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Key Points:
- A fluvial blanket peat erosion model was driven by seven GCMs to predict future erosion of Northern Hemisphere blanket peatlands
- Total hemispheric blanket peat erosion rates are likely to increase during 2070–2099 compared with 1961–1990
- Low-latitude and warm blanket peatlands are at most erosion risk from climate change

Supporting Information:
- Supporting Information S1

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Erosion of Northern Hemisphere blanket peatlands under 21st-century climate change

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Abstract Peatlands are important terrestrial carbon stores particularly in the Northern Hemisphere. Many peatlands, such as those in the British Isles, Sweden, and Canada, have undergone increased erosion, resulting in degraded water quality and depleted soil carbon stocks. It is unclear how climate change may impact future peat erosion. Here we use a physically based erosion model (Pan-European Soil Erosion Risk Assessment-PEAT), driven by seven different global climate models (GCMs), to predict fluvial blanket peat erosion in the Northern Hemisphere under 21st-century climate change. After an initial decline, total hemispheric blanket peat erosion rates are found to increase during 2070–2099 (2080s) compared with the baseline period (1961–1990) for most of the GCMs. Regional erosion variability is high with changes to baseline ranging between -1.27 and $+21.63$ t ha^{-1} yr^{-1} in the 2080s. These responses are driven by effects of temperature (generally more dominant) and precipitation change on weathering processes. Low-latitude and warm blanket peatlands are at most risk to fluvial erosion under 21st-century climate change.

1. Introduction

Peatlands are formed via the accumulation of peat, which results from impeded vegetation decomposition under waterlogged conditions [*Charman*, 2002]. Northern Hemisphere peatlands store ~575 Gt of carbon [*Strack*, 2008; *Yu et al.*, 2010]. Blanket peatlands, covering around 105,000 km^2, are precipitation-fed, and often occur under cool, wet climates. Blanket peatlands have a scattered distribution in the Northern Hemisphere (Figure 1) with greatest abundance in hyperoceanic regions such as northwestern Europe, eastern Canada, North American Pacific coast, northeastern coast of Asia, and mountainous regions of central Africa [*Lindsay et al.*, 1988; *Gallego-Sala and Prentice*, 2012]. They often occur on sloping terrain covering hill ridges, slopes, and valley bottoms. They may therefore be more susceptible to fluvial erosion (Figure S1 in the supporting information) than other peatland types which are more typical in very gentle gradient basins. Therefore, blanket peatlands require special attention, particularly when considering the impact of climate change on the stability of the peat sediment store.

Transitions from stable blanket peat systems to degradation can be rapid. Small changes in climate can affect water budgets to the detriment of peat-forming vegetation [*Bragg and Tallis*, 2001], while empirical studies have shown that freeze-thaw and desiccation are important weathering processes in blanket peatlands [*Labadz et al.*, 1991; *Francis*, 1990] which could be sensitive to climate change. As blanket peatlands often occur on sloping terrain [*Charman*, 2002], but tend to have shallow water tables, they are dominated by overland flow that is highly connected across slopes even after small rainfall events [*Holden and Burt*, 2003]. Hence, exposed, weathered peat can be rapidly transported by fluvial processes [*Evans and Warburton*, 2007]. Several meters of peat denudation can occur in only 20 years if both rates of weathering and sediment transport are high (e.g., as reported in *Evans and Lindsay* [2010], *Salvador et al.* [2014], and *Birnie* [1993]) forming badland landscapes (Figure S1). Erosion of blanket peatlands has been widely reported [*Evans and Warburton*, 2007; *Glaser and Janssens*, 1986; *Foster et al.*, 1988; *Parry et al.*, 2014] with major adverse impacts on downstream water quality, aquatic ecology, and physical infrastructure such as reservoirs [*Labadz et al.*, 1991; *Rothwell et al.*, 2005; *Siegel*, 1988].

Bioclimatic modeling at national and global scales suggests that as climate changes during the 21st century, there may be a change in locations suitable for blanket peatlands [*Clark et al.*, 2010; *Gallego-Sala and Prentice*, 2012; *Gallego-Sala et al.*, 2010]. However, it remains unknown whether blanket peatlands will degrade via erosion where climate is no longer favorable for rapid peat formation, or whether they may remain stable.

