Latitudinal limits to the predicted increase of the peatland carbon sink with warming

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The carbon sink potential of peatlands depends on the balance between carbon uptake by plants and microbial decomposition. The rates of both these processes will increase with warming but it remains unclear which will dominate the global peatland response. Here we examine the global relationship between peatland carbon accumulation rates during the last millennium and planetary-scale climate space. A positive relationship is found between carbon accumulation and cumulative photosynthetically active radiation during the growing season for mid- to high-latitude peatlands in both hemispheres. However, this relationship reverses at lower latitudes, suggesting that carbon accumulation is lower under the warmest climate regimes. Projections under RCP2.6 and RCP8.5 scenarios indicate that the present-day global sink will increase slightly until ~2100 AD but decline thereafter. Peatlands will remain a carbon sink in the future, but their response to warming switches from a negative to a positive climate feedback (decreased carbon sink with warming) at the end of the 21st century.

Analysis of peatland carbon accumulation over the last millennium and its association with global-scale climate space indicates an ongoing carbon sink into the future, but with decreasing strength as conditions warm.

The carbon cycle and the climate form a feedback loop and coupled carbon cycle climate model simulation results show that this feedback is positive[1]. In simple terms, warming of the Earth's surface results in a larger fraction of the anthropogenically and naturally released CO_2 remaining in the atmosphere, inducing further warming. However, the strength of this feedback is highly uncertain; indeed, it is now one of the largest uncertainties in future climate predictions[2]. The terrestrial carbon cycle feedback is potentially larger in magnitude when compared to the ocean carbon cycle feedback, and it is also the more poorly quantified[1,3]. In coupled climate models, there is still no consensus on the overall sensitivity of the land processes, or whether changes in net primary productivity versus changes in

108 respiration will dominate the response[1]. Furthermore, most models have so far ignored the

109 potential contribution of peatlands, even though they contain 530-694 Gt C[1,4]; equalling the

110 amount of carbon in the pre-industrial atmosphere. The few models that have taken into

111 account the role of peatlands in the carbon cycle predict a sustained carbon sink (global

112 dynamic vegetation models[5,6]) or a loss of sink potential in the future (soil decomposition

113 model[7]) depending on the climate trajectories and the specific model[5,6,7].

114 Evidence from field manipulation experiments suggests major future carbon losses from

115 increased respiration in peatlands with warming[8], but these projections do not take into account

116 the potential increased productivity due to increased temperatures and growing season length,

117 especially in mid- to high-latitude peatlands. Additionally, increased loss of carbon due to

118 warming may be limited to the upper layers of peat but it may not affect the buried deeper

119 anoxic layers[9,10].

120 Peatlands preserve a stratigraphic record of net carbon accumulation, the net outcome of both

121 respiration and plant production, and these records can be used to examine the behaviour of

122 the peatland sink over time. This has been done successfully since the last deglaciation (11,700

123 years ago to the present) at lower resolution[4,11] and for the last millennium (850-1850 AD) at

124 higher temporal resolution[12]. These studies have focused on high latitude northern peatlands

125 and have shown that in warmer climates increases in plant productivity overcome increases in

126 respiration and that these peatlands will likely become a more efficient sink if soil moisture is

127 maintained[11,12,13].

128 Here we use 294 profiles from globally distributed peatlands to build a dataset of global carbon

129 accumulation over the last millennium (850-1850 AD) (Figure 1a). We improve the coverage

130 of northern high latitudes and expand the dataset to low latitudes and southern high latitudes

131 by including over 200 new profiles compared to previous data compilations[12]. There are areas

132 of the world where extensive peatlands exist where data are still lacking (e.g. East Siberia,

133 Congo Basin[14]), but our data pr comprehensive coverage of peatland carbon accumulation

134 records over this time period. The last millennium is chosen as a time span because it is

135 climatically relatively similar to the present day enabling comparisons with modern planetary-

136 scale climate space, it is possible to date this part of the peat profile accurately, and the data

137 density is greatest for this period as almost all existing peatlands contain peat from this time.

138 **Planetary-scale climate effects on the carbon sink**

139 The profiles are predominantly from low nutrient sites (213 sites, Fig 1b), and the spatial

140 patterns of the distribution show that oceanic peatlands tend to be characterised by low

141 nutrients (bogs) while there are continental areas (e.g. central Asia, North America, Arctic

142 Eurasia) where there are extensive higher nutrient peatlands (fens, including poor fens).

143 Mean carbon accumulation rates for the last millennium vary between 3 and 80 g C m^{-2} yr^{-1}

144 (see Methods, and Figure 1c).

