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RESEARCH ARTICLE

Climate change impacts on blanket peatland in Great Britain

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Abstract

1. Peatland restoration has been suggested as a key method for the UK to meet national, legally binding climate targets. This can involve blocking up drainage ditches or erosion features, as well as encouraging regeneration of peatland vegetation through *Sphagnum* reintroduction or removal of scrub or trees. It is unclear, however, how suitable future conditions will be for both peat accumulation and *Sphagnum* survival.
2. We applied three bioclimatic envelope models for blanket bogs in Britain to assess how future climate is likely to deviate from current conditions, focussing on four national parks with significant peatland area (Dartmoor, the Flow Country, the Peak District and Snowdonia). We also assessed the likelihood of thresholds being passed at which irreversible desiccation of *Sphagnum* moss may occur.
3. Our bioclimatic envelope models use updated climate projections (bias-corrected UKCP18 projections under Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5) that are more accurate in the upland regions in which blanket bogs can occur, and use thresholds of blanket bog occurrence which are tailored to Britain. This gives us higher confidence in the results as compared to previous models.
4. Our results show substantial losses in areas suitable for peatland by 2061–2080 under all RCPs. Under RCP8.5 there is virtually no peatland within its current bioclimatic envelope in our case study areas and only limited areas in Snowdonia under RCP4.5, suggesting these regions will be outside the ideal conditions that lead to peat accumulation. Only western Scotland retains substantial areas suitable for peat.
5. The frequency of *Sphagnum* desiccation events is projected to increase by between 44% and 82% which will likely result in decreased success of hummock forming species, particularly at easterly sites where rainfall is lower, though wetter microsites will likely allow more drought-tolerant species to persist.
6. *Policy implications*. Action should be taken to raise water tables at degraded sites to limit the impact of future drought conditions. However, climatic conditions being outside the current bioclimatic envelope may make full restoration

challenging. *Sphagnum* reintroduction programmes may have greater success utilising drought-tolerant species as hummock forming species are at greater risk of die off during desiccation events.

KEYWORDS
bioclimatic envelope modelling, climate change, peat, peat restoration, *Sphagnum*

1 | INTRODUCTION

Peatlands are a globally important habitat, characterised by a layer of carbon rich organic matter accumulated in anoxic conditions caused by near permanent waterlogging, making them climatically vulnerable if hydrological conditions change (UNEP, 2022). They are the largest terrestrial carbon store, holding ca. 2000 t C ha^{-1} (Evans et al., 2016; Natural England, 2010; Ostle et al., 2009), or around 50% of the total soil carbon stock (Milne & Brown, 1997). Peatlands also provide a wide range of ecosystem services, including unique assemblages of flora and fauna, water retention and filtration (Labadz et al., 2010; Xu et al., 2018), culture and recreation, and carbon storage (Evans et al., 2016).

Peatlands occupy around 12 per cent (3 million ha) of the UK land area (Office for National Statistics [ONS], 2019). These ecosystems are defined in England as having a peat thickness of at least 30 cm, whilst in Scotland the definition requires at least 50 cm of peat (Finlayson & Milton, 2016). However, ~80% of UK peatlands are, to some extent, degraded due to land use issues like overgrazing, plantation forestry, drainage, pollution and wildfires (Ramchunder et al., 2009; Page & Baird, 2016) making their conservation and sustainable management a priority.

Most peatland degradation or loss in the UK, as is true worldwide, is due to changing land use (IUCN UK, 2018). Peatland drainage for agriculture and forestry emits 7.6 Mt CO_2 year^{-1} in the UK (ONS, 2019) and 36 Mt CO_2 year^{-1} across Europe (Joosten, 2009). As a result, the Committee on Climate Change, who advise the UK government on climate policy, suggests 50% of upland peatlands and 25% of lowland peatlands should be restored to near natural condition by 2050, to meet legally binding UK climate policy (Committee on Climate change, 2020). The cost of restoring UK peatlands from degraded to near natural condition has been estimated to be between £8 and £21 billion over the next 100 years, with the benefits of restoration estimated at £109 billion (ONS, 2019). Management efforts include the conservation and enhancement of high-quality peatlands together with the restoration of heavily degraded peatlands through drain or gully blocking (Armstrong et al., 2009) and re-vegetation (Evans & Warburton, 2007). A further goal of many restoration schemes, once water tables have been raised and bare peat revegetated, is the re-introduction of *Sphagnum* moss, a genus which is beneficial to peatland ecosystem service provision, particularly carbon sequestration and natural flood management (Rochefort, 2000; Shuttleworth et al., 2019).

