

Expert assessment of future vulnerability of the global peatland carbon sink

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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 listed below:

Table S1: census questions

Table S2: number of respondents, high-latitude peatlands

Table S3: number of respondents, tropical peatlands

Table S4: descriptive statistics, high-latitude peatlands

Table S5: descriptive statistics, tropical peatlands

Table S6: confidence of survey respondents, high-latitude peatlands

Table S7: confidence of survey respondents, tropical peatlands

Table S8: expertise of survey respondents, high-latitude peatlands

Table S9: expertise of survey respondents, tropical peatlands

Table S10: descriptive statistics, high-latitude peatlands (expertise E>2 only)

Table S11: descriptive statistics, tropical peatlands (expertise E>2 only)

Appendices

Appendix 1: expert opinion survey

Appendix 2: case studies cited by survey respondents and used to make the maps shown in the main text

Appendix 3: key comments from survey respondents

Appendix 4: references cited by survey respondents

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

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 Network¹. 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 ED3). 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 ED3).

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 expert². 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 stakeholders³. Building a bridge between scientists and other stakeholders is important, particularly in situations where policy decisions must be made based on limited or conflicting data⁴. 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 ED1) 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 ED1. 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 ED1). 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 distribution⁷⁻⁸. 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(10 th – 90 th 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(10 th – 90 th 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, respectively⁹. Our expert-derived estimates are also approximately twice as large as suggested by simulation efforts that aim at balancing the post-LGM C cycle¹⁰⁻¹¹. While peatland C stock estimates in the order of 1000Gt have been suggested before¹², mechanisms for additional post-LGM CO₂ release (likely from the ocean) would be needed to conceive such a large land sink¹³. This discussion is well beyond the scope of this study.

4. Self-assessment of confidence and expertise

Our results indicate low to medium confidence in our projections (Tables S6 and S7; Figure ED2). 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
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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 ED2). 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 ED3); 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).

Agents of change	Post-LGM	Anthropocene	Near Future	Far Future
Temperature	627(mean) / 500(med) / 565(geo) 216 – 1402(10 th – 90 th 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(10 th – 90 th 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.

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 ED1). 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 CH₄ (and CO₂ following CH₄ 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.

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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).

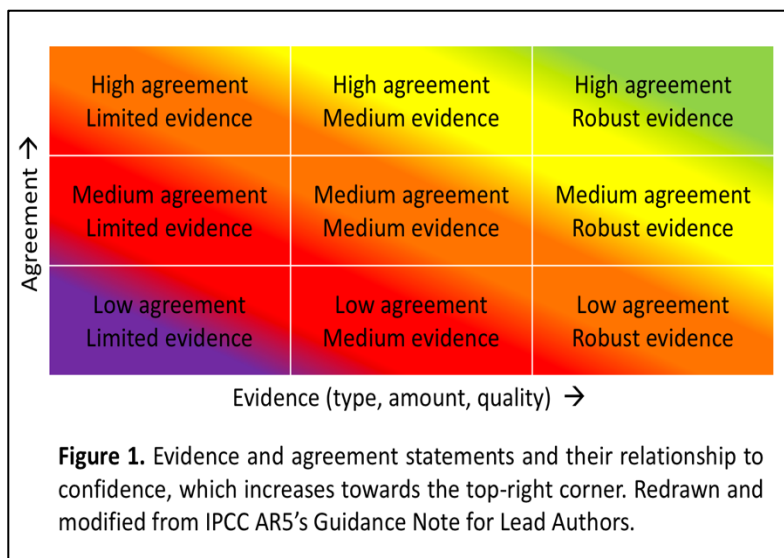
We recognize that all the different components of peatland carbon dynamics are difficult to quantify and are not, and cannot be, precisely and definitively modeled or measured. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. 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.