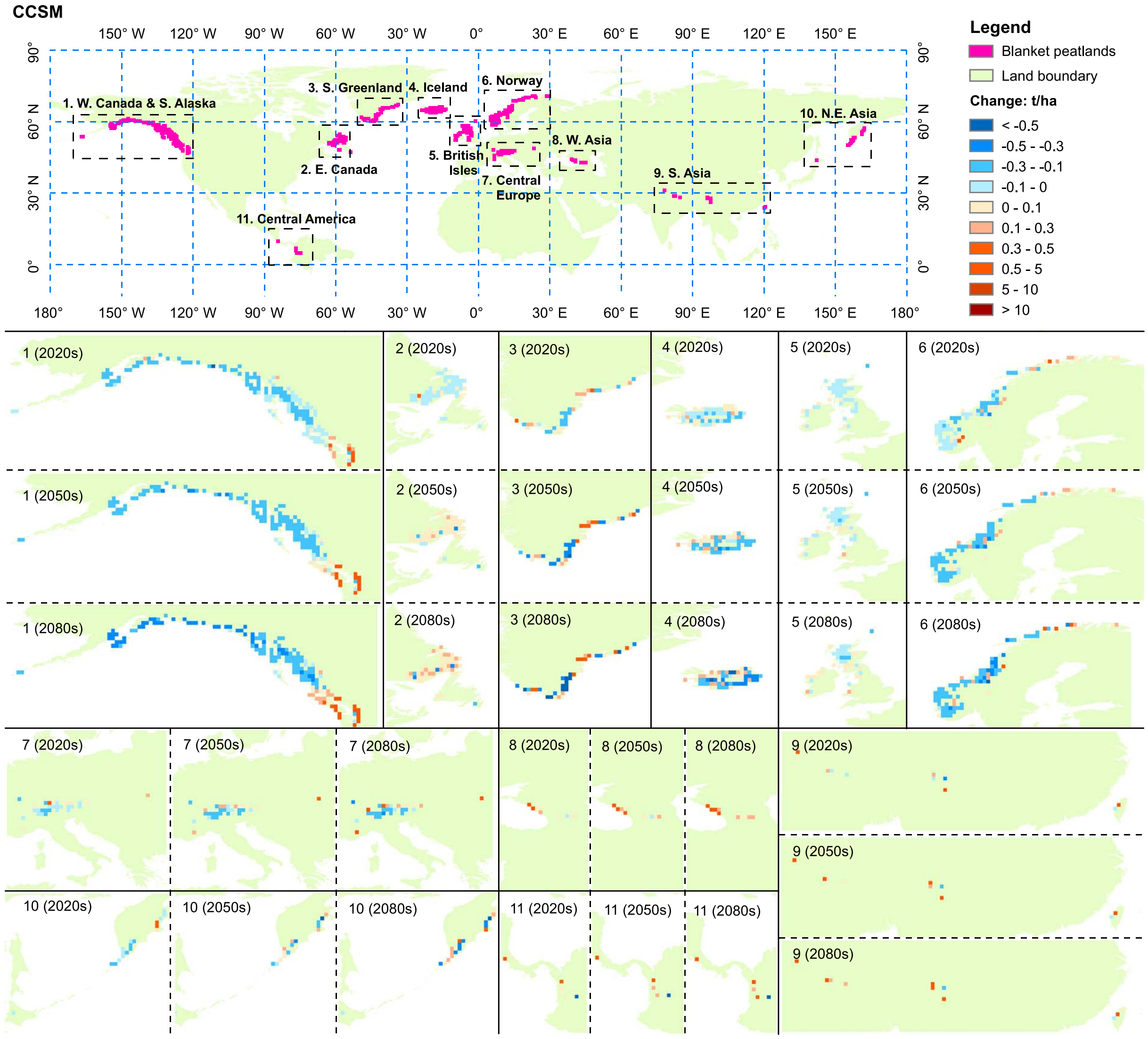

Figure 1. Spatial pattern of changes in mean annual predicted erosion from baseline to future periods under the CCSM model for Northern Hemisphere blanket peatlands. The dashed rectangles outline blanket peat zones. The mapped results for the other six GCMs and predicted baseline erosion are shown in Figure S5.

Some blanket peatland areas may be subject to reduced erosion risk under climate change if climate conditions are less conducive to freeze-thaw or desiccation [*Labadz et al.*, 1991; *Francis*, 1990]. However, there have been no studies to evaluate peatland erosion risk for future climate change scenarios.

In order to understand and map climate change impacts on blanket peat erosion it is essential to model effects and test different scenarios. A fluvial erosion model for blanket peatlands, Pan-European Soil Erosion Risk Assessment (PESERA)-PEAT [*Li et al.*, 2016], was recently developed through modifying PESERA-GRID [*Kirkby et al.*, 2008], to explicitly account for freeze-thaw and desiccation processes in peatlands. The model is sensitive to change in climate (i.e., temperature and precipitation) and vegetation cover [*Li et al.*, 2016]. PESERA-PEAT has, to date, been calibrated and validated in England and Wales [*Li et al.*, 2016], and a lack of measured field runoff and soil erosion data limits the calibration and validation of the model in other blanket peat regions of the Northern Hemisphere, which is where >80% of global blanket peatlands occur [*Gallego-Sala and Prentice*, 2012]. However, the model is theoretically applicable across Northern Hemisphere blanket peatlands because (i) PESERA-GRID was developed to simulate fluvial soil erosion over a large area (e.g., continental or global scales), so parameters and algorithms can deal with different environmental conditions [*Kirkby et al.*, 2008]; (ii) PESERA-PEAT considers both sediment production and transport and links these with climate and ground surface conditions in a transferable, physically based way

[*Li et al.*, 2016]; and (iii) seasonal patterns are aligned in the same hemisphere. We adopted PESERA-PEAT to estimate the temporal and spatial patterns of changes in fluvial erosion risk for Northern Hemisphere blanket peatlands under 21st-century climate change and to examine the climatic driving force of erosion.

2. Methods and Materials

2.1. The PESERA-PEAT Model

PESERA-PEAT was based on PESERA-GRID, heavily modified to ensure suitability for the blanket peatland case (Figure S2). PESERA-GRID is a process-based, spatially distributed, long-term erosion model. The approaches used in PESERA-GRID have been deliberately selected to reduce the impact of scale [*Kirkby et al.*, 2008]. For example, the use of relief has been found to be much less sensitive to digital elevation model (DEM) resolution than gradients.

PESERA-GRID (Figure S2a) has modules of hydrology, vegetation growth, and erosion [*Kirkby et al.*, 2008]. Precipitation is separated into interception, overland flow, evapotranspiration, and changes in soil moisture storage. Overland flow is estimated as proportion of rainfall exceeding a runoff threshold, equaling the soil moisture deficit for blanket peatlands. For actual evapotranspiration, potential evapotranspiration is adjusted by a unitless water use efficiency index and then reduced exponentially at a rate of soil moisture deficit divided by rooting depth, to an actual rate. TOPography-based hydrological MODEL (TOPMODEL) is employed to update the soil moisture deficit every month, and subsurface flow is estimated as the monthly change of soil moisture deficit [*Kirkby et al.*, 2008]. The vegetation growth model primarily estimates gross primary productivity (GPP), soil organic matter, and vegetation cover based on the biomass carbon balance, with leaf fall processes included [*Kirkby et al.*, 2008]. Sediment yield produced by PESERA-GRID represents the erodible material transported to stream channels, while sediment delivery through the river system is not modeled. Sediment yield is estimated as the transporting capacity of overland flow, which is driven by erodibility, overland flow, and local relief, weighted for fractional vegetation cover [*Kirkby et al.*, 2008].