145

146 Photosynthetically active radiation summed over the growing season (PAR0) is the best

147 explanatory variable of all of the bioclimatic variables that were statistically fitted to carbon

148 accumulation (Figure 2a), in agreement with a previous study of northern peatlands[12]. Carbon

149 accumulation increases almost linearly with increasing PAR0 up to PAR0 values of around

150 8000 mol phot m^{-2}, which correspond to peatland sites in the mid-latitudes, including those

151 from the Southern Hemisphere. The positive relationship for PAR0 is spatially explicit at

152 these mid- to high latitudes, with temperate sites accumulating more carbon than boreal or

153 arctic areas (Figure 1c). The positive relationship peaks at values of PAR0 ~ 8000 mol phot

154 m^{-2} (8000 mol phot m^{-2} for bogs and 10,000 mol phot m^{-2} for fens), representing sites from

155 mid latitudes, and appears to reverse when PAR0 >11,000 mol phot m^{-2}, values which

156 represent the tropical sites (Figure 2b). The growing season length at mid latitude locations is

157 at or very close to 365 days a year, so further warming no longer extends the length of the

158 growing season at these sites. The relationship is similar but weaker for growing degree days

159 (GDD0, Figure 2c) and growing season length (GSL, Figure SI1c), suggesting that increased

160 accumulation is primarily driven by growing season length, and partly by light availability.

161

162 For the lower latitude peatlands, we suggest that the higher temperatures drive increased

163 microbial activity and decomposition rates in the peat and surface litter, but this is not fully

164 compensated by increases in plant productivity (Figure SI4), leading to reduced carbon

165 accumulation rates compared to higher latitude peatlands. It has been shown that plant

166 productivity does not increase with temperature after accounting for the increased length of

167 the growing season[15]. This has important implications in terms of the future carbon sink. Our

168 results suggest that under a future warmer climate, the increase in net primary productivity,

169 due to longer and warmer growing seasons, results in more carbon accumulation only at mid-

170 to high-latitudes. Conversely, increased respiration dominates the response of peatlands to

171 warming at lower latitudes, even if this warming is predicted to be less compared to the more

172 amplified warming at high latitudes. Thus, the carbon sink of low latitude peatlands will

173   decrease with warmer temperatures, although uncertainty in the carbon accumulation trend

174   for low latitudes is higher, due to the more limited extent of data for these areas. Furthermore,

175   the greater predictive power of PAR0 suggests that light availability is a critical factor in

176   driving the increase in net primary productivity at higher latitudes, in agreement with

177   previous theoretical analysis of plant photosynthesis[16]. Cloud cover and PAR0 remain highly

178   uncertain in future climate projections, and this needs to be considered in estimates of the

179   precise effect of future climate change on peatland carbon accumulation rates.

180

181   We expected moisture to be an important controlling variable for carbon accumulation.

182   However, the effect of moisture was not detected using a moisture index (Figure 2d) and

183   instead the relationship between moisture index and carbon accumulation indicates that

184   moisture acts as an on-off switch, i.e. there needs to be sufficient moisture to retard decay but

185   increases to very high moisture levels do not promote higher rates of accumulation. A

186   precipitation deficit analysis was also carried out (Figure SI5) to ascertain whether a greater

187   precipitation shortage drives reduced carbon accumulation, but there are no clear patterns

188   emerging using this moisture parameter either. None of the moisture indexes used account for

189   local small-scale hydrological or water chemistry variations. Because our data does not

190   support a moisture control on global-scale variations in vertical peat accumulation, we have

191   not used moisture as a predictor variable in our future estimates of the carbon sink.

192

193   **The present and future of the carbon sink**

194   We estimated the total present and future global peatland carbon sink strength using both

195   spatially interpolated observations and statistically modelled data (see methods). According

196   to the spatially interpolated observations (Figure 3a) of last millennium carbon accumulation

197   rates, global peatlands represent an average apparent carbon sink of 142 ± 7 Tg C yr^{-1} over the

198   last millennium. This is equivalent to a total millennial sink of 33 ± 2 ppm CO_2, based on a

199   simple conversion from change in carbon pool to atmospheric CO_2 of 2.123GtC=1ppm and

200   an airborne fraction of 50 % to account for the carbon cycle response to any carbon dioxide

201   released to or captured from the atmosphere[17]. This figure corresponds to the near-natural

202   sink and does not account for anthropogenic impacts such as land use change, drainage or

203   fires, and also excludes the very slow decomposition that continues in the deeper anoxic

204   layers of peat older than 1000 years.