- 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 CO₂, CH₄ 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	<i>Sink =?Gt due to ?</i> <i>Source= ?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink =?Gt due to ?</i> <i>Source =?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink=?Gt due to ?</i> <i>Source=?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink=?Gt due to ?</i> <i>Source=?Gt due to?</i> <i>Overall net sink =?Gt</i>		
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	<i>Sink =?Gt due to ? Source= ?Gt due to? Overall net sink =?Gt</i>			<i>Sink =?Gt due to ? Source =?Gt due to? Overall net sink =?Gt</i>			<i>Sink=?Gt due to ? Source=?Gt due to? Overall net sink =?Gt</i>			<i>Sink=?Gt due to ? Source=?Gt due to? Overall net sink =Gt</i>		
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 CO₂, CH₄ 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	<i>Sink =?Gt due to ?</i> <i>Source= ?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink =?Gt due to ?</i> <i>Source =?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink=?Gt due to ?</i> <i>Source=?Gt due to?</i> <i>Overall net sink =?Gt</i>			<i>Sink=?Gt due to ?</i> <i>Source=?Gt due to?</i> <i>Overall net sink =?Gt</i>		
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	<i>Sink =?Gt due to ? Source= ?Gt due to? Overall net sink =?Gt</i>			<i>Sink =?Gt due to ? Source =?Gt due to? Overall net sink =?Gt</i>			<i>Sink=?Gt due to ? Source=?Gt due to? Overall net sink =?Gt</i>			<i>Sink=?Gt due to ? Source=?Gt due to? Overall net sink =Gt</i>		
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
<i>Deglacial climate warming</i>	.Rapid peat initiation .Rapid lateral expansion .Rapid vertical accumulation	northern high-latitudes, south Patagonia	. <u>Synthesis work</u> : 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
<i>Neoglacial climate cooling</i>	.Slow vertical accumulation	northern high-latitudes	Synthesis work: Yu et al. 2009; Loisel et al. 2014 ; Garneau et al. 2014 .Individual sites: Yu 2006
<i>MCA climate warming</i>	.Rapid vertical accumulation	northern high-latitudes	Synthesis work: Charman et al. 2013
<i>LIA climate cooling</i>	.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
<i>Lower surface moisture</i>	.Lake-to-peat transition .Fen-to-bog transition	south Patagonia; east Canada	. <u>Synthesis work</u> : Loisel & Yu 2013; Väiranta et al. 2017 .Individual sites: Heusser 1993; Markgraf & Huber 2010; van Bellen et al. 2013; De Vleeschouwer et al. 2014; Mansilla et al. 2018
<i>Higher surface moisture</i>	.Rapid lateral expansion .Pool inception .Bog-to-fen transition .Rapid vertical accumulation	northern high-latitudes; NE China; Congo Basin	. <u>Synthesis work</u> : 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
<i>Multi-decadal droughts</i>	.Slow vertical accumulation .Rapid vertical accumulation	continental North America, Amazon	.Synthesis work: Booth et al. 2005 .Individual sites: Swindles et al. 2018
<i>Early-Holocene high fire frequency</i>	.Peat loss (burnt)	south Patagonia, Canada	. <u>Synthesis work</u> : Huber & Markgraf 2003 .Individual sites: Kuhry 1994; Camill et al. 2009
<i>Sea level rise / Marine incursion</i>	.Peat loss (eroded) .Peat flooding and burial	SE Asia, south Africa, south Patagonia	. <u>Synthesis work</u> : Dommain et al. 2011 .Individual sites: McCulloch & Davies 2001; Unkel et al. 2010; Gabriel et al. 2017
<i>Sea level fall / Isostatic rebound</i>	.Peat initiation	Southeast Asia, Hudson Bay lowlands	. <u>Synthesis work</u> : Dommain et al. 2014; Packalen et al. 2014; Packalen & Finkelstein 2014 .Individual sites: Glaser et al. 2004; Rieley et al. 2008
<i>Neoglacial permafrost aggradation</i>	.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
<i>Peat initiation in thermokarsts</i>	.Rapid vertical accumulation	Alaska	.Individual sites: Jones et al. 2013