However, these cost estimates and restoration schemes do not take the potential impacts of climate change on peatland resilience into account. In northern peatlands, peat forms under cool and wet climatic conditions, and it is likely that the projected increases in temperature and drought under future anthropogenic climate change (Rahiz & New, 2013) will add additional stress to these ecosystems. Understanding the influence of anthropogenic climate change on peatland distribution and persistence is of vital importance to peatland restoration efforts, to better assess the long-term viability of these projects. *Sphagnum* moss is particularly vulnerable to periods of extreme drought (Bragazza, 2008), implying that die off of *Sphagnum* is more likely under future climate conditions. This suggests that the reintroduction of *Sphagnum* species with low drought tolerance for restoration of habitats that will experience more drought in the future may fail.

Globally, climate-induced alterations to peatland composition and phenology are expected to degrade peatlands and reduce their ability to store carbon (Antala et al., 2022; Bragazza, 2008; Oke & Hager, 2020). Recent studies have shown that resilience in UK peatlands is dependent on the interactions between climate and management (Lees, Artz, et al., 2021; Lees, Buxton, et al., 2021). Historic management including drainage is likely to decrease peatland resilience and increase vulnerability to a changing climate. On the other hand, peatland restoration has the potential to improve peatland resilience. Management is therefore a key consideration when modelling future peatland range and condition.

Bioclimatic envelope and dynamic models have been used to map the potential future distributions of UK peatlands under climate change (Clark, Billett, et al., 2010; Clark, Gallego-Sala, et al., 2010; Gallego-Sala et al., 2010). These models indicate that peatlands will be sensitive to future increases in summer temperature and reductions in total annual precipitation, with as much as an 84% retreat under high emission scenarios (Gallego-Sala et al., 2010). However, studies that model UK peatland distributions are limited and those models that do exist are now outdated, having used projections from the UK Climate Projection exercise from 2002 (Clark, Billett, et al., 2010; Clark, Gallego-Sala, et al., 2010; Gallego-Sala et al., 2010) which have been updated in the 2009 and 2018 versions. The most recent version, UKCP18, is of particular interest for upland peat habitats as it offers greater accuracy in mountainous regions compared to previous iterations (Murphy et al., 2018).

Envelope models use static statistical tests to define the niche within which a habitat or species can hypothetically occupy (Guisan & Zimmermann, 2000). The static way in which relationships between habitat presence and explanatory variables are represented in these models is considered a limitation, since they cannot account for potential dynamic feedbacks (Heikkinen et al., 2006; Page & Baird, 2016). Despite this limitation, envelope models can still provide a valuable assessment of climate change impacts on habitats at a broad geographic scale, where climate is known to be a key constraint on habitat distribution, as is the case with peatlands (Yu et al., 2010).

Our aim is to employ updated bioclimatic envelope models and high-resolution climate projections to forecast the suitable range of UK peatlands under future climate change scenarios, to better understand how climate change will affect the areas most suitable for peatland and the likely success of associated restoration schemes. We also assess the likelihood of *Sphagnum* die off events using previously published thresholds of temperature and rainfall as a metric to assess the likely success of *Sphagnum* reintroduction projects.

2 | MATERIALS AND METHODS

2.1 | Peat distribution data

Peat soil distributions were obtained from a range of sources. Peaty Soils Location England, also known as the Peat Layer, was produced by Natural England in 2008 as part of the Partnership Project to Protect and Enhance Peat Soils (Shepherd, 2008). We downloaded a subset of the data, known as Moorland Deep Peat AP Status (Natural England, 2021), which includes only deep peat (minimum depth of 40 cm, or 30 cm if resting on solid rock). This dataset contains IPR from Cranfield University (NSRI) soils data and BGS geological data. It is derived from 1:50,000 scale BGS Digital Data under Licence 2006/072 British Geological Survey. Copyright NERC National Soils map, copyright Cranfield University (NSRI), Crown Copyright and database rights 2023, Natural England copyright 2023, Ordnance Survey licence number 100022021. For Wales, we used the Peatlands of Wales dataset, downloaded from https://datamap.gov.wales in December 2023. This dataset provides the distribution of peat with a minimum thickness of 40 cm within the upper 80 cm of soil. We rasterised the deep peat soils polygons to a 1 km grid to give the fraction of each grid cell containing moorland deep peat soils, using the *terra* package for R (Hijmans, 2024). For Scotland, we used the Carbon and Peatland 2016 dataset, produced by Scottish Natural Heritage from existing soil and vegetation data from the James Hutton Institute and Land Cover Scotland 1988. The data provides an indication of the likely presence of peat. The dataset was downloaded from https://soils.environment.gov.scot in December 2023. Five peat soil classes are recognised, varying in the quantity and quality of peat present. The combined area of two classes of peat soil were rasterised to 1 km resolution: Class 1, defined as nationally important carbon-rich soils, deep peat and priority peatland habitat (likely to be of high conservation value); and Class 2, defined as nationally important carbon-rich soils, deep peat and priority peatland habitat (of potentially high conservation value and restoration potential). We combined the peat soil areas in England, Scotland and Wales to give a distribution of deep peat soils for Great Britain (i.e. the United Kingdom excluding Northern Ireland), recognising that the methodologies and definitions for peat soils in the three datasets differ.

