



# Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain

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**ABSTRACT:** Blanket peatlands are rain-fed mires that cover the landscape almost regardless of topography. The geographical extent of this type of peatland is highly sensitive to climate. We applied a global process-based bioclimatic envelope model, PeatStash, to predict the distribution of British blanket peatlands. The model captures the present areal extent ( $Kappa = 0.77$ ) and is highly sensitive to both temperature and precipitation changes. When the model is run using the UKCIP02 climate projections for the time periods 2011–2040, 2041–2070 and 2071–2100, the geographical distribution of blanket peatlands gradually retreats towards the north and the west. In the UKCIP02 high emissions scenario for 2071–2100, the blanket peatland bioclimatic space is ~84% smaller than contemporary conditions (1961–1990); only parts of the west of Scotland remain inside this space. Increasing summer temperature is the main driver of the projected changes in areal extent. Simulations using 7 climate model outputs resulted in generally similar patterns of declining areal extent of the bioclimatic space, although differing in degree. The results presented in this study should be viewed as a first step towards understanding the trends likely to affect the blanket peatland distribution in Great Britain. The eventual fate of existing blanket peatlands left outside their bioclimatic space remains uncertain.

**KEY WORDS:** Bioclimatic envelope · Model · Blanket peatlands · Peat · Climate change · Great Britain

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## 1. INTRODUCTION

Blanket peatlands are ombrotrophic mires that cover the landscape, developing on ground sloping as steeply as 25 degrees or even steeper, albeit only on small patches (Moore & Bellamy 1973, Moore 2002, BRIG

2008, S. J. Chapman pers. obs.). Since they occur in regions of extremely oceanic climate, they constitute a rare ecosystem type at the global scale, found only in the maritime fringes of the continental masses, e.g. in Iceland, Ireland, western Britain, coastal Fennoscandia, Kamchatka, the Falkland Islands, Patagonia, Tasmania,

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New Zealand, Nova Scotia, the Pacific coast of Alaska and Newfoundland (Lindsay et al. 1988, Wieder & Vitt 2006). Blanket peatlands in Great Britain are important not only because they are examples of a globally rare ecosystem type, but because they provide a wealth of ecosystem services—e.g. livestock production, carbon storage, water regulation and natural hazard regulation (floods, wildfires)—and recreational and aesthetic benefits, as well as act as archives of the past (Cornell 2010, this Special, Maltby 2010, this Special). British blanket peatlands also support significant biodiversity, including an abundant representation of species that are rare at a global scale, such as the higher plants *Scirpus cespitosus*, *Erica tetralix* and *Eriophorum vaginatum* and the macroinvertebrates *Rhithrogena* mayflies, lucrid stoneflies, limnephilid caddisflies and elminthid coleoptera (Pearce-Higgins et al. 2009, Ramchunder et al. 2009).

Bioclimatic envelope modelling, also referred to as ecological niche modelling, is widely used to study the current distribution of species and to project potential changes under future climate scenarios (e.g. Sykes et al. 1996, Berry et al. 2002, Tuck et al. 2006, Huntley et al. 2007). In this type of model, a bioclimatic envelope (or space) is characterized by climatic tolerance limits (thresholds) expressed in terms of one or (usually) several climate variables. Statistical envelope models, which now exist in many variants, statistically correlate the current species spatial distribution with climate variables. These models can be contrasted with process-based envelope models in which limit values are fitted for selected bioclimatic variables chosen because of their relation to known or hypothesized physiological causes of the distributional limits (Pearson & Dawson 2003). The model presented in this study falls into the latter category. Both statistical and process-based bioclimatic envelope models can, in principle, be applied to ecosystems (habitats) as well as species. Peatland ecosystems exist within well-defined climatic thresholds (Wieder & Vitt 2006) and their observed distributions are therefore amenable to description using a bioclimatic envelope model. Regional distributions of peatlands have already successfully been mapped in Canada (Gignac et al. 2000) and Fennoscandia (Parviainen & Luoto 2007) using various statistical bioclimatic envelope models.

The limitations of bioclimatic envelope models for species distribution have been extensively described and mainly stem from disregarding factors such as biotic interactions, evolutionary change or dispersal ability; it has been suggested that dynamic vegetation models are better equipped to predict changes in species distribution (Woodward & Beerling 1997, Davis et al. 1998, Pearson & Dawson 2003). However, bioclimatic envelope models can still provide a first approximation to the fate of species or habitats in a changed climate

and may be able to highlight ecosystems at risk under a changed climate. As such, they are easily applicable tools suitable to inform policy and environmental management (Pearson & Dawson 2003, Heikkinen et al. 2006).

Direct human impacts (e.g. fires, peat extraction for energy purposes and horticulture, and drainage) and indirect impacts through climate change pose a threat to British blanket peatlands (Moore 2002). Owing to the now widely accepted significance of these ecosystems, a number of studies have been undertaken to ascertain how these various processes will shape the future of British peatlands (e.g. Barkham 1993, Bragg & Tallis 2001, Dawson et al. 2003, Davies et al. 2008, Bonn et al. 2009, Reed et al. 2009). The present study contributes to continuing investigations into the fate of British peatland ecosystems by applying a simple but globally applicable and process-based bioclimatic envelope model using present and projected future climates. We use UKCIP02 future climate projections at a fine scale ( $5 \times 5$  km grid cells) to investigate changes in the areal extent of the blanket peatland envelope. These climate projections are downscaled from the HadCM3 global climate model, GCM (Met Office Hadley Centre, UK). Additionally, we examine future projections of the geographical distribution of blanket peatland bioclimatic space based on 7 GCM outputs at a coarser scale ( $0.5^\circ \times 0.5^\circ$  grid cells) to place the results obtained with UKCIP02 projections into a wider context of climate model uncertainty.

