Expert assessment of future vulnerability of the global peatland carbon sink

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89   Running title
90   The future of peatland carbon stocks
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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].

124   Peatland C stocks and fluxes have yet to be incorporated into Earth System Models (ESMs),

125   though they are beginning to be implemented in global terrestrial models[9-10]. As these models are

126   moving towards the integration of permafrost dynamics, LULCC, and other disturbances such as

127   fire, the absence of peatland C dynamics could lead to many problems in the next generation of

128   models (Figure 1a). For example, the omission of organic-rich soils was a key contributor to the

129   inaccurate estimates of organic soil mass, heterotrophic respiration, and methane (CH_4)

130   emissions in recent Climate Model Intercomparison Project (CMIP5) simulations[11]. Likewise, the

131   successful integration of permafrost dynamics into land surface models necessitates the inclusion

132   of peatlands, as the latter occupy approximately 10% of the northern permafrost area and

133   account for at least 20% of the permafrost C stocks[12], of which a sizable fraction is susceptible to

134   wildfire[13]. LULCC scenarios must also account for temperate and tropical peatland degradation to

135   derive better estimates of C fluxes[14] and associated impacts on radiative forcing[15]. The inclusion

136   of peatlands in ESMs should help address the complexity of the interacting, cross-scale drivers of

137   change that control peat-C dynamics and quantify their contribution to a positive C cycle feedback

138   now and in the future.

139

140   Peatland conversion and restoration are also not considered in Integrated Assessment Models

141   (IAMs), although there is growing anthropogenic pressure on peatland ecosystems worldwide[16-17].

142   Atmospheric carbon dioxide (CO_2) emissions associated with degraded peatlands account for 5-

143   10% (0.5-1 GtC) of the global annual anthropogenic CO_2 emissions[18-19], despite their small

144   geographic footprint (Figure 1b). While the preservation of pristine peat deposits would be ideal,

145   the restoration of degraded sites, particularly through rewetting, could prevent additional CO_2

146   release to the atmosphere and reduce the risk of peat fires[20-21]. Even if restoration leads to C

147   neutrality (i.e., sites stop losing C but do not start gaining it), their global greenhouse gas (GHG)

148   saving potential would be similar to the most optimistic sequestration potential from biochar and

149   cover cropping from all agricultural soils combined[19,22]. As IAMs move towards the integration of

150   nature-based climate solutions to limit global temperature rise, peatland restoration and

151   conservation are poised to gain in importance in those models, as well as in the international

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152   political arena[23]. In turn, the socio-economic scenarios developed in IAMs could help inform the

153   role of management interventions on future peatland use and guide policy options to best inform

154   the implementation of GHG emission control strategies for decision makers. Ultimately, these

155   model outputs will help predict the effect of peatland management on the global C cycle.

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

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159   Here, we review the main agents of change of peatland C stocks and fluxes, including drivers that

160   can induce rapid peatland C losses (peat fire, land-use change, and permafrost thaw) and

161   gradual drivers that can lead to rapid, nonlinear responses in peatland ecosystems (temperature

162   increases, water table drawdowns, sea-level rise, and nutrient addition) (Figure 2). We use an

163   expert elicitation to assess the perceived importance of these agents of change on C stocks,

164   asking one question: "What is the relative role of each agent of change for shifting the peatland C

165   balance in the past, present, and future?" Estimates are based on responses from 44 peat

166   experts (see SI for details). Four time periods are studied: post-LGM (21,000 yr BP – 1750 CE),

167   Anthropocene (1750-2020 CE), rest of this century (2020-2100 CE), and far future (2100-2300

168   CE). The confidence and expertise levels are tallied for each of the experts' responses (Tables

169   S6 to S9; Figure S2), along with the sources that guided their estimates (Appendix 4). Arithmetic

170   means and 80% central ranges (10th to 90th percentiles) are presented in the text and in Figure 3;

171   other measures of central tendencies can be found in Tables S4 and S5. While central values

172   provide order-of-magnitude estimates that may be useful to the reader, the strength of this

173   elicitation is in its ability to identify where experts agree and disagree, and to recognize ranges of

174   responses across experts. Thus, the elicitation findings can inform how integrating peatlands into

175   modeling frameworks such as ESMs and IAMs could advance peatland process understanding

176   and further test hypotheses that emerge from different schools of thought.

