioxide from the atmosphere than an adjacent pristine bog in Newfoundland, Canada? Agricultural and Forest Meteorology 248, 91-108.

Wang M., Wu J., Lafleur P., Luan J., Chen H. and Zhu X. 2018. Temporal shifts in controls over methane emissions from a boreal bog. Agricultural and Forest Meteorology 262, 120-134.

Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F.C. and Cadillo-Quiroz, H. 2018. Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. PNAS 115, 12407–12412.

Wania, R., Ross, I., Prentice, I.C., 2009. Integrating peatlands and permafrost into a dynamic global vegetation model: 2. Evaluation and sensitivity of vegetation and carbon cycle processes. Global Biogeochemical Cycles 23, GB3015.

Ward, S.E., Orwin, K.H., Ostle, N.J., Briones, M.J.I., Thomson, B.C., Griffiths, R.I., Oakley, S., Quirk, H. and Bardgett, R.D. 2015. Vegetation exerts a greater control on litter decomposition than climate warming in peatlands. Ecology 96, 113–123.

Warren, M., Frolking, S., Dai, Z. and Kurnianto, S. 2017. Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation. Mitigation and Adaptation Strategies for Global Change 22, 1041–1061.

Webster, E.J. 2017. How will projected sea-level rise affect carbon storage in floodplain fens? PhD thesis: Queen Mary University of London.

Weckström, J., Seppä, H., & Korhola, A. (2010). Climatic influence on peatland formation and lateral expansion in sub-arctic Fennoscandia. Boreas, 39(4), 761-769.

Wieder R.K., Scott K.D., Kamminga K., Vile M.A., Vitt D.H., Bone T., Xu B., Benscoter B.W., Bhatti J.S. 2009. Postfire carbon balance in boreal bogs of Alberta, Canada. *Global Change Biology*, 15, 63-81.

Wieder R.K., Vile M.A., Albright C.M. et al. 2016. Effects of altered atmospheric nutrient deposition from Alberta oil sands development on *Sphagnum fuscum* growth and C, N and S accumulation in peat. *Biogeochemistry*, 129(1-2), 1-19.

Weiss, D., Shotyk, W., Rieley, J., Page, S., Gloor, M., Reese, S. and Martinez-Cortizas, A. 2002. The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition. Geochimica et Cosmochimica Acta 66, 2307–2323.

Whittle, A. and Gallego-Sala, A. V. 2016. Vulnerability of the peatland carbon sink to sea-level rise. Scientific Reports, 6, 28758.

Wieder R.K., Vitt D.H., Vile M.A., Graham J.A., Hartsock J.A., Fillingim H., House M., Quinn J.C., Scott K.D., Petix K.D., McMillen K.J. 2019. Experimental nitrogen addition alters structure and function of a boreal bog: critical load and thresholds revealed. *Ecological Monographs* 89(3):e01371. 10.1002/ecm.1371.

Wiggins E.B., Czimczik C.I., Santos G.M., Chen Y., Xu X.M., Holden S.R., Randerson J.T., Harvey C.F., Kai F.M. and Yu L.E. 2018. Smoke radiocarbon measurements from Indonesian fires provide evidence for burning of millennia-aged peat. PNAS 115, 12419-12424.

Wijedasa L.S., Sloan S., Page S.E., Clements G.R., Lupascu M. and Evans T.A. 2018. Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. Global Change Biology 24, 4598-4613.