Clark et al. (2010, this Special) have applied a suite of statistical bioclimatic envelope models calibrated using climatic conditions and present-day blanket peatland extent in Great Britain to simulate future distributions of blanket peatland bioclimatic envelope. Application of a globally calibrated model to Great Britain provides an independent comparison of the performance and future projections of the statistical models calibrated on data from Great Britain alone.

## 2. METHODOLOGY

### 2.1. PeatStash

A simple process-based bioclimatic model (STASH), originally used to estimate the present distribution of boreal and temperate forest trees in Europe (Sykes et al. 1996), was adapted to delimit the potential distribution of different types of peatland ecosystems globally, including aapa, palsa, blanket and raised mires (A. V. Gallego-Sala, J. Clark, J. House, I. C. Prentice and others unpubl.). The resulting model (PeatStash) was then applied to predict the distribution of blanket peatlands within Great Britain.

PeatStash calculates bioclimatic variables from long-term mean monthly values of temperature, precipitation and the fraction of possible sunshine hours (a measure inversely related to cloud cover). For blanket peatlands, the bioclimatic variables employed are mean annual temperature, mean temperature of the warmest month and a moisture index, on a grid-cell basis. The moisture index (MI) is calculated following the definition given by the United Nations Environment Programme (1992):

$$\text{MI} = P/\text{PET} \quad (1)$$

where  $P$  is the mean annual precipitation (mm) and PET is the mean annual potential evapotranspiration (mm). However, because there are various non-equivalent definitions of PET, we substitute an estimate of the equilibrium evapotranspiration (EET), which is a function of net radiation and temperature only. For empirical relationships among different moisture indices, including MI as calculated here, see Harrison et al. (2010).

MI provides an indirect bioclimatic measure of annual plant water availability, which might be expected to capture the distribution of peatlands better than mean annual precipitation because the latter neglects the large differences in evaporative demand between climates at different latitudes and with differing degrees of cloudiness. The lower bound of MI is zero; there is no theoretical upper bound, but values in the range of 3 to 6 are encountered in the wettest regions.

Sykes et al. (1996) expressed the water requirements of tree species in STASH in terms of the now widely used index  $\alpha$ , which is an estimate of the ratio of actual evapotranspiration (AET) to EET (Harrison et al. 2010). AET is computed using the simple soil-moisture accounting scheme of Prentice et al. (1993), who provided literature sources for all of the equations and parameters listed below. In the accounting scheme, daily soil moisture ( $\Omega_i$ ) is calculated as the minimum of 2 functions:

$$\Omega_i = \min\{[\Omega_{i-1} + (P_i - \text{AET}_i)], \Omega_{\max}\} \quad (2)$$

where  $P_i$  is daily (interpolated) precipitation (mm),  $i$  is the day of the year,  $\Omega_{\max}$  is the soil water-holding capacity (mm), and AET is calculated as the minimum of supply ( $S$ ) and demand ( $D$ ) functions:

$$\text{AET} = \min\{S, D\} \quad (3)$$

$$S = C_w(\Omega_{i-1}/\Omega_{\max}) \quad (4)$$

where  $C_w$  ( $1 \text{ mm h}^{-1}$ ) is the maximum evapotranspiration rate from wet soils under conditions of high demand. The demand function  $D$  is equated with the equilibrium evapotranspiration:

$$D = \text{EET} \quad (5)$$

determined from the energy supply for evaporation:

$$\text{EET} = 3600[s/(s + \gamma)]R_n/L \quad (6)$$

where  $R_n$  is net radiation ( $\text{W m}^{-2}$ ) and  $s$  is the rate of increase of saturated vapour pressure with temperature ( $\text{Pa K}^{-1}$ ), given by:

$$s = 2.503 \times 10^6 \times \exp[17.269T/(273.3 + T)]/(273.3 + T)^2 \quad (7)$$

where  $T$  is the daily (interpolated) temperature in  $^{\circ}\text{C}$ ,  $\gamma$  is the psychrometer constant (ca.  $65 \text{ Pa K}^{-1}$ ) (Simões-Moreira 1999) and  $L$  is the latent heat of vaporization of water ( $2.5 \times 10^6 \text{ J kg}^{-1}$ ) (Lide & Frederikse 2001).

The instantaneous net radiation ( $R_n$ ) is calculated as the difference between net downward shortwave flux ( $R_s$ ) and net upward longwave flux ( $R_l$ ):

$$R_s = (c + dn_i)(1 - \beta)Q_o \cos z \quad (8)$$

where  $c$  and  $d$  are empirical constants ( $c = 0.25$ ,  $d = 0.50$ ;  $c + d = \text{clear-sky transmissivity}$ ),  $n_i$  is the daily (interpolated) fraction of sunshine hours,  $\beta$  is the shortwave albedo (assumed constant at 0.17 for this calculation) and  $z$  is the sun angle.  $Q_o$ , the insolation on a horizontal surface at the top of the atmosphere, is calculated as:

$$Q_o = Q_{oo}[1 + 2 \times 0.01675 \times \cos(360i/365)] \quad (9)$$

where  $Q_{oo}$  is the solar constant ( $1360 \text{ W m}^{-2}$ ) (Willson & Mordvinov 2003) and:

$$\cos z = \sin l \sin \delta \cos h \quad (10)$$

where  $l$  is latitude,  $\delta$  is the solar declination:

$$\delta = -23.4^{\circ} \cos[360(i + 10)/365] \quad (11)$$

and  $h$  is the time of day, in angular units from solar noon.

The net upward long-wave flux is approximated by:

$$R_l = [b + (1 - b)n_i](A - T) \quad (12)$$

where  $b$  and  $A$  are empirical constants equal to 0.2 and  $107^{\circ}\text{C}$ , respectively, and  $T$  is the mean daily temperature in  $^{\circ}\text{C}$ .

