Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models

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ABSTRACT: We assessed the vulnerability of blanket peat to climate change in Great Britain using an ensemble of 8 bioclimatic envelope models. We used 4 published models that ranged from simple thresh-old models, based on total annual precipitation, to Generalised Linear Models (GLMs, based on mean annual temperature). In addition, 4 new models were developed which included measures of water deficit as threshold, classification tree, GLM and generalised additive models (GAM). Models that included measures of both hydrological conditions and maximum temperature provided a better fit to the mapped peat area than models based on hydrological variables alone. Under UKCIP02 projections for high (A1F1) and low (B1) greenhouse gas emission scenarios, 7 out of the 8 models showed a decline in the bioclimatic space associated with blanket peat. Eastern regions (Northumbria, North York Moors, Orkney) were shown to be more vulnerable than higher-altitude, western areas (Highlands, Western Isles and Argyle, Bute and The Trossachs). These results suggest a long-term decline in the distribution of actively grow-ing blanket peat, especially under the high emissions scenario, although it is emphasised that existing peatlands may well persist for decades under a changing climate. Observational data from long-term monitoring and manipulation experiments in combination with process-based models are required to explore the nature and magnitude of climate change impacts on these vulnerable areas more fully.

KEY WORDS: Climate change · Peat · Bioclimatic envelope model · Great Britain · Uplands

1. INTRODUCTION

Blanket peat is the main peat type in Great Britain (GB, comprising England, Scotland and Wales), account-ing for 92% of the total peatland area covering around 23 300 km^2 (10% of GB land area), and is located almost exclusively in the uplands (see Fig. 1a). It is the single largest terrestrial carbon store in GB, account-ing for ca. 50% of the total carbon stock (Milne & Brown 1997). However, many of these areas have been

degraded due to drainage, air pollution, rotational burning and wildfires, plantation forestry and over-grazing (Ramchunder et al. 2009). Restoration efforts are underway to block drains (Armstrong et al. 2009), re-vegetate areas of bare peat (Evans et al. 2004), change fire management (Davies et al. 2008) and reduce air pollution (RoTAP in press). Given the close relationship between peat formation and cool and wet climatic conditions, it is likely that future climate change will place additional pressure on these systems, particularly in degraded areas that are already subject to stress. However, it is currently unclear how vulnerable upland blanket peat across the various regions of GB will be to climate change. Understanding the climatic vulnerability of these issues will help prioritise and potentially 'climate-proof' blanket peat management and restoration work by informing policy debates about future protection and management of these areas and the services these ecosystems deliver.

Ombrotrophic peatlands tend to be found in wet and humid areas with no sustained dry periods (Moore & Bellamy 1973). Organic matter accumulates in peat because of low decomposition rates (due to waterlogging and anoxia) rather than high plant productivity (Clymo 1984, Malmer 1992). Blanket peat vegetation is adapted to these saturated conditions, and is highly sensitive to changes in water availability (Bragg & Tallis 1999). In these ombrotrophic systems, high water tables are maintained by precipitation and poor drainage due to impermeable underlying deposits (Taylor 1983). The reliance on precipitation makes blanket peat highly sensitive to climate changes that affect the net water balance (precipitation – potential evapotranspiration), as this alters the balance between decomposition and primary production (Heathwaite 1993).

Bioclimatic envelope models (BCEM) have been used to map the current and possible future distribution of various types of peatlands (Gignac et al. 1998, Fronzek et al. 2006, Parviainen & Luoto 2007). Envelope models are static statistical models used to define the 'environmental space' where a habitat or species is present (Guisan & Zimmermann 2000). Most applications are for species, with only a few considering land-forms and habitats (e.g. Parviainen & Luoto 2007). BCEMs can usefully inform policy development provided their limitations are understood (Heikkinen et al. 2006, Walmsley et al. 2007). These limitations relate to the static and empirical representation of relationships between habitat/species presence and explanatory variables which cannot account for possible dynamic feedbacks (Pearson & Dawson 2003, Heikkinen et al. 2006). In spite of these limitations, BCEMs can provide a valuable first approximation of climate change impacts at broad geographic scales where climate is the pri-

mary constraint on the distribution (Pearson & Dawson 2003, Heikkinen et al. 2006, Ellis et al. 2007).

Within the climate space associated with boreal peatlands, blanket peat tends to form under the warmest and wettest conditions (Wieder & Vitt 2006), where precipitation is around 3 times greater than potential evaporation (Pearsall 1965). Globally, these areas typically occur in mid to high latitudes on the ocean fringes where precipitation is high and mean annual temperature range is low (Lindsay et al. 1988). Climatic variables that have been used to determine blanket peat bioclimatic space include temperature, growing degree days, precipitation and water balance (precipitation – potential evaporation) (see Table 1). Precipitation has been shown to be more important than temperature in explaining blanket bog distribution in Fennoscandia (Parviainen & Luoto 2007), although in GB the distribution of precipitation measured in terms of the number of days with rainfall was considered to be more important than the total precipitation in explaining blanket peat distribution (Tansley 1939, Goode & Ratcliffe 1977, Lindsay et al. 1988). This is most likely because the number of rain days has been linked with *Sphagnum* moss growth and primary production (Backeus 1988, Lindsay 1995). Mean temperature has also been used as an explanatory variable for blanket peat in GB in the absence of maximum temperature data (Hossell et al. 2000). Maximum temperature is thought to be the main factor limiting the distribution of upland montane plant species (Rodwell et al. 1992) as invasion of faster growing species becomes more likely with warmer temperatures (Hossell et al. 2000).

Climate projections for the 21st century for GB suggest an overall increase in temperatures and change in the distribution of rainfall with warmer, wetter winters and warmer, drier summers (Hulme et al. 2002, Jenkins et al. 2009). Given that wet and cool conditions are associated with blanket peat, these projected changes could affect the species composition and the balance between carbon accumulation and decomposition. While the potential risks to blanket peat stability in a changing climate are known qualitatively (e.g. potential for shift from net carbon sink to source as decomposition increases under warmer and drier conditions), the degree to which these changes may place additional stress on blanket peat systems is unclear. In particular, the relative climatic vulnerability between regions across GB is unknown. Previous work within GB has focused on temperature alone as a key BCEM model variable using UKCIP98 scenarios (Hossell et al. 2000), although precipitation and changes in the water balance have been shown to be a key explanatory variables of blanket peat elsewhere (Parviainen & Luoto 2007). Therefore, the objectives of this study were to (1) develop new suitable BCEMs for British blanket

peat that incorporate measures of the water balance; (2) compare the performance of the new BCEMs with previously published models; (3) identify regions within GB that are likely to be the most vulnerable to climate change; and (4) apply an ensemble of these new and existing BCEMs, together with recent climate projections, to examine future changes in the 'climate space' associated with blanket peat.

2. METHODS

2.1. Derived peat map

No unified soil or blanket peat map was available for GB; therefore a derived blanket map was produced by combining the mapped area of blanket peat from the Digital National Soil Map for England and Wales (NATMAPvector, 1:250 000) and Scotland (National Soils Map, NSM, 1:250 000), which have different classification systems. 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) there are no superficial non-humose mineral horizons with a colour value of ≥4 extending below 30 cm depth (Clayden & Hollis 1984). Blanket peat was 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 >50 cm. The soil map unit 'Blanket Peat' was mapped into 4 classifications: Blanket Peat, Deep Blanket Peat, Eroded Blanket Peat and Eroded Deep Blanket Peat. There are additional soil map units where peat is a major component that has developed in patches with other organic soils over glacial moraine in 'organic soil complexes' (Chapman et al. 2009). These areas of semi-confined peat were not included in our derived blanket peat map.

The National Soil Map for Scotland was published in 1982, combining detailed soil surveys carried out in the 1950s for lowland areas and 1970s for upland areas. Given that blanket peat is predominately in the uplands, the National Soil Map for Scotland best represents the mapped distribution in the 1970s. The National Soil Map for England and Wales was mapped between 1979 and 1982. The peat maps show the area of blanket peat extent at the time of field survey. While it is known that blanket peat in GB has been impacted by land use (e.g. forestry, drainage and cutting), the impact of this on the mapped distribution of blanket peat areas across the whole country is currently unknown. However, it is important to note that drained and afforested areas of peat where the organic layer is still of sufficient depth will

have been mapped as peat. Therefore, work presented here shows BCEM models calibrated to the mapped distribution of blanket peat from the 1970s.

The mapped polygons of these soil associations and series were combined to produce a single blanket peat layer for GB. The polygons were then converted to a 5 km grid based on the presence (3110 cells) or absence (7765 cells) of blanket peat within each grid cell. A 5 km grid was chosen to match the resolution of the available climate data (Fig. 1a).

2.2. Climate data

2.2.1. Observed data

Monthly gridded climate data (5 km resolution) from the UK Met Office were used (www.metoffice.gov.uk). The gridded data were produced by interpolating long-term meteorological measurements using multiple regression models accounting for location and elevation in addition to other factors (Perry & Hollis 2005). Datasets used in this paper were monthly mean of the minimum and maximum daily temperature (°C), total precipitation (mm), cloud cover (%) and days with rainfall >1 mm (d). Mean temperature was calculated as the mean of maximum and minimum temperature. Monthly data were averaged over the 1961–1990 baseline period.

2.2.2. Climate projections

Climate scenarios were available for GB from the UK Climate Impacts Programme (UKCIP, www.ukcip. org.uk) (Hulme et al. 2002). These scenarios were derived from the Hadley Centre Global Climate Model (HadCM3) for 4 global emission profiles (IPCC 2000): A1F1 (high emissions), A2 (medium-high emissions), B2 (medium-low emissions), B1 (low emissions). We used the high and low emissions scenarios. Changes in monthly mean climate values were available for the periods 2011–2040 (2020s), 2041–2070 (2050s) and 2071–2100 (2080s) at a 50 km scale. The projected change in climate variables at the 50 km scale were applied to the observed 1961–1990 5 km baseline data. Projected changes used were for monthly change in maximum and minimum temperature (°C), total precipitation (%) and cloud cover (%). No direct data were available for future raindays.

