**Blanket bog, an endangered biome**

Angela V. Gallego-Sala1,2,3\*, I. Colin Prentice1,4,5

1QUEST, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol, BS8 1RJ, UK.

2Department of Earth and Ecosystem Sciences, Division of Physical Geography and Ecosystems Analysis, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sweden.

3Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK

4Department of Biological Sciences, Macquarie University, North Ryde, NSW 2109, Australia.

5Grantham Institute for Climate Change and Division of Ecology and Evolution, Imperial College, Silwood Park, Ascot, Berks SL5 7PY, UK.

\*Corresponding author: A.Gallego-Sala@exeter.ac.uk

**Blanket bog is a highly distinctive biome restricted to disjunct hyperoceanic regions. It is characterized by a landscape covering of peat broken only by the steepest slopes**[**1**](#_ENREF_1)**. Plant and microbial life are adapted to anoxia, low pH and low nutrient availability. Plant productivity exceeds soil organic matter decomposition so carbon is sequestered over time. Unique climatic requirements, including high year-round rainfall and low summer temperatures**[**2**](#_ENREF_2)**, make this biome amenable to bioclimatic modelling. But projections of the fate of peatlands in general, and blanket bogs in particular, under climate change have been contradictory**[**3-7**](#_ENREF_3)**. Here we use a simple, well-founded global bioclimatic model**[**8**](#_ENREF_8)**, with climate-change projections from seven climate models, to indicate this biome’s fate. We show dramatic shrinkage of its present bioclimatic space with only a few, restricted areas of persistence. Many blanket bog regions are thus at risk of progressive peat erosion and vegetation changes as a direct consequence of climate change. New areas suitable for blanket bog are also projected, but are often disjunct from present areas and their location inconsistently predicted by different climate models.**

Blanket bogs (Supplementary Figure 1) are found almost exclusively in the high-latitude, oceanic fringes of the continents and on subpolar islands[1](#_ENREF_1). In Europe they occur in Iceland, Ireland, Great Britain, coastal Norway (*terrengdekkende myr)* and Faroe Islands. In North America they occur in parts of Nova Scotia, Quebec, southern Labrador and Newfoundland and near the Pacific coast of Alaska. In South America they are widespread on the Falkland Islands and in Patagonia (*turberas magallanicas* or *turberas de cobertura*) and in the Paramos of Ecuador and Colombia. They are found in Asia on Kamchatka and Hokkaido and in Australasia at high elevations in New Guinea (hard-cushion bogs), western Tasmania (button-grass moorlands) and New Zealand (*pakihi* or cushion bogs), although these have been described as “incipient” blanket bogs. Another type of blanket bog, also called orogenic blanket bog or condensation mire, occurs in certain high elevation wet areas of the Alps in Central Europe, the Ruwenzori Mountains in Uganda. Wherever they occur, blanket bogs are treeless peatlands dominated by hummock- or cushion-forming vascular plants, typically with an understorey of *Sphagnum* and other bryophytes[9](#_ENREF_9). They present a distinctive surface pattern that can vary from slight cushioning to a full microtope zonation consisting of wet pools or hollows, lawns, and drier hummocks. Deer grass (*Trichophorum cespitosum*), and cotton grass (*Eriophorum* spp.) impart to the blanket bogs of Britain their typical hummocky appearance, while purple moor grass (*Molinia caerulea*) and black bog rush *(Schoenus nigricans*) are common in Ireland[10](#_ENREF_10). These species are also found in blanket bogs in Norway and along the eastern Canadian coast, Newfoundland and coastal Alaska, together with labrador tea (*Ledum groenlandicum*), bog laurel (*Kalmia* spp.) and crowberry (*Empetrum nigrum*)[11](#_ENREF_11). Other cushion-forming species, such as asterid (*Donatia fascicularis),* oreob (*Oreobolus obtusangulus*) and astelia (*Astelia pumila)* dominate blanket bog in Patagonia[12](#_ENREF_12). A different asterid (Donatia novae-zelandiae) and a restionaceous sedge *(*Calorophus minor) are typical of blanket bog in New Zealand while buttongrass (Gymnoschoenus sphaerocephalus) is representative for blanket bog in Tasmania[13](#_ENREF_13).