In PESERA-PEAT (Figure S2b) the hydrology and vegetation growth modules are inherited from PESERA-GRID, while sediment yield, unlike that in PESERA-GRID, is a result of the balance between sediment transport and supply [*Li et al.*, 2016]. The transporting capacity of overland flow was derived as in PESERA-GRID. The soil erodibility in PESERA-PEAT represents the erodibility of materials produced by freeze-thaw and desiccation. Sediment supply was parameterized with a sediment supply index, defined as suspended sediment concentration normalized by runoff. The index is negatively related to temperature and water table to account for freeze-thaw and desiccation contributions based on a long-term empirical data set (Table S1 in the supporting information) [*Li et al.*, 2016]. Both sediment transport and supply decrease linearly with vegetation cover [*Li et al.*, 2016]. A storage component was introduced to represent surplus erodible materials when erodible materials exceed transporting capacity. The stored weathered peat was added to erodible materials in subsequent months. The final sediment yield equals either the erodible materials if transporting capacity was more than erodible materials; otherwise, it equals the transporting capacity.

There are two versions of PESERA-PEAT: the time series and equilibrium models [*Li et al.*, 2016]. Here we applied the time series version which considers erosion for every single month over time based on a time series of monthly climatic conditions.

2.2. Preparation of Inputs for PESERA-PEAT

There are limited data on global distributions of blanket peatlands [*Gallego-Sala et al.*, 2010]. Therefore, the area and distribution of blanket peatlands (Figure 1) were defined by the bioclimatic extent predicted by PeatStash [*Gallego-Sala and Prentice*, 2012], calibrated with the global blanket peatland map of *Charman* [2002]. Climate, land cover/management, and topographic and soil information are required by PESERA-PEAT to estimate the spatial pattern and amount of erosion for each month during the study period. Detailed model inputs are provided in Table S2.

Here land cover of blanket peatlands was set to natural vegetation, with the values of relevant parameters being assigned according to *Irvine and Kosmas* [2003]. The topographic input (i.e., local relief) was derived from a global DEM GTOPO30 (https://lta.cr.usgs.gov/GTOPO30) developed by U.S. Geological Survey (USGS). Soil parameters were set with values suggested by *Kirkby et al.* [2008] and *Irvine and Kosmas* [2003]. The erodibility of fresh peat is estimated to be 1.16 mm by using the pedo-transfer function of

Irvine and Kosmas [2003]. The erodibility of weathered peat was demonstrated to be 2–3 times that of intact peat [*Mulqueen et al.*, 2006] and was therefore set to 2.5 mm.

PESERA-PEAT was operated with baseline (1961–1990) and future (2010–2099) climate. Baseline climate was extracted from the gridded time series data set of the Climate Research Unit (CRU TS 3.0), University of East Anglia, UK (http://www.cru.uea.ac.uk/cru/data/hrg/). Climate projections for 2010–2099 were derived, as part of the QUEST-GSI initiative, from the outputs of seven global climate models (GCMs) under the A1B carbon emission scenario (http://www.cru.uea.ac.uk/~timo/climgen/data/questgsi/) including Coupled Global Climate Model version 3 (CGCM3), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Institut Pierre-Simon Laplace (IPSL), European Centre/Hamburg version 5 (ECHAM5), Community Climate System Model (CCSM), Hadley Centre Coupled Model version 3 (HadCM3), and Hadley Centre Global Environmental Model version 1 (HadGEM1) (Table S3). The climate scenarios were produced by a spatial generator, ClimGen [*Todd et al.*, 2011], based on a pattern-scaling approach [*Mitchell*, 2003] for a given global-mean temperature change.

2.3. Analysis of Modeling Results

The impact of climate change on blanket peat erosion was examined through comparing baseline modeling results with modeled erosion driven by outputs of the seven GCMs. During the analysis, future time (2010–2099) was separated into three periods which are 2010–2039 (2020s), 2040–2069 (2050s), and 2070–2099 (2080s). There were seven outputs of modeled erosion (driven by the seven GCMs) for each future time period (2020s, 2050s, and 2080s), providing simulated responses of blanket peat erosion for a range of climate uncertainties.

3. Results

In the baseline period, fluvial blanket peat erosion was relatively low, while between 2010 and 2099, fluvial blanket peat erosion increases rapidly for several GCMs such as HadCM3 and HadGEM1 (Figure 2a). The mean annual baseline erosion for Northern Hemisphere blanket peatlands was estimated as 1.41 t ha^{-1}. For future periods, the mean annual fluvial blanket peat erosion was predicted to be 1.38–1.45 t ha^{-1}, 1.37–1.61 t ha^{-1}, and 1.39–1.82 t ha^{-1} for 2020s, 2050s, and 2080s, respectively, under the seven GCMs. The range of predicted erosion changes since the baseline period under the GCMs becomes greater from the 2020s to the 2080s (Figure 2b). Two, four, and four out of seven GCMs for 2020s, 2050s, and 2080s, respectively, show, when used in PESERA-PEAT, increased erosion for the hemisphere as a whole compared to that for the baseline period. Taking each of the seven GCMs as being equally plausible, these results suggest that average fluvial blanket peat erosion for the 2050s and 2080s is more likely to be higher than that for the baseline period, while for 2020s a mean fluvial blanket peat erosion rate lower than the baseline value is more likely.

Mean baseline annual erosion for blanket peatlands ranged between 0.11 t ha^{-1} and 20.86 t ha^{-1}, with between 0.10 t ha^{-1} and 34.8 t ha^{-1} for future periods (Figure S3). The ranges of change in mean annual fluvial erosion for the 2020s, 2050s, and 2080s were found to be −1.02 to +6.82 t ha^{-1}, −1.33 to +14.09 t ha^{-1}, and −1.27 to +21.63 t ha^{-1} (Figure S4). Both predicted erosion rates and their change from baseline to future periods are spatially variable, generally declining from the equator to high latitudes (Figures S3 and S4). The mean annual fluvial erosion rates of Western Asia (Zone 8), Southern Asia (Zone 9), and Central America (Zone 11) were predicted to be 2.24–11.04 t ha^{-1}, 3.61–8.6 t ha^{-1}, and 6.11–12.7 t ha^{-1}, respectively, which are systematically higher than those of other blanket peat zones, where erosion rates seldom exceeded 2.0 t ha^{-1} (Figure 3a). From baseline to future periods, predicted erosion increases were found for Zones 8, 9, and 11 under all seven GCMs, while for other blanket peatland zones decreased erosion rates were often found (Figure 3b).