UKCIP02 was used, as the more recent UKCP09 scenarios were not available at the time the work was carried out. In general, UKCIP02 projections show a rise in average annual temperature of 1 to 5°C, a decrease in summer precipitation by up to 50% and an
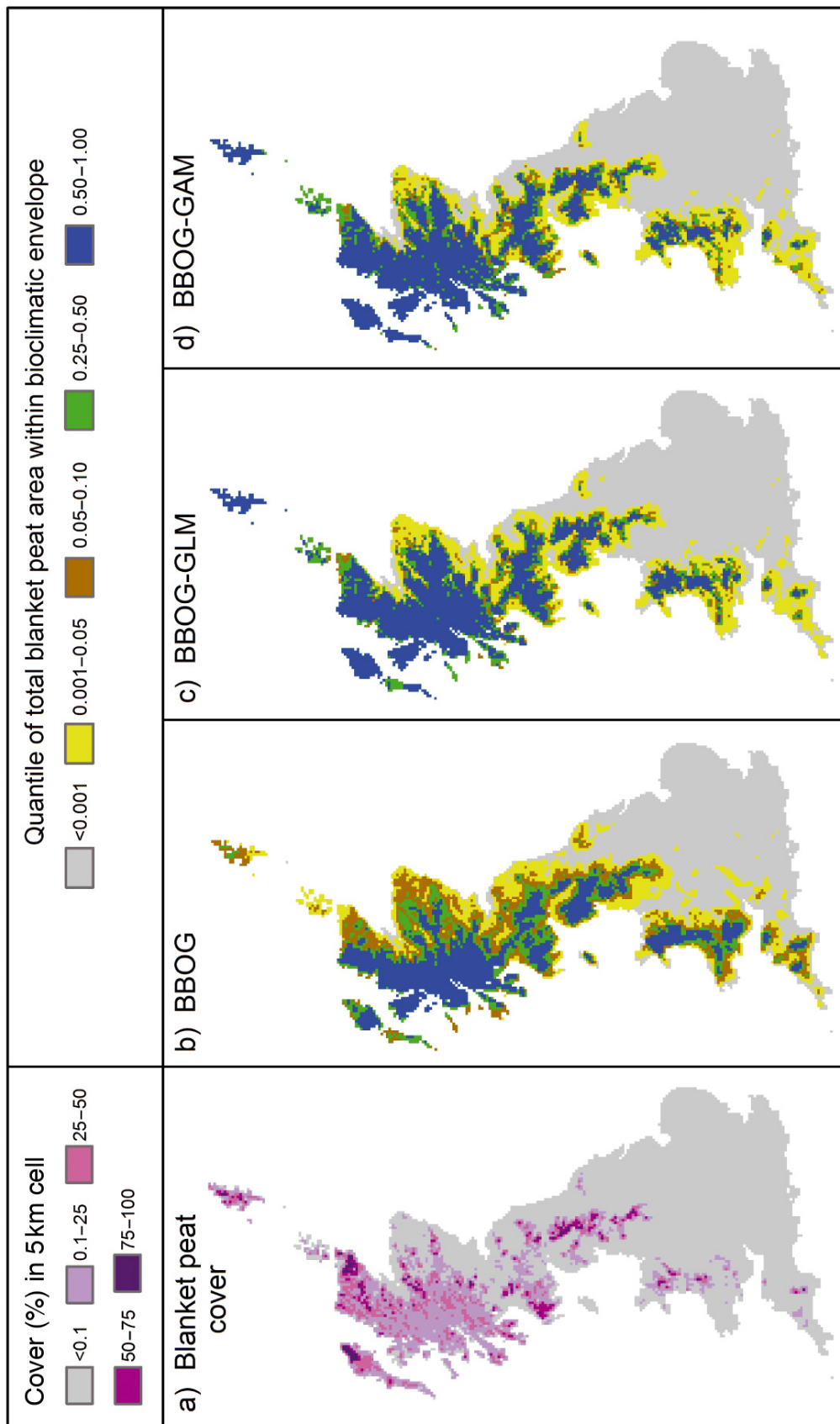
Fig. 1. Comparison between (a) mapped blanket peat cover and (b) BBOG, (c) BBOG-GLM and (d) BBOG-GAM bioclimatic envelope models (BCEMs) fitted to the 1961–1990 baseline climate data at 5 km grid scale. (a) Percentage blanket peat cover in each 5 km grid cell. (b–d) Quantile of the area where continuous BCEMs predict blanket peat presence with values greater than the threshold value (see Table 3). For instance, a quantile of 0.001 to 0.05 shows the areas predicted to be towards the bottom 0.1 to 5 % of the total GB blanket peat bioclimatic space; and a quantile 0.50 to 1.00 shows the areas predicted to be in the upper 50 % range of the defined bioclimatic space. BCEMs are defined in Table 1

increase in winter precipitation by up to 30% by 2071–2100, relative to the 1961–1990 baseline, depending on region and emission scenario (Hulme et al. 2002). In UKCIP02, there is only one model output for each of the 4 different emissions scenarios. In comparison, UKCP09 projections are based on 10000 model outputs for 3 emission scenarios, and provide more complex probabilistic projections. Projected increases in mean winter and summer temperature across administrative regions from UKCP09 range from 0.9 to 8.1°C, with 50% probability of an increase of 2.0 to 5.0°C for low to high emission scenarios. In terms of precipitation, projections show a 50% probability of a 9 to 35% decrease in mean summer precipitation and a 50% probability of an 11 to 30% increase in winter precipitation across each administrative region (Murphy et al. 2009). Hence the range of projections under UKCIP02 is similar in magnitude to the range of projections under UKCP09 with 50% probability.

2.2.3. Derived climate variables

Potential evapotranspiration (PET): Estimates of PET were needed to estimate changes in the water balance. Many equations are available with differing data requirements. As the statistical envelope models developed were applied over a wide area, 3 models were chosen with minimal data requirements: the modified Thornthwaite (Thornthwaite 1948, Mather 1978), Priestley-Taylor (Priestley & Taylor 1972) and Hargreaves (Hargreaves et al. 1985, Allen et al. 1998) equations (see Supplement 1, available at www.int-res.com/articles/suppl/c045p131_supp.pdf). Although the Penman-Montieth equation is regarded as the most physically-based model, it was not used due to the impossibility of specifying some of its parameters, including wind speed and conductances. Greater uncertainty with some of the projected climate variables needed for the Penman-Monteith model (e.g. wind speed) can result in unreliable forecasts of PET (Kay & Davies 2008).

Modified Thornthwaite-Mather moisture index: The Thornthwaite-Mather moisture index (TMI) is a measure the annual balance between precipitation (*P*) and PET (Thornthwaite & Mather 1955, Willmott & Feddema 1992):

$$\text{TMI} = \begin{cases} P/\text{PET} - 1, & P < \text{PET} \\ 1 - \text{PET}/P, & P \geq \text{PET} \end{cases} \quad (1)$$

PET was estimated using the modified Thornthwaite equation. The TMI presents values scaled between –1 (very dry) to 1 (very wet), providing a relative measure of the degree of wetness or aridity that would be hard to determine from the difference between the absolute values alone.

Annual accumulated monthly water deficit (AAMWD):

$$\text{AAMWD} = \sum_{m=1}^{12} \text{MWD} \quad (2)$$

$$\text{where MWD} = \begin{cases} P - \text{PET} & [P < \text{PET}] \\ 0 & [P > \text{PET}] \end{cases}$$

where MWD is the monthly water deficit (*P* – PET) for month *m*; *P* is precipitation (mm mo^{-1}); PET is potential evapotranspiration (mm mo^{-1}). The AAMWD was calculated for each of the 3 evaporation models. The AAMWD takes into account seasonality in the balance between *P* and PET, which is not considered in annual indices like TMI. Seasonality can be a better, and more appropriate, explanatory variable for bog distributions than annual indexes (Gignac et al. 2000). The approach is also consistent with previous methods used to analyse paleoecological reconstructions of water tables with respect to observed climate data and calculated total seasonal water deficit accumulated over a year (Charman 2007, Charman et al. 2009).

Continentality: Continentality was calculated as the difference between maximum and minimum monthly mean temperature (after Parviainen & Luoto 2007). Minimal seasonal variation in temperature is associated with blanket bog distribution (Lindsay et al. 1988). This variable has also been found to be a good predictor of blanket peat areas amongst a peatland complex of other mire types (Parviainen & Luoto 2007).

Accumulated temperature: Accumulated temperature is the annual sum of the monthly mean temperature multiplied by the number of days in each month (Gregory 1954). Although not the same as growing degree days, analysis showed a good correlation between these 2 variables (Clark et al. 2010, this Special), and the accumulated temperature is easier to calculate. Most notably, it provides a key physiological variable in terms of plant growth.