Wijedasa, L.S., Jauhiainen, J., Könönen, M., Lampela, M., Vasander, H., LeBlanc, M-C., Evers, S., Smith, T.E.L., Yule, C.M., Varkkey, H., Lupascu, M., Parish, F., Singleton, I., Clements, G.R., Aziz, S.A., Harrison, M.E., Cheyne, S., Anshari, G.Z., Meijaard, E., Goldstein, J.E., Waldron, S., Hergoualc'h, K., Dommain, R., Frolking, S., Evans, C.D., Posa, M.R.C., Glaser, P.H., Suryadiputra, N., Lubis, R., Santika, T., Padfield, R., Kurnianto, S., Hadisiswoyo, P., Lim, T.W., Page, S.E., Gauci, V., van der Meer, P.J., Buckland, H., Garnier, F., Samuel, M.K., Kim Choo, L.N.L., O'Reilly, P, Warren, M., Suksuwan, S., Sumarga, E., Jain, A., Laurance, W.F., Couwenberg, J., Joosten, H., Vernimmen, R., Hooijer, A., Malins, C., Cochrane, M.A., Perumal, B., Siegert, F., Peh, K.S.-H., Comeau, L.-P., Verchot, L.V., Harvey, C.F., Cobb, A., Jaafar, Z., Wösten, H., Manuri, S., Müller, M., Giesen, W., Phelps, J., Ding, L.Y., Silvius, M., Wedeux, B.M.M., Hoyt, A., Osaki, M., Takashi, H., Takahashi, H., Kohyama, T.S., Haraguchi, A., Nugroho, N.P., Coomes, D.A., Le, P.Q., Dohong, A., Gunawan, H., Gaveau, D.L.A., Langner, A., Lim, F.K.S., Edwards, D.P., Giam, X., van der Werf, G., Carmenta, R., Verwer, C.C., Gibson, L., Grandois, L., Graham, L.L.B., Regalino, J., Wich, S.A., Rieley, J., Kettridge, N., Brown, C., Pirard, R., Moore, S., Capilla, B.R., Ballhorn, U., Hua, C.H., Hoscilo, A., Lohberger, S., Evans, T.A., Yulianti, N., Blackham, G., Onrizal, S.H., Murdiyarso, D., Pangala, S., Cole, L.E.S., Tacconi, L., Segah, H., Tonoto, P., Lee, J.S.H., Schmilewski, G., Wulffraat, S., Putra, E.I., Cattau, M.E., Clymo, R.S., Morrison, R., Mijahid, A., Miettinen, J., Soo, C.L., Valpola, S., Wilson, D., D'Arcy, L., Gerding, M., Sundari, S., Thorton, S.A., Kalisz, B., Chapman, S.J., Mat Su, A.S., Basuki, I., Itoh, M., Traeholt, C., Sloan, S., Sayok, A.K. and Andersen, R. 2017. Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. Global Change Biology, 23, 977–982.

Wilson, R.M., Hopple, A.M., Tfaily, M.M., Sebestyen, S.D., Schadt, C.W., Pfeifer-Meister, L., Medvedeff, C., McFarlane, K.J., Kostka, J.E., Kolton, M., Kolka, R.K., Kluber, L.A., Keller, J.K., Guilderson, T.P., Griffiths, N.A., Chanton, J.P., Bridgham, S.D. and Hanson, P.J. 2016. Stability of peatland carbon to rising temperatures. Nature Communications 7, 13723.

Wilson, D., Tuitilla, E-S., Alm, J., Laine, J., Farrell, E.P., Byrne, K.A. 2017. Carbon dioxide dynamics of a restored maritime peatlands. Ecoscience 14, 71-80.

Wisser, D., Marchenko, S., Talbot, J., Treat, C. and Frolking, S. 2011. Soil temperature response to 21st century global warming: the role of and some implications for peat carbon in thawing permafrost soils in North America. Earth System Dynamics 2, 121-138.

Wooster, M.J., Perry, G.L.W. and Zoumas, A. 2012. Fire, drought and El Niño relationships on Borneo (Southeast Asia) in the pre-MODIS era (1980–2000). Biogeosciences 9, 317-340,

Worrall, F., Burt, T., Adamson, J., Reed, M., Warburton, J., Armstrong, A. and Evans, M. 2007. Predicting the future carbon budget of an upland peat catchment. Climatic Change 85, 139–158.

Wu J. and Roulet N.T. 2014. Climate change reduces the capacity of northern peatlands to absorb the atmospheric carbon dioxide: the different responses of bogs and fens. Global Biogeochemical Cycles 28, 1005-1024.

Wu, Y., Blodau, C., Moore, T.R., Bubier, J., Juutinen, S. and Larmola, T. 2015. Effects of experimental nitrogen deposition on peatland carbon pools and fluxes: a modelling analysis. Biogeosciences 12, 79-101.

Xing, W., Guo, W., Liang, H., Li, X. et al. (2016). Holocene peatland initiation and carbon storage in temperate peatlands of the Sanjiang Plain, Northeast China. The Holocene, 26(1), 70-79.

Yu, Z. C. 2011. Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. The Holocene 21, 761-774.

Yu, Z. (2006). Holocene carbon accumulation of fen peatlands in boreal western Canada: A complex ecosystem response to climate variation and disturbance. Ecosystems, 9(8), 1278-1288.

Yu, Z.C. 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9, 4071-4085.

Yu, Z., Beilman, D.W. and Jones, M.C. 2009. Sensitivity of northern peatland carbon dynamics to Holocene climate change. In Baird, A., Belyea, L., Comas, X., Reeve, A.S. and Slater, L.D. (Eds.). Carbon cycling in northern peatlands. AGU Geophysical Monograph Series 184, 55-69.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W. and Hunt, S.J. 2010. Global peatland dynamics since the Last Glacial Maximum. Geophysical Research Letters 37, L13402.