205   There are few directly comparable estimates of the total peatland sink, but a simplistic

206 estimate based on a series of assumptions of average peat depth, extent and bulk density

207 suggested a current rate of 96 Tg C yr^{-1} for northern peatlands alone[15]. A subsequent estimate

208 suggests a figure of approximately 110 Tg C yr^{-}1 global peatland net carbon uptake for the

209 last 1000 years[4] (see Figure 5 in ref. 4), with 90 Tg C yr^{-1} in northern peatlands. These

210 estimates are based on averages across very large regions. Our spatially explicit modelling

211 suggests a larger overall carbon sink than these earlier estimates and implies that the size of

212 the global peatland carbon sink is substantially larger than previously thought. This is also a

213 larger value than estimates of the average carbon accumulation rates over the entire Holocene

214 (>50 to 96 Tg C yr^{-1})[4,18], principally because the total area of peatlands is at its greatest in the

215 last millennium when compared with the earlier in the Holocene. In addition, many high

216 latitude peatlands only accumulated small amounts of peat during the early stages

217 (minerotrophic) of their development, often for several millennia after their initiation[19,20].

218

219 None of the above estimates take into account the long-term decay of previously deposited

220 deeper/older peat. Prior estimates[4] (Figure 5 in ref. 4) suggest that this loss is substantial at

221 around 65 Tg C yr^{-1}, producing a net carbon balance of around 45 Tg C yr^{-1} compared to a

222 net uptake value of 110 Tg C yr^{-1} in the same study. For northern peatlands alone, an earlier

223 estimate of the deep carbon loss[4] was approximately less than half of the equivalent later

224 estimate[9] for the same region, c. 48 Tg C yr^{-1}. However, all of these estimates are based on

225 modelling using a 'super-peatland' approach combining data from across large areas to

226 estimate mean long term peat decay rates and thus are subject to considerable error.

227 Nevertheless, the net carbon balance including the decay of deeper/older peat is likely to be

228 around a third less than our 142±7 Tg C yr^{-1} estimate of the apparent global net uptake over

229 the last millennium, assuming a long-term decay rate between 20 and 50 Tg C yr^{-1}.

230

231 Modelled changes in the future peatland carbon sink under a warmer climate show a slight

232 increase in the global peatland sink compared to the present-day sink until 2100 AD (RCP

233 2.6 scenario: 147 ± 7 Tg C yr^{-1}; RCP 8.5 scenario: 149± 7 Tg C yr^{-1}) and a decrease in the

234 sink thereafter (Figure SI3, Table SI3). The results suggest that initially, and approximately

235 for the next century, peatlands will be a small negative feedback to climate change, i.e. the

236 global peatland carbon sink increases as it gets warmer. However, this negative feedback

237 does not persist in time and the strength of the sink starts to decline again after 2100 AD,

238 although it remains above the 1961-1990 values throughout the next c.300 years (RCP 2.6

239   scenario: 146 ± 7 Tg C yr^{-1}; RCP 8.5 scenario: 145 ± 7 Tg C yr^{-1} for the period 2080-2300).

240   Despite large uncertainties in these projections due to uncertainties originating from both the

241   statistical modelling and from the climate model projections, the direction of change and a

242   shift from initially negative to subsequent positive feedback is a plausible and robust result.

243

244   An explanation for the mechanism of change in the sink capacity of the global peatland area

245   can be inferred from the spatial distribution of the modelled changes (Figure 4). While the

246   carbon sink at very high latitudes increases in both RCP2.6 and RCP8.5 scenarios

247   continuously to 2300 AD, the lower latitudes experience an ongoing decrease in carbon

248   sequestration over the same period. Simultaneously, peatlands in the mid latitudes gradually

249   move past the optimum level of photosynthesis/respiration into the decline phase (Figure 2a,

250   Figure SI4) where respiratory losses are rising faster than net primary productivity. This is

251   likely to be determined by the poleward migration of the latitudinal line where the growing

252   season length is near 365 days, moderated by changes in cloud cover and thus PAR. The

253   balance between the increasing high latitude sink, and the decreasing low latitude sink

254   changes over time, such that the global sink eventually begins to decrease. This estimate

255   takes into account only the changes in the surface accumulation rates of extant peatlands and

256   other factors will affect the total peatland carbon balance. Deeper peat may also warm and

257   provide a further source of peatland carbon release in peatlands worldwide, but there is still

258   some debate as to how large this effect may be, especially in the transition from permafrost to

259   unfrozen peatlands[21,22]

260   Conversely, peatlands may expand into new areas that have previously been too cold or too

261   dry for substantial soil carbon accumulation especially in northern high latitudes, where there

262   are large topographically suitable land areas. The magnitude of these potential changes is

263   unknown, but it would offset at least some of the additional loss of carbon from enhanced

264   deep peat decay. Carbon dioxide fertilization is also likely to increase the peatland carbon

265   sink via increases in primary productivity. Furthermore, vegetation changes and specifically

266   more woody vegetation might result in a larger peatland sink, if moisture is maintained[23].