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

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Drivers of Peatland Carbon Stocks since the Last Glacial Maximum

During the post-LGM time period, experts consider temperature the most important long-term

driver of peat accumulation in extra-tropical peatlands (arithmetic mean = 524 (10th – 90th

percentiles = 60 to 890) GtC; Figure 3). A positive moisture balance is deemed a necessary

condition for peatland development, maintenance, and C preservation (238 (10 to 570) GtC).

Several respondents comment that it is difficult, if not impossible, to separate the respective role

of these two agents of change (Appendix 3). This exemplifies the need to integrate peatlands in

ESMs, as cross-scale interactions between agents of change on peatland C dynamics could be

further evaluated. Permafrost is also thought to be of importance due to its capacity to inhibit peat

decay in northern high-latitude peatlands (218 (-14 to +531) GtC). That said, experts note that

permafrost also likely contributes to slower C accumulation rates (when compared to non-

permafrost sites); permafrost also possibly contributes to peat erosion in regions where wind-

drifted snow and ice crystals can abrade dry peat surfaces[24]. The large range of values for

permafrost (Figure S1) stems from the fact that some respondents attribute the entire permafrost

peatland C pool to the presence of permafrost itself, while others attribute the C pool mainly to

temperature and moisture, with permafrost aggradation playing the secondary role of protecting C

stocks. In the tropics, experts suggest that long-term peat C sequestration is mainly driven by

moisture availability (268 (24 to 360) GtC), with wetter conditions slowing down peat

decomposition. Temperature and sea-level are identified as secondary agents promoting peat

formation and growth (43 (0 to 128) GtC and 7 GtC (-13 to +52), respectively). Estimates for the

net role of sea-level on tropical C stocks is near zero because some of the rapid C accumulation

rates following sea-level rise in certain regions are counterbalanced by C losses due to

continental shelf flooding and associated peat erosion or burial in other regions[25] (Figure 3).

These results are largely corroborated by the literature review. On the basis of extensive paleo

records, we know that peatlands have spread across vast landscapes following the LGM[4]. As

long as sufficient moisture conditions are maintained, warmer and longer growing seasons can

208   contribute to increases in plant productivity and peat burial in many extra-tropical regions[26-28], but

209   to enhanced decomposition and carbon loss in the tropics[29-30], where growing season length and

210   temperature are not limiting factors for photosynthesis[1,31]. Indeed, water saturation is a key

211   control on oxygen availability in peat and on plant community composition, and thus an important

212   determinant for CO_2 and CH_4 emissions and on net ecosystem C balance in both intact and

213   drained peatlands[32-34]. Soil moisture excess is a necessary condition for long-term peat

214   development; surface wetness must remain sufficient to minimize aerobic respiration losses and

215   provide conditions inhibiting the activity of phenol oxidase[35]. In the tropical and mid-latitude

216   regions, water table depth is recognized as the main agent driving long-term peat accumulation[36-

217   38]. At the regional scale, the literature review tells us that sea-level rise may either lead to net C

218   losses[39] or net C gains[40]. For example, sea-level decline in the tropics[41] and land uplift following

219   deglaciation in the north[42] contributed to peat expansion over the past 5000 years. Conversely, in

220   the (sub-) tropics, sea-level rise can drive groundwater levels up regionally, which allows coastal

221   peatlands to expand and accrete at greater rates[43-44]. This process, which took place during the

222   previous interglacial[25] and other past warm climates, is likely to be most pronounced in the large

223   coastal peatlands of the (sub-)tropics. While tectonic subsidence can lead to vast accumulations

224   of lignite over millions of years[45-46], its conjunction with rapid sea-level rise, rapid subsidence, or

225   peat surface collapse due to water abstraction or LUC can lead to peatland loss[47-48]. In general,

226   sea-level rise has been suggested to be a threat for coastal peatlands[49-50], as these systems

227   have limited capacity to move inland because of topography or human development.