Regions with elevated erosion from baseline increased over time under the seven GCMs (Figure S4), accounting for 23.5%–35.0%, 31.1%–43.7%, and 32.8%–46.6% of the total blanket peat-covered area in the 2020s, 2050s, and 2080s, respectively. These areas were mainly concentrated in Western Canada and Southern Alaska (Zone 1), Eastern Canada (Zone 2), Western Asia, (Zone 8), Southern Asia (Zone 9), and Central America (Zone 11) (Figure S5). Enhanced erosion areas were also scattered within other blanket peatland zones.

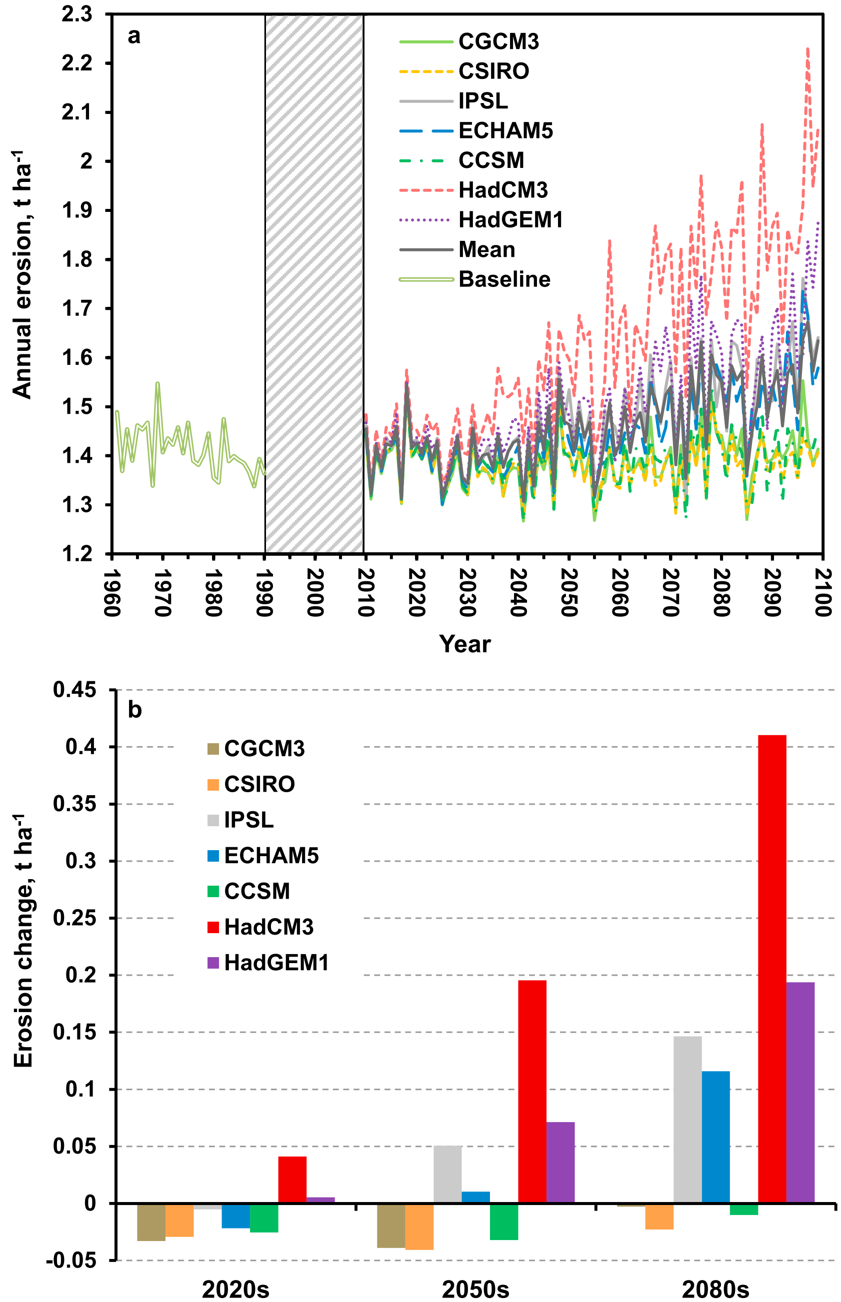

Figure 2. Temporal patterns of predicted blanket peat erosion: (a) time series of predicted annual erosion averaged over all studied blanket peatlands and (b) changes of predicted mean annual erosion from the baseline to future periods.

We found extremely high variability in monthly sediment yield from blanket peatlands (Figure S6) with large peaks in those wet months that followed a sequence of dry months during which loosened sediment accumulated. However, the overall pattern of erosion change for blanket peatlands was more dominated by temperature variation than precipitation variation (Figure 4). Modeled erosion mainly increased with elevated temperature or decreased precipitation, and peaked at 1.82 t ha^{-1} under the warmest and moderately wet condition.