We obtained bog distributions at 1 km resolution from the UK CEH Land Cover Map for 2021, available from https://catalogue.ceh.ac.uk/ (Marston et al., 2022). The bog land use class includes ericaceous, herbaceous and mossy swards in areas with peat depth >0.5 m. Peat soil parent material distributions at 1 km resolution were obtained from the British Geological Society (Lawley & Rawlins, 2012), available from https://www.bgs.ac.uk/download/esri-soil-parent-material-model-1km-resolution/.

As well as a national analysis, we focus on three National Parks, namely Dartmoor and the Peak District in England, Snowdonia (Eryri) in Wales and one new UNESCO World Heritage Site, the Flow Country in Scotland.

2.2 | Geographical data

Polygons for the borders of England, Wales and Scotland were obtained from the geoBoundaries (https://www.geoboundaries.org/) using the rgeoboundaries v.1.3 package for R. Polygons for the borders of National Parks in England and Wales were obtained from Natural England (https://naturalengland-defra.opendata.arcgis.com/) and the Welsh Government (https://datamap.gov.wales/), respectively. Polygons for the proposed Flow Country World Heritage Site were obtained from the Flow Country project website (https://www.theflowcountry.org.uk/).

2.3 | Climate data

For modelling of peat distributions under current and future climates, we used monthly CHESS-SCAPE 1 km climate projections from 1981 to 2080 under the Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5 emissions scenarios (Robinson, Huntingford, et al., 2023). The values 2.6, 4.5 and 8.5 denote radiative forcing levels in Wm^{-2} by the year 2100 (van Vuuren et al., 2011). RCP2.6 is a very stringent scenario in which emissions start to decline in 2020 and fall below zero (i.e. net carbon sequestration) by 2100, keeping global temperature rise below 2°C. RCP4.5 is a moderate-emissions scenario in which global carbon emissions peak in 2040 then gradually decline to around one quarter of 2020 levels by the end of the 21st century, accompanied by a global temperature rise of 1.1–2.6°C. RCP8.5 is a worst-case scenario in which emissions rise rapidly to more than three times 2020 levels by 2080, leading to a global mean temperature of 2.6–4.8°C. Atmospheric carbon dioxide and other greenhouse gas concentrations in the atmosphere continue to rise, with the rate of increase growing since 2000 (WMO, 2024). Current UNFCCC Nationally Determined Contributions (NDCs), that is emissions reduction commitments to 2030, would keep global emissions at or slightly below 2020 levels (UNFCCC, 2023). As there is currently no sign of progress towards rapid global emissions reductions, we focus on reporting results from models driven by RCP4.5 and 8.5 climate projections, while also reporting results from RCP2.6.

CHESS-SCAPE is derived from the Met Office Hadley Centre UKCP18 Land Projections at 12 km resolution, downscaled and bias-corrected to 1 km resolution using a combination of methods to account for local topography. CHESS-SCAPE provides four physics perturbation results, of which we used the first (01). Met Office Hadley Centre monthly HadUK-Grid Gridded Climate Observations from 1981 to 2022 on a 1 km grid (v1.2.0.ceda) were obtained from the CEDA Archive (https://archive.ceda.ac.uk/) (Met Office et al., 2022), for comparison with CHESS-SCAPE data. CHESS-PE daily potential evapotranspiration (PET) (Robinson, Blyth, et al., 2023) at 1 km^2 resolution from 1981 to 2000 was obtained from https://catalogue.ceh.ac.uk/ and aggregated to annual PET. UKSCAPE-G2G monthly soil moisture estimates (m water/m soil) at 1 km^2 resolution for historical (1981–2011) and RCP8.5 projections (1981–2080, physics perturbation 01) were obtained from https://catalogue.ceh.ac.uk/ (Kay et al., 2022, 2023). Other RCP projections are not available for soil moisture.