2.3. Statistical envelope model ensemble

2.3.1. Published blanket peat BCEMs

There are few published statistical blanket peat envelope models. Four models found in the literature were used here. Pearsall noted that blanket bog in GB tends to occur in areas of precipitation >1250 mm yr^{-1} (Pearsall 1950) and where precipitation is >3 times the annual potential evapotranspiration (Pearsall 1965). We have formalised these observations as simple threshold models (Table 1). Hossell et al. (2000) derived a model based on mean annual temperature (T) (Table 1), which was chosen in the absence of available data on maximum average temperature (T$_{max}$). Lindsay et al. (1988) defined conditions associated with blanket bog

Table 1. Statistical bioclimatic envelope models for blanket peat from published sources and derived in this paper. Models range from simple thresholds or 'rule of thumb' to classification tree (CLT), generalised linear models (GLM) and generalised additive models (GAM). P(BP): probability of blanket peat occurrence (presence = 1, absence = 0). All other variables defined in Table 2

Abbreviation	Method	Model	Source
P50	Threshold	$P(BP) = 1$ if $P > 1250$ mm yr^{-1}	Pearsall (1950)
P65	Threshold	$P(BP) = 1$ if $P > 3(PET)$	Pearsall (1965)
H-GLM	GLM	$P(BP) = \dfrac{\exp[21.64 - 2.6145T]}{1 + \exp[21.64 - 2.6145\mathbf{T}]}$	Hossell et al. (2000)
L	Threshold	$P(BP) = 1$ if $P > 1000$ mm yr^{-1} $T_m < 15°C$ > 160 RD	Lindsay et al. (1988)
L-GLM	GLM	$P(BP) = \dfrac{\exp(3.472 - 1.046T_m + 0.001140P + 0.05379RD)}{1 + \exp(3.472 - 1.046T_m + 0.001140P + 0.05379RD)}$	after Lindsay et al. (1988)
L-GAM	GAM	$P(BP) = f_1(T_m) + f_2(P) + f_3(RD)$ where f_1, f_2 and f_3 are cubic smoothing splines with smoothing parameters 6.8, 8.6 and 7.4, respectively	after Lindsay et al. (1988)
LM	Threshold	$P(BP) = 1$ if $P > 1000$ mm yr^{-1} $T_m < 15°C$	after Lindsay et al. (1988)
LM-GLM	GLM	$P(BP) = \dfrac{\exp(16.12 - 1.512T_m + 0.003452P)}{1 + \exp(16.12 - 1.512T_m + 0.003452P)}$	after Lindsay et al. (1988)
LM-GAM	GAM	$P(BP) = f_4(T_m) + f_5(P)$ where f_4 and f_5 are cubic smoothing splines with smoothing parameters 6.4 and 8.8, respectively	after Lindsay et al. (1988)
BBOG	Threshold	$P(BP) = 1$ if $AAMWD_{PT} > -45.1$ mm yr^{-1}	Present study
BBOG-TREE	CLT	$P(BP) = 1$ if $T_{max} < 17.4$, $TMI > 0.41$ $T_{max} > 17.4$, $AAMWD_{PT} < -28.6$ mm yr^{-1}	Present study
BBOG-GLM	GLM	$P(BP) = \dfrac{\exp(13.51 - 1.341T_m + 9.165TMI)}{1 + \exp(13.51 - 1.341T_m + 9.165TMI)}$	Present study
BBOG-GAM	GAM	$P(BP) = f_6(T_{min}) + f_7(C) + f_8(TMI)$ where f_6, f_7 and f_8 are cubic smoothing splines with smoothing parameters 8.4, 6.0 and 6.1, respectively	Present study

distribution as occurring in areas with precipitation > 1000 mm yr^{-1}, mean monthly temperature of the warmest month (T_m) less than 15°C and more than 160 days per year with rainfall. As future raindays were not readily available from some climate model projections, the Lindsay model was modified by removing the raindays term. The effect of removing raindays was compared with the original threshold model using the observed baseline data (1961–1990).

2.3.2. Derived blanket peat BCEMs

Measured and derived climatic variables thought to be associated with blanket peat development were considered in statistical analysis between baseline climate data (1961–1990) and the presence/absence blanket peat map for GB. We adopted a similar approach to Fronzek et al. (2006) and Parviainen and Luoto (2007). The blanket peat and climate data were split into calibration and validation data sets, with 70%

of the presence and absence data randomly selected for model calibration and the remaining data kept for evaluation. Fifteen climate variables used were (see also Table 2): mean annual temperature (T), maximum of the mean monthly daily maximum temperature (referred to as maximum temperature) (T_{max}), minimum of the mean monthly daily minimum temperature (referred to as minimum temperature) (T_{min}), maximum T_m (as used by Lindsay et al. 1988), accumulated temperature (T_{ac}), continentality (C), total annual precipitation (P), total annual PET (estimated after Thornthwaite (PET_{Th}), Preistley-Taylor (PET_{PT}) and Hargreaves (PET_H)), and AAMWD (estimated using each of the 3 evaporation methods ($AAMWD_{Th}$, $AAMWD_{PT}$, $AAMWD_H$)). Raindays were included for comparative analysis in initial stages, although were removed from final models (see Section 2.3.2).

A set of 4 statistical models for British blanket bog (BBOG ensemble) were derived. A range of statistical models commonly used for the development of habitat models were used (Guisan & Zimmermann 2000): simple

threshold, regression and classification tree (TREE), logistic regression with logit link function (generalized linear model, GLM) and generalized additive model (GAM). GAM analysis was carried out using cubic regression smoothing splines (Zuur et al. 2009). A simple threshold model (BBOG) was chosen by selecting the most appropriate single variable that best matched the mapped blanket peat area. Thresholds were set at the 5th or 95th percentile for the climate variable covering cells containing blanket peat used for model calibration to ensure that 95% of the current mapped blanket peat area was included within the model. The choice of climate variable was based on the minimum area falling outside the mapped peat area (i.e. the ability of the climate variable to closely define the niche space) and expert opinion about the relevance of the climatic variable with respect to understanding how it influences peat formation. For the classification/regression tree (BBOG-TREE), logistic regression (BBOG-GLM) and GAM (BBOG-GAM), a 2 stage search procedure was carried out. (1) Significant variables ($p < 0.05$) were selected automatically within the regression tree and by step-wise backward selection within the GLM and GAM from all the climate variables used in the analysis. Expert opinion was then used to create meaningful combinations of the significant climatic variables, taking care to ensure models were not over fitted by including highly correlated variables. Each model combination was evaluated, and model selection was based on the minimal number of variables needed to explain the variance in the data (i.e. the most parsimonious model), the lowest residual deviance, AIC (Akaike's Information Criterion) and whether a change in variables was significant according to ANOVA between model fits (using a chi-squared distribution). To further compare the effect of different statistical models used, the simple threshold models were compared with GLM and GAM models fitted to the same climate variables used for both the original and modified Lindsay threshold models.

2.4. Data analysis

Assessment of the bioclimatic model fit was carried out on the verification data set. Model sensi-

tivity, accuracy and Kappa statistic (Cohen 1960) were calculated for all models based on presence/absence of blanket peat defined from a critical threshold. For threshold and classification tree models, these critical thresholds were defined as part of the model structure. For GLM and GAM models, the critical predicted probability P(BP) was selected as the value covering 95% of the blanket peat area in the verification data set. 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 presence and absence recorded in the whole data set (Pearce & Ferrier 2000). The Kappa statistic was used because it provides a more meaningful measure of classification accuracy, as it compares actual classification with the classification that may have occurred by chance (Monserud & Leemans 1992).

For GLM and GAM models, the square of the residual deviance (D^2) and the AUC (area under a relative operating characteristic curve) were also used. D^2 is a measure of deviation of residual from the fitted model to the null model, and is analogous to R^2 in normal regression models (Guisan & Zimmermann 2000). Unlike Kappa, the AUC provides a threshold independent estimate of model performance (Pearce & Ferrier 2000).

Table 2. Threshold for each climate variable required to cover 95% of the mapped blanket peat area in the calibration data set from baseline 1961–90 climate data. Area without blanket peat cover is shown. 5th or 95th percentile was selected. °D: degree-days

Variable	Abbreviation	Units	95% threshold	No blanket peat (%)
Maximum temperature	T_{max}	°C	17.91	34.6
Maximum monthly mean temperature	T_m	°C	13.94	34.9
Potential evapotranspiration (Hargreaves)	PET_H	mm yr^{-1}	589.50	42.6
Annual accumulated monthly water deficit (Hargreaves)	$AAMWD_H$	mm yr^{-1}	−103.98	43.8
Annual accumulated monthly water deficit (Priestley-Taylor)	$AAMWD_{PT}$	mm yr^{-1}	−45.14	44.1
Potential evapotranspiration (Priestley-Taylor)	PET_{PT}	mm yr^{-1}	405.84	45.8
Thornthwaite-Mather Index	TMI	no units	0.37	46.7
Accumulated temperature	T_{ac}	°D	3150.60	49.8
Mean temperature	T	°C	8.61	50.0
Total precipitation	*P*	mm yr^{-1}	898.71	50.9
Potential evapotranspriation (Thornthwaite)	PET_{Th}	mm yr^{-1}	596.24	51.1
Annual accumulated monthly water deficit (Thornthwaite)	$AAMWD_{Th}$	mm yr^{-1}	−102.90	52.8
Continentality	C	°C	18.63	55.0
Minimum temperature	T_{min}	°C	1.64	75.6
Raindays[a]	RD	d yr^{-1}	156	18.0

[a]Raindays were not selected for the model analysis, as data on projected changes in raindays were not directly available, although raindays were included for comparison

The BCEMs with continuous outputs (i.e. BBOG-GLM, BBOG-GAM, LM-GLM) were used to rank different geographic regions based on their relative position within the defined bioclimatic space. For each BCEM, the continuous output for each 5 km grid cell across GB was ordered from low to high, and reassigned the appropriate quantile value between 0 and 1 for the position within the data. Data were then regrouped based on geographic regions. Regions were then ranked in order of low (rank = 1) to high (rank = 20) based on the median quantile value for all the 5 km grid cells within each region. As each region varied in size from 325 to 19 350 km^2, the median value was chosen to provide the most consistent simple statistic describing the relative position of each region within the bioclimatic space. Although there is inherent variability within each region, these rankings give a simple overview of which regions were relatively closer to the lower limit of the defined bioclimatic space.

Model sensitivity analysis was carried out with respect to each of the 3 input climate variables: temperature, precipitation and cloud cover. Factorial changes for precipitation and cloud cover and difference changes for temperature were applied to the monthly 1961–1990 baseline climate data. The percentage change in the bioclimatic space for each of the models was compared relative to the model fitted to the 1961–1990 climate data.