The roles that precipitation and temperature played in blanket peat erosion were different among blanket peatland zones (Figure 4). For blanket peatlands of Southern Greenland (Zone 3), Iceland (Zone 4), Central Europe (Zone 7), Western Asia (Zone 8), Southern Asia (Zone 9), and Central America (Zone 11) the pattern

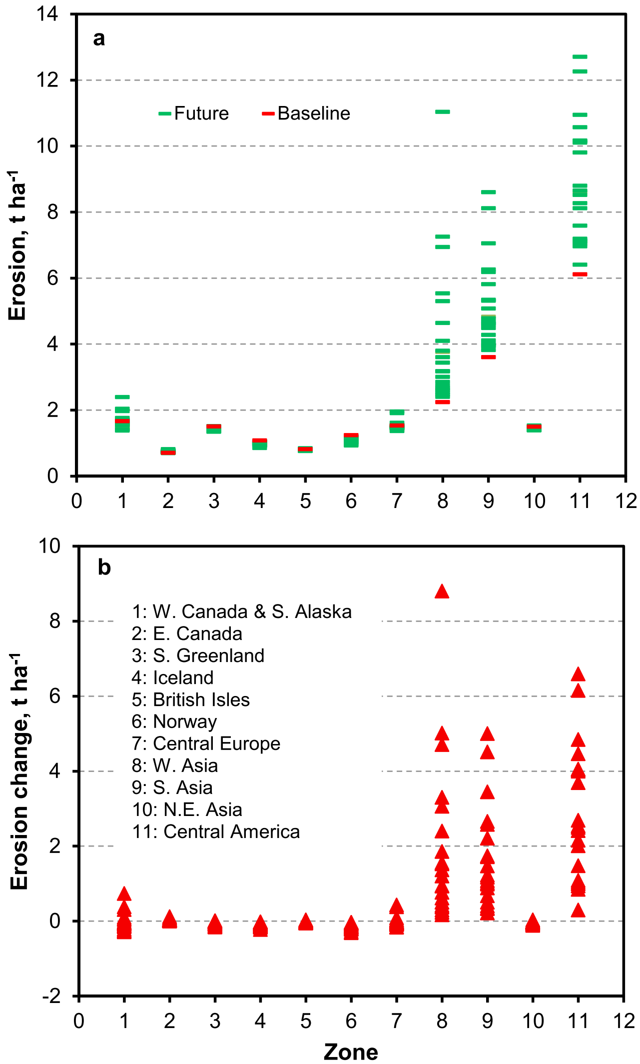

Figure 3. Predicted erosion rates and changes for the eleven blanket peat zones: (a) fluvial blanket peat erosion for the baseline and future periods and (b) erosion change from the baseline to future periods.

of erosion change was predicted to be dominated by temperature change. The predicted mean annual fluvial erosion decreased with elevated temperature and peaked at 1.51 t ha^{-1} and 1.08 t ha^{-1}, respectively, under coldest conditions in Zones 3 and 4. In Zone 7 mean annual erosion was predicted to increase under climate warming when precipitation was relatively low ($<$1450 mm) and decrease with elevated temperature when precipitation was high ($>$1450 mm), peaking at 1.24 t ha^{-1} under the warmest condition. In Zones 8 and 9 predicted mean annual erosion increased with climate warming and peaked at 11.04 t ha^{-1} and 8.60 t ha^{-1}, respectively, under the warmest condition. The mean annual erosion for Zone 11 generally increased with temperature. However, predicted erosion increased with decreased precipitation under dry conditions. As a result, the predicted mean annual erosion of Zone 11 had two peaks, which were 12.70 t ha^{-1} under the warmest and wettest condition and 12.26 t ha^{-1} under the driest condition.

For blanket peatlands of Western Canada and Southern Alaska (Zone 1), British Isles (Zone 5), and Norway (Zone 6), erosion change was driven by temperature and precipitation. The mean annual erosion for Zone 1 increased with increased temperature and precipitation, peaking at 2.4 t ha^{-1} under the moderately warm and wet climate condition, and then decreased as precipitation further increased. The mean annual fluvial erosion for Zone 5 increased with increased temperature and decreased precipitation, peaking at 0.84 t ha^{-1} under the warmest and moderately dry condition. The mean annual fluvial erosion for Zone 6 was found to peak at 1.24 t ha^{-1} under the warmest and driest condition and then decrease with increased temperature and precipitation.

For Eastern Canada (Zone 2) the modeled mean annual fluvial erosion mainly increased with precipitation and peaked at 0.82 t ha^{-1} under the wettest and moderately warm condition. The predicted mean annual fluvial erosion for Northeastern Asia (Zone 10) was found to peak at 1.53 t ha^{-1} under the moderately warm and wet condition, and the impact of temperature and precipitation on erosion change showed a complicated pattern.

4. Discussion

The total predicted fluvial blanket peat erosion to the end of the 21st century for the Northern Hemisphere increased under four GCMs, while it declined under the other three. Under GCMs with higher temperature projections such as HadCM3, HadGEM1, IPSL, and ECHAM5 (Figure S7), although precipitation increases