Instantaneous  $R_n$  is integrated analytically over the daylight hours to yield daily  $R_n$ , disregarding an effect of diurnal variations in temperature on  $R_n$ . The index  $\alpha$  is calculated by equating annual PET with the evaporative demand term  $D$ . Water in excess of the soil water-holding capacity is routed to runoff.

MI and  $\alpha$  are conceptually and empirically related (e.g. Zhang et al. 2004). However, for modelling peatland distribution, the assumptions of the soil moisture accounting scheme (required for AET) might be a poor approximation for the particular hydrological properties of peat. Furthermore, we found empirically that limit values of MI fitted the distribution of blanket peatlands more accurately than limit values of  $\alpha$ . Accordingly, MI is used as the index of water availability in the

present study. The calculation of MI depends on the algorithm used to calculate EET; it does not depend on AET, the supply function  $S$  or the prescribed soil properties. It is known that  $\alpha$  is insensitive, from a biological point of view, at the wet end of the scale (Harrison et al. 2010). This is probably due to the monthly rainfall being artificially distributed through all the days of the month, neither MI nor  $\alpha$  account for the possibility of runs of dry days, even in relatively wet climates. In fact, MI is independent of the timing of precipitation events and of seasonality of rainfall. However, these limitations are not serious at the wet end of the scale, when the bioclimatic envelope of blanket peatlands is approached, because, in practice, these climates experience year-round precipitation. The advantage of using MI is that it continues to increase with increasing precipitation, when  $\alpha$  has reached its maximum value.

## 2.2. Data sets

### 2.2.1. Blanket peatland maps

*Global blanket peatland map.* There are only very limited data available on the global distributions of mire complexes. The map used in the present study for the global calibration of PeatStash of blanket peatlands is the one compiled by Lindsay et al. (1988).

*Blanket peatland map of Great Britain.* A blanket peatland map was produced by combining the mapped area of blanket peatlands from the soil survey map for England and Wales (NATMAPvector, 1:250 000) and Scotland (National Soils Map, NSM, 1:250 000) (as described fully in Clark et al. 2010). In England and Wales, peat soils meet both of the following criteria: (1) either >40 cm of organic material is found within the upper 80 cm of the soil profile, or >30 cm of organic material rests directly on bedrock or skeletal material; and (2) no superficial non-humose mineral horizons with a colour value of 4 or more that extends below 30 cm depth (Clayden & Hollis 1984). Blanket peatlands were mapped under 3 soil associations: Winter Hill (1011b), Crowdy 1 (1013a) and Crowdy 2 (1013b), belonging to the raw peat soils group (10.1) (Avery 1980). In Scotland, peat is classified as an organic deposit (>60% organic matter) with a depth greater than 50 cm (Chapman et al. 2009).

### 2.2.2. Climate data

*Climate baseline data.* Monthly 5 km gridded climate data from the Met Office were used ([www.metoffice.gov.uk](http://www.metoffice.gov.uk)). The gridded data were produced by integrating long-term meteorological measurements

using interpolation and multiple regression models based on location (easting and northing), terrain elevation, open water and urban land use (Perry & Hollis 2005). Monthly data for precipitation (mm), cloud cover (%) and mean temperature (°C) averaged over the 1961–1990 period were used. The potential for a poor representation of upland precipitation in the Met Office data due to fewer rain gauges at high elevations is not addressed.

*Future climate projections: UKCIP02.* Climate scenarios were obtained for the UK from the UK Climate Impacts Programme (UKCIP, [www.ukcip.org.uk](http://www.ukcip.org.uk)) (Hulme et al. 2002). These scenarios were derived from the Hadley Centre Global Climate Model (HadCM3) output for 4 global emissions profiles, developed by the IPCC Special Report on Emissions Scenarios (IPCC 2000): A1FI (high emissions), A2 (medium-high emissions), B2 (medium-low emissions) and B1 (low emissions); only A1F1 and B1 are used in the present study. Changes in monthly mean climate values were available at a 50 km scale for 3 different periods: 2011–2040, 2041–2070 and 2071–2100, hereafter referred to as the 2020s, 2050s and 2080s, respectively. The projected change in climate variables at the 50 km scale was applied to the observed 1961–1990 5 km baseline data. Projected changes used were for monthly change in mean temperature (°C), total precipitation (%) and cloud cover (%).

*Future climate projections: GCMs.* Future climate projections derived from a suite of 7 different climate models were also used to capture some of the uncertainty due to the choice of GCM. These runs were carried out as part of the QUEST GSI project (Quantifying and Understanding the Earth SysTem—Global-Scale Impacts of climate change; [www.cru.uea.ac.uk/~timo/climgen/data/questgsi/](http://www.cru.uea.ac.uk/~timo/climgen/data/questgsi/)) using ClimGen, which is a tool developed by Mitchell & Osborn (2005) to generate fields of climate data using a ‘pattern scaling’ approach (Mitchell et al. 2004), whereby patterns of change simulated by a suite of GCMs for a prescribed scenario of +2°C warming by 2050 were applied to an observed 0.5° × 0.5° gridded baseline climatology (New et al. 2000). The suite of 7 models included (1) CGCM3, the third generation Canadian coupled GCM from the Canadian Centre for Climate Modelling and Analysis (CCCMA); (2) the Australian GCM from the Commonwealth Scientific and Industrial Research Organisation (CSIRO); (3) the new IPSL climate system model (IPSLCM4) from the Institut Pierre Simon Laplace (France); (4) ECHAM GCM5, a comprehensive general circulation model of the atmosphere from the Max Planck Institute (Germany); (5) the community climate system model (CCSM) version 3.0 from the US National Centre for Atmospheric Research (NCAR); (6) the Hadley Centre Coupled Model, version 3

(HadCM3), a coupled atmosphere–ocean general circulation model (AOGCM) from the Hadley Centre; and (7) the coupled Hadley Centre Global Environmental Model, version 1 (HadGEM1).