267   Increases in shrubs and trees have also been shown to increase the pools of phenolic

268   compounds and decrease the losses of peat carbon to the atmosphere due to inhibitory effects

269   on decay[24]. All of these changes will be compounded by changes in hydrology, which will

270   also affect overall peatland functioning. None of these potential changes have been taken into

271   account in our projections of the future peatland carbon sink. Finally, human impact on the

272 peatland carbon store is still likely to be the most important determinant of global peatland
273 carbon balance over the next century. Ongoing destruction of tropical peatlands is the largest
274 contributor at present and at current rates, the losses from this source outweigh carbon
275 sequestration rates in natural peatlands[25,26]. Whilst our results are reassuring in showing that
276 the natural peatland C sink will likely increase in future, reducing anthropogenic release of
277 peatland carbon is the highest priority in mitigation of peatland impacts on climate change.
278

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297 **Author Contributions**
298 A.G.S. carried out analysis and interpretation of the data and wrote the first draft of the paper.
299 D.J.C. supervised the project and contributed to experimental design, interpretation of results,
300 and the final draft. S.B. carried out the statistical and spatial analysis of the data and contributed
301 to the design of the final figures. S.M. was responsible for new radiocarbon analyses. Z.Y.
302 provided the peatland map used in the modelling and contributed data and material. C.J.
303 provided climate and gross primary productivity (GPP) data. L.O. carried out the age-depth
304 models for all cores. All authors contributed either data or material to be analysed in the

305   Geography laboratories at the University of Exeter. All authors contributed to the preparation

306   of the final paper.

307

308   **Additional Information**

309   The authors declare no competing financial interest.

310

311   **Figure captions**

312

313   Figure 1: Distribution of sampling sites in geographical space. Note that a single point may
314   represent more than one site. (a) Locations of sites shown as either high-resolution records
315   (white circles) or low-resolution records (black circles). (b) Distribution of fen (nutrient rich,
316   green circle) and bog (nutrient poor, blue circle) or mixed (yellow circles) study sites. (c)
317   Distribution of the mean annual carbon accumulation rate during the last millennium (gC m^{-2}
318   yr^{-1}) for all sites. Light yellow represents the lowest range of mean annual C accumulation (0-
319   10 gC m^{-2} yr^{-1}) while dark brown represents the highest range (50-60 gC m^{-2} yr^{-1}). Colours in
320   between these two shades represent intermediate ranges, separated in 10 gC m^{-2} yr^{-1} intervals.

321

322   Figure 2: Controls on peat accumulation rate. Mean annual accumulation over the last 1000
323   years at each site compared to a) cumulative annual photosynthetically active radiation (PAR0)
324   b) latitude (degrees North are represented by positive numbers and degrees South by negative
325   numbers) c) annual growing degree-days above 0°C (GDD0) and d) the ratio of precipitation
326   over equilibrium evapotranspiration (moisture index, MI). Bog and fen sites (see Figure 1a and
327   supplementary Table 1) are shown in blue and green respectively, and separate regressions
328   have been calculated for each site type for PAR0 (R^2 is shown on the graph). The grey line is
329   the overall regression for all peat types. The regression for GDD0 yielded a much lower R^2
330   (only shown for all peat types). Errors represent uncertainty in carbon accumulation rates
331   stemming from the age depth model errors (95 percentile range).

332

333   Figure 3: Spatial analysis of the overall carbon sink. (a) Gridded spatial distribution of the
334   annual carbon sink based on kriging of observations over the last millennium. Values have
335   been kriged over a present-day peatland distribution map[4]. (b) Gridded spatial distribution of
336   the annual carbon sink based on modelling of carbon accumulation for the last millennium
337   calculated using the statistical relationship between the annual carbon sink and PAR0 (c)
338   Difference between (a) and (b), negative values in red mean an overestimation of the sink
339   using the statistically modelled data when compared with the observations, positive values in
340   blue mean an underestimation of the sink by the model. Note: OK = Observation kriging. RK
341   = Regression kriging

342

343   Figure 4: Projected anomalies (future – historic) of annual carbon accumulation rates for
344   three time periods: a) 2040-2060 b) 2080-2100, c) 2180-2200 and d) 2280-2300, based on
345   PAR0 derived from climate data outputs from the Hadley Centre climate model. The climate
346   runs chosen reflect the two end-member representative concentration pathways detailed in the
347   IPCC Fifth Assessment Report[31]: 1) RCP2.5 and 2) RCP8.5.