Yule, C.M. and Gomez, L.N. 2009. Leaf litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. Wetland Ecology and Management 17, 231–241.

Yulianti, N., Hayasaka, H. and Usup, A. 2012. Recent Forest and Peat Fire Trends in Indonesia: The Latest Decade by MODIS Hotspot Data. Global Environmental Research 16, 105–116.

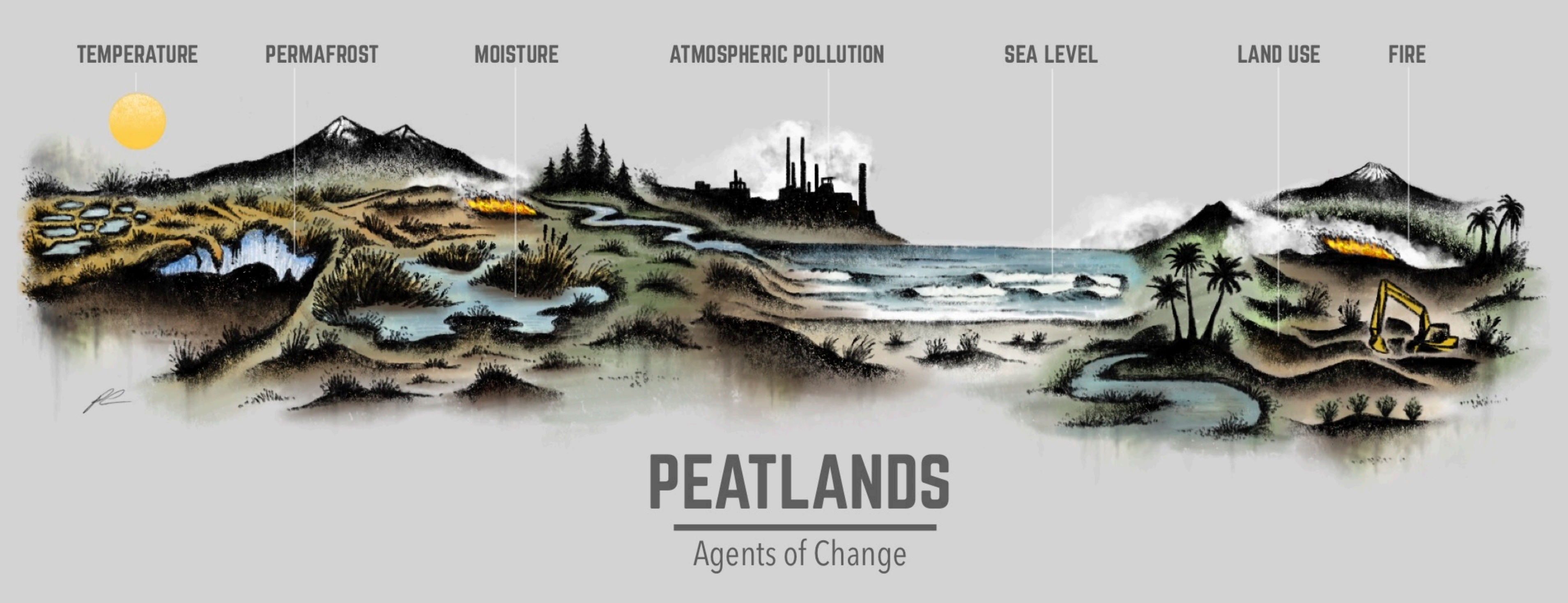
Zhang, Y. 2015. Higher recent peat C accumulation than that during the Holocene on the Zoige Plateau. Quaternary Science Reviews 114, 116-125.

Zhang, H., Piilo, S. R., Amesbury, M. J., Charman, D. J. et al. (2018). The role of climate change in regulating Arctic permafrost peatland hydrological and vegetation change over the last millennium. Quaternary Science Reviews, 182, 121-130.

Zimov, S.A. 2006. Climate Change: Permafrost and the Global Carbon Budget. Science 312, 1612–1613.

Zoltai, S.C., Morrissey, L.A., Livingston, G.P. and Groot, W.J. 1998. Effects of fires on carbon cycling in North American boreal peatlands. Environmental Reviews 6, 13-24.

Appendix 5: Peatland infographic without text and brief review of the main peatland agents of change.



1. Drivers of peatland carbon stock changes – a brief review

Temperature. The primary driver for extra-tropical peatland carbon (C) accumulation over the Holocene, along with land availability and topographic settings. Peatlands have spread across vast landscapes following the Last Glacial Maximum (LGM)[1] and may spread towards the poles under warming scenarios. 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[2-4], but to enhanced decomposition and carbon loss in the tropics[5-6], where growing season length and temperature are not limiting factors for photosynthesis[7].