### 2.3. Model calibration

The threshold values used in PeatStash were: an MI above 2.1, a mean annual temperature above  $-1.0^{\circ}\text{C}$  and a mean temperature of the warmest month not to exceed  $14.5^{\circ}\text{C}$ . These are simply the values that best fitted the global distribution of blanket peatlands (A. V. Gallego-Sala, J. Clark, J. House, I. C. Prentice and others unpubl.). These same thresholds were used to predict the distribution of blanket peatlands in the UK. Thus, the model was calibrated at a global scale and directly applied to the UK without additional calibration.

### 2.4. Data analysis

#### 2.4.1. Model performance statistics

Model sensitivity, accuracy and Kappa statistics (Cohen 1960) were calculated for all models based on the ability to predict presence/absence of present-day blanket peatlands. Sensitivity was defined as the total number of recorded presences correctly predicted, as a fraction of the total number of presences recorded in the data (Pearce & Ferrier 2000). Accuracy was defined as the number of correctly identified presences and absences recorded in the whole data set (Pearce & Ferrier 2000). The Kappa statistic measures the correct classification rate after the probability of chance agreement has been removed (Cohen 1960), which is often considered to be a better measure of predictive accuracy than sensitivity or accuracy. We also recorded the errors of omission, i.e. the number of grid cells where the model failed to predict peat where peat has been observed, and errors of commission, i.e. the number of grid cells where the model predicts peat but there is none.

#### 2.4.2. Sensitivity analysis independent of climate scenario

Model sensitivity analysis was carried out with respect to each of the 3 input climate variables: temperature, precipitation and cloud cover. Factorial changes for cloud cover and difference changes for temperature and precipitation were applied, one at a time, to the monthly 1961–1990 baseline climate data. The percent-

age change in the bioclimatic spatial distribution for the model was compared relative to the results obtained using the 1961–1990 baseline climate data.

#### 2.4.3. Scenario-dependent sensitivity analysis: drivers of change

An additional sensitivity test was performed on PeatStash to assess which climate variable(s) drive the predicted changes in blanket peatland extent for the different scenarios. These tests use the UKCIP02 climate data sets based on 2 different IPCC SRES emissions scenarios (A1F1 and B) for 3 different periods: the 2020s, 2050s and 2080s. The projected changes in climate are not always just a constant increase or decrease in mean monthly variables, but usually include a change in seasonality. For example, rain patterns are likely to change differently during the winter and summer months, and UKCIP02 predicts drier summers and wetter winters (Hulme et al. 2002). For this reason, we use the projections for each variable (rain, temperature and sunshine fraction), while keeping the rest of the variables constant at the baseline value. This further sensitivity test is used to examine the cause of the predicted changes in the area within the bioclimatic envelope under future climate scenarios.

## 3. RESULTS

### 3.1. Model calibration

The threshold values used in PeatStash were those that best fitted the global distribution of blanket peatlands (Table 1); these limit values were directly applied to Great Britain without additional calibration (Fig. 1).

### 3.2. Model fit to present-day blanket peatland distribution

PeatStash performed well and was able to correctly predict blanket peatland presence and absence compared to the present-day blanket peatland distribution map, with high values of sensitivity, accuracy and Kappa statistic (Table 2). According to the Kappa statistic, PeatStash performed within the upper limit of the interval 0.6 to 0.8, which is considered to be a substantial agreement beyond chance (Landis & Koch 1977). There were more errors of commission than omission, i.e. PeatStash tends to slightly overestimate the total extent of blanket peatlands (Fig. 1).

Table 1. Chosen thresholds for the global distribution of blanket peatlands for 3 bioclimatic variables: moisture index (MI, unitless), mean annual temperature ( $T_{\text{mean}}$ ) and mean temperature of the warmest month ( $T_{\text{warm}}$ ). n/a: not applicable, only a minimum or maximum threshold were set for these variables

Threshold	MI	$T_{\text{mean}}$ (°C)	$T_{\text{warm}}$ (°C)
Upper	n/a	n/a	14.5
Lower	2.1	-1.0	n/a

### 3.3. Sensitivity analysis independent of climate scenario

The results of the sensitivity analysis indicate that the modelled peat area decreases with increased temperature, decreased precipitation and decreased cloud cover (increased sun fraction) (Fig. 2). The slope of each curve in Fig. 2 is an indication of the sensitivity of the bioclimatic envelope to the change in the variable. The modelled area is very sensitive to increases in temperature (especially the interval 0 to +2°C), i.e. a relatively small change in temperature results in a large change in bioclimatic envelope extent. The curve tails off as the blanket peatland envelope disappears. The envelope is more sensitive to decreases than to increases in precipitation, probably because, in the model, the bioclimatic envelope cannot extend to grid cells where the maximum mean monthly temperature is above a given threshold (+14.5°C). There are therefore areas that could not be covered in blanket peatlands, even if precipitation were to increase substantially. The model is less sensitive to potential changes in cloud cover than to the other 2 variables.

### 3.4. Projected future changes in blanket peatland bioclimatic area

The general response to the predicted changes in climate for the UKCIP02 high and low emissions scenarios is a retreat in the peat bioclimatic area to the north and west of Great Britain (Fig. 3). In the high emissions scenario, for the 2080s period, there is a loss of ~84% of the present-day peatland bioclimatic area, whereas, even for the low emissions scenario during the same period, the decline represents more than half of the present area (Table 3).