3. RESULTS

3.1. Calibration

The threshold model (BBOG) chosen was based on expert judgement about peat formation. As peat formation is primarily controlled by saturation associated with a positive water balance (Wieder & Vitt 2006), the annual accumulated monthly water deficit (AAMWD) was selected (Table 1, Fig. 1b) in preference to maximum temperature, even though the threshold based on maximum temperature contained a smaller area where blanket peat was predicted to be absent (Table 2). Priestley-Taylor (threshold value −45.1 mm yr^{-1}) was chosen in preference to Hargreaves to compute AAMWD. While the results were similar, Priestley-Taylor is more physically based (Table 2). Although used only for comparison, raindays was the single variable (>156 d yr^{-1}) that had the smallest area with no blanket peat cover (18%, Table 2).

Regression tree analysis of all climatic variables (excluding raindays) identified maximum temperature, TMI and AAMWD, using Priestley-Taylor evaporation, as explanatory variables (BBOG-TREE; see Fig. S1, available at www.int-res.com/articles/suppl/c045p131_
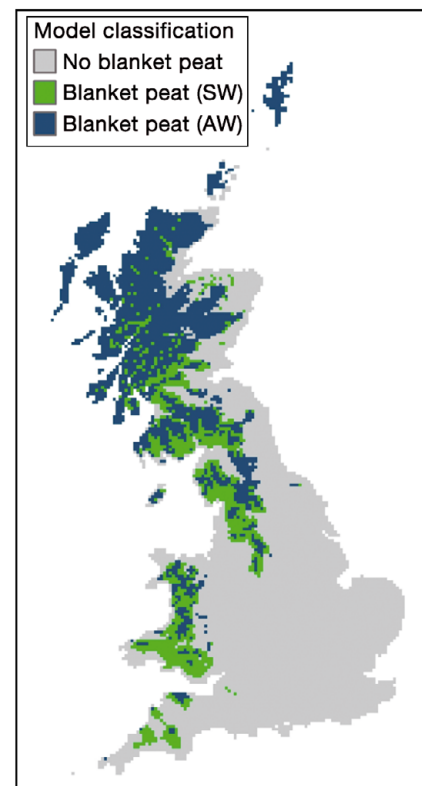

Fig. 2. BBOG-TREE classification of blanket peat area using baseline climate data (1961–1990). AW: areas classified on the basis of an annual wetness index (Thornthwaite-Mather Index); SW: areas classified on the basis of seasonal wetness index (annual accumulated monthly water deficit). BBOG-TREE is defined in Table 1

supp.pdf). Probability of blanket peat presence was replaced by a classification based on a presence/absence within the tree. A 3-level model was chosen as this had a lower misclassification rate for the blanket peat area (8.9% of blanket peat area) than the 5-level model selected automatically (12.5% of blanket peat area). Data were first split based on maximum temperature (threshold 17.4°C). In the group where maximum temperature was <17.4°C, blanket peat areas were classified where the TMI > 0.41 (i.e. in the 'wettest' areas within this group based on an annual index). In the group where maximum temperature was >17.4°C, blanket peat areas were found where the AAMWD (estimated using the Priestley-Taylor equation) was >−28.6 mm yr^{-1}. Therefore, in the 'warmer' areas a seasonal index of 'wetness' was selected to identify blanket peat areas, whereas an annual 'wetness' index was selected to identify blanket peat in cooler areas (Table 1, Fig. 2).

Backward selection of explanatory variables by logistic regression found the following significant regression parameters (p < 0.01): precipitation, mean

temperature, accumulated temperature, minimum temperature, maximum monthly mean temperature, TMI and PET estimated using the Thornthwaite equation. Many of these variables represent similar factors (e.g. mean temperature and accumulated temperature), therefore further selection and simplification of the model was carried out by combining data that were not directly related (e.g. precipitation and temperature). Of the possible combinations of variables, monthly maximum mean temperature (T_m) and TMI resulted in the lowest AIC (AIC = 2890) (BBOG-GLM; Table 1, Fig. 1c). Similar stepwise backward selection using the GAM model found a different combination of significant explanatory variables: minimum temperature, accumulated temperature, continentality, TMI and PET estimated using the Hargreaves and Priestley-Taylor equations (p < 0.001). As in the GLM analysis, meaningful combinations of variables were again explored, with the most parsimonious model with significant regression parameters selected as minimum temperature, continentality and TMI (BBOG-GAM; Table 1, Fig. 1d).

For comparison, GLM and GAM models were fitted to the climate variables used by Lindsay et al. (1988). Significant regression model fits (p < 0.0001) within similar AIC values were obtained with GLM models fitted using all raindays, P and T_m (AIC = 2796) and a modified version with P and T_m and raindays excluded (AIC = 2971) (Table 1), suggesting these models were similar to both BBOG-GLM and BBOG-GAM in terms of their fit to the mapped area of blanket peat and 1961–1990 baseline climate data used in the calibration data set.

3.2. Comparison of model fit to baseline climate (1961–1990)

In general, GLM and GAM models performed better than the threshold and classification tree models in terms of the ability to correctly predict blanket peat presence and absence, with greater sensitivity, accuracy and Kappa (Table 3). BBOG-GLM and BBOG-GAM had similar classification accuracy (accuracy 90.6%, Kappa 0.79), which were greater than BBOG-TREE (accuracy 87.5%, Kappa 0.72) and BBOG (accuracy 83.3%, Kappa 0.65). The maps showing the area of blanket peat covered by each envelope model show that BBOG and BBOG-TREE did not cover parts of northeast Scotland and Orkney, whereas BBOG-GLM and BBOG-GAM show good cover across the country (Fig. 3a–d).

Both the GLM and GAM fits to the data using the variables from the original and modified Lindsay models (L and LM, respectively) were similar (accuracy 90.4 to 91.1%; Kappa 0.78 to 0.80) and greater than the threshold based models (accuracy 83.3 to 89%; Kappa 0.73 to 0.75), although the differences were small. As with the BBOG models, both threshold based L and LM models did cover parts of north and east Scotland, and also northeast England (Fig. 3e–h). As LM models appeared to provide a comparable fit to the original models, L, L-GLM and L-GAM were not used further due to the absence of projected changes in raindays.

Whilst the H-GLM model threshold was chosen so that it covered 95% of the blanket peat area, with high sensitivity (96.1%), the accuracy and Kappa were low, as most of northern GB rather than just upland areas were covered by the model (Fig. 3i). A low sensitivity (66.1%) and low Kappa (0.59) for the rainfall based threshold model (P50), leaves a large area of mapped blanket peat uncovered to the east (Fig. 3j). Of the possible precipitation/potential evaporation models, P65$_{PT}$ (i.e. evaporation calculated using the Priestley-Taylor model) provided the best fit (Fig. 3k) and was similar to the L and LM threshold models (accuracy 88.3%, Kappa 0.72). P65$_{Th}$ and P65$_H$ (Fig. 3l and not shown, respectively) produced a poor fit to the currently mapped data and were not used further.

Table 3. Assessment of bioclimatic envelope model fit to the blanket peat verification data set. Threshold cover for 95% blanket peat area in calibration data set was chosen for the continuous probability models. Models are described in Table 1. P65$_H$, P65$_{PT}$ and P65$_{Th}$ are calculated using Hargreaves, Priestley-Taylor and Thornthwaite evaporation models, respectively. AUC: area under a relative operating characteristic curve; D^2: residual deviance squared

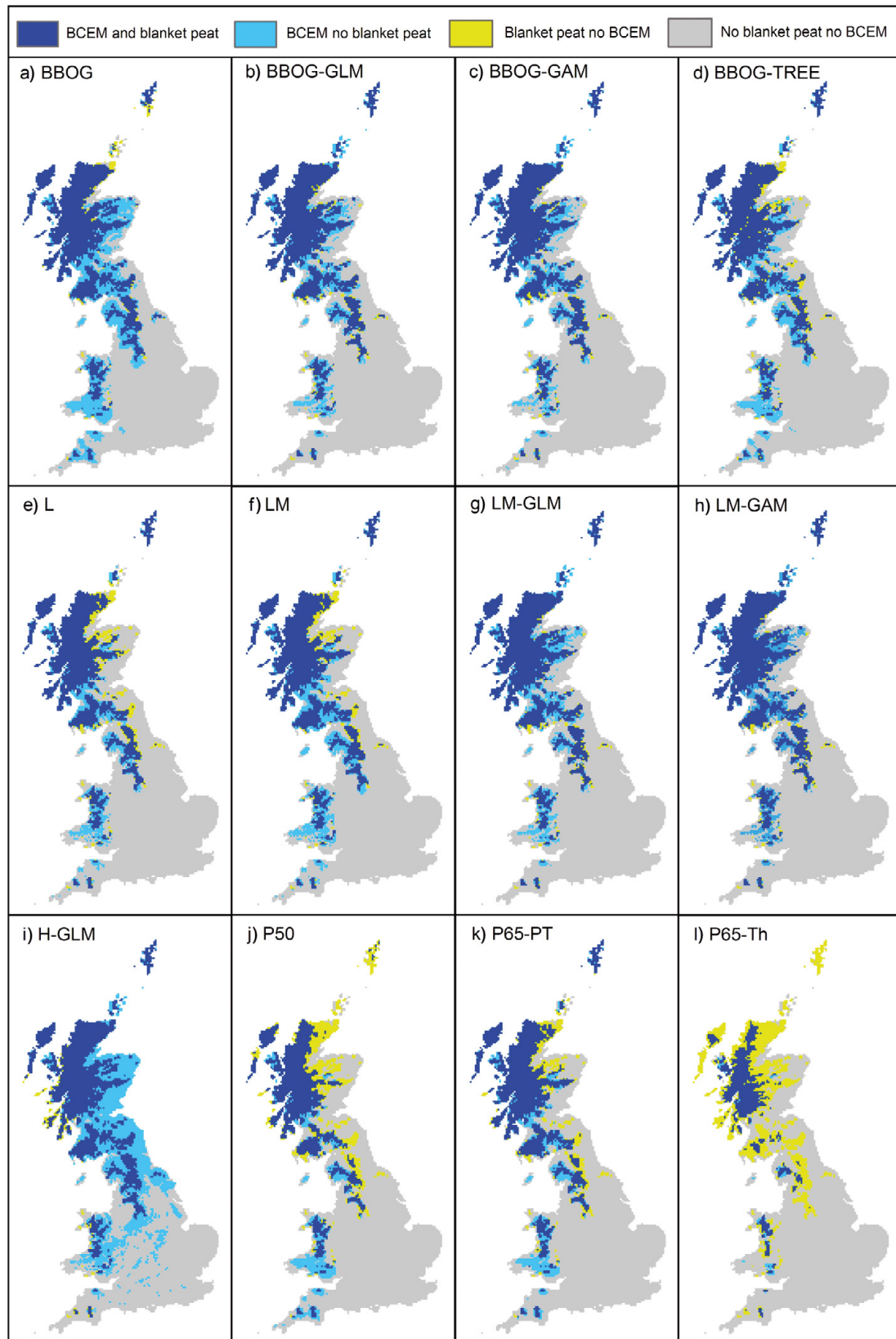| Model	D^2	Threshold (0 < P(BP) < 1)	Determined for threshold value Sensitivity (%)	Accuracy (%)	Kappa	AUC
P50	–	–	66.1	83.6	0.59	–
P65$_H$	–	–	34.1	79.5	0.40	–
P65$_{PT}$	–	–	81.4	88.3	0.72	–
P65$_{Th}$	–	–	42.7	81.9	0.49	–
L	–	–	86.2	89	0.75	–
LM	–	–	89.3	87.9	0.73	–
BBOG	–	–	96.1	83.3	0.65	–
BBOG-TREE	–	–	91.2	87.5	0.72	–
H-GLM	–	0.18	96.1	74.4	0.50	0.90
L-GLM	66.5	0.24	94.3	90.4	0.78	0.97
L-GAM	69.0	0.27	94.7	90.8	0.79	0.97
LM-GLM	64.4	0.25	94.6	90.4	0.79	0.97
LM-GAM	67.5	0.28	94.9	91.1	0.80	0.97
BBOG-GLM	65.4	0.27	94.7	90.6	0.79	0.97
BBOG-GAM	67.6	0.27	95	90.6	0.79	0.97