2.4 | Peat distribution models

We used four published models to investigate potential changes in peat distribution in the UK. The first estimates the risk of irreversible desiccation of peat mosses based on monthly temperature and precipitation, while the others estimate the probability of the presence of blanket peatland based on climatic conditions. We also investigated projected future trends in annual minimum soil moisture content within parks.

The peat moss desiccation model (Bragazza, 2008) estimates the risk of irreversible desiccation of peat mosses, which was found to occur in the Italian Alps when the mean monthly precipitation:mean monthly temperature (P:T_a) ratio dropped below 6.5 mm/°C. Bragazza's ratio at which irreversible desiccation occurred was across a 4 month period, however we show our results as the number of months (May to September inclusive) in which this threshold is breached as a measure of risk of desiccation occurring.

The LM-GLM model (Clark, Billett, et al., 2010; Clark, Gallego-Sala, et al., 2010; Lindsay et al., 1988) estimates the probability of blanket peat occurrence P(BP) from the mean monthly temperature of the warmest month (T_{max}, °C) and total annual precipitation (P, mm):

$$P(\mathrm{BP}) = \frac{\exp(16.12 - 1.52T_{\max} + 0.003452P)}{1 + \exp(16.12 - 1.52T_{\max} + 0.003452P)}.$$

The BBOG-GLM model (Clark, Billett, et al., 2010; Clark, Gallego-Sala, et al., 2010) estimates P(BP) from T_{max} and the modified Thornthwaite-Mather moisture index (TMI):

$$P(\mathrm{BP}) = \frac{\exp(13.51 - 1.341T_{\max} + 9.165\mathrm{TMI})}{1 + \exp(13.51 - 1.341T_{\max} + 9.165\mathrm{TMI})}.$$

TMI is derived from the annual balance between P and PET (mm month^{-1}) (Thornthwaite & Mather, 1955):

$$\mathrm{TMI} = \begin{cases} P/\mathrm{PET} - 1, P < \mathrm{PET} \\ 1 - \mathrm{PET}/P, P \geq \mathrm{PET} \end{cases}.$$

Monthly PET was estimated using the modified Thornthwaite equation (Thornthwaite, 1948):

$$\mathrm{PET} = 16\left(\frac{N}{12}\right)\left(\frac{10T_a}{H}\right)^m,$$

where T_a is the mean monthly temperature (°C), defined as the mean of daily maximum and minimum temperature. PET was taken to be zero when $T_a < 0$°C. H is the annual heat index, m is a parameter based on H, and N is the mean number of daylight hours (Allen et al., 1998),

$$H = \sum_{i=1}^{12}\left(\frac{T_{ai}}{5}\right)^{1.514},$$

$$m = 6.7 \times 10^{-7}H^3 - 7.7 \times 10^{-5}H^2 + 1.8 \times 10^{-2}H + 0.49,$$

$$N = \frac{24}{\pi}\left(\arccos\left[-\tan(L)\tan\left(0.409\sin\left[\frac{2\pi}{365}J - 1.39\right]\right)\right]\right),$$

where J is the day of the year and L is the latitude (radians).

The PEATSTASH bioclimatic envelope model for blanket peat employs thresholds of mean annual temperature ($T_{mean} > -1$°C), mean temperature of the warmest month ($T_{max} < 14.5$°C) and a moisture index (MI > 2.1) derived from the ratio of mean annual precipitation (P) and equilibrium evapotranspiration (Gallego-Sala et al., 2010). Here we substitute PET for equilibrium evapotranspiration, following the MI definition given by the United Nations Environment Programme (Middleton & Thomas, 1992):

$$\mathrm{MI} = P / \mathrm{PET}.$$

We used HADUK monthly gridded temperature and precipitation, and CHESS-PE PET at 1 km^2 resolution to obtain historical (1981–2000) climate estimates for three land cover and soil types: deep peatland soils, CEH bog land classification and BGS peat soil parent material. These land classes are not mutually exclusive.

Given that mean annual temperatures across the UK exceed −1°C, we assessed only T_{max} and MI as classifiers for peat and bog distributions, but included a comparison with a classifier using T_{max} and P. Rather than a set of rectilinear thresholds, we used a Linear Discriminant Analysis (LDA) to separate peat from non-peat land on the basis of T_{max} and either MI or P. We termed these models LDA-M and LDA-P, respectively. LDA finds the optimal linear function of predictors that separate samples belonging to different classes. The peat soil parent material dataset was omitted from the classifier because it includes both ombrotrophic and minerotrophic peat soils (i.e. peat soils derived by flooding in regions like the Somerset Levels), and we compared grid cells which were either classed as deep peat or bog (or both) with those classed as non-peat. LDA was fitted

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using the *lda* function in package *MASS* v.7.3-60.2 for R (Venables & Ripley, 2002). LDA predictions for the full dataset were compared with observed values and model accuracy calculated as the number of correct predictions divided by the total number of grid cells.