The same pattern of retreat towards the west and north of Great Britain was observed when PeatStash was run using climate projections from 7 climate models (Fig. 4). All simulations agree on the loss of blanket peatland bioclimatic space in England, Wales and the east of Scotland. The climate projected by

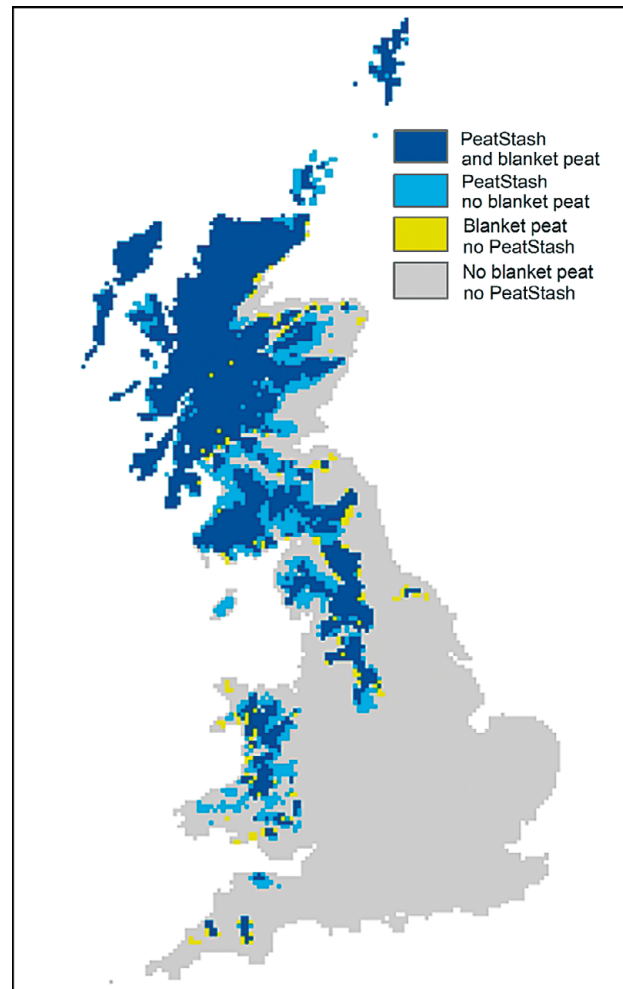


Fig. 1. Overlay of the PeatStash predicted area of blanket peatland bioclimatic envelope for the baseline climate period (1961–1990) on the mapped 5 km gridded data of blanket peatland presence. An Ordnance Survey/EDINA supplied service (© Crown Copyright/database 2009) and Met Office/UKCIP gridded climate data (UKCIP02 © Crown Copyright 2002)

IPSLCM4 leads to the greatest shrinkage of the area incorporated within the blanket peatland envelope, such that no areas of Great Britain have a climate that matches this bioclimatic space. Climates projected by

Table 2. Model fit and accuracy, comparing the output of PeatStash for the baseline climate data with the observed blanket peatland map. Sens.: sensitivity; Acc.: accuracy; Kappa: Kappa statistic; Omiss.: errors of omission; Commiss.: errors of commission; Grid cells: total no. of grid cells

Test	Sens. (%)	Acc. (%)	Kappa	Omiss.	Commiss.	Grid cells
PeatStash	88.7	89.7	0.77	192	843	9757

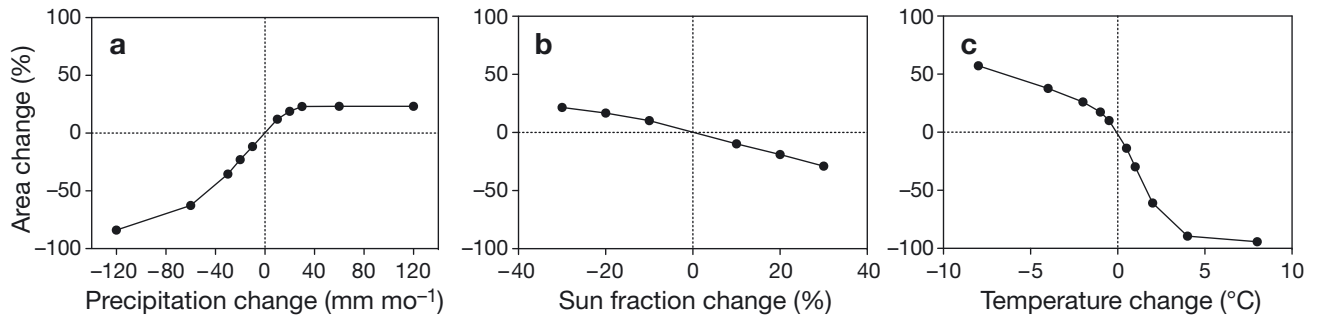


Fig. 2. Sensitivity analysis of PeatStash independent of climate scenario: percentage change in the area covered by blanket peatland bioclimatic space for a constant change in: (a) mean monthly precipitation, (b) mean monthly sun fraction and (c) mean monthly temperature for the 1961–1990 baseline climate data