348

349   **References**

350   1   Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M. Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C. and Zeng, N. Climate-Carbon cycle feedback analysis: results from the C^{4}MIP Model Intercomparison. Journal of climate **19** 3337-3353 (2006).

356   2   Gregory, J.M., Jones, C.D., Cadule, P. and Friedlingstein, P. Quantifying Carbon Cycle Feedbacks. Journal of Climate **22** 5232-5250 (2009).

358   3   Matthews, H. D., Eby, M., Ewen, T., Friedlingstein, P. and Hawkins, B.J. What determines the magnitude of carbon cycle-climate feedbacks? Global Biogeochemical Cycles **21** 12 (2007).

361   4   Yu, Z.C., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J. Global peatland dynamics since the Last Glacial Maximum. Geophysical Research Letters, **37** L13402 (2010)

364   5   Spahni, R., Joos, F., Stocker, B.D., Steinacher, M. and Yu, Z.C. 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 (2013)

367   6   Chaudhary, N., Miller, P. A., and Smith, B.: Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model, Biogeosciences, **14**, 2571-2596 (2017).

370   7   Ise, T., Dunn, A.L., Wofsy, S.C. and Moorcroft, P.R. High sensitivity of peat decomposition to climate change through water-table feedback. Nature Geoscience **1** 763-766 (2008)

373   8   Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T.V. and Aerts, R. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. Nature **460** 616-619 (2009)

376   9   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. Stability of peatland carbon to rising temperatures. Nature Communications **7** 13723 (2011)

381   10   Blodau, C., Siems, M. and Beer, J. Experimental burial inhibits methanogenesis and anaerobic decomposition in water-saturated peats. Environmental Science and Technology **45** 9984-9989 (2011)

384   11   Loisel, J., Yu, Z., Beilman D.W., Camill, P., Alm, J., Amesbury, M.A., Anderson,
385   D., Andersson, S., Bochicchio, C., Barber, K., Belyea, L.R., Bunbury, J.,
386   Chambers, F.M. Charman, D.J., De Vleeschouwer, F., Fiałkiewicz-Kozieł, B.,
387   Finkelstein, S.A., Gałka, M., Garneau, M., Hammarlund, D., Hinchcliffe, W.,
388   Holmquist, J., Hughes, P., Jones, M.C., Klein, E.S., Kokfelt, U., Korhola, A.,
389   Kuhry, P., Lamarre, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G.,
390   Magnan, G., Mäkilä, M. Mallon, G., Mathijssen, P., Mauquoy, D., McCarroll, J.,
391   Moore, T.R., Nichols J., O'Reilly, B., Oksanen, P., Packalen, M., Peteet, D.,
392   Richard, P.J.H., Robinson, S., Ronkainen, T., Rundgren, M., Britta, A., Sannel, K.,
393   Tarnocai, C., Thom, T., Tuittila, E.-S., Turetsky, M., Väliranta, M., van der
394   Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y., and Zhou W. A
395   database and synthesis of northern peatland soil properties and Holocene carbon
396   and nitrogen accumulation. The Holocene **24** (9) 1028-1042 (2014).

397   12   Charman, D. J., Beilman, D. W., Blaauw, M., Booth, R. K., Brewer, S., Chambers,
398   F. M., Christen, J. A., Gallego-Sala, A. V., Harrison, S.P., Hughes P.D.M., Jackson
399   S.T., Korhola A., Mauquoy D., Mitchell F.J.G., Prentice I.C., van der Linden M.,
400   De Vleeschouwer F., Yu Z.C., Alm J., Bauer I.E., Corish Y.M.C., Garneau M.,
401   Hohl V., Y. Huang, E. Karofeld, G. Le Roux, J. Loisel, R. Moschen, Nichols J.E.,
402   Nieminen T. M., MacDonald G.M., Phadtare N.R., Rausch N., Sillasoo Ü.,
403   Swindles G.T., Tuittila E.-S., Ukonmaanaho L., Väliranta M., van Bellen S., van
404   Geel B., Vitt D.H. and Zhao, Y. Climate-related changes in peatland carbon
405   accumulation during the last millennium. Biogeosciences **10** 929–944 (2013).

406   13   Yu, Z. Holocene carbon flux histories of the world's peatlands: Global carbon
407   cycle implications. Holocene **21** (5) 761-774 (2010).