Blanket bog is a waterlogged and unproductive environment, but a haven for wildlife nonetheless, providing shelter to birds, small mammals, amphibians and reptiles. Within this ecosystem, there is also a great diversity of microbial metabolic processes adapted to anoxia and low nutrients, including syntropic or homoacetogenic bacteria, and hydrogenotrophic methanogenic archaea18.

Blanket bogs are sensitive to climate because their existence depends on a permanently high water table[7](#_ENREF_7) and because the characteristic *Sphagnum* spp. rapidly suffer damage at temperatures > 15˚C[3](#_ENREF_3). Bioclimatic models have been used to model the regional extent of different peatland types[14-16](#_ENREF_14), but to our knowledge no global model for blanket bog distribution was published before Gallego-Sala *et al.* (2010)[8](#_ENREF_8). Other models of wetland distribution based on the topographic index have been used recently to predict the global distribution of peatlands in general[17](#_ENREF_17),[18](#_ENREF_18) but do not distinguish blanket bog.

PeatStash[8](#_ENREF_8) is an extremely simple, yet process-oriented, model. It is not a statistical “niche model”. Instead it defines independent limit values for three bioclimatic variables, each representing a different controlling process. The blanket bog distribution map compiled in ref. 1 was used to calibrate the limit values for the climatic moisture index (see Methods) (MI > 2.1), mean annual temperature (MAT > −1˚C) and mean temperature of the warmest month (MTWA < 14.5 ˚C), resulting in the global distribution shown in Figure 1. These variables stand for year-round moisture (required to maintain the water table), absence of permafrost (avoiding cryoturbation and ice-wedge formation, which are responsible for quite different peatland morphologies in very cold climates), and avoidance of high temperatures (damaging to *Sphagnum*). When forced by a high-resolution climate data set, the model closely reproduces the distribution of blanket bog in Great Britain[8](#_ENREF_8), which is much more accurately known than the global distribution. Sensitivity analysis underlines the vulnerability of the blanket bog climate space to increases in temperature above all (Figure 2), but also to reductions in precipitation - in agreement with independent statistical modelling[16](#_ENREF_16),[19](#_ENREF_19) - and to a lesser extent to reductions in cloudiness. Note that the model describes controls on the *occurrence* of blanket bog; it does not make predictions about peat accumulation rates. These behave in a substantially different way, responding positively to warming and negatively to cloudiness[20](#_ENREF_20).

The model predicts the known occurrence areas of blanket bog. It also suggests that climatically, blanket bogs could exist near the Northwestern Black Sea coast of Georgia and in the border region of Georgia/Azerbaijan, in the Himachal Pradesh, Uttarakhand and Arunachal Pradesh regions of the Himalayan foothills and high elevation areas in Taiwan. We have not been able to confirm or reject the occurrence of blanket bogs in these regions as there is very little published information on wetlands or peatlands of any sort.

To analyse potential climate change impacts we used climate change scenarios for the last three decades of the 21st century derived from seven general circulation models, normalized so that all scenarios produced a warming of 2 K by mid-century[21](#_ENREF_21) (see Methods). A consistent pattern across models involves shrinkage of the climate space for blanket bog (Figures 3 and 4a) with only small core areas persisting within each region. Some new areas potentially suitable for blanket bog appear, for example, at higher elevations in Norway, northern Labrador, higher elevations in Kamchatka, and the Chukotka peninsula and St Lawrence Island on the Bering Strait (Figure 3). Across all regions, however, there is better agreement among models on the prediction of shrinkage (a 50 to 59% decrease within the existing area) than expansion (9 to 39% additional area). The driver of this shrinkage is increasing temperature (Figure 4b), which acts both directly through warming summers and indirectly by lowering MI. Precipitation increases are the main driver of the modelled expansion to new areas, and climate model projections of precipitation are less consistent than temperature. These findings are in line with analyses suggesting an expansion of bogs and retreat of the tree-line in some northern oceanic regions[4](#_ENREF_4) even as the suitability of the present distribution area for blanket bog is reduced.