Fig. 3. Overlay of different bioclimatic envelope models (BCEMs) for baseline climate period (1961–1990) on the mapped 5 km gridded data of blanket peat presence. Envelope models are described in Table 1

3.3. Sensitivity analysis

Simple sensitivity analysis of the 10 best fitting models to independent changes in precipitation, temperature, and cloud cover broadly showed the climate space to decline with decreasing precipitation, increasing temperature and decreasing cloud cover (Fig. 4). BBOG-GLM and BBOG-GAM showed similar responses to changes in precipitation and temperature in spite of the differences in climatic variables used (Table 1). BBOG-TREE and BBOG were slightly more sensitive to changes in precipitation than BBOG-GLM and BBOG-GAM, and considerably less sensitive to change in temperature. LM, LM-GLM and LM-GAM also showed similar response to changes in precipitation and temperature <+4°C. Although the same variables were used, the model structures were subtly different. At a temperature change >+4°C, LM-GAM showed an increase in bioclimatic space. This result seems to be counter intuitive and is probably due to over fitting the GAM model to the observed data, such that results become unrealistic once temperatures go beyond the data within the fitted range. Hence, LM-GAM was not used for further analysis. The only 3 models that show sensitivity to changes in cloud cover are the models using the Priestley-Taylor PET model.

The comparative sensitivity of each BCEM with respect to the fit to the 1961–1990 base line climate data can be considered by comparing the 'LD50'; that is the amount of climate change (or 'lethal dose') needed to cause a reduction in the climate space so that only 50% of the 5 km grid cells with blanket peat presence are covered (Table S1, available at www.int-res.com/articles/suppl/c045p131_supp.pdf). In terms of precipitation change, the precipitation based models P50 and $P65_{PT}$ were most sensitive (–13 to –22% decline), although that is in part because these areas cover a lower proportion of blanket peat (67 to 82%). The other threshold modes, LM, BBOG and BBOG-TREE, which covered slightly larger areas (89 to 95%) require a change in precipitation of –30 to –32% before reaching the 'LD50'. BBOG-GLM and BBOG-GAM required the greatest change (–43 to –46%) although they covered larger areas (95%). However, BBOG-GLM, BBOG-GAM, H-GLM and LM required a smaller change in temperature (+1.8 to 2.2°C) than BBOG, BBOG-TREE and $P65_{PT}$ (+8.2 to 11°C) to be reduced to 50% cover of the grid cells where blanket peat was present. So in general, in spite of covering a smaller number of blanket peat grid cells under 1961–1990 baseline climate data, the threshold-based models were more sensitive than the GLM and GAM models to changes in precipitation and less sensitive to changes in temperature.
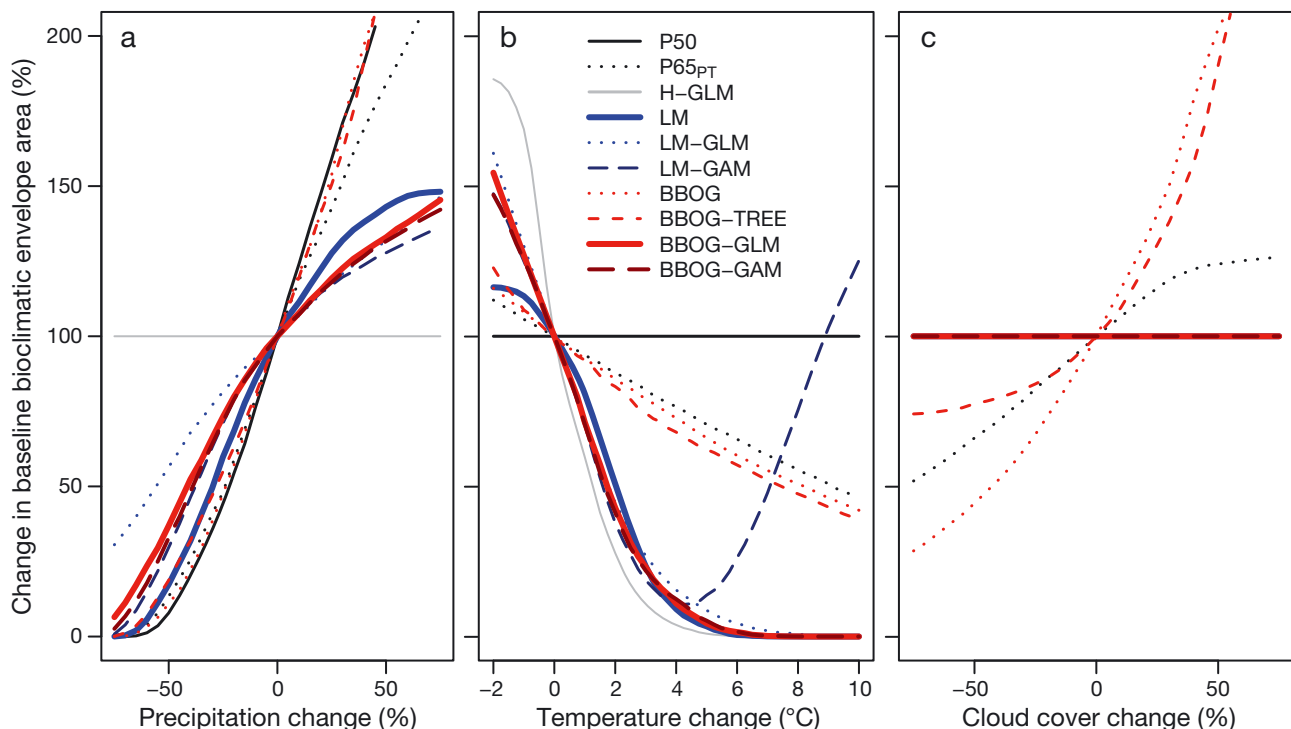

Fig. 4. Sensitivity analysis of bioclimatic envelope models for a single fixed change in either (a) precipitation (b) temperature or (c) cloud cover to 1961–1990 baseline climate data. Changes were applied as single values to the mean monthly data. Models are defined in Tables 1 & 3

Table 4. Mapped peat area and rank of climatic vulnerability by region. Ranks based on order of median quantiles for each continuous bioclimatic envelope model output from the baseline (1961–1990) climate data (see Fig. 4). Rank 1 is at the lower limit of the bioclimatic space and Rank 20 is at the upper limit of bioclimatic space. Fig. S2 (available at www.int-res.com/articles/suppl/c045p131_supp.pdf) delineates the blanket peat regions. E: England; W: Wales; S: Scotland

Country and Region			Mapped blanket peat area		Rank order based on BCEM			
			(km^2)	(% of total)	BBOG-GLM	BBOG-GAM	LM-GLM	Average rank
E	NB	Northumbria	325	2.1	1	1	1	1
E	DE	Dartmoor, Exmoor & Bodmin moor	146	0.9	3	3	2	2
E	PD	Peak District	476	3	2	4	3	3
W	BB	Brecon Beacons & South Wales	52	0.3	4	2	4	4
E	NY	North York Moors	40	0.3	6	6	5	5
S	OR	Orkney	115	0.7	5	5	11	6
S	CB	Central Belt	238	1.5	8	7	8	7
E	NP	North Pennines	691	4.5	9	11	6	8
S	DG	Ayrshire, Dumfries & Galloway	1118	7.1	10	9	9	9
S	CS	Caithness & East Sutherland	1903	12	7	8	15	10
E	YD	Yorkshire Dales & Bowland	765	4.8	11	14	7	11
W	CM	Cambrian Mountains	209	1.3	13	10	12	12
S	SB	Scottish Borders	238	2	14	13	10	13
W	SN	Snowdonia & North Wales	393	2.5	12	12	13	14
S	GR	Grampians	718	4.5	19	15	14	15
S	WI	Western Isles	1366	8.6	15	16	19	16
S	AB	Argyle, Bute & Trossachs	2142	13.5	17	17	17	17
E	CF	Cumbria Fells & Dales	182	1.2	18	18	16	18
S	SH	Shetland	648	4.1	16	19	18	19
S	HI	Highlands	3995	25.2	20	20	20	20
All			15830	100				

3.4. Regional climatic vulnerability

An understanding of the relative climatic vulnerability of each region within GB, independent of choice of GCM and/or emission scenario, could inform policy decisions and blanket peat management, such as prioritisation of restoration work. Although a rough picture of the comparative vulnerability can be seen at a national scale (Figs. 1 & 2), a more formal assessment is possible. BCEMs providing continuous data can be used to determine the relative vulnerability of each 5 km grid cell in terms of its relative position in the data set. Therefore, grid cells with values within the lowest 0.05 quantile (or lowest 5%) of the data set are sites closest to the lowest limit of the bioclimatic space, and are therefore likely to be more vulnerable to climate change. Individual grid cells can be ranked nationally (Figs. 1 & 2; Table S2, available at www.int-res.com/articles/suppl/c045p131_supp.pdf), but an assessment of comparative 'regional' vulnerability may be more useful to decision makers.