228

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

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231

232   ***Drivers of Peatland Carbon Stocks during the Anthropocene***

233   During the Anthropocene, short-term peat C losses across the northern high latitudes are linked

234   to LUC (-7 (-23 to 0) GtC) and fire (-3 (-8 to 0) GtC) by the experts (Figure 3). As for permafrost

235   dynamics, small C gains (2 (0 to 10) GtC) are suggested, though many experts warn that large

236   and rapid losses of old C have only recently begun and are expected to increase in the future

237   (Appendix 3). Peat drainage for agriculture, forestry, industrial-scale peat extraction, and grazing

238   were identified as the main sources of anthropogenic pressure on these peatlands (Figure 3).

239   While peat C lost to human activity must have been considerable during the pre-Industrial time

240   and the start of the Industrial era across Europe, historical reports are too few to provide a

241   reliable estimate[18]. In this case, LULCC simulations from IAMs could reduce this uncertainty, or

242   provide several scenarios. The C loss to fire is attributed to an increase in both natural and

243   anthropogenic burning. Similarly, the main suggested causes of peat C losses in the tropics are

244   LUC (-8 (-14 to -2) GtC) and fire (-4 (-10 to 0) GtC). Despite these losses, the trend suggests that

245   northern high-latitude peatlands have persisted as C sinks throughout the Anthropocene. Experts

246   primarily attribute the net C gain across the northern high latitudes to faster accumulation rates

247   induced by longer and warmer growing conditions from climate warming (16 (0 to 38) GtC). An

248   increase in moisture from greater precipitation is suggested as an additional agent leading to C

249   gain in the Arctic, though several experts mention C losses due to drought across the boreal and

250   mid-latitude regions; an overall increase of 11 (-1 to +31) GtC from moisture is suggested by the

251   survey respondents. Lastly, nitrogen (N) deposition and other atmospheric pollution are thought

252   to have a negligible impact (<1 (-1 to +1) GtC) on the peatland C sink capacity worldwide.

253

254   The importance of permafrost and fire seen in the expert elicitation are reflected in the main

255   findings from the literature review. For instance, across the northern high-latitude regions,

256   increasing air temperatures and winter precipitation have been linked to a >50% reduction in

257   palsa or peat plateau area since the late 1950s[51-53], although this is variable by region[54]. In

258   general, thermokarst landforms such as ponds or collapse-scar wetlands with saturated soils form

259   when ice-rich peat thaws and collapses. These mainly anaerobic environments are characterized

260   by high CH_4 emissions[55-57]; mass-balance accounting for C stocks indicates as much as 25-60%

261   of "old" permafrost C is lost in the years to decades following thaw[58-60]. Over time, increased C

262   sequestration and renewed peat accumulation occurs in drained thermokarst lake basins[61-62] and

263   collapse-scar wetlands, but it can take decades to centuries and sometimes millennia for

264   collapse-scar wetlands to transition from having a positive (warming) to a negative (cooling) net

265   radiative forcing[59,63]. Moreover, the combustion of peat layers has led to direct losses of plant and

266   peat C (Figure 3). Fire-derived emissions can be substantial, exceeding biological emissions from

267   peat decomposition in some years[64]. The highest emissions are observed from drained tropical

268   peatlands in extreme dry years such as the 1997 El Niño (810-2570 TgC yr^{-1})[65] and the 2015 fire

269   season (380 Tg C yr^{-1})[66] in Indonesia. However, as a result of drainage, peat fires are even

270   observed in wet years[67]. Although peat C losses from northern peat fires are smaller (e.g., 5 TgC

271   yr^{-1} from Alaskan wetlands)[68], there is a need to consider wildfires in permafrost thaw dynamics

272   due to their effects on soil temperature regime[69]. Peatland surface drying, both as a result of

273   droughts and human activity, has been shown to increase the frequency and extent of peat

274   fires[13,70], which could lead to deeper burns and hindered recovery[71] as well as peat water

275   repellency[72]. In terms of LUC, it is well accepted that widespread peatland conversion, drainage,

276   and mining across the temperate and tropical regions has led to large C losses[73-76], in addition to

277   immediate ecosystem damage and land subsidence[47,77]. While most peatland management