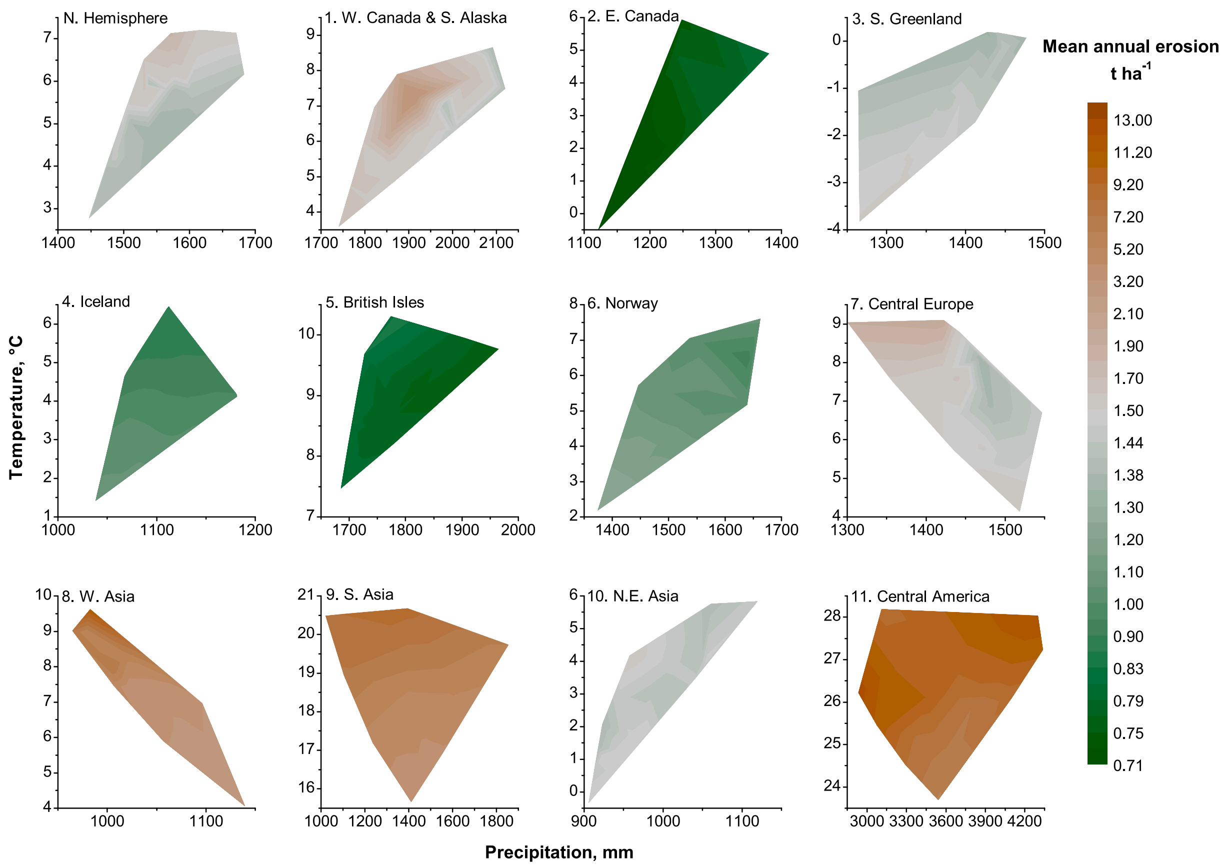

Figure 4. Predicted mean annual erosion against mean annual temperature and precipitation for the all Northern Hemisphere blanket peatlands and the 11 blanket peatland zones. The predicted time series of monthly erosion for each of the seven GCMs was assessed for 2020s, 2050s, and 2080s, plus the baseline condition, yielding 22 data sets of mean annual erosion.

(Figure S8) the greater rate of climate warming encourages evapotranspiration and eventually enhances desiccation at both high and low latitudes in the future. Enhanced desiccation offsets the impact of reduced future freeze-thaw at higher latitudes. However, for the other GCMs, CGCM3, CSIRO, and CCSM, the increase of desiccation in a warmer climate (Figures S7 and S8) is not great enough to offset the decrease of peat erosion caused by weakened freeze-thaw and enhanced precipitation (which reduces desiccation).

We found changes in peat erosion from the baseline period decreased from the equator toward higher-latitude regions. This may be because for low-latitude areas such as Zones 9 and 11 the relatively warm climate (Figures S7 and S9) leads to high evapotranspiration, suppressing water tables, and producing erodible materials via desiccation [*Francis*, 1990; *Li et al.*, 2016]. However, for high-latitude blanket peatlands, warming of a relatively cool climate (Figures S7 and S9) means freeze-thaw becomes less dominant in sediment production [*Evans and Warburton*, 2007; *Labadz et al.*, 1991; *Li et al.*, 2016]. More precipitation may elevate water tables and weaken desiccation effects. Hence, future reductions in peat erosion are expected in high latitudes due to weakened freeze-thaw and desiccation. For mid-latitude blanket peatlands (Central Europe (Zone 7) and Western Asia (Zone 8)) there is a similar pattern of predicted climate change (i.e., warmer and drier future climate; Figure S8), but Zone 8 has higher predicted erosion increases than Zone 7. Zone 7 currently has considerably higher precipitation, which is conducive to active peat growth and makes blanket peatlands more resilient to climate change [*Charman*, 2002; *Gallego-Sala and Prentice*, 2012].

Predicted general spatial patterns of change and absolute values of peat erosion under future climate change are consistent with findings of previous studies for peatlands [e.g., *Gignac et al.*, 1998; *Clark et al.*, 2010; *Gallego-Sala et al.*, 2010]. A model-based study has suggested that peatlands in Western Canada may "migrate" northward as a result of elevated temperatures and drought [*Gignac et al.*, 1998]. Bioclimatic modeling for the British Isles demonstrated a retreat of bioclimatic space suitable for blanket peatlands toward the north and west [*Clark et al.*, 2010; *Gallego-Sala et al.*, 2010]. Our results confirmed that with future climate change, blanket peatlands outside their suitable bioclimatic space would be subject to more erosion. However, high-latitude peatlands demonstrate some resilience, so shrinkage of areas suitable for active peat growth does not necessarily entail net loss of peat through fluvial erosion in all locations.

Our results demonstrate that blanket peat erosion was generally more sensitive to temperature than precipitation change. This is important since enhanced precipitation is traditionally thought to be one of the most important drivers of fluvial soil erosion [*Yang et al.*, 2003]. We found increased fluvial erosion for places with reduced precipitation (e.g., Western Canada and Southern Alaska and British Isles and Norway) which emphasises the need for wet conditions to conserve blanket peatlands [*Parry et al.*, 2014]. However, we did find for some blanket peatlands of Eastern Canada (Zone 2) and Central America (Zone 11) that erosion increases under wetter conditions (Figure 4). Blanket peat erosion is usually supply-limited (Figure S6) [*Carling et al.*, 1997; *Mulqueen et al.*, 2006]. However, for Zones 2 and 11, as previously demonstrated for some blanket peatlands [*Francis*, 1990; *Evans and Warburton*, 2007; *Li et al.*, 2016], it may be that the system crosses a future threshold and becomes transport-limited due to a plentiful availability of weathered peat.