Areas were grouped into 20 known geographic regions, with blanket peat cover ranging from 52 to 3995 km^2 within each region (Fig. S2, Table S3, both available at www.int-res.com/articles/suppl/c045p131_supp.pdf). Ranked output from the continuous probability models, BBOG-GLM, BBOG-GAM and LM-GLM were aggregated to provide an overall regional vulner-

ability (Table 4). Although based on a continuous variable, BBOG could not be used as it was not possible to rank sites above the median distribution as many cells had the same value of 0 mm yr^{-1} (Table S1). H-GLM was not used, given the large overestimation of area (Fig. 3). In general, BBOG-GLM, BBOG-GAM and LM-GLM produced similar, although not identical, regional rankings with Northumbria (NB) found at the lowest end of the bioclimatic space and the Highlands (HI) found at the top (Table 4, Fig. 5). Dartmoor, Exmoor and Bodmin moor (DE), the Peak District (PD), the Brecon Beacons and South Wales (BB) were also consistently found in the lower 5 ranks, suggesting these regions are perhaps the most climatically vulnerable as they are at the lower edge of the bioclimatic space. In contrast the Shetland (SH), Western Isles (WI), Argyle, Bute and Trossachs (AB) and Cumbria Fells and Dales (CF) were consistently found in the upper 5 ranks, and are perhaps relatively the least vulnerable, as they are at the upper edge of the defined bioclimatic space.

Although a southeast–northwest gradient might be expected in vulnerability, as temperatures typically fall and rainfall increases in the north and west of GB, regional vulnerability does not necessarily follow this exact pattern. For instance, the North York Moors and Orkney are ranked 5 and 6, respectively, in spite of distances between each region; similarly, Caithness and
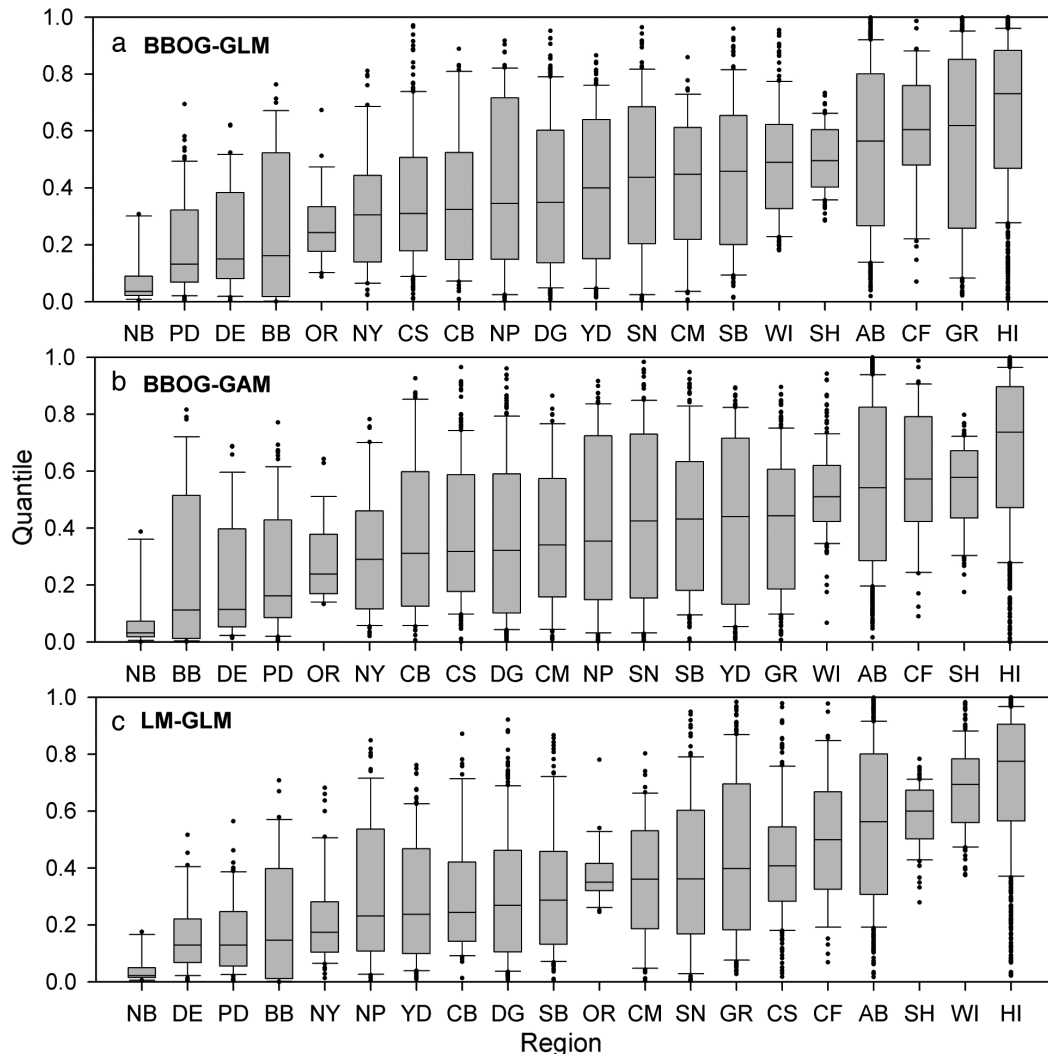
Fig. 5. Rank of the bioclimatic space covered by 3 continuous bioclimatic envelope models (BCEM) models. Quantile values closer to 0 are at the lower limit of the bioclimatic space (i.e. most marginal areas), and quantile values closer to 1 are towards to upper limit of the bioclimatic space. Boxes: interquartile range; whiskers: 5th and 95th percentiles; dots: outliers. Regions are defined in Table 4 and shown in Fig. S2 (available at www.int-res.com/articles/suppl/c045p131_supp.pdf)

East Sutherland were ranked alongside Yorkshire Dales and Bowland as Rank 10 and 11, respectively (Table 4). However, these rankings are based on median values, and many regions contain grid cells within the lowest 20%, therefore including potentially vulnerable areas of blanket peat. Table S2 can be used for a more detailed assessment of specific 5 km sites to investigate within-region heterogeneity.

3.5. Projected future changes in blanket peat bioclimatic space

An ensemble of the 8 statistical BCEMs was used to examine possible change in the bioclimatic space asso-

ciated with the mapped distribution of blanket peat. The 4 BBOG models were combined with 4 published models (P50, P65$_{PT}$, H-GLM and LM). Other tested BCEMs were removed due to poor fit or double counting of combinations of climate variables (e.g. LM and LM-GM). Together, they represent a range of possible outcomes, given the problem that all these models could be calibrated to provide a similar fit to the blanket peat map using the baseline climate data (Fig. 3).

Response to UKCIP02 projections for high and low emission scenarios showed a general retreat in the bioclimatic space to the north and west (Fig. 6). The models that were most sensitive to changes in temperature showed retreat to the high altitude areas towards the north (e.g. BBOG-GLM, BBOG-GAM, LM, H-GLM),