Moisture. Water saturation is a key control on oxygen availability in peats 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[8-10]. 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[11]. In the tropical and mid-latitude regions, water table depth is considered the main agent driving long-term peat accumulation[12-14].

Sea-level. At the regional scale, sea-level rise may either lead to net C losses[15] or net C gains[16]. For example, sea-level decline in the tropics[17] and land uplift following deglaciation in the north[18] contributed to peat expansion over the past 5000 years. Conversely, in the (sub-)tropics, sea-level rise can drive groundwater levels up regionally, which can allow coastal peatlands to expand and accrete at greater rates[19-20]. This process, which took place during the previous interglacial[21] 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[22-23], its conjunction with rapid sea-level rise, rapid subsidence, or peat surface collapse due to water abstraction or land-use change can lead to peatland loss[24-25]. In general, sea-level rise has been suggested to be a threat for coastal peatlands[26-27], as these systems have limited capacity to move inland because of topography or human development.

Peat Fire. Around the world, the combustion of peat layers has led to direct losses of plant and peat C. Studies have shown that fire-derived emissions can be substantial, even exceeding biological emissions from peat decomposition in some years[28]. The highest emissions are observed from drained tropical peatlands in extreme dry years such as the 1997 El Niño (810-2570 TgC yr^{-1})[29] and the 2015 fire season (380 Tg C yr^{-1})[30] in Indonesia. However, as a result of drainage, peat fires are even observed in wet years[31]. Although peat C losses from northern peat fires are smaller (e.g., 5 TgC yr^{-1} from Alaskan wetlands)[32], there is a need to consider wildfires in permafrost thaw dynamics due to their effects on soil temperature regime[33]. Peatland surface drying, both as a result of droughts and human activity, has been shown to increase the frequency and extent of peat fires[34]. Lastly, while peatlands tend to recover from fires, an increase in frequency or intensity could lead to deeper burns and hindered recovery[35] as well as peat water repellency[36].

Land-use change. Widespread peatland conversion, drainage, and mining across the temperate and tropical regions has led to large C losses. A few examples include Indonesia, where approximately 880,000 hectares of tropical peatlands had been converted to oil-palm plantations by 2010[37], and only 6% of pristine peat swamp forests in insular Southeast Asia remained intact by 2015. In Alberta's oil sand region, at least 30,000 hectares of peatland habitat had been destroyed by open-pit mining by 2010[38]. In Finland, approximately 4,500,000 hectares have been drained for forestry, peat extraction, and agriculture since World War II[39]. These land-use practices lead to immediate ecosystem damage, CO_2 emissions[40], DOC leaching[41-42], and land subsidence[43]. While most peatland management practices result in decreased CH_4 emissions due to drainage, peatland inundation or rewetting can lead to episodic CH_4 releases[44-45].

Permafrost. 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[46-48], although this is variable by region[49]. 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[50-52]; 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[53-55]. Over time, increased C sequestration and renewed peat accumulation occurs in drained thermokarst lake basins[56-57] 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[58].

Nitrogen deposition. Increased emissions of nitrogen (N) through agricultural and industrial activities have augmented the rate of atmospheric deposition of ammonium and nitrate[59] and will continue unless emission controls are enforced[60]. The structure and function of peatlands are now threatened by increased N availability and atmospheric phosphorus (P) deposition[59]. It was shown for example that the *Sphagnum* moss cover dies off after a few years of sustained N loading, through a combination of direct N action and increased shrub canopy coverage[61-63], and that changes in climate can exacerbate these negative effects[64]. Changes in microbial communities and litter quality associated with N deposition can also contribute to increased peat decomposition[65-66], along with the lowering of the peatland surface due to faster decomposition[67] causing a rise in the water table and increased CH_4 emission[68]. 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[69], illustrating differences, and perhaps a threshold response, in C balance response to N deposition.

2. References

1- Yu Z., Loisel J., Brosseau D.P., Beilman D.W., Hunt S.J. 2010. Global peatland dynamics since the Last Glacial Maximum. Geophysical Research Letters, 37, L13402, doi:10.1029/ 2010GL043584.

2- Beilman D.W., MacDonald G.M., Smith L.C., Reimer P.J. 2009. Carbon accumulation in peatlands of West Siberia over the last 2000 years. Global Biogeochemical Cycles 23, GB1012. doi: 10.1029/2007GB003112.