2.5 | Model validation

We validated mean model predictions for the 1981–2000 historical period against the current observed deep peat distribution in England, Scotland and Wales. First, model predictions were compared to the fraction of deep peat per km^2 grid cell. Then, receiver-operator characteristic (ROC) curves and area under curve (AUC) statistics were generated for model predictions of peat presence (i.e. peat fraction >0). Youden's *J* and the closest to top left corner thresholds were calculated for each model, along with the prediction accuracy for those thresholds. Finally, Cohen's κ was calculated for the confusion matrix generated from presence-absence predictions obtained by applying the closest to top left corner threshold. Though not a peat presence probability model, these statistics were also generated for the Bragazza dessication model, for comparison.

3 | RESULTS

3.1 | Peatland distribution

The total area of deep peat soil in each focal area was estimated as 168,338 ha in the Flow Country, 43,884 ha in Snowdonia, 33,732 ha in the Peak District and 21,590 ha in Dartmoor (Figure 1). The total area of deep peat soils in Great Britain was 2,655,006 ha. The Flow Country has the largest areal coverage of deep peat (90.0%), followed by the Peak District (23.4%), Dartmoor (22.6%) and Snowdonia (20.5%).

In combination with T_{max}, both MI and *P* provide good separation of peat from non-peat land when used in the LDA classifier (Figure 2). Minerotrophic peat soils, found primarily in the Somerset Levels and East Anglian Fens, have a high T_{max} and low MI (and *P*) compared with ombrotrophic peat soils. The LDA discriminant functions were $T_{max} = 12.33 + 0.776 \times \text{MI}$ and $T_{max} = 12.02 + 0.00196 \times P$, respectively. The LDAs for deep peatland or bog predicted by T_{max} and either *P* or MI had an accuracy (fraction of correct classifications for the whole dataset) of 88.5%. The Pearson correlation between *P* and MI was 0.96. Thus, there was no benefit to employing the MI rather than *P* for predicting peat bog distributions.

3.2 | Model validation

All model predictions based on 1981–2000 climate showed high accuracy in predicting current deep peat distributions (see Figure S1). Though not a peat distribution model, the Bragazza model was strongly correlated with peat fraction, declining to zero when the number of months exceeding the dessication threshold reached 4 (see Figure S1a). Peat probability derived from the other models was roughly linearly correlated with peat fraction (see Figure S1b). ROC curves for prediction of peat presence (peat fraction >0) revealed excellent classifier accuracy, with AUC scores of 0.95 and above for BBOG-GLM, LM-GLM, LDA-P and Bragazza (see Figure S1c). PEATSTASH demonstrated a lower sensitivity (true positive rate)