278   practices result in decreased CH_4 emissions due to drainage[32], peatland inundation or rewetting

279   can lead to episodic CH_4 releases[78-79]. Lastly, the structure and function of peatlands are now

280   threatened by increased N availability and atmospheric phosphorus (P) deposition[80] from

281   anthropogenic emissions[81]. For example, *Sphagnum* moss cover dies off after a few years of

282   sustained N loading[82-84]; changes in climate can exacerbate these negative effects[85]. Changes in

283   microbial communities and litter quality associated with N deposition can also contribute to

284   increased decomposition[86-87] by lowering the peatland surface[88] and causing a rise in the water

285   table and CH_4 emission[89]. Conversely, a study reported C gain with modest N deposition in a

286   Swedish peatland, driven by a greater increase in plant production than in decomposition[90],

287   illustrating differences, and perhaps a threshold response, in C balance response to N deposition.

288

289   ***Quantification of Future Peatland Stocks***

290   During the rest of this century (2020 – 2100 CE) and the far future (2100 – 2300 CE), experts

291   expect the C loss mechanisms presented above to be amplified (Figure 3). In the northern high

9

292   latitudes, while C gains are still linked to shifts in temperature and precipitation (17 (-16 to +47)

293   and 3 (-37 to +32) GtC, respectively), C losses to fire are expected (-7 (-10 to 0) GtC). Many

294   respondents suggest that better fire management could mitigate this. These losses are predicted

295   to be accompanied by additional ones from permafrost degradation (-30 (-102 to +12) GtC), sea-

296   level rise that would inundate coastal peatlands (-3 (-9 to +1) GtC), and LUC (-14 (-38 to +3)

297   GtC). The latter, and primarily drainage for agriculture, is expected to cause significant peatland

298   C losses, though many experts expect the rate to slow with increasing conservation and

299   restoration efforts. Regional drought-induced C losses are also suggested for the mid-latitude

300   regions. In the tropics, experts generally agree that every agent of change will negatively impact

301   C stocks. Net peat C losses are predicted due to warmer temperatures (-22 (-14 to +4) GtC;

302   mean skewed outside $10^{th} – 90^{th}$ percentile range by an outlier), fires (-23 (-54 to -2) GtC),

303   negative moisture balance (-9 (-31 to +3) GtC), and sea-level rise (-3 (-5 to 0) GtC). Of particular

304   importance is the evolution of the El Niño Southern Oscillation, as El Niño droughts may lead to

305   substantial C losses to the atmosphere. LUC (-13 (-44 to +3) GtC) is also predicted to play a key

306   role in the future, as it could lead to the drainage of large peat basins, such as the Amazon and

307   Congo.

308

309   Experts' confidence in their predictions declines for the far future (Tables S6 and S7; Figure S2),

310   in part due to the lack of models capable of simulating the effect of agents of change on peatland

311   C stocks, but also because policy and land management decisions will influence the future of

312   peatlands. This is an area where the integration of peatlands into IAMs would allow the

313   generation of pertinent scenarios to help inform the science, as well as policy options and land

314   management decisions. A growing world population may put additional pressure on peatlands, as

315   farming becomes possible at higher latitudes, and further deforestation may occur in the tropics,

316   but the need to conserve peat resources may eventually outweigh these pressures. In this case,

317   the adoption of policies designed to protect peatlands would greatly limit C losses. Likewise, the

318   pricing of C could change the way peatlands are perceived, valued, and managed. These

319   diverging opinions are all included in our assessment (Appendix 3), but explicit IAM simulations

320   would allow exploration of different policies and socio-economic scenarios. Noteworthy is that

321   extra-tropical peatlands could play an important role, second only to the oceans, in reducing the

322   global atmospheric CO_2 concentration if cumulative anthropogenic emissions are kept below

323   1000 GtC[91-92]. Mitigation is therefore highly important in counterbalancing the climate impact of

324   peatland C loss[93].