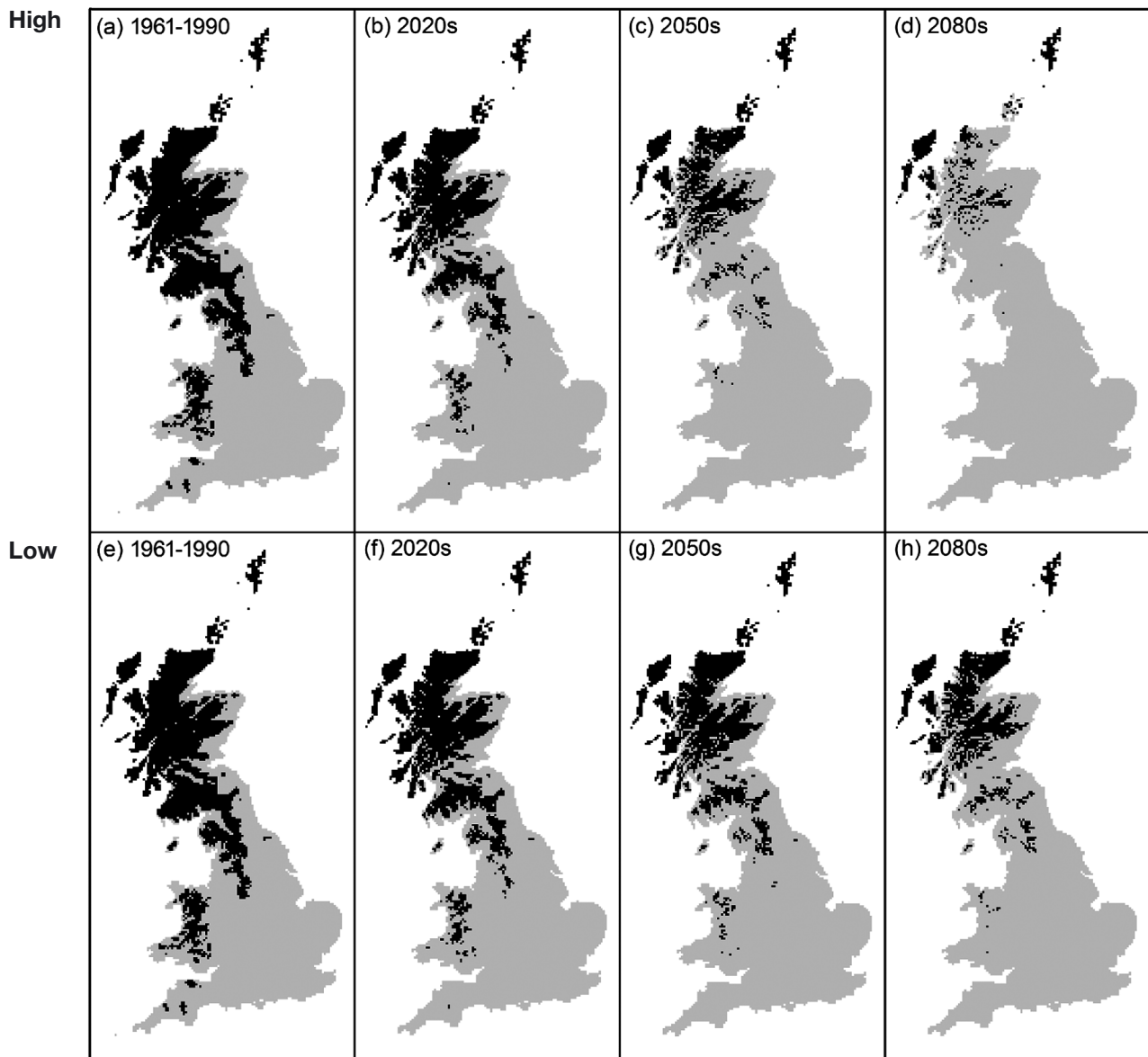


Fig. 3. Area covered by the bioclimatic envelope of blanket peatlands predicted by PeatStash using the bioclimatic thresholds associated with the 1961–1990 baseline climate for the UKCIP02 high and low emissions scenarios ('High' and 'Low', respectively) for 3 time periods: 2020s, 2050s and 2080s. An Ordnance Survey/EDINA supplied service (© Crown Copyright/database 2009) and Met Office/UKCIP gridded climate data (UKCIP02 © Crown Copyright 2002)

Table 3. Percentage decrease of areal extent of the blanket peatland bioclimatic envelope compared with its present-day distribution for 3 time periods: 2020s, 2050s and 2080s; and 2 UKCIP02 emissions scenarios: high and low

Emmissions scenario	2020s	2050s	2080s
High	32	60	84
Low	28	43	53

ECHAM GCM5 and CCCMA CGCM3 models result in the least shrinkage. When PeatStash is run using the climate space predicted by the CSIRO and NCAR CCSM3 models, the resulting geographical distribution of the peat bioclimatic envelope is similar to that obtained using the 2 Hadley Centre model predictions HadCM3 and HadGEM1, and falls somewhere between the 2 extremes. Because HadCM3 is the GCM model output underlying the downscaled UKCIP02 projections, this implies that the projected change in blanket peatland climate space shown by UKCIP02 (Fig. 3) is somewhere in the middle ground of GCM projections.

### 3.5. Drivers of change

The scenario-dependent sensitivity test highlights temperature as the main input variable driving the changes in the areal extent of the peat bioclimatic envelope under the UKCIP02 projected future climate (Fig. 5). UKCIP02 probabilistic summer temperature projections range from an increase of at least 3.8°C (low emissions scenario, 90% confidence) to up to 8.1°C (high emissions scenario, 90% confidence) during the 2080s. Changes in precipitation and cloud cover are such that they have only a small influence (only up to 4%) on the extent of the envelope.