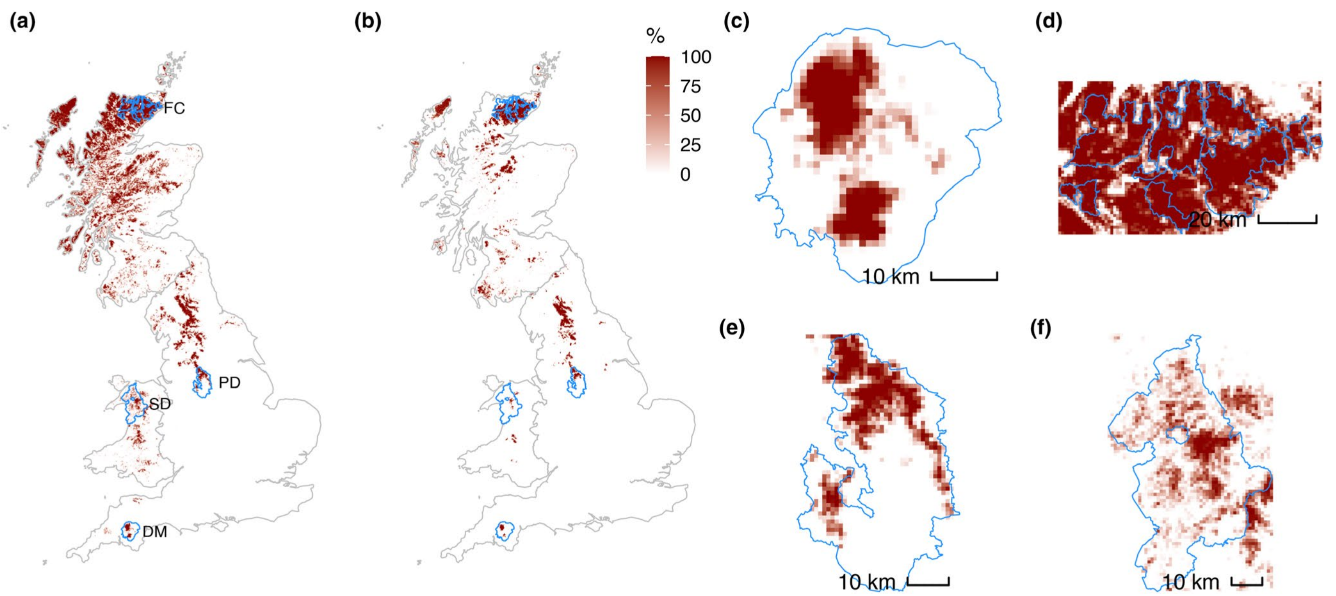

FIGURE 1 Peat and peat bog distribution. (a) Fraction of 1 km grid cells containing deep peat. Data are a combination of datasets from England, Wales and Scotland (see Methods for details). Labels of national parks (blue outlines) are Dartmoor (DM), Flow Country (FC), Peak District (PD) and Snowdonia (SD). (b) Fraction of 1 km grid cells containing UK CEH bog habitat classification. (c) Peatland in Dartmoor, (d) Flow Country, (e) Peak District and (f) Snowdonia.

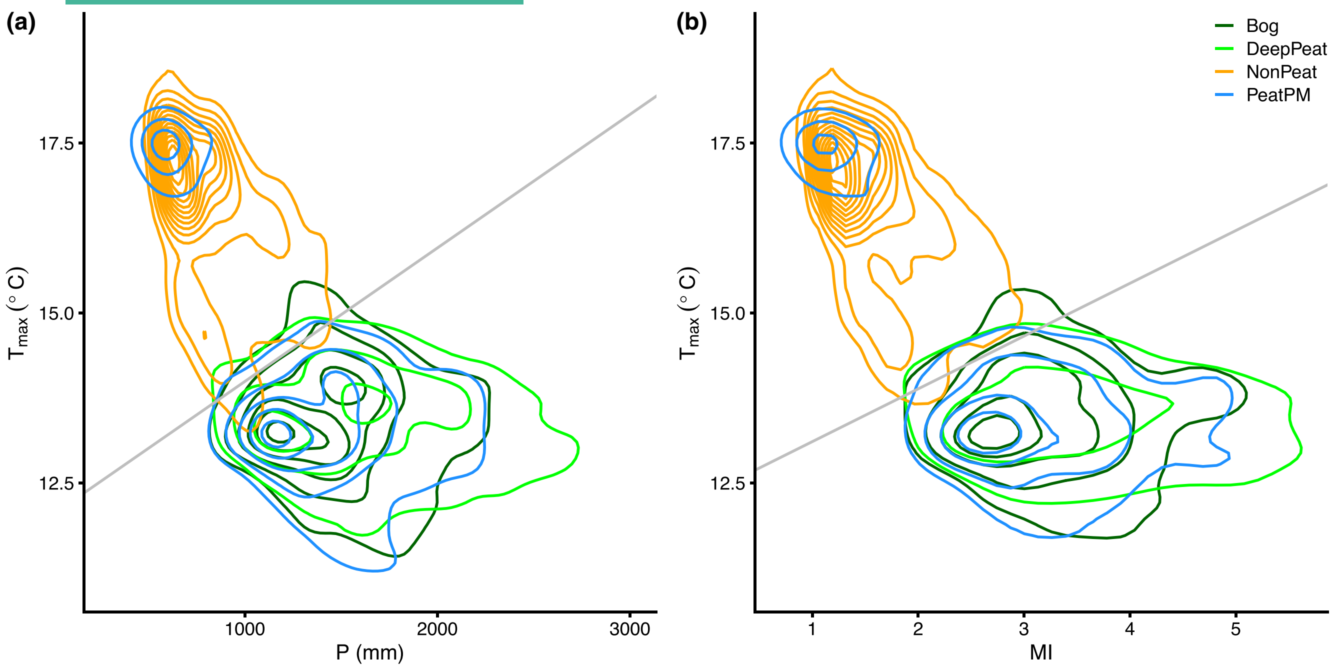

FIGURE 2 Climate space for peat soils and bogs. (a) Density of bog (dark green), deep peat (green), peat soil parent material (PeatPM, blue) and other non-peat (orange) 1 km^2 grid cells by T_{max} and *P*, 1981–2000 mean. Contours indicate grid cell density. (b) Density of grid cells by T_{max} and moisture index (MI). Grey lines show Linear Discriminant Analysis discriminant functions classifying peat (bog and deep peat) versus non-peat. Peat parent material was omitted from the classification as this soil type includes minerotrophic peatland (blue contours in top left of plots).