<i>LIA permafrost aggradation</i>	.Slow vertical accumulation	eastern Canada	.Individual sites: Lamarre et al. 2012
<i>Atmospheric dust / tephra deposition</i>	.Rapid vertical accumulation .Slow vertical accumulation	south Patagonia, Japan, eastern Europe	.Synthesis work: Fontijn 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
<i>Climate warming</i>	.Fen-to-bog transition .Rich-to-Poor fen transition .Rapid vertical accumulation .Shrub expansion	Alaska, Scandinavia, Zoige Plateau	Last 100 yr	Gain	<u>Synthesis work</u> : <u>Individual sites</u> : 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
<i>Lower surface moisture</i>	. <i>Sphagnum</i> expansion .Rapid vertical accumulation .Peat loss (decay)	western Canada, Finnish Lapland, European Russia, south Patagonia, Poland	Last 200 yr	Unk.	<u>Synthesis work</u> : <u>Individual sites</u> : 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
<i>Permafrost degradation</i>	.Rapid vertical accumulation .Peat loss (decay)	High boreal and subarctic	Last ~250 yr	Unk.	<u>Synthesis work</u> : Treat & Jones 2018 <u>Individual sites</u> : 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
<i>High fire frequency and intensity</i>	.Peat loss (burnt and smoldering)	boreal region, Indonesia, southern Patagonia	Last 200 yr	Unk.	<u>Synthesis work</u> : Turetsky et al. 2004, 2011; Kasischke & Bruhwiler 2002; van der Werf et al. 2010 <u>Individual sites</u> : 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
<i>Land-use change: clear-cutting, agriculture, forestry, pasture, peat mining, flooding</i>	.Peat loss (decay) .Peat flooding and burial	Finland, Europe, Canada, Congo, Indonesia, south Africa, Poland, New Zealand, south Patagonia	Last 200 yr	Loss	<u>Synthesis work</u> : Houghton 2012; Carlson et al. 2013; Leifeld et al. 2018; Wijedasa et al. 2018; Byun et al. 2018 <u>Individual sites</u> : 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 Obremaska 2010; Gabriel et al. 2017; Hansen et al. 2008; Lamentowicz 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
<i>Atmospheric pollution</i>	. <i>Sphagnum</i> changes	Germany, Poland, Russia, south Patagonia	Last 200 yr	Unk.	<u>Individual sites</u> : Gałka et al. 2019; De Vleeschouwer et al. 2014; Fialkiewicz-Koziel et al. 2016
<i>Nitrogen deposition</i>	.Peat loss (decay) .Rapid vertical accumulation .Vegetation change	eastern Canada, western Canada, Sweden, UK, Europe, south Patagonia	Last ~150 yr	Gain/Loss	<u>Synthesis work</u> : Turunen et al. 2004; Limpens et al. 2011; Kleinbecker et al. 2008 <u>Individual sites</u> : 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)
<i>Temperature</i> (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
<i>Moisture</i> (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	Galka et al. 2015
	5	China	Xing et al. 2015
	6	Southeast Asia	Rieley et al. 2008; Dommain et al. 2014
<i>Moisture</i> (Mid/late Holocene fen-bog shifts)	1	Fennoscandia	Väliranta et al. 2017
	2	South Patagonia	Loisel & Yu, 2013; De Vleeschouwer et al. 2014
<i>Moisture</i> (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
<i>Moisture</i> (Early Holocene flooding)	1	Indonesia	Dommain et al. 2011
<i>Moisture</i> (Mid-Holocene droughts)	1	Mid-continental USA	Booth et al. 2005
	2	Amazon	Swindles et al. 2018
<i>Atmospheric pollution</i> (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
<i>Permafrost</i> (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
<i>Fire</i> (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)
<i>Permafrost</i> (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
<i>Fire</i> (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
<i>Land use</i> (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
<i>Temperature</i> (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
<i>Nitrogen deposition</i>	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
<i>Moisture</i> (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).