Projections of warming decrease MI everywhere, since the PET increases with temperature. Moreover, because a large area of Great Britain falls above the summer temperature limit for blanket peatland survival (Table 1), increasing summer temperatures directly cause a reduction in the area within this limit. Projected changes in cloud cover slightly increase MI in many lowland areas, with the sharpest increases on the west coast of Scotland, Skye and the Outer Hebrides; i.e. these areas have wetter soils, owing to changes in cloud



Fig. 4. Changes in the extent of the blanket peat bioclimatic envelope area compared with (a) present-day climate, as predicted by PeatStash using 7 different GCM predictive outputs for 2070–2099 at 0.5° resolution: (b) CCCMA CGCM3, (c) CSIRO, (d) IPSLCM4, (e) ECHAM GCM5, (f) NCAR CCSM 3.0, (g) HadCM3 and (h) HadGEM1. Climate projections are based on a scenario of 2.0°C warming by 2050. Dark grey areas are within the blanket peatland bioclimatic envelope and light grey areas are those outside



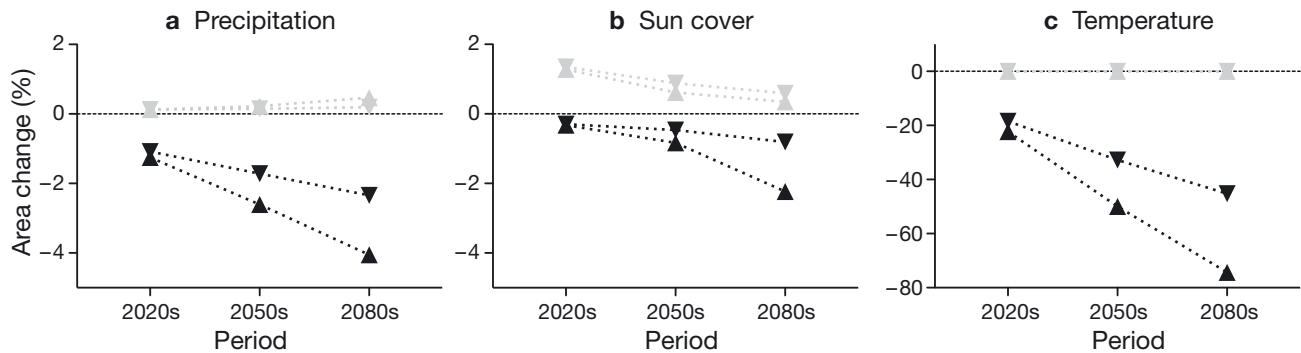


Fig. 5. Scenario-dependent sensitivity analysis of PeatStash. Percentage decrease (black triangles) and increase (grey triangles) in the area covered by the blanket peatland bioclimatic space due to the predicted changes of the climatic variables (a) precipitation, (b) sun cover and (c) temperature under UKCIP02 high (upwards-pointing triangles) and low (downwards-pointing triangles) emissions scenarios for 3 time periods: the 2020s, the 2050s and the 2080s. Note the change of scale in panel c

cover alone. But at the same time, predicted changes in cloud cover decrease MI in the high-elevation areas where most blanket peatlands are located. Projected changes in precipitation patterns slightly increase MI values in the eastern and western coasts of Scotland, but decrease MI elsewhere.

Projected changes in the bioclimatic space for blanket peatland growth are the result of the combined effect of these variables, and the combined effect is overwhelmingly to reduce the area within bioclimatic space for blanket peatlands. In general, the projected future climates are warmer and drier in summer than present-day climates, causing a reduction in the geographical extent of the blanket peatland bioclimatic envelope because of both the direct effect of warmer summers, and the indirect effects of increased PET and reduced precipitation on MI.

## 4. DISCUSSION

### 4.1. Model performance and sensitivity

Blanket mires are more directly controlled by climate than some other types of peatland because of their reliance on precipitation alone to replenish soil moisture and maintain a high water table level. To a certain extent, this may explain why the predicted distribution of blanket peatlands from the model matches the observed distribution so closely. These ecosystems are very sensitive even to decadal variability in climate (Ellis & Tallis 2000). It is therefore likely that the present distribution of blanket peatlands in Great Britain is close to equilibrium with the current climate, notwithstanding anthropogenic disturbances such as drainage and other land-use changes.

Our model is remarkably transparent and parsimonious, depending on just 3 bioclimatic limits (MI, mean annual temperature and mean temperature of the

warmest month), acting independently, to accurately describe the distribution of blanket peatlands. Despite being calibrated on a global data set, PeatStash compares well to statistical models that were calibrated on Great Britain data sets; its performance measures are close to those of the best-fit statistical bioclimatic models presented in Clark et al. (2010).

The geographic distribution of the blanket peatland bioclimatic envelope, as predicted by PeatStash, is very sensitive to increases in temperature and, to a lesser degree, decreases in precipitation. Parviainen & Luoto (2007) also reported that both precipitation and temperature were the main explanatory variables for the occurrence of blanket peatlands, unlike the occurrences of every other type of mire in Fennoscandia, which were explained by temperature alone.

### 4.2. The future of blanket peatlands in Great Britain

All PeatStash simulations run using climate input from the UKCIP02 high and low emissions scenarios and from 7 different GCM projections predict a retreat of the area covered by the blanket peatland bioclimatic envelope compared to the present distribution of peatlands. The general pattern of change is a gradual shift towards the north and west. Our application of a globally calibrated process-based bioclimatic envelope model is consistent with findings from statistical bioclimatic envelope models specifically calibrated for Great Britain (Clark et al. 2010). To account for the uncertainty in using what are, in essence, the predictions of a single GCM, i.e. the Hadley Centre model, PeatStash was additionally run at a lower resolution using a suite of 7 different GCMs. All 7 simulations run with climate projections based on a scenario of 2.0°C warming by 2050 predict the disappearance or shrinkage of the areas inside the blanket peatland bioclimatic envelope in England and Wales, and eastern parts of Scotland.

Our study is consistent with previous model-based studies, which have suggested that peatlands in Canada may 'migrate' northwards as a result of elevated temperatures and drought (Gignac et al. 1998). Some field studies also suggest that peatland ecosystems at lower latitudes may not be well adapted to survive the more frequent extreme heat waves predicted in Europe and North America as part of global warming (Meehl & Tebaldi 2004, Bragazza 2008).