408   14   Dargie, G.C., Lewis, S. L., Lawson, I.T., Mitchard E.T.A., Page, S.E., Bocko,
409   Y.E., and Ifo S.A. Age, extent and carbon storage of the central Congo Basin
410   peatland complex. Nature **542**, 86-90 (2017).

411   15   Michaletz, S.T., Cheng, D., Kerkhoff, A.J. & Enquist, B.J. Convergence of
412   terrestrial plant production across global climate gradients. Nature **512** 39–43
413   (2014).

414   16   Wang, H., Prentice, I. C., Keenan, T. F., Davis, T. W., Wright, I. J., Cornwell, W.
415   K., Evans, B. J. & Peng, C. Towards a universal model for carbon dioxide uptake
416   by plants. Nature Plants **3** 734–741 (2017).

417   17   Jones C, Robertson E, Arora V, Friedlingstein P, Shevliakova E, Bopp L, Brovkin
418   V, Hajima T, Kato E, Kawamiya M. Twenty-first-century compatible CO_2
419   emissions and airborne fraction simulated by CMIP5 Earth System models under
420   four representative concentration pathways. Journal of Climate **26**(13): 4398-4413,
421   (2013).

422   18   Gorham E. Northern peatlands: Role in the carbon cycle and probable responses to
423   climatic warming. Ecological Applications **1** 182–195 (1991).

424   19   Korhola, A., Alm, J., Tolonen, K., Turunen, J. & Jungner, H. Three-dimensional
425   reconstruction of carbon accumulation and CH_4 emission during nine millenia in a
426   raised mire. Journal of Quaternary Science, **11**, 161-165 (1996).

427   20   Väliranta, M., Salojärvi, N., Vuorsalo, A., Juutinen, S., Korhola, A., Luoto, M.,
428   Tuittila, E.-S. Holocene fen-bog transitions, current status in Finland and future
429   perspectives. The Holocene **27**(5): 752-764 (2016).

430   21   Cooper, M. D.A., Estop-Aragonés, C., Fisher, J. P., Thierry, A., Garnett, M. H.,
431   Charman, D. J., Murton, J. B., Phoenix, G. K., Treharne, R., Kokelj, S. V., Wolfe,
432   S. A., Lewkowicz, A. G., Williams, M., and Hartley, I. P. Limited contribution of
433   permafrost carbon to methane release from thawing peatlands. Nature Climate
434   Change, **7**, 507-511 (2017).

435   22   Jones, M. C., Harden, J., O'Donnell, J., Manies, K., Jorgenson, T., Treat, C. and
436   Ewing, S. Rapid carbon loss and slow recovery following permafrost thaw in
437   boreal peatlands. Global Change Biology **23** 1109–1127 (2017).

438   23   Ott, C.A. and Chimner, R.A. Long-term peat accumulation in temperate forested
439   peatlands (Thuja occidentalis swamps) in the Great Lakes region of North
440   America. Mires and Peat **18** 1–9 (2016).

441   24   Wang, H., Richardson, C. J. and Ho, M. Dual controls on carbon loss during
442   drought in peatlands. Nature Climate Change **5** 584-588 (2015).

443   25   Page, S. E., Siegert F., Rieley J.O., Boehm H.D., Jaya A. and Limin S. The amount
444   of carbon released from peat and forest fires in Indonesia during 1997. Nature **420**
445   61–65 (2002).

446   26   Moore, S., Evans, C. D.; Page, S. E.; Garnett, M. H.; Jones, T. G.; Freeman, C.;
447   Hooijer, A., Wiltshire, A. J., Limin, S. H. and Gauci, V. Deep instability of
448   deforested tropical peatlands revealed by fluvial organic carbon fluxes. Nature **493**
449   660-663 (2013).

450

451

Methods

Carbon accumulation estimates. Mean annual carbon accumulation over the last millennium was estimated for 294 peatland sites (Table SIT1). In line with climate modelling studies, we use the term 'last millennium' to refer to the pre-industrial millennium between AD 850-1850). The total carbon accumulated over this period was calculated for all sites in Table SI1 by using a flexible Bayesian approach that incorporated estimates of age and minimum and maximum accumulation rates[12]. A number of sites were previously published (Reference 12 and references therein), but we added over 200 sites to the database from new field coring, as well as additional analysis for bulk density, carbon and radiocarbon dating from a range of existing samples held in laboratories around the world to bring the data to comparable standards. Age models were constructed from at least 2 radiocarbon dates (low resolution sites) or more than 4 radiocarbon dates (high resolution sites) (see Table SI1 for details). For each of these records, bulk density was measured on contiguous samples. Carbon content was calculated based on either elemental carbon measurements or loss-on-ignition, when this was the case, loss-on-ignition was converted to total carbon assuming 50% of organic matter is carbon[27].