for specificity (true negative rate) values below around 0.9, meaning that PEATSTASH is slightly less effective at capturing peat presence while avoiding false positives. For this reason we focus on LDA-P projections rather than PEATSTASH. Model accuracy for the optimal (closest to top left corner) threshold exceeded 87.5% for each model, with Cohen's κ exceeding 0.75 for all peat presence probability models (see Table S1).

3.3 | Climate change

Under all emissions scenarios, much of the UK is projected to become drier on average and to experience higher maximum monthly average temperatures in coming decades (Figure 3). Northwest Scotland will experience the strongest drying trend, while under RCP8.5 Scotland, Wales and the South West also show the strongest reductions in annual precipitation (Figure 3a). By 2061–2080 the mean temperature of the warmest month is projected to increase by around 2°C under RCP4.5, 3°C under RCP4.5 and 5°C under RCP8.5, with larger increases in the south (Figure 3b). The four focal national parks are projected to become warmer and in some cases drier during the 21st century (Figure 3c,d; see also Figure S2 and Table S2). Warming trends are significant for all parks under all three RCPs, ranging from around 3°C per century for RCP2.6 and 6°C per century for RCP8.5. Drying trends are significantly negative in the Flow Country under all RCPs, but only under RCP8.5 in Dartmoor and the Peak District. Precipitation trends for Snowdonia are not statistically different from zero. Annual minimum monthly soil moisture declines significantly under RCP8.5 in all parks (see Figure S3).

3.4 | Climate change and peatland distribution

The number of months exceeding the Bragazza model threshold for desiccation of *Sphagnum* showed a N-S and W-E gradient in risk (Figure 4a). Under recent historical climate, only Snowdonia has a significant area with less than 1 month per year on average exceeding the threshold (Figure 5). The number of months per year exceeding the threshold is projected to increase across Scotland, Wales and western England under all RCPs, with the majority of all four parks exceeding the threshold in at least 2 months per year by the 2061–2080 period.

The probability of peat presence declines strongly for all three models (LM-GLM, BBOG-GLM and LDA-P) under all RCPs (Figures 4b–d and 5). For all models, northwest Scotland retains the largest areas which are climatically suitable for peat. Taking the model prediction thresholds which result in the most accurate classification of peat-containing grid cells, dramatic declines in suitability are projected even under the most stringent emissions reduction scenario (Table 1). Under RCP2.6, Dartmoor is projected to lose between 68% and 100% of suitable area, Flow country 55% to 68%, the Peak District 96% to 100% and Snowdonia 33% to 80%. Under RCP8.5, the area suitable for any peat decreases to near zero for all parks. Detailed results of model projections for all four national parks are given in Figures S4–S7.