3- Loisel J., Gallego-Sala A.V., Yu Z. 2012. Global-scale pattern of peatland Sphagnum growth driven by photosynthetically active radiation and growing season length. Biogeosciences, 9, 2737–2746, doi:10.5194/bg-9-2737-2012.

4- Charman D., Beilman D., Blaauw M., Booth R.K., Brewer S., Chambers F., Christen J.A., Gallego-Sala A.V., Harrison S.P., Hughes P.D.M., Jackson S., Korhola A., Mauquoy D., Mitchell F., Prentice I.C., van der Linden M., De Vleeschouwer F., Yu Z., Alm J., Bauer I.E., McCorish Y., Garneau M., Hohl V., Huang Y., Karofeld E., Le Roux G., Loisel J., Moschen R., Nichols J.E., Nieminen T.M., MacDonald G.M., Phadtare N.R., Rausch N., Sillasoo Ü., Swindles G.T., Tuittila E.-S., Ukonmaanaho L., Väliranta M., van Bellen S., van Geel B., Vitt D., Zhao Y. 2013. Climate-related changes in peatland carbon accumulation during the last millennium. Biogeosciences 10: 929-944. doi: 10.5194/bg-10-929-2013.

5- Jauhiainen J., Kerojoki O., Silvennoinen H., Limin S. Vasander H. 2014. Heterotrophic respiration in drained tropical peat is greatly affected by temperature – a passive ecosystem cooling experiment. Environmental Research Letters, 9, doi:10.1088/1748-9326/9/10/105013.

6- Wang S., Zhuang Q., Lähteenoja O., Draper F.C., Cadillo-Quiroz H. 2018. Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. Proceedings of the National Academy of Sciences, 115, 12407-12412.

7- Sjögersten S., Aplin P., Gauci V., Peacock M., Siegenthaler A., Turner B.L. 2018. Temperature response of ex-situ greenhouse gas emissions from tropical peatlands: interactions between forest type and peat moisture conditions. Geoderma, 324, 47-55.

8- Couwenberg J., Dommain R., Joosten H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. Global Change Biology, 16, 1715-1732, doi: 10.1111/j.1365-2486.2009.02016.x

9- Carlson K.M., Goodman L.K., May-Tobin C.C. 2015. Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. Environmental Research Letters, 10, 074006, doi:10.1088/1748-9326/10/7/074006.

10- Hoyt A.M., Gandois L., Eri J., Kai F.M., Harvey C.F., Cobb A.R. 2019. CO2 emissions from an undrained tropical peatland: Interacting influences of temperature, shading and water table depth. Global Change Biology, 25, 2885–2899, doi: 10.1111/gcb.14702.

11- Freeman C., Ostle N.J., Kang H. 2001 An enzymatic ‘latch’ on a global carbon store. Nature, 409, 149.

12- Lund M., Christensen T.R., Lindroth A., Schubert P. 2012. Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. Environmental Research Letters, 7, 045704.

13- Cobb A.R., Hoyt A.M., Gandois L., Eri J., Dommain R., Salim K.A., Kai F.M., Su'ut N.S.H., Harvey C.F. 2017. How temporal patterns in rainfall determine the geomorphology and carbon fluxes of tropical peatlands. Proc. Natl. Acad. Sci., E5187-E5196.

14- Dargie G.C., Lewis, S.L., Lawson I.T., Mitchard E.T.A., Page S.E., Bocko Y.E., Ifo S.A. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature, 542, 86-90.

15- Henman J., Poulter B. 2008. Inundation of freshwater peatlands by sea level rise: uncertainty and potential carbon cycle feedbacks. Journal of Geophysical Research 113 G01011.

16- Rogers K., Kelleway J.J., Saintillan N., Megonigal P., Adams J.B., Holmquist J.R., Lu M., Schile-Beers L., Zawadzki A., Mazumder D., Woodroffe C.D. 2019. Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature, 567, 91-96.

17- Dommain R., Couwenberg J., Joosten H. 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and Holocene climate variability. Quaternary Science Reviews, 30, 999–1010.

18- Packalen M.S., Finkelstein S.A. 2014. Quantifying Holocene variability in carbon uptake and release since peat initiation in the Hudson Bay Lowlands, Canada. The Holocene, 24, 1063-1074.

19- Grundling P. 2004. The role of sea-level rise in the formation of peatlands in Maputaland. In: Boletim Geológico 43, Ministerio dos Recursos Minerais e Energia, Direccao Geral de Geologia Mozambique, 58–67.

20- Kirwan M.L., Mudd S.M. 2012. Response of salt-marsh carbon accumulation to climate change. Nature, 489, 550-553.