The fen (minerotrophic or high nutrient, including poor fens) and bog (ombrotrophic or low nutrient) classification (Figure 1b) is a simplification and more information relating to each individual record is given in the supporting information (SI) section (Table SIT1). There are 212 bogs versus 82 fens (which include 5 mixed sites).

We analysed the relationship between total carbon accumulation and a wide range of different climate parameters, including seasonal and mean annual temperature, precipitation and moisture balance indices (Figures 1d and SI1). Climate parameters were calculated using the CRU 0.5° gridded climatology for 1961-1990 (CRU CL1.0)[28].

Modern day PAR0 and MI calculations. PeatStash[29] was used to calculate the accumulated PAR0 by summing the daily PAR0 over the growing season (days above freezing) for each peatland grid cell. The daily PAR0 is obtained by integrating the instantaneous PAR between sunrise and sunset. The seasonal accumulated PAR0 depends on latitude and cloudiness, and indirectly on temperature, because temperature determines the length of the growing season, i.e. which days are included in the seasonal accumulated PAR0 calculation. The Moisture Index (MI) was calculated as P/Eq, where P is annual precipitation and Eq is annually integrated equilibrium evapotranspiration calculated from daily net radiation and temperature[29]. P and Eq were also derived from CRU CL1.0.

484

485 *Statistical model.* The statistically modelled data are based on a relationship between C

486 accumulation (g C m^{-2} yr^{-1}) and PAR0 (mol phot m^{-2} yr^{-1}) ($R^2 = 0.25$, $F_{2,292} = 49.35$, p-value =

487 2.5×10^{-19}) as follows (Figure SI2, Table SI2):

488

489 $$log_{10}\, C = 0.3 + 0.0003 \times PAR0 - 1.6 \times 10^{-8} \times PAR0^2 \hspace{3cm} (1)$$

490

491 This function is used when deriving a spatially explicit estimate of net carbon uptake using

492 modern-day gridded PAR0 values (Figure 3b). The general trend is for the model to over-

493 estimate the peatland carbon sink at high latitudes and underestimate it at low latitudes, when

494 compared to the spatially interpolated data (Figure 3c). However, this is not uniform and the

495 spatially interpolated data and the statistically derived model results compare well in areas of

496 Eastern Siberia, China, Europe, southern North America, the tropical and Andean regions in

497 South America and certain areas of central Africa. There is less congruence between spatially

498 interpolated and statistically modelled estimates in areas where observations are lacking.

499

500 *Spatial interpolation.* To model the variation in spatial data, we use the model-based

501 geostatistical approach described by Diggle and Riberio[30], which decomposes the variation in

502 a spatially distributed variable as follows:

503

504 $$Y(x) = \mu(x) + S(x) + \epsilon \hspace{3cm} (2)$$

505

506 where

507   • x is a spatial location; the coring sites

508   • Y is the value of the variable of interest; the carbon accumulation rate

509   • $\mu(x)$ is the mean field component, either as a constant mean or modelled using

510   covariates (i.e. $\mu(x) = \beta X$)

511   • $S(x)$ is the spatially random error, described by two parameters, the range (ϕ), giving

512   the limit of spatial dependency and variance (σ^2)

513   • ϵ is the residual non-spatial random error, described by its variance (τ^2)

514

515 The spatially random error describes the spatial dependence and can be modelled using one

516 of a set of positive definite spatial covariance functions, which describe the decay in

517   covariance over distance[31]. Prediction for a new location (x') then follows the classic kriging

518   approach of estimating the mean field component ($\mu(x)$) and the deviation ($S(x)$) from this at

519   the new location, based on the covariance of this latter term with nearby locations[32]. The

520   residual non-spatial error (ϵ) is then estimated as the kriging variance, giving estimation

521   error. An alternative to method of estimating interpolation uncertainty is by a sequential

522   simulation approach. Here, the spatially random error is simulated as multiple Gaussian

523   random fields[32], constrained on the observations, and the range of outcomes provides as

524   estimate of the non-spatial error. All spatial analysis was carried out in R 3.3.2 using the

525   packages 'gstat'[33] and 'raster'[34].

526

527   *Gridding observed accumulation rates.* In a first step, we grid the observed carbon

528   accumulation rates to a 0.5° grid clipped to a peatland mask[4] using ordinary sequential

529   simulation. The mean field ($\mu(x)$) is taken as the mean of the log10 carbon accumulation rates.