In some places, erosion risk may be affected by human management interventions, but these have not been modeled herein. Most commonly, these interventions (e.g., drainage and overgrazing, pollution) have damaged peat-forming vegetation and degraded peatlands [*Holden et al.*, 2007]. Thus, some of our modeled estimates of erosion rates may be conservative in those areas. Peatlands may be more sensitive to management interventions during times of rapid climate change [*Bragg and Tallis*, 2001] so blanket peatland management now urgently needs to focus on maximising surface vegetation cover [*Brown et al.*, 2015] and increasing wetness (e.g., by bunding ditches) to reduce the dominance of desiccation-driven erosion at lower latitudes. At higher latitudes, the focus should be on actively encouraging revegetation of bare peat to reduce the connectivity between sediment sources and stream channels.

We did not estimate carbon budgets for blanket peatlands, but blanket peat river water dry sediment has typically been reported to be ~50% carbon by mass [*Pawson et al.*, 2008; *Worrall et al.*, 2003]. Therefore, it is possible to use our data as a proxy for future particulate carbon losses. Such fluvial carbon loss from low-latitude blanket peatlands under climate change may contribute a positive feedback because recent studies have shown that peat-derived organic carbon can be rapidly converted in the fluvial system and lost to the atmosphere [*Evans et al.*, 2015; *Goulsbra et al.*, 2015; *Evans and Thomas*, 2016; *Palmer et al.*, 2016]. However, reduced erosion in high-latitude blanket peatlands may also coincide with additional carbon sequestration in some regions related to enhanced GPP [*Charman et al.*, 2013]. Combined, these factors may result in a positive shift of the net carbon budget for high-latitude blanket peatlands. For net blanket peat erosion across the Northern Hemisphere toward the end of the 21st century, the balance between changes at high and low latitudes varied by GCM which demonstrates how critical it is to improve GCM forecasts and reduce uncertainty for the late 21st century

In addition to reducing GCM uncertainty, our results could be improved by collection of peat erosion data, as part of new long-term erosion monitoring programmes, from more Northern Hemisphere sites. Inclusion of spatial management data would enable relative roles of climate change and land management interventions to be tested [*Li et al.*, 2017]. The vegetation growth module in PESERA-PEAT appears to work well for British blanket peatlands [*Li et al.*, 2016], but further work is required to further test and potentially adjust the vegetation growth model for other regions particularly because bryophyte GPP, hydrology, and litter production processes can be different to those that operate for vascular plants [*Riutta et al.*, 2007].

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References

Birnie, R. V. (1993), Erosion rates on bare peat surfaces in Shetland, *Scottish Geogr. Mag.*, *109*(1), 12–17, doi:10.1080/00369229318736871.

Bragg, O., and J. Tallis (2001), The sensitivity of peat-covered upland landscapes, *Catena*, *42*(2–4), 345–360, doi:10.1016/S0341-8162(00)00146-6.

Brown, L. E., S. M. Palmer, C. Wearing, K. Johnston, and J. Holden (2015), Vegetation management with fire modifies peatland soil thermal regime, *J. Environ. Manage.*, *154*, 166–176, doi:10.1016/j.jenvman.2015.02.037.

Carling, P. A., M. S. Glaister, and T. P. Flintham (1997), The erodibility of upland soils and the design of preafforestation drainage networks in the United Kingdom, *Hydrol. Processes*, *11*(15), 1963–1980, doi:10.1002/(SICI)1099-1085(199712)11:15<1963::AID-HYP542>3.0.CO;2-M.

Charman, D. (2002), *Peatlands and Environmental Change*, Wiley, Chichester, U. K.

Charman, D. J., D. W. Beilman, S. T. Jackson, A. Korhola, D. Mauquoy, F. J. Mitchell, I. C. Prentice, L. M. van der Linden, F. de Vieeschouwer, and Z. C. Yu (2013), Climate-related changes in peatland carbon accumulation during the last millennium, *Biogeosciences*, *10*, 929–944, doi:10.5194/bgd-9-14327-2012.

Clark, J., A. Gallego-Sala, A. Allott, and S. Chapman (2010), Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models, *Clim. Res.*, *10*(45), 131–150, doi:10.3354/cr00929.

Evans, C. D., and D. N. Thomas (2016), Controls on the processing and fate of terrestrially-derived organic carbon in aquatic ecosystems: Synthesis of special issue, *Aquat. Sci.*, *78*(3), 415–418, doi:10.1007/s00027-016-0470-7.

Evans, C. D., F. Renou-Wilson, and M. Strack (2015), The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands, *Aquat. Sci.*, *78*(3), 1–18, doi:10.1007/s00027-015-0447-y.

Evans, M., and J. Lindsay (2010), High resolution quantification of gully erosion in upland peatlands at the landscape scale, *Earth Surf. Processes Landforms*, *35*(8), 876–886, doi:10.1002/esp.1918.

Evans, M., and J. Warburton (2007), *Geomorphology of Upland Peat: Erosion, Form and Landscape Change*, Blackwell Publishing Ltd, Oxford.

Foster, D., H. Wright, M. Thelaus, and G. King (1988), Bog development and landform dynamics in central Sweden and south-eastern Labrador, Canada, *J. Ecol.*, *76*(4), 1164–1185, doi:10.2307/2260641.

Francis, I. S. (1990), Blanket peat erosion in a Mid-Wales catchment during two drought years, *Earth Surf. Processes Landforms*, *15*(5), 445–456, doi:10.1002/esp.3290150507.

Gallego-Sala, A. V., and I. C. Prentice (2012), Blanket peat biome endangered by climate change, *Nat. Clim. Change*, *3*, 152–155, doi:10.1038/nclimate1672.

Gallego-Sala, A. V., J. M. Clark, J. I. House, H. G. Orr, I. C. Prentice, P. Smith, T. Farewell, and S. J. Chapman (2010), Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain, *Clim. Res.*, *45*(1), 151–162, doi:10.3354/cr00911.

Gignac, L., B. Nicholson, and S. Bayley (1998), The utilization of bryophytes in bioclimatic modelling: Predicted northward migration of peatlands in the Mackenzie River Basin, Canada, as a result of global warming, *Bryologist*, *101*(4), 572–587, doi:10.2307/3244531.