Shrinkage of the bioclimatic space for blanket bog in many areas does not necessarily entail rapid disappearance of the biome with consequent oxidation of the accumulated peat to atmospheric CO2. This kind of prediction is outside the capability of our model. Nevertheless, regions falling outside the envelope will be under stress from climate change and unlikely to continue growing and acting as carbon sinks[6](#_ENREF_6). The resilience of peat to environmental changes has been highlighted previously and rapid carbon losses may be avoidable especially if *Sphagnum* moss cover can be maintained[22](#_ENREF_22). Blanket bogs have survived climatic changes in the past through internal changes in microtope patterns and changes in vegetation assemblages. However the biome cannot remain indefinitely in a relict state and it is likely that the cover of *Sphagnum* and other bryophytes will decline, leaving the affected regions vulnerable to peat erosion. This decline may be counterbalanced to an unknown extent by development of blanket bog in the limited areas at higher latitudes and/or elevations that become newly suitable for blanket bog to develop, a process requiring the replacement of existing vegetation and the initiation of peat growth in a new location.

**Methods**

 *The PeatStash model*. The program STASH, originally used to estimate the present distribution of European trees[23](#_ENREF_23), was adapted to delimit the potential distribution of blanket bog[8](#_ENREF_8). STASH calculates several bioclimatic variables from long-term monthly means of temperature, precipitation, and the fraction of possible sunshine hours (a measure inversely related to cloud cover). PeatStash calculates mean temperature of the warmest month, mean annual temperature, and a moisture index (MI) following the definition given by the United Nations Environment Programme (1992)[24](#_ENREF_24):

  [1]

where *P* is the mean annual precipitation (mm) and *PET* is the mean annual potential evapotranspiration (mm). We substitute equilibrium evapotranspiration, calculated from monthly net radiation and temperature as in Prentice *et al.* (1991)[25](#_ENREF_25) for PET. This substitution is neutral from the modelling point of view because PET according to the Priestley-Taylor equation is proportional to the equilibrium evapotranspiration.

*Climate data.* We used a gridded long-term mean climatology (temperature, precipitation, fractional sunshine hours) for the period 1931-1960 (CLIMATE 2.2) as the baseline for our modelling experiments. Version 2.2 of CLIMATE includes more high-latitude station data and an improved estimation of the elevational gradients of climate variables[26](#_ENREF_26) relative to the original version by Leemans and Cramer[27](#_ENREF_27).

*Future climate projections*. Future climate projections for the period 2070-2099 were based on seven climate models’ A1B scenario runs carried out for the IPCC Fourth Assessment Report[28](#_ENREF_28). The runs were processed by the QUEST GSI project (<http://www.cru.uea.ac.uk/~timo/climgen/data/questgsi/>) using ClimGen, a tool developed by Mitchell and Osborn (2005)[29](#_ENREF_29) to generate normalized climate change fields using pattern scaling[30](#_ENREF_30). The fields were normalized to yield a 2 K global mean temperature increase at 2050. The global average increase of land temperature for 2070-2099 relative to the baseline period (1931-1960) was between 3.9 and 4.3 K (Table 1), a much smaller range than the “native” predictions of the models because of their differing climate sensitivities to radiative forcing. The normalization effectively removes the effect of climate sensitivity so that the remaining differences between the models are in the simulated seasonal and spatial patterns of temperature and precipitation changes. The models used were CGCM3, the third-generation coupled global climate model from the Canadian Centre for Climate Modelling and Analysis (CCCma); the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mark III model (Australia); the IPSL (version IPSLCM4) model from the Institute Pierre Simon Laplace (France); the ECHAM5 model from the Max Plank Institute for Meteorology (Germany); CCSM (Community Climate System Model) version 3.0, from the US National Center for Atmospheric Research (NCAR); HadCM3 from the Met Office Hadley Centre (UK); and HadGEM1 from the Met Office Hadley Centre (UK).

*Scenario-independent sensitivity analysis.* Temperature, precipitation and fractional sunshine hours were varied, one at a time, by adding or subtracting a given amount or percentage to/from all monthly values.