Number of bioclimatic envelope models covering each 5 km grid cell

| | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 |

UKCIP02 High Emissions Scenario

a) 1961–90   b) 2020s   c) 2050s   d) 2080s

UKCIP02 Low Emissions Scenario
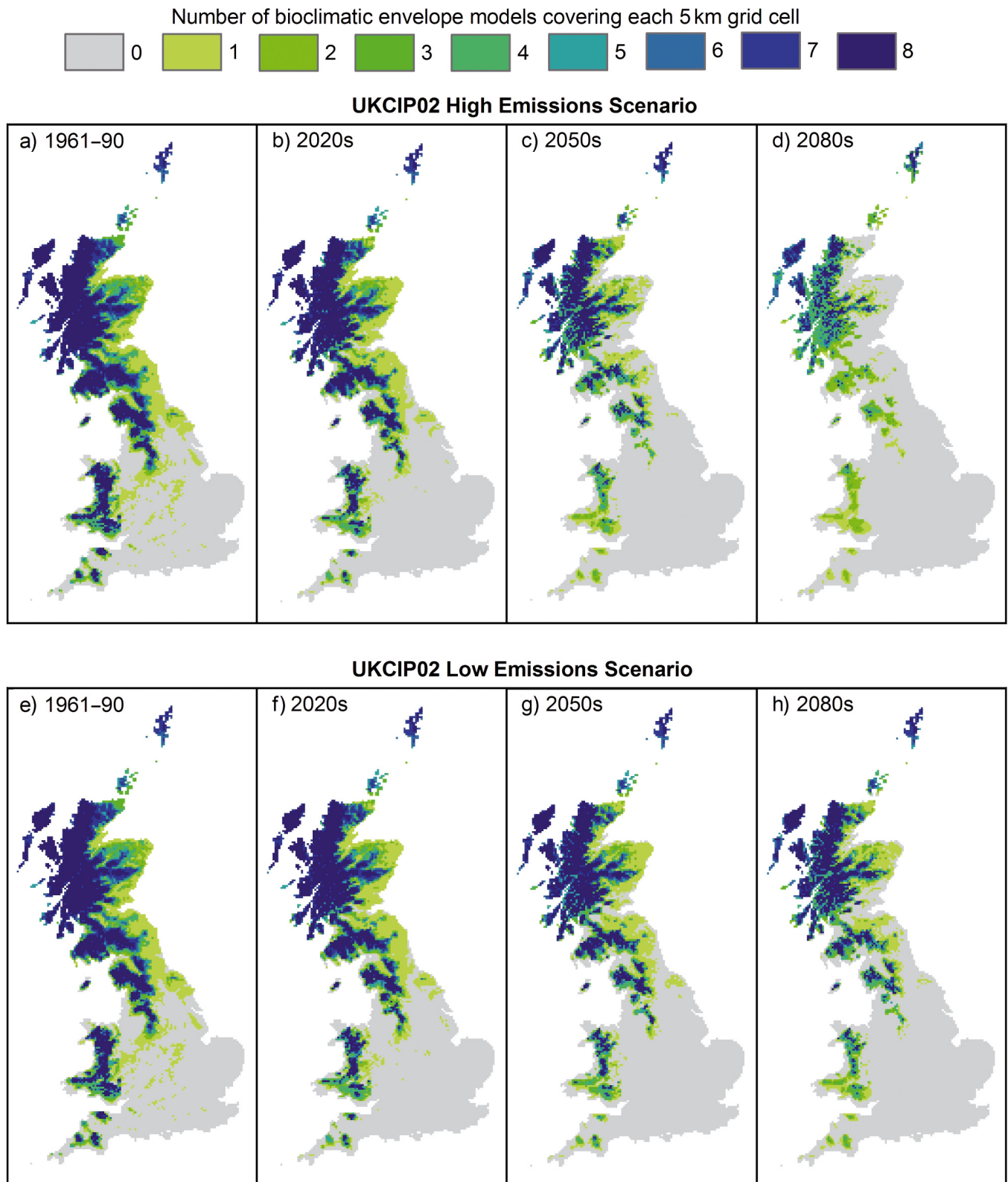

e) 1961–90   f) 2020s   g) 2050s   h) 2080s

Fig. 6. Projected changes in bioclimatic space associated with the 1961–1990 baseline climate and mapped area of blanket peat using UKCIP02 high and low emissions scenarios. 2020s: 2011–2040; 2050s: 2041–2070; 2080s: 2071–2100. Bioclimatic envelope models used were P50, P65$_{PT}$, LM, H-GLM, BBOG, BBOG-TREE, BBOG-GLM, BBOG-GAM (see Tables 1 & 3 for details). Change in each individual model output is shown in Figs. S3 & S4 (available at www.int-res.com/articles/suppl/c045p131_supp.pdf)
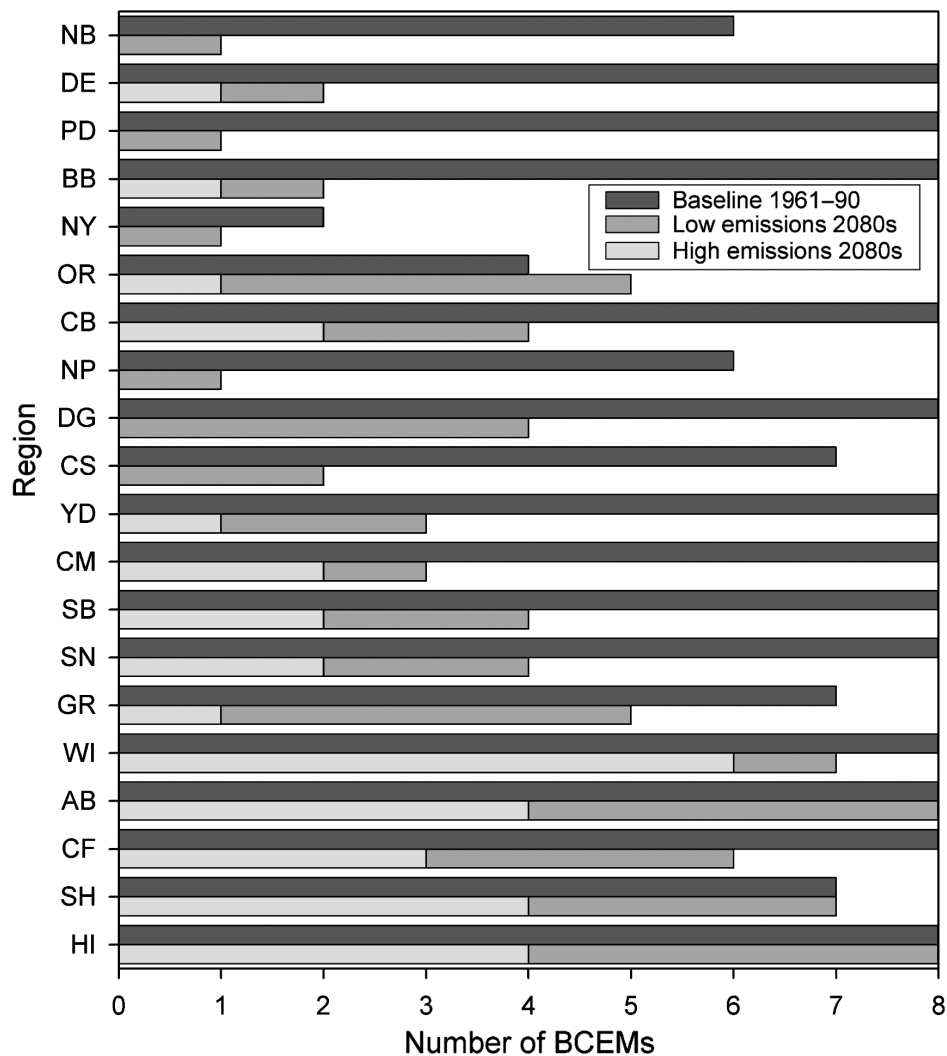
Fig. 7. Number of bioclimatic envelope models (BCEMs) covering at least 50% of each region using UKCIP02 high and low emission scenarios. 2080s: 2071–2100. BCEMs ordered based on overall ranking shown in Table 4

whereas the models based on water deficit showed a retreat towards the north and west (e.g. BBOG, BBOG-TREE, P65$_{PT}$). The model based on annual precipitation alone showed little change (P50) (see Figs. S3 & S4, available at www.int-res.com/articles/suppl/c045p131_supp.pdf).

Projected regional changes broadly followed the pattern of regional sensitivity presented in Table 4, as the 5 regions at the lower end of the bioclimatic space showed the greatest decline in blanket peat presence estimated by the 8-BCEM ensemble; and the 5 regions at the upper end of the climate space showed the least change (Fig. 7). However, there are slight differences as areas such as the North Pennines and Caithness and Sutherland appear to show greater retreat in the BCEM space than areas initially ranked lower like

Orkney and the Central Belt. This difference in response may be due to subtle differences in the ranking approach, as all 8 models for the ensemble were included based on a presence/absence classification rather than quantile of each 5 km grid cell. In the ranking shown in Fig. 5, North York Moors, Orkney, Northumberland, North Pennines and Caithness and East Sutherland have the lowest initial BCEM cover during 1961–1990, with Caithness and East Sutherland and Orkney replacing the Peak District and Brecon Beacons. However, the difference may also be caused by variation in the magnitude of climate change between regions. For instance, projections for changes in temperature for the Eastern and Southern parts of GB were greater than for other regions of the country (Hulme et al. 2002).

4. DISCUSSION

4.1. Comparison between 4 BBOG bioclimatic models and other published BCEMs

Broadly speaking, BCEMs could be split into 2 groups irrespective of structure and climatic variables used: (1) models that were more sensitive to changes in temperature than precipitation and (2) models that were more sensitive to changes in precipitation or 'wetness' than temperature. For instance, BBOG-TREE was more sensitive to changes in rainfall and less sensitive to changes in temperature than BBOG-GLM and BBOG-GAM in spite of containing similar climatic variables and providing a similar fit to the baseline climate and mapped peat area. Also, the threshold and GLM versions of the modified Lindsay et al. (1988) (LM) models showed a similar sensitivity and fit to both BBOG-GLM and BBOG-GAM, even though the climatic variables chosen in each model differed. LM contained precipitation only whereas BBOG-GLM and BBOG-GAM had measures of the balance between precipitation and potential evaporation. However, threshold models based on either precipitation, mean temperature, or the balance between precipitation and evapotranspiration alone did not fit the calibration data as well as models that contained measures of both 'water deficit' and temperature. Although a positive water balance and saturation is essential for peat formation, additional measures of temperature (particularly maximum temperature) were needed to improve the definition of the bioclimatic space associated with blanket peat.

As many of the BCEMs include explicit representations of the water balance, it seems unlikely that inclusion of temperature represents its effects on evapotranspiration alone. Maximum temperature has been identified as an important limiting factor controlling the distribution between upland and lowland grass species (Rodwell et al. 1992), such that warming may have caused invasion of upland areas by lowland species (Hossell et al. 2000) which could have higher rates of transpiration than peatland vegetation and act to 'dry out' the peat. Temperature also influences the rate of organic matter decomposition, which in turn affects carbon turnover and the accumulation of organic matter. Although temperature range (i.e. 'continentality') was identified as a key variable defining blanket peat bioclimatic space globally (Lindsay et al. 1988) and in Fennoscandia (Parviainen & Luoto 2007), maximum temperature provided a far better predictor for GB blanket peats.