325

326

327   ***Insights from the Expert Elicitation and their Limits***

328   Expert assessment is critical to inform decisions that require judgements that go beyond

329   established knowledge and model simulations[94]. For this reason, expert opinion is often used in

330   environmental assessments either as a means to assess confidence levels or rank potential

331   outputs[7], or as data points that offer estimates that could not be provided otherwise[95,96]. This

332   expert assessment also highlights key knowledge gaps and uncertainties such as, for example,

333   the impact of permafrost aggradation and degradation on the future peatland C balance (see SI

334   and Figure S1). Our dataset reflects two main schools of thought that are anchored in conflicting

335   evidence from the literature: (1) rapid C loss from deep peats and a slow recovery of the

336   peatlands following permafrost thaw[59-60], and (2) net C gain from rapidly recovering plant

337   production due to warm and moist conditions following thaw[1,28]. Overall, results from the expert

338   elicitation can be used to help prioritize which ecosystem mechanisms and properties should be

339   integrated into ESMs; in turn, those model outputs will help constrain the peat-carbon-climate

340   feedback and inform future data collection strategies.

341

342   Our results indicate low to medium confidence in future C flux estimates. Confidence levels are

343   highest for the post-LGM and Anthropocene time periods, in part reflecting the majority of paleo

344   researchers in the survey respondents, but also because of compounding uncertainties pertaining

345   to future levels of GHG emissions from the energy and land systems, patterns of land-use

346   change, etc., which are affected by social, economic, political, and policy drivers (Appendix 3).

347   The overall confidence levels for the post-LGM and Anthropocene is medium (a value of 3 on a

348   scale of 1 to 5); even highly self-rated experts (4-5) give low to medium confidence to some of

349   their answers, which could suggest great uncertainty based on current literature (Tables S6 and

350   S7, Figures S2, S3). For the rest of this century and the far future, confidence drops to low (a

351   value of 2), likely reflecting the low confidence in our projection of human-based decisions (Figure

352   S2, Appendix 3). Areas of research for which expertise is lowest include LUC, N deposition, and

353   atmospheric pollution (Tables S8 and S9, Figure S2), which may have contributed to some of the

354   low confidence levels mentioned above. Here again, results from the expert elicitation provide a

355   unique opportunity to generate pertinent socio-economic scenarios that will help inform our

356   science, policy options, and land management decisions.

357

358   While this present assessment may be used as a bridge towards policy –decisions need to be

359   made even when uncertainty is high and confidence is low – we are not interested in offering

360   "consensus statements" on peatland C storage. Rather, our intent is to contribute a novel

361   perspective that identifies the central tendencies, communicates uncertainties, and highlights

362   contradictions to improve peat-C process understanding and press the community to add organic

363   soils and peatland plant functional types in ESMs and IAMs (see SI for further discussion).

364   Overall, results from the expert elicitation can help prioritize which ecosystem mechanisms and

365   properties should be integrated into ESMs; in turn, those model outputs will help constrain the

366   peat-carbon-climate feedback, inform future data collection strategies, and advance

367   understanding by further testing different hypotheses. As such, the inclusion of peatland process

368   understanding in models, and particularly better attribution of the role of each agent of change on

369   peatland C dynamics, would help increase confidence in C flux predictions. Modeling efforts that

370   include peatland dynamics would improve ESM and IAM outputs and benefit the peatland and

371   climate research communities, in a positive feedback loop.

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398 ***Author Contributions***

399 J.L., A.G.-S., M.A., and G.M. performed the majority of analyses and wrote the majority of the

400 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.,

401 J.M., S.v.B., J.B.W., and Z.Y. formulated the research goals and ideas during the 2018 C-PEAT

402 workshop in Texas. J.L.B., M.G., T.M., A.B.K.S., S.P., M.V., A.H., S.J., T.L., A.L., K.M., and C.T.

wrote parts of the Review section. Other co-authors contributed with unpublished data or

completed the expert opinion survey. All co-authors contributed to data analysis and writing of the

manuscript. All survey data generated and analyzed during this study are available from the

corresponding author on reasonable request. The references used to generate the maps for this

study are included in the supplementary information files of this article.

Data Availability

The authors declare that data supporting the findings of this study are available within the

supplementary information files; anonymized survey data are available from the corresponding

authors upon request.

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Figure Captions

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

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

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