21- Treat C., Kleinen T., Broothaerts N., Dalton A.S., Dommain R., Douglas T.A., Drexler J.Z., Finkelstein S.A., Grosse G., Hope G., Hutchings J., Jones M.C., Kuhry P., Lacourse T., Lähteenoja O., Loisel J., Notebaert B., Payne R.J., Peteet D.M., Sannel A.B.K., Stelling J.M., Strauss J., Swindles G.T., Talbot J., Tarnocai C., Verstraeten G., Williams C.J., Xia Z., Yu Z., Väliranta M., Hättestrand M., Alexanderson H., Brovkin V. 2019. Widespread global peatland establishment and persistence over the last 130,000 y. Proceedings of the National Academy of Sciences USA, 116 (11) 4822-4827, doi:10.1073/pnas.1813305116.

22- Briggs J., Large D.J., Snape C., Drage T., Whittles D., Cooper M., Macquaker J.H.S., Spiro B.F. 2007. Influence of climate and hydrology on carbon in an early Miocene peatland. Earth and Planetary Science Letters, 253, 445-454.

23- Lähteenoja O., Reátegu Y.R., Räsänen M., Torres D.D.C., Oinonen M., Page. S. 2011. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. Global Change Biology, 18, 164-178, doi: 10.1111/j.1365-2486.2011.02504.x

24- Hooijer A., Page, S., Jauhiainen J., Lee W.A., Lu X.X., Idris A., Anshari G. 2012. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences, 9, 1053-1071.

25- Whittle A., Gallego-Sala A. 2016. Vulnerability of the peatland carbon sink to sea-level rise. Scientific Reports 6, 28758, doi.org/10.1038/srep28758.

26- Blankespoor B., Dasgupta S., Laplante B. 2014. Sea-level rise and coastal wetlands. Ambio, 43, 996-1005.

27- Spencer, T., Schürch, M., Nicholls, R. J., Hinkel, J., Vafeidis, A., Reef, R., McFadden, L., & et al. 2016. Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Global and Planetary Change, 139 15-30. https://doi.org/10.1016/j.gloplacha.2015.12.018

28- Rossi S., Tubiello F.N., Prosperi P., Salvatore M., Jacobs H., Biancali R., House J.I., Boschetti L. 2016. FAOSTAT estimates of greenhouse gas emissions from biomass and peat fires. Climatic Change, 135(3-4): 699,711.

29- Page S., Siegert F., Rieley J. et al. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature, 420, 61–65, doi:10.1038/nature01131.

30- Field R.D., van der Werf G.R., Fanin T., Fetzer E.J., Fuller R., Jethva H., Levy R., Livesey N.J., Luo M., Torres O., Worden H.M. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. Proceedings of the National Academy of Sciences, 113(33): 9204-9209.

31- Gaveau D.L.A., Salim, M.A., Hergoualc'h K., Locatelli B., Sloan S., Wooster M., Marlier M.E., Molidena E., Yaen H., DeFries R., Verchot L., Murdiyarso D., Nasi R., Holmgren P., Sheil D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific Reports, 4, 6112.

32- Lyu Z., Genet H., He Y., Zhuang Q., McGuire D., Bennett A., Breen A., Clein J., Euskirshen E.S., Johnson K., Kurkowski T., Pastick N.J., Rupp S., Wylie B.K., Zhu Z. 3019. The role of environmental driving factors in historical and projected carbon dynamics of wetland ecosystems in Alaska. Ecological Applications, 28(6), 1377-1395.

33- Gibson C.M., Chasmer L.E., Thompson D.K., Quinton W.L., Flannigan M.D., Olefeldt D. 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications, 9, 3041.

34- Dadap N.C., Cobb A.R., Hoyt A.M., Harvey C.F., Konings A.G. 2019. Satellite soil moisture observations predict burned area in Southeast Asian peatlands. Environmental Research Letters, 14, 094014, doi.org/10.1088/1748-9326/ab3891

35- Zaccone C., Guillermo R., D'Orazio V., Hadden R.M., Belcher C.M., Miano T.M. 2014. Smouldering fire signatures in peat and their implications for palaeoenvironmental reconstructions. Geochimica Cosmochimica Acta, 137, 134-146.

36- Kettridge N., Humphrey R.E., Smith J.E., Lukenbach M.C., Devito K.J., Petrone R.M., Waddington J.W. 2014. Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire. Journal of Hydrology, 513, 335-341.

37- Koh L.P., Miettinen J., Liew S.C., Ghazoul J. 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. Proc. Natl. Acad. Sci., 201018776, doi.org/10.1073/pnas.1018776108.

38- Rooney R.C., Bayley S.E., Schindler D.W. 2012. Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proceedings of the National Academies of Sciences of the USA, 109(13), 4933-4937, doi.org/10.1073/pnas.1117693108.