As rainfall is transported from catchment hillslopes to streams within hours of falling (Evans et al. 1999), the distribution of rainfall through the year could be as important as the total amount in maintaining the persistently wet conditions essential for *Sphagnum* species (Backeus 1988, Lindsay 1995). Exclusion of raindays from the selected BCEMs was unavoidable as raindays were not directly available from climate projections. However, in the initial analysis, raindays emerged as the single most important predictor variable, consistent with other observations (Tansley 1939, Goode & Ratcliffe 1977, Lindsay et al. 1988). Further development and use of site specific computationally expensive tools like weather generators (e.g. Kilsby et al. 2007) at a wide national scale could improve BCEMs in future. Nevertheless, other combinations of climatic variables were able to provide almost as good a fit. For instance, excluding raindays from the Lindsay et al. (1988) model made little difference to the fit (Fig. 3). Raindays and total precipitation in practice are highly correlated (Clark et al. 2010), therefore precipitation can be used as a proxy for raindays. However, as climate change projections suggest a likely change in the distribution of precipitation throughout the year, with less change in total annual precipitation (Hulme et al. 2002, Jenkins et al. 2009), it is possible that the relationship between raindays and total annual rainfall may change somewhat over time.

4.2. Climatic vulnerability of blanket bog bioclimatic space

Seven out of the 8 bioclimatic models used in the ensemble showed a decline in the climate space associated with blanket peat using UKCIP02. Models that were more sensitive to changes in temperature, however this was represented, generally showed a retreat to high altitudes. Models that were more sensitive to changes in the water balance showed a retreat to the north and west following the gradient in precipitation. Threshold models based entirely on precipitation (P50) showed little change. Similarly, models that included total precipitation rather than an explicit measure of water balance followed the pattern of temperature-driven models. We infer that the retreat shown by the models driven by water balance seems likely to be influenced principally by projections for decreased summer precipitation, given the pattern of retreat and the explicit representation of monthly precipitation within the models calculated using the AAMWD. Paleoclimate studies have shown that the total accumulated seasonal water deficit is comparatively insensitive to changes in potential evaporation and is more sensitive to changes in summer precipitation (Charman 2007).

Given the known dependence of blanket bogs on water saturation for key peatland species, and for the required slow rates of decomposition, it seems likely

a priori that the water balance-driven BCEM group is the most realistic. However, water balance alone was not able to define the bioclimatic space associated with blanket peat as well as combinations of water balance with temperature. Changes in temperature, particularly maximum temperature, may be (at the least) equally important as a driver of changes in blanket bog distribution. As noted above, changes in temperature could influence both species composition and carbon accumulation.

Interestingly, the finding that maximum temperature was an important explanatory variable within BCEMs is consistent with paleoecological studies, where reconstructions of the surface wetness of GB raised bogs have shown a good relationship with summer temperature over centennial time periods that are likely to be important for net peat accumulation (Barber & Langdon 2007, Charman et al. 2009). The significance of temperature in comparison to precipitation and water deficit in controlling peatland surface wetness has been a recent topic of debate, with contrasting views (Barber & Langdon 2007, Charman 2007, Charman et al. 2009, Booth 2010). Higher resolution reconstructions have shown that measures of water deficit, rather than temperature or precipitation alone, are more clearly correlated with surface wetness and reconstructed water table fluctuations over shorter 5 to 10 yr time periods (Charman 2007, Charman et al. 2009, Booth 2010). It is unclear whether climatic variables driving shorter-term water table fluctuations (i.e. water deficit or AAMWD) or longer term measures of surface wetness (i.e. maximum or summer temperature) are more important for net peat accumulation in terms of the relative influence on peatland vegetation and structure relative to net organic matter decomposition. Non-linearities in proxy-climate response can hamper paleoclimate reconstructions, therefore dynamic models accounting for changes in peatland hydrology, accumulation and structure are needed to explore these relationships further (Charman 2007).

Differences between the bioclimatic space defined by temperature- and water balance-based BCEMs may explain some of the subtle differences between the regional ranking shown in Table 4 and Fig. 7. Across the different ranking methods, certain regions were consistently towards the lower limit of the bioclimatic space (e.g. Northumbria, North York Moors and Orkney) and others were towards the upper end (e.g. Highlands, Western Isles and Argyle, Bute and the Trossachs). However, other regions like Dartmoor, Exmoor, the Peak District and the Brecon Beacons did not appear as vulnerable when all 8 BCEMs were used, possibly due to the increased water surplus in these regions relative to others. The North Pennines and Caithness and East Sutherland appeared more vulnerable under the 8-BCEM ranking, and showed a comparable decline in bioclimatic space under projections for the 2080s to the most vulnerable regions.

A reduction in the bioclimatic space associated with blanket peat is consistent with findings of Hossell et al. (2000) under UKCIP98 projections using a GLM model based on mean temperature. However, these findings differ from other BCEM work, where artificial neural networks using measures of soil water deficit and surplus as well as maximum and minimum temperature showed little overall change in blanket bog habitat under the same UKCIP98 scenarios (Berry et al. 2003). Differences between projections here based on UKCIP02 and projections made by Berry et al. (2003) may be due to differences between climate projections, although a difference due to different BCEMs used seems likely. Berry et al. (2003) calibrated their models over a wider geographic area than the BBOG models that were trained solely on GB data. However, Berry et al. (2003) focused on plant species whereas the BBOG models were trained on mapped soil data. Blanket peat soils can be covered by a range of different species that can be found in a range of habitat types, e.g. *Sphagnum* mosses are found in rain-fed blanket peats and groundwater fed flushes, and *Calluna vulgaris* can be found on peat, peaty gleys and other organo-mineral soils under peatland and heathland habitats. Therefore, it is possible that species-based BCEMs may cover a wider range of habitat or soils across a broader bioclimatic zone than BCEMs based on soil survey data.

4.3. Limitations

Statistical BCEMs presented here are based on derived statistical relationships between the known mapped distribution of blanket peat or blanket bog habitats and climatic variables. While the simplicity of this approach allows for a widespread national assessment of climatic vulnerability, some limitations constrain the interpretation of these model outputs. Most notably, projected changes in the bioclimatic space associated with the current distribution of blanket peat are not the same as projected changes in the actual distribution of blanket peat over the next century; a reduction in the bioclimatic space for blanket peat will not result in the immediate disappearance of blanket peat, which may well persist over decades or longer even if not in a state of active growth.

Another caveat is that statistical relationships with climatic variables do not necessarily imply causal relationships, thus blanket peat distribution may only respond to some of the many climatic drivers used in the ensemble of BCEMs while the real distribution

may respond to others that were not used, e.g. climatic extremes such as frost and high intensity rainfall, (e.g. Bragazza 2008; Evans & Warburton 2007).

Climate overall is accepted as the key factor influencing the distribution of rain-fed blanket peat (Wieder & Vitt 2006), but geology and topography also contribute. Blanket peat tends to form on impermeable rocks or thick layers of glacial till on shallow slopes (typically <10°, although slopes up to 25° have been noted) where saturated conditions are allowed to develop because of impeded and/or slow drainage (Taylor 1983). In other wetland areas, topography has been used to map the distribution of saturated areas in topographic hollows and floodplains (Creed et al. 2008, Debella-Gilo & Etzelmüller 2009). However, blanket peat tends not to be confined to hollows or footslopes and is often found on hill-top plateaus (Taylor 1983).

As noted above the BCEMs have been calibrated against the current mapped distribution of blanket peat. It is currently unknown whether this mapped distribution reflects blanket peat that is in equilibrium with the current climate. Therefore the bioclimatic space calibration within the BBOG models may not reflect the actual bioclimatic envelope for blanket peat sustainability. Once peat initiation has been triggered, peat growth can sustain its own hydrology even in the absence of a suitable climate if the peat mass is in good condition; if not in good condition, peat formation may not re-establish itself in unfavourable climates (Lindsay 1995). Previous work has suggested that some blanket bogs in North Scotland are degrading because the climate has become too dry (Pearsall 1956). Confirmation of peat net accumulation can only be gained from field measurements of net peat accumulation rates using either a paleoecological or mass balance approach. At present, only few such data are available for GB.

Projected changes in the bioclimatic space associated with blanket peat by the BCEMs also do not provide information about the likely changes that may occur or the possible feedbacks that could operate, that could either stabilise the system (negative feedback) or promote change to a new equilibrium (positive feedback). Changes in biotic interactions, seed dispersal and invasive species have been cited as possible limitations with BCEMs (Pearson & Dawson 2003). Within other peatland systems, manipulation experiments have shown that both temperature and water table elevation (driven by the water balance) affect the competitive balance between different *Sphagnum* species and between *Sphagnum* species and other vascular plants (Breeuwer et al. 2008, Robroek et al. 2009). Increased vascular plant cover has also been associated with a decline in *Sphagnum*, and the possibility of change from peatland to a grassland or heathland system

(Berendse et al. 2001). However, plant succession and change to a new ecosystem depends on the initial state of the peatland, as some states are able to adapt to perturbations, whereas other (drier) initial states are more likely to change in response to perturbation (Strack et al. 2006). Historically, warmer conditions have been associated with an increase in drier hummock-type peatland species that are more productive and build peat at a faster rate than the wetter peat species (Barber 1981, Lindsay et al. 1988). Manipulation studies in Finland have also found increased carbon accumulation in response to drainage (Laiho et al. 2003). Climate change may result in blanket peat being replaced by another mire type with the same peat characteristics, but different structural and hydromorphological features (Lindsay et al. 1988). In more degraded and drier sites, it may result in ecological succession, and in terms of soil formation a shift to a peaty podzol or other shallow organic soil. The strength of predictions made with BCEMs and climatic projections is that they show the *potential* for change, and the regions where change is most likely to occur; however their limitation is that they do not realistically represent the actual magnitude or exact nature of this change.

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