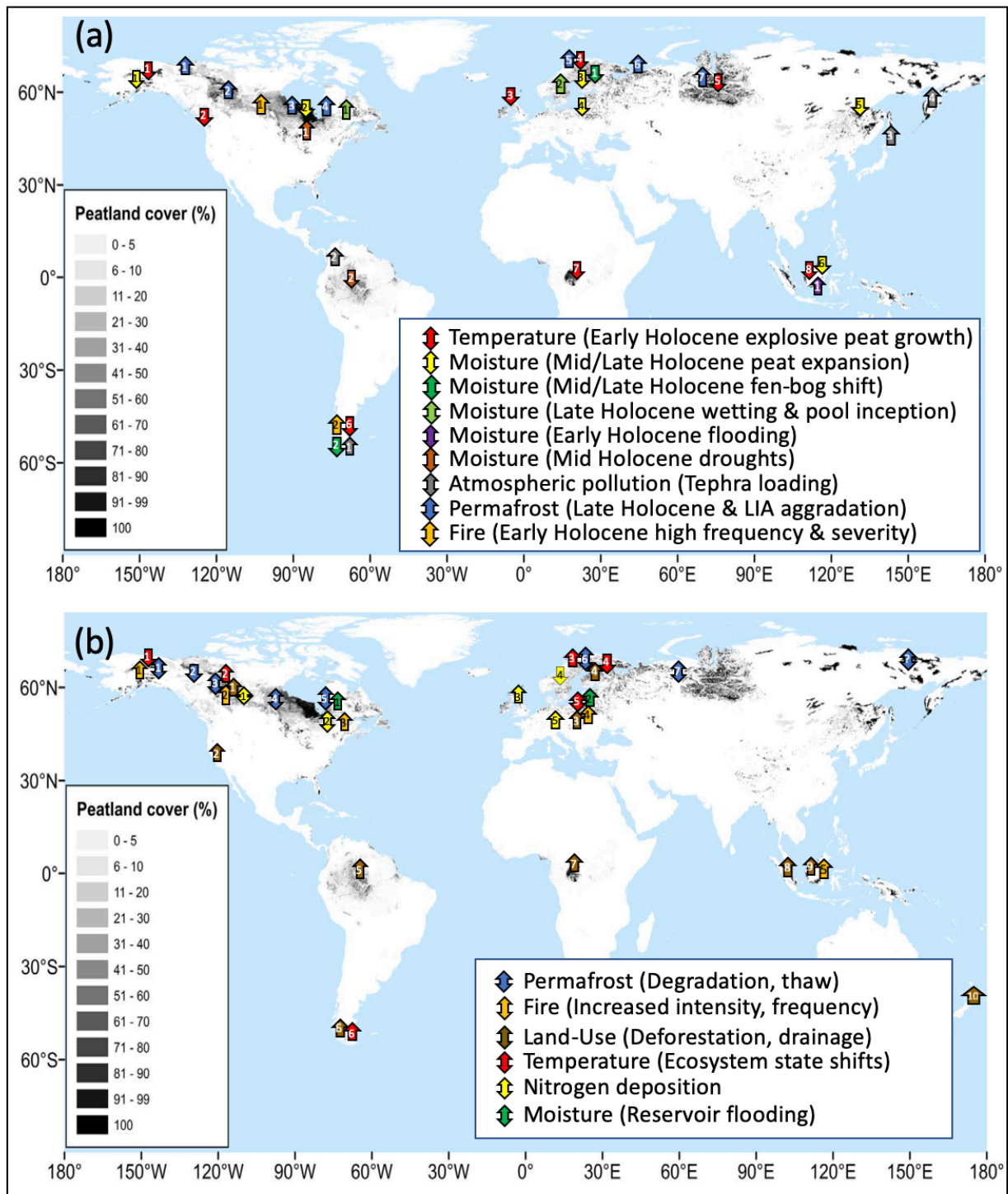


Figure A2.1. The main agents of change responsible for increased (arrows pointing up) or diminished C gains (arrows pointing down) (a) since the post-LGM warming (21ka – 1750 CE), and (b) during the Anthropocene (1750 – 2020 CE). Upward arrows indicate C losses; downward arrows indicate C gains. LIA: 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, silviculture, peat extraction/mining, but also restoration and protection

18. Pollution: includes CO₂ 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

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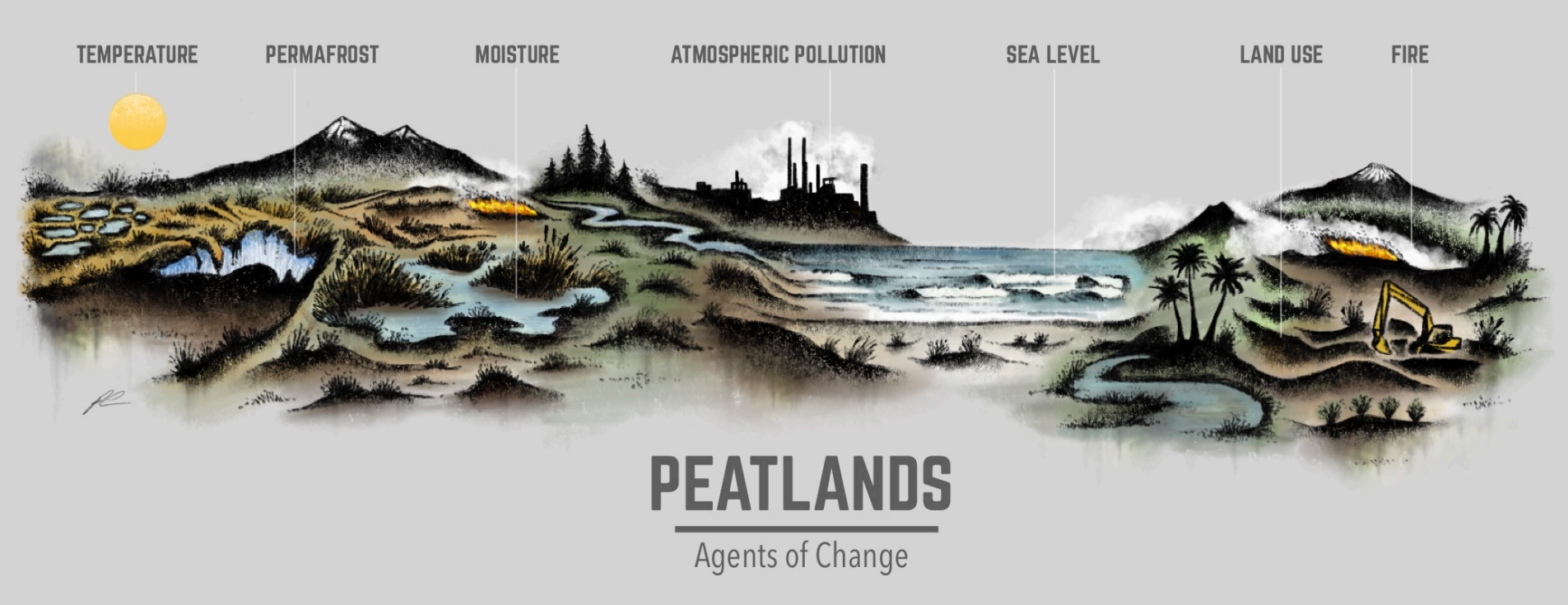
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Appendix 5: Peatland infographic without text and brief review of the main peatland agents of change.