39- Turunen J. 2008. Development of Finnish peatland area and carbon storage 1950-2000. Boreal Environmental Research, 13, 319-334.

40- Parish F., Sirin A., Charman D., Joosten H., Minayeva T., Silvius M., Stringer L. (Eds.) 2008. Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

41- Wit F., Muller D., Baum A., Warneke T., Pranowo W.S., Muller M., Rixen T. 2015. The impact of disturbed peatlands on river outgassing in Southeast Asia. Nature Communications, 6, 10155.

42- Wild B., Andersson A., Bröder L., Vonk J., Hugelius G., McClellan J.W., Song W., Raymond P.A., Gustafsson Ö. 2019. Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. Proc. Nat. Aca. Sci..,116(21), 10280-10285.

43- Erkens G., van der Meulen M., Middelkoop H. 2016. Double trouble: subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatlands cultivation. Journal of Hydrogeology, 24: 551-568.

44- Tuittila E.-S., Komulainen V.-M., Vasander H., Nykänen H., Martikainen P.J., Laine J. 2000. Methane dynamics of a restored cut-away peatland. Global Change Biology, 6, 569-581.

45- Waddington J.M., Day S.M. 2007. Methane emissions from a peatland following restoration. Journal of Geophysical Research, 112, G03018, doi:10.1029/2007JG000400.

46- Zuidhoff F.S., Kolstrup E. 2000. Changes in palsa distribution in relation to climate change in Laivadalen, northern Sweden, especially 1960-1997. Permafrost and Periglacial Processes, 11, 55-69.

47- Payette S., Delwaide A., Caccianiga M., Beauchemin M. 2004. Accelerated thawing of subarctic peatland permafrost over the last 50 years. Geophysical Research Letters, 31(18), L18208, doi:10.1029/2004GL020358.

48- Borge A.F., Westermann S., Solheim I., Etzelmüller B. 2017. Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years. The Cryosphere, 11, 1-16, doi:10.5194/tc-11-1-2017.

49- Cooper M.D.A., Estop-Aragones C., Fisher J.P., Thierry A., Garnett M.H., Charman D.J., Murton J.B., Phoenix G.K., Treharne R., Kokelj S.V., et al. 2017. Limited contribution of permafrost carbon to methane release from thawing peatlands. Nature Climate Change, 7, 507-511.

50- Bubier J., Moore T., Bellisario L., Comer N.T., Crill P.M. 1995. Ecological controls on methane emissions from a northern peatland complex in the zone of discontinuous permafrost, Manitoba, Canada. Global Biogeochemical Cycles, 9, 455-470.

51- Christensen T.R., Johansson T., Åkerman H.J., Mastepanov M., Malmer N., Friborg T., Crill P., Svensson B.H. 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. Geophysical Research Letters, 31, L04501, doi:10.1029/2003GLO18680.

52- Olefeldt D., Turetsky M.R., Crill P.M., McGuire A.D. 2013. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. Global Change Biology, 19, 589-603, doi: 10.1111/gcb.12071.

53- O'Donnell J.A., Jorgenson M.T., Harden J.W., McGuire A.D., Kanevskiy M., Wickland K.P. 2012. The effects of permafrost thaw on soil hydrologic, thermal, and carbon dynamics in an Alaskan peatland. Ecosystems, 15: 213-229. doi: 10.1007/s10021-011-9504-0.

54- Jones M.C., Harden J., O'Donnell J., Manies K., Jorgenson T., Treat C., Ewing, S. 2017. Rapid carbon loss and slow recovery following permafrost thaw in boreal peatlands. Global Change Biology, 23, 1109-1127.

55- Turetsky M.R., Abbott B.W., Jones M.C., Walter Anthony K., Olefeldt D., Schuur E.A.G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D.M., Gibson C., Sannel A.B.K., McGuire A.D. 2020. Carbon release through abrupt permafrost thaw. Nature Geoscience, 13, 138-143, doi : 10.1038/s41561-019-0526-0.

56- Jones M.C., Grosse G., Jones B.M., Walter Anthony K. 2012. Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. Journal of Geophysical Research – Biogeosciences, 117, G00M07, doi:10.1029/2011JG001766.

57- Walter Anthony K.M., Zimov S.A., Grosse G., Jones M.C., Anthony P.M., Chapin III F.S., Finlay J.C., Mack M.C., Davydov S., Frenzel P., Frolking S. 2014. A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. Nature, 511, 452-456, doi:10.1038/nature13560.