The temperature changes projected by UKCIP02 are the most important driver in the change of geographical distribution of the peat bioclimatic envelope predicted by PeatStash. The importance of temperature as a factor controlling the destabilization of peatlands has been pointed out in other studies (Freeman et al. 2001, Ise et al. 2008). Paludification is the accumulation of soil organic carbon and the resulting water table rise due to the high water holding capacity of peat and its low hydraulic conductivity, which results in anoxia and further slowing down of the decomposition processes in the soil and consequent peat growth. This feedback between water table and peat depth has been suggested to increase the sensitivity of peat decomposition to temperature and to accelerate carbon loss whenever the climate is unfavourable to peat accumulation (Ise et al. 2008).

By contrast, future changes in cloudiness and precipitation are less well defined in climatic projections, and global water availability projections remain uncertain (Kingston et al. 2009). The increase in the North Atlantic Oscillation index and related increase in precipitation over western Europe may, in part, compensate for the possible increase in temperature (Moore 2002). However, changes in the distribution of rainfall, with wetter winters and drier summers (Jenkins et al. 2009), may exacerbate the impact of increased temperatures and increase the water deficit in British peatlands during summer months.

Being outside the blanket peatland bioclimatic envelope would not necessarily imply a sudden and complete loss of the peatland habitat or its carbon storage capabilities, especially if the sphagnum cover is maintained (Woike & Schmatzler 1980), because of peat resilience once established. A more complex process-based coupled physical-biogeochemical soil model was used to examine climate impact in Canadian peatlands (Ise et al. 2008). Both shallow and deep peat soils were subjected to an instantaneous 4°C increase in temperature and the soil organic carbon (SOC) was modelled over a period of 2000 yr. The results from this model suggest that shallow peat layers will lose 40% of their SOC within 700 yr. Deep peat layers were shown to exhibit some resilience to SOC loss over the first 200 yr, but in the longer term (from 300 to 600 yr), 86% losses in SOC were predicted. At the fastest rate of decline, this is a loss of SOC of  $\sim 0.3\% \text{ yr}^{-1}$ .

Climate change is not the only factor driving carbon losses from soil. Between 1978 and 2003, the mean temperature across England and Wales increased by approximately 0.5°C (Hulme et al. 2002). The measured actual loss of carbon from topsoils in England and Wales during this period (NSRI 2010) has shown a rate of SOC loss, in the region of 0.6%  $\text{yr}^{-1}$  on average and up to 2%  $\text{yr}^{-1}$  in organic soils (Bellamy et al. 2005). Smith et al. (2007) and Kirk & Bellamy (2010) suggest that only at most 10% of the carbon losses observed in Bellamy et al. (2005) could be attributed to climate change and that the majority of the loss is a consequence of land-use change. This would lower the rate of SOC loss due to climate change to a level comparable with that reported by Ise et al. (2008). A review of the current state of UK peatlands (Billett et al. 2010, this Special) suggests that the present carbon accumulation rates of a number of blanket peatlands may have slowed down compared with the last century. It is important to highlight that peatlands are flexible ecosystems, able to respond to and survive change, and their exact response to climate change remains ambiguous (Lindsay 2009). A rate of carbon loss or possible resilience of peat to a changing climate is beyond the scope of the present study.

There have been suggestions that the oceanic mires of Great Britain might not be under the same threat from climate change as other more continental mires; for example, it has even been proposed that northern oceanic peatlands are increasing in area, due to a retreat of the tree line and an ecological succession towards bogs where there were previously forests (Crawford et al. 2003). Our results do not provide support for this view.

The future distributions of the blanket peatland bioclimatic envelope under different emissions scenarios imply that blanket peatlands in England and eastern Scotland in particular will be under stress from changes in climate. The eventual fate of these ecosystems remains uncertain. Peatlands falling outside the bioclimatic envelope in the future might not disappear completely or swiftly, but will not be actively growing and, therefore, are unlikely to continue acting as carbon sinks.

#### 4.3. Model limitations

There is continuing debate on the limitations and usefulness of bioclimatic envelope models (Pearson & Dawson 2003, Hampe 2004, Thomas et al. 2004, Thuiller et al. 2004, Heikkinen et al. 2006). One criticism of these models is that they do not take into account biotic interactions, such as predation, competition or mutualism, when these are key mechanisms determining the distribution of species (Hampe 2004), but these interactions are not relevant for assessing habitat suitability. Further, these processes may be more im-

portant at finer scales (Pearson & Dawson 2003) and in situations where the predicted change to the present distribution is an expansion rather than shrinkage.

Another criticism of this type of model is the disregard of adaptive genetic variations (Woodward & Beerling 1997). Peatland ecosystems may be robust, to a certain extent, to changes in the environment, and they have been capable of adapting to past environmental or climatic changes (Lindsay 2009). However, blanket peatlands are special ecosystems in that they are ombrotrophic mires dependent on high water table levels, which are maintained solely by the right climatic conditions, i.e. high precipitation and low temperature, and as such, they are highly vulnerable to climate change (Gignac et al. 1998, Ellis & Tallis 2000).

A drawback of the MI employed in PeatStash is that it is calculated using mean annual variables and therefore may not pick up extreme weather events, or seasonal variation, e.g. drought periods in the summer months.

## 5. CONCLUSIONS

PeatStash correctly predicts the current geographical distribution of blanket peatlands in Great Britain using just 3 bioclimatic variables: MI, temperature of the warmest month and mean annual temperature. Simulations run using future UKCIP02 climate projections suggest the retreat of the areal extent of the blanket peatland bioclimatic envelope towards the north and west of Great Britain. Peatland areas that become excluded from the bioclimatic envelope are likely to experience changes in hydrology and vegetation and to cease active growth. However, the detailed fate of these threatened blanket peatland ecosystems is unknown and depends not only on pressures stemming from climate change, but on management practices and policy. Our results aim to provide information on one key factor—the potential effect of climate change on the extent of blanket bogs—that may influence decisions concerning the conservation and restoration of British peatlands.

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