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 regions²⁻⁴, but to enhanced decomposition and carbon loss in the tropics⁵⁻⁶, where growing season length and temperature are not limiting factors for photosynthesis⁷.

Moisture. Water saturation is a key control on oxygen availability in peats and on plant community composition, and thus an important determinant for CO₂ and CH₄ emissions and on net ecosystem C balance in both intact and drained peatlands⁸⁻¹⁰. 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 oxidase¹¹. In the tropical and mid-latitude regions, water table depth is considered the main agent driving long-term peat accumulation¹²⁻¹⁴.

Sea-level. At the regional scale, sea-level rise may either lead to net C losses¹⁵ or net C gains¹⁶. For example, sea-level decline in the tropics¹⁷ and land uplift following deglaciation in the north¹⁸ 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 rates¹⁹⁻²⁰. This process, which took place during the previous interglacial²¹ 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 years²²⁻²³, 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 loss²⁴⁻²⁵. In general, sea-level rise has been suggested to be a threat for coastal peatlands²⁶⁻²⁷, 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 years²⁸. 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 years³¹. 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 regime³³. Peatland surface drying, both as a result of droughts and human activity, has been shown to increase the frequency and extent of peat fires³⁴. Lastly, while peatlands tend to recover from fires, an increase in frequency or intensity could lead to deeper burns and hindered recovery³⁵ as well as peat water repellency³⁶.

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 2010³⁷, 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 2010³⁸. In Finland, approximately 4,500,000 hectares have been drained for forestry, peat extraction, and agriculture since World War II³⁹. These land-use practices lead to immediate ecosystem damage, CO₂ emissions⁴⁰, DOC leaching⁴¹⁻⁴², and land subsidence⁴³. While most peatland management practices result in decreased CH₄ emissions due to drainage, peatland inundation or rewetting can lead to episodic CH₄ releases⁴⁴⁻⁴⁵.

Permafrost. Across the northern high-latitude regions, increasing air temperatures and winter precipitation have been linked to a >50% reduction in tundra or peat plateau area since the late 1950s⁴⁶⁻⁴⁸, although this is variable by region⁴⁹. In general, thermokarst landforms such as ponds or collapse-scar wetlands with saturated soils form when ice-rich peat thaws and collapses. These mainly anaerobic environments are characterized by high CH₄ emissions⁵⁰⁻⁵²; mass-balance accounting for C stocks indicates as much as 25-60% of "old" permafrost C is lost in the years to decades following thaw⁵³⁻⁵⁵. Over time, increased C sequestration and renewed peat accumulation occurs in drained thermokarst lake basins⁵⁶⁻⁵⁷ 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 forcing⁵⁸.

Nitrogen deposition. Increased emissions of nitrogen (N) through agricultural and industrial activities have augmented the rate of atmospheric deposition of ammonium and nitrate⁵⁹ and will continue unless emission controls are enforced⁶⁰. The structure and function of peatlands are now threatened by increased N availability and atmospheric phosphorus (P) deposition⁵⁹. 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 coverage⁶¹⁻⁶³, and that changes in climate can exacerbate these negative effects⁶⁴. Changes in microbial communities and litter quality associated with N deposition can also contribute to increased peat decomposition⁶⁵⁻⁶⁶, along with the lowering of the peatland surface due to faster decomposition⁶⁷ causing a rise in the water table and increased CH₄ emission⁶⁸. Conversely, a study reported C gain with modest N deposition in a Swedish peatland, driven by a greater increase in plant production than in decomposition⁶⁹, illustrating differences, and perhaps a threshold response, in C balance response to N deposition.

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