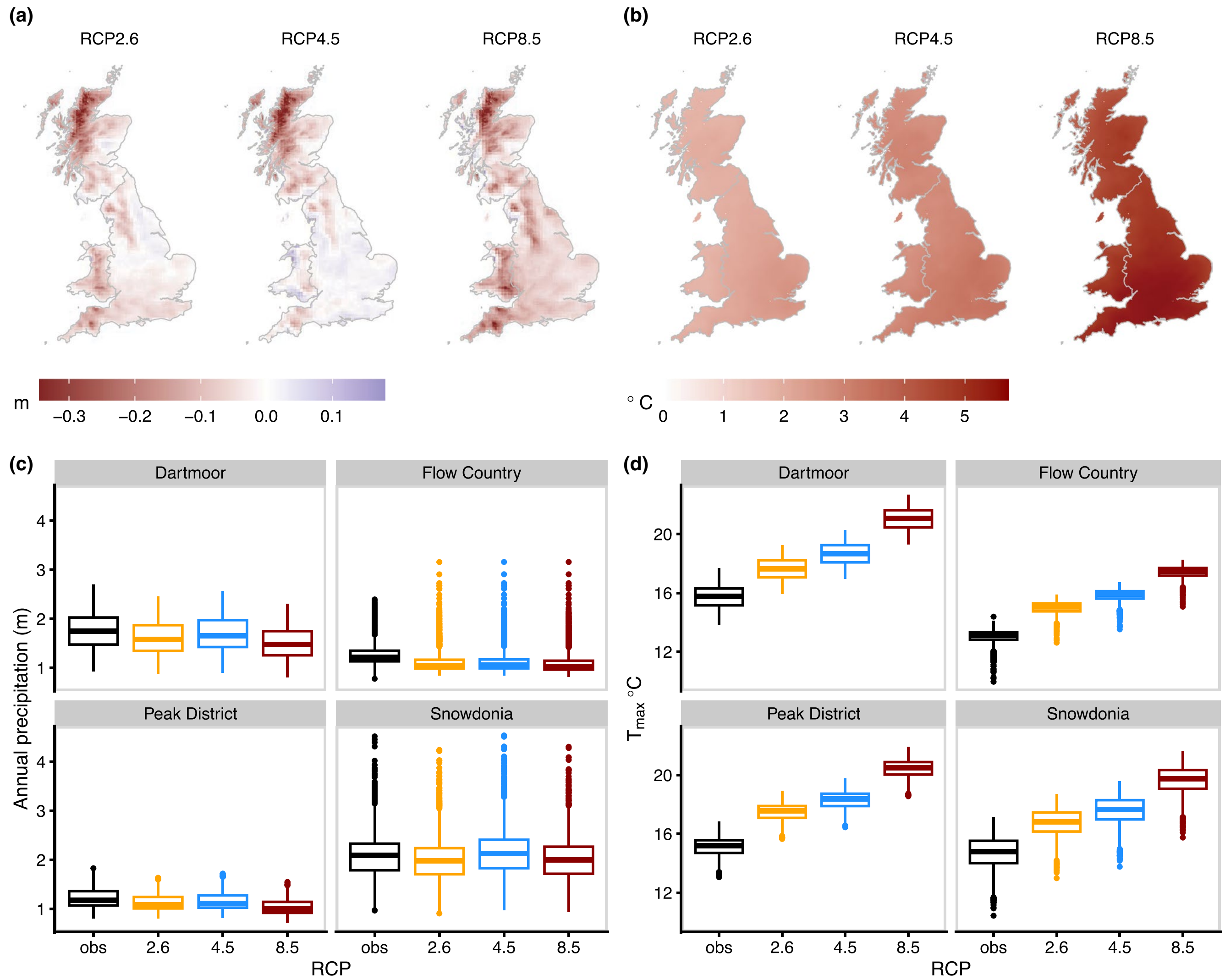

FIGURE 3 Projected climate change. (a) Change in annual precipitation (*P*, m) between 1981–2000 observed mean and 2061–2080 projected mean. (b) Change in temperature of warmest month (T_{max}, °C). (c) Change in *P* in National Parks, 1981–2080 observed mean and 2061–2080 Representative Concentration Pathway (RCP) projections. (d) Change in T_{max}. Boxplots show distributions for all km^2 grid cells within parks.

4 | DISCUSSION

4.1 | Limitations

Our study has a number of key limitations which must be recognised in the interpretation of our findings. Firstly, the UKCP18 projections use a different baseline period (1981–2000) compared to the climate projections used by Clark, Billett, et al. (2010), Clark, Gallego-Sala, et al. (2010) and Gallego-Sala et al. (2010) which had the period 1961–1990 as the baseline. This makes direct comparison between these studies difficult and also means greater warming above pre-industrial levels is already present in our baseline condition.

Secondly, our dataset on peat distribution contains only the current extent of deep peat in Great Britain, meaning many areas of historic 'lost' or 'wasted' peat (that which has been oxidised or eroded enough to no longer count as deep) are not included, despite being within the bioclimatic envelope of peat occurrence. This effect could be significant as, for example, a survey of sites across the northwest of England suggested that only 13% of lowland raised bogs mapped in the 1850s remained in the 1970s (Bragg et al., 1984). This means our envelope is likely artificially narrow, however this is most likely to be relevant in a lowland context where greater use of peat for agriculture has occurred, creating areas of wasted peat.

Third, the Bragazza threshold for irreversible desiccation of *Sphagnum* is based on a single heatwave in the Alps and therefore may not be directly applicable to UK conditions. Further work is needed to understand at what point irreversible desiccation occurs and how this varies among *Sphagnum* microhabitats as, for example, hummock and lawn species have different tolerance to drought conditions (Bengtsson et al., 2020). Furthermore, resilience to drought may be lower in recently planted *Sphagnum* introduced during restoration programmes when compared to larger areas of hummocks and lawns which are more able to make use of feedback mechanisms to limit the effect of drought (bleaching, capillary action).