*Scenario-dependent sensitivity analysis*. To assess the drivers of modelled changes, we applied projected climate values for each variable (temperature, precipitation and sunshine fraction) one at a time while keeping the other variables constant at their baseline values.

**Acknowledgements**

We are grateful to the Environment Agency (Science project sc070036) and the Natural Environment Research Council (NERC), through the Quantifying and Understanding the Earth System (QUEST) programme, for funding the development of PeatStash. Martin Sykes at Lund University provided the STASH code, and Fran Bragg at Bristol helped with the climate change scenarios. Climate change scenarios were provided by the QUEST GSI project, funded by NERC. We are indebted to Joy Hecht, Ben Ridge, Susana Velásquez-Franco, Rene Limeres and Martin Rimmer for providing pictures of blanket bogs.

**Author Contributions**

A.G.S. carried out model runs and analysis and wrote the first draft. I.C.P. supervised the project and contributed to experimental design, interpretation of results, and the final draft.

**Additional Information**

The authors declare no competing financial interest.

**Figure captions**

Figure 1. The global potential area of blanket bog, predicted from climate data using the PeatStash model. Ice caps and areas where no climate data are available (e.g. Antarctica) are shown in light grey.

Figure 2. Percentage change in blanket bog potential area for a constant change in (a) mean monthly temperature (°C), (b) mean monthly precipitation, or (c) mean monthly sunshine fraction.

Figure 3. Projected changes to blanket bog potential area for seven climate change scenarios compared to the standard period. The scenarios were derived by pattern scaling, assuming a 2 K warming by 2050, resulting in a warming of 3.9 to 4.5 K over land during 2070-2099. The colour scale represents number of climate models predicting new appearance (blue) or disappearance (red) of blanket bog potential area. Light grey shading as in Figure 1.

Figure 4. a) Projected changes to blanket bog potential area for different regions: EUR = Europe, SA = South America, WNA = western coast of North America, ENA= eastern coast of North America, KAM = Kamchatka, Hokkaido and the Bering Strait, NZ = New Zealand (South Island) and Tasmania. These regions have different surface areas; the changes shown are percentages of present area. b) Percentage decrease or increase of blanket bog potential area due to the projected changes of climatic variables taken one at a time: T = temperature, P = precipitation, S = sunshine fraction.

**Tables:**

**Table 1:** Predicted increase of terrestrial mean annual temperature for the period 2070-2099, according to pattern-scaled scenarios based on seven climate models: all normalized to yield a global warming of 2 K at 2050.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **GCM** | **CCCMA** | **CSIRO** | **HadCM3** | **HadGEM** | **IPSL** | **ECHAM** | **NCAR** |
| ∆Tmean | 4.5 | 4.4 | 4.4 | 3.9 | 4.5 | 4.3 | 3.9 |

1 Charman, D. J. in *Peatlands and Environmental Change* Ch. 1, 3-23 (John Wiley & Sons Ltd, 2002).

2 Wieder, R. K. & Vitt, D. H. Boreal Peatland Ecosystems. 435 (2006).

3 Bragazza, L. A climatic threshold triggers the die-off of peat mosses during an extreme heat wave. *Global Change Biology* **14**, 2688-2695 (2008).

4 Crawford, R. M. M., Jeffree, C. E. & Rees, W. G. Paludification and Forest Retreat in Northern Oceanic Environments. *Ann Bot* **91**, 213-226, doi:10.1093/aob/mcf185 (2003).

5 Gignac, L. D., Nicholson, B. J. & Bayley, S. E. The Utilization of Bryophytes in Bioclimatic Modeling: Predicted Northward Migration of Peatlands in the Mackenzie River Basin, Canada, as a Result of Global Warming. *The Bryologist* **101**, 572-587 (1998).

6 Ise, T., Dunn, A. L., Wofsy, S. C. & Moorcroft, P. R. High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience* **1**, 763-766, doi:10.1038/ngeo331 (2008).