Glaser, P. H., and J. A. Janssens (1986), Raised bogs in eastern North America: Transitions in landforms and gross stratigraphy, *Can. J. Bot.*, *64*(2), 395–415, doi:10.1139/b86-056.

Goulsbra, C. S., M. G. Evans, and T. E. Allott (2015), Rates of CO_2 efflux and changes in DOC concentration resulting from the addition of POC to the fluvial system in peatlands, *Aquat. Sci.*, *78*(3), 1–13, doi:10.1007/s00027-016-0471-6.

Holden, J., and T. P. Burt (2003), Runoff production in blanket peat covered catchments, *Water Resour. Res.*, *39*(7), 1191, doi:10.1029/2002WR001956

Holden, J., L. Shotbolt, A. Bonn, P. J. Chapman, A. J. Dougill, E. D. G. Fraser, K. Hubacek, B. Irvine, and M. Kirkby (2007), Environmental change in moorland landscapes, *Earth Sci. Rev.*, *82*(1), 75–100, doi:10.1016/j.earscirev.2007.01.003.

Irvine, B., and C. Kosmas (2003), *Pan-Europe Soil Erosion Risk Assessment*, Univ. of Leeds, U. K.

Kirkby, M., B. Irvine, R. Jones, and G. Govers (2008), The PESERA coarse scale erosion model for Europe. I. Model rationale and implementation, *Eur. J. Soil Sci.*, *59*(6), 1293–1306, doi:10.1111/j.1365-2389.2008.01072.x.

Labadz, J., T. Burt, and A. Potter (1991), Sediment yield and delivery in the blanket peat moorlands of the Southern Pennines, *Earth Surf. Processes Landforms*, *16*(3), 255–271, doi:10.1002/esp.3290160306.

Li, P., J. Holden, B. Irvine, and R. Grayson (2016), PESERA-PEAT: A fluvial erosion model for blanket peatlands, *Earth Surf. Processes Landforms*, *41*(14), 2058–2077, doi:10.1002/esp.3972.

Li, P., B. Irvine, J. Holden, and X. Mu (2017), Spatial variability of fluvial blanket peat erosion rates for the 21st Century modelled using PESERA-PEAT, *Catena*, *150*, 302–316, doi:10.1016/j.catena.2016.11.025.

Lindsay, R., D. J. Charman, F. Everingham, R. M. O'reilly, M. A. Palmer, T. A. Rothwell, and D. A. Stroud (1988), *The Flow Country: The Peatlands of Caithness and Sutherland*, Joint Nature Conservation Committee, Peterborough, U. K.

Mitchell, T. D. (2003), Pattern scaling: An examination of the accuracy of the technique for describing future climates, *Clim. Change*, *60*(3), 217–242, doi:10.1023/A:1026035305597.

Mulqueen, J., M. Rodgers, N. Marren, and M. Healy (2006), Erodibility of hill peat, *Irish J. Agr. Food. Res.*, *45*(2), 103–114.

Palmer, S. M., C. D. Evans, P. J. Chapman, A. Burden, T. G. Jones, T. E. H. Allott, M. G. Evans, C. S. Moody, F. Worrall, and J. Holden (2016), Sporadic hotspots for physico-chemical retention of aquatic organic carbon: From peatland headwater source to sea, *Aquat. Sci.*, *78*(3), 491–504, doi:10.1007/s00027-015-0448-x.

Parry, L. E., J. Holden, and P. J. Chapman (2014), Restoration of blanket peatlands, *J. Environ. Manage.*, *133*, 193–205, doi:10.1016/j.jenvman.2013.11.033.

Pawson, R., D. R. Lord, M. Evans, and T. Allott (2008), Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK, *Hydrol. Earth Syst. Sci.*, *12*, 625–634, doi:10.5194/hess-12-625-2008.

Riutta, T., J. Laine, and E.-S. Tuittila (2007), Sensitivity of CO_2 exchange of fen ecosystem components to water level variation, *Ecosystems*, *10*(5), 718–733, doi:10.1007/s10021-007-9046-7.

Rothwell, J. J., S. G. Robinson, M. G. Evans, J. Yang, and T. E. H. Allott (2005), Heavy metal release by peat erosion in the Peak District, southern Pennines, UK, *Hydrol. Processes*, *19*(15), 2973–2989, doi:10.1002/hyp.5811.

Salvador, F., J. Monerris, and L. Rochefort (2014), Peatlands of the Peruvian Puna ecoregion: Types, characteristics and disturbance, *Mires Peat*, *15*(3), 1–17.

Siegel, D. I. (1988), Evaluating cumulative effects of disturbance on the hydrologic function of bogs, fens, and mires, *Environ. Manage.*, *12*(5), 621–626, doi:10.1007/BF01867540.

Strack, M. (2008), *Peatlands and Climate Change*, Int. Peat Soc., Vapaudenkatu.

Todd, M. C., R. G. Taylor, T. J. Osborn, D. G. Kingston, N. W. Arnell, and S. N. Gosling (2011), Uncertainty in climate change impacts on basin-scale freshwater resources–preface to the special issue: The QUEST-GSI methodology and synthesis of results, *Hydrol. Earth Syst. Sci.*, *15*, 1035–1046, doi:10.5194/hess-15-1035-2011.

Worrall, F., M. Reed, J. Warburton, and T. P. Burt (2003), Carbon budget for a British upland peat catchment, *Sci. Total Environ.*, *312*(1–3), 133–146, doi:10.1016/S0048-9697(03)00226-2.

Yang, D., S. Kanae, T. Oki, T. Koike, and K. Musiake (2003), Global potential soil erosion with reference to land use and climate changes, *Hydrol. Processes*, *17*, 2913–2928, doi:10.1002/hyp.1441.

Yu, Z., J. Loisel, D. P. Brosseau, D. W. Beilman, and S. J. Hunt (2010), Global peatland dynamics since the Last Glacial Maximum, *Geophys. Res. Lett.*, *37*, L13402, doi:10.1029/2010GL043584.