530   The spatially random error term ($S(x)$) was modelled from the observations using an

531   exponential covariance function. This was then used to produce 1000 random spatial fields,

532   conditional on both the covariance function and the locations of the observations. These fields

533   were added back to the mean field to produce 1000 simulated carbon accumulation values, with

534   the final values reported as the mean at each grid point. Interpolation uncertainties were

535   estimated as the 95% confidence interval around the mean.

536

537   *Gridding accumulation rates using PAR0.* Here, the constant mean field of the previous model

538   was replaced with the model described in equation 1. This provides estimates of estimate

539   variations in the spatial mean field of log10 carbon accumulation rates across the 0.5° peatland

540   grid based on modern PAR0 values (see Table SI2 for statistical significance of the different

541   models). As in the previous step, the spatial random error term was estimated by sequential

542   simulation of the model residuals at the observations sites, producing 1000 random spatial

543   fields of residuals, which were then added back to the interpolated mean field to yield the

544   present time carbon accumulation rate for the grid cell. Final values reported are the mean of

545   the 1000 mean plus residual values at each grid point. The non-spatial error is then given by

546   the 95% confidence interval from the 1000 simulations.

547

548   *Estimating the future carbon sink.* A similar approach was taken for the estimated future carbon

549   accumulation. The mean field was estimated using equation 1, based on PAR0 projections for

550   two representative concentration pathways RCP2.5 and RCP8.5[35], using climate projections

551   for the periods 2040-2060, 2080-2100 and 2180-2200, as well as the historical period (1990-

552   2005) [36,37]. To avoid bias from the climate model, future estimates of PAR0 are calculated as

553   the anomaly between future and historical PAR0, added to the modern observed PAR0 field.

554   The interpolated residuals from the previous step were then added to these to give estimates of

555   future carbon accumulation rate for each grid cell with uncertainty estimated as before. It is

556   important to note that while this approach allows the spatial mean field to change as a function

557   of projected PAR0, the spatially auto-correlated error term is assumed to remain constant.

558
559   *Data Availability*

560   The data set generated and analysed during the current study are available in the
561   supplementary information section of this article and from the corresponding authors on
562   reasonable request.

563   *References (Methods Section)*
564

565   27   Bol, R. A., Harkness, D. D., Huang, Y. and Howard, D. M. The influence of soil

566   processes on carbon isotope distribution and turnover in the British Uplands.

567   European Journal of Soil Science **50** 41-51 (1999).

568   28   New, M., Hulme, M. and Jones, P.D. Representing twentieth century space- time

569   climate variability. Part 1: development of a 1961-90 mean monthly terrestrial

570   climatology. Journal of Climate **12** 829-856 (1999).

571   29   Gallego-Sala, A. V. and Prentice, I. C. Blanket peat biome endangered by climate

572   change. Nature Climate Change **3** 152–155 (2013).

573   30   Diggle, P. and Riberio Jr, P.J. Model-based geostatistics. Springer-Verlag, New

574   York, USA, 232 pp. (2007).

575   31   Cressie, N. A. C. Statistics for spatial data. New York, John Wiley & Sons Inc.

576   (1993).

577   32   Goovaerts, P. Geostatistics for natural resources evaluation. Oxford University

578   Press, Oxford, UK. 483 pp. (1997).

579   33   Pebesma, E.J. Multivariable geostatistics in S: the gstat package. Computers &

580   Geosciences, **30**: 683-691 (2004).

581   34   Robert J. H, and van Etten, J. Raster: Geographic analysis and modeling with raster

582   data. R package version 2.5-8. (2016).

583   35   Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report
584   2014. Climate Change: Synthesis report (eds. Pachauri R.K. et al.) (2014)
585   36   Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J.,
586   Liddicoat, S., O'Connor, F. M., Andres, R. J., Bell, C., Boo, K.-O., Bozzo, A.,
587   Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P.,
588   Gornall, J., Gray, L., Halloran, P. R., Hurtt, G., Ingram, W. J., Lamarque, J.-F.,
589   Law, R. M., Meinshausen, M., Osprey, S., Palin, E. J., Parsons Chini, L., Raddatz,
590   T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward,
591   S., Yoshioka, M., and Zerroukat, M.: The HadGEM2-ES implementation of
592   CMIP5 centennial simulations, Geoscientific Model Development **4** 543-570
593   (2011).
594   37   Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P.,
595   Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor,
596   F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S.:
597   Development and evaluation of an Earth-System model – HadGEM2,
598   Geoscientific Model Development **4** 1051-1075 (2011).
599