7 Ellis, C. J. & Tallis, J. H. Climatic control of blanket mire development at Kentra Moss, north-west Scotland. *Journal of Ecology* **88**, 869-889 (2000).

8 Gallego-Sala, A. V. *et al.* Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain. *Climate Research* **Uplands Special Issue**, 151-162 (2010).

9 Moore, P. D. The future of cool temperate bogs. *Environmental Conservation* **29**, 3-20, doi:10.1017/s0376892902000024 (2002).

10 Laine, A., Byrne, K., Kiely, G. & Tuittila, E.-S. Patterns in vegetation and CO2 dynamics along a water level gradient in a lowland blanket bog. *Ecosystems* **10**, 890-905, doi:citeulike-article-id:7853064 (2007).

11 Davis, A. M. Ombrotrophic peatlands in Newfoundland, Canada: Their origins, development and trans-Atlantic affinities. *Chemical Geology* **44**, 287-309 (1984).

12 Kleinebecker, T., HÖLzel, N. & Vogel, A. Patterns and gradients of diversity in South Patagonian ombrotrophic peat bogs. *Austral Ecology* **35**, 1-12, doi:10.1111/j.1442-9993.2009.02003.x (2010).

13 Whinam, J. & Hope, G. S. The peatlands of the Australasian region. *Moore - von Sibirien bis Feuerland - Mires - from Siberia to Tierra del Fuego.* **Biologiezentrum der Oberoesterreichischen Landesmuseen Neue Serie 35** (2005).

14 Gignac, L. D., Nicholson, B. J. & Bayley, S. E. The utilization of bryophytes in bioclimatic modeling: Present distribution of peatlands in the Mackenzie River Basin, Canada. *Bryologist* **101**, 560-571 (1998).

15 Gignac, L. D., Halsey, L. A. & Vitt, D. H. A bioclimatic model for the distribution of *Sphagnum*-dominated peatlands in North America under present climatic conditions. *Journal of Biogeography* **27**, 1139-1151 (2000).

16 Parviainen, M. & Luoto, M. Climate envelopes of mire complex types in Fennoscandia. *Geografiska Annaler Series a-Physical Geography* **89A**, 137-151 (2007).

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

18 Ringeval, B. *et al.* An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales, under review. *Global Biogeochemical Cycles* (2010).

19 Clark, J. *et al.* Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models *Climate Research* **Uplands Special Issue** (2010).

20 Charman, D. J. *et al.* Climate-driven changes in peatland carbon accumulation during the last millennium. *PNAS* (in revision).

21 Natural Environment Research Council. QUEST Global-Scale Impacts (GSI) of climate change: an integrated multi-sectoral assessment, [Internet]. Accessed 2009. <http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_12233055204826764>. *NCAS British Atmospheric Data Centre* (2008).

22 Woike, M. & Schmatzler, E. *Moore. Bedeutung - Schutz - Regeneration. In Lindsay (2009) Peatlands and carbon - a critical synthesis to inform policy development. A Report for Discussion.*, (Deutscher Naturschutzring, 1980).

23 Sykes, M. T., Prentice, I. C. & Cramer, W. A Bioclimatic Model for the Potential Distributions of North European Tree Species Under Present and Future Climates. *Journal of Biogeography* **23**, 203-233 (1996).

24 United Nations Environment Programme. World Atlas of Desertification. (1992).

25 Prentice, I. C., Sykes, M. T. & Cramer, W. The Possible Dynamic Response of Northern Forests to Global Warming. *Global Ecology and Biogeography Letters* **1**, 129-135 (1991).

26 Kaplan, J. O. *et al.* Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections. *Journal of Geophysical Research-Atmospheres* **108**, doi:10.1029/2002jd002559 (2003).

27 Leemans, R. & Cramer, W. The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. Report RR-91-18. (1991).

28 IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (2007).

29 Mitchell, T. D. & Osborn, T. J. ClimGen: a flexible tool for generating monthly climate data sets and scenarios. Tyndall Centre for Climate Change Research Working Paper (in preparation). (2005).

30 Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M. & M.G., N. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall Centre Working Paper No.55, Tyndall Centre. (2004).