58- Turetsky M.R., Wieder R.K., Vitt D.H., Evans R.J., Scott K.D. 2007. The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. Global Change Biology, 13(9), 1922-1934, doi:10.1111/j.1365-2486.2007.01381.x.

59- Vet, R., Artz, R. S., Carou, S., Shaw, Ro, C-U., Aas, W., Baker, A., Bowersox, V. C., Dentener, F., Galy-Lacaux, C., Hou, A., Pienaar, J. J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P. S. P., Reid, N. W. 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. Atmospheric Environment, 93, 3-100.

60- Dentener F., Drevet J., Lamarque J.F., Bey I., Eickhout B., Fiore A.M., Hauglustaine D., Horowitz W.W., Krol M., Kulshrestha U.C., Lawrence M., Galy-Lacaux C., Rast S., Shindell D., Stevenson D., Van Noije T., Atherton C., Bell N., Bergman D., Butler T., Cofala J., Collins B., Doherty R., Ellingsen K., Galloway J., Gausee M., Montanaro V., Müller J.F., Pitari G., Rodriguez J., Sanderson M., Solmon F., Strahan S., Schultz M., Sudo K., Szopa S., Wild O. 2006. Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation. Global Biogeochem. Cycles, GB4003, http://dx.doi.org/10.1029/2005GB002672.

61- Bubier J., Moore T., Bledzki L. 2007. Effects of nutrient addition on vegetation and carbon cycling in an ombrotrophic bog. Global Change Biology, 13: 1168-1186, doi: 10.1111/j.1365-2486.2007.01346.x.

62- Juutinen S., Moore T.R., Laine A., Bubier J.L., Tuittila E., De Young A., Chong M. 2016. Responses of mosses Sphagnum capillifolium and Polytrichum strictum to nitrogen deposition in a bog: height growth, ground cover, and CO2 exchange. Botany 94, 127-138, dx.doi.org/10.1139/cjb-2015-0183.

63- Wieder R.K., Vitt D.H., Vile M.A., Graham J.A., Hartsock J.A., Fillingim H., House M., Quinn J.C., Scott K.D., Petix K.D., McMillen K.J. 2019. Experimental nitrogen addition alters structure and function of a boreal bog: critical load and thresholds revealed. Ecological Monographs, 89(3):e01371, doi:10.1002/ecm.1371.

64- Limpens J., Granath G., Gunnarson U., Aerts R., Bayley S., Bragazza L., Bubier J., Buttler A., van den Berg L., Francez A.-J., Gerdol R., Grosvernier P., Heijmans M.M.P.D., Hoosbeek M.R., Hotes S., Ilomets M., Leith I., Mitchell E.A.D., Moore T., Nilsson M.B., Nordbakken J.-F., Rochefort L., Rydin H., Sheppard L.J., Thormann M., Wiedermann M.M.Williams B., Xu B. 2011. Climatic modifiers of the response to N deposition in peat-forming Sphagnum mosses: a meta-analysis. New Phytologist, 191, 496-507, doi: 10.1111/j.1469-8137.2011.03680.x.

65- Larmola T., Bubier J.L., Kobyljanec C., Basiliko N., Juutinen S., Humphreys E., Preston M., Moore T.R. 2013. Vegetation feedbacks of nutrient deposition lead to a weaker carbon sink in an ombrotrophic bog. Global Change Biology, 19, 3729-3739.

66- Pinsonneault, A.J., Moore T.R., Roulet N.T. 2016. Effects of long-term fertilization on belowground stoichiometry and microbial enzyme activity in an ombrotrophic bog. Biogeochemistry, 129, 149-164. doi: 10.1007/s10533-016-0224-6.

67- Bragazza L., Freeman C., Jones T., Rydin H., Limpens J., Fenner N., Ellis T., Gerdol R., Hájek M., Hájek T., Iacumin P., Kutnar L., Tahvanainen T., Toberman H. 2006. Atmospheric nitrogen deposition promotes carbon loss from peat bogs. Proceedings of the National Academy of Sciences, 103, 19386–19389.

68- Juutinen S., Moore T.R., Bubier J.L., Arnkil S., Humphreys W., Marincak B., Roy C., Larmola T. 2018. Long-term nutrient addition increased CH4 emission from a bog through direct and indirect effects. Scientific Reports, 8:3838, doi:10.1038/s41598-018-22210-2.

69- Olid, C., Nilsson M.B., Eriksson T., Klaminder J. 2014. The effects of temperature and nitrogen and sulfur additions on carbon accumulation in a nutrient-poor boreal mire: Decadal effects assessed using ^{210}Pb peat chronologies. J. Geophys. Res. Biogeosci., 119, doi:10.1002/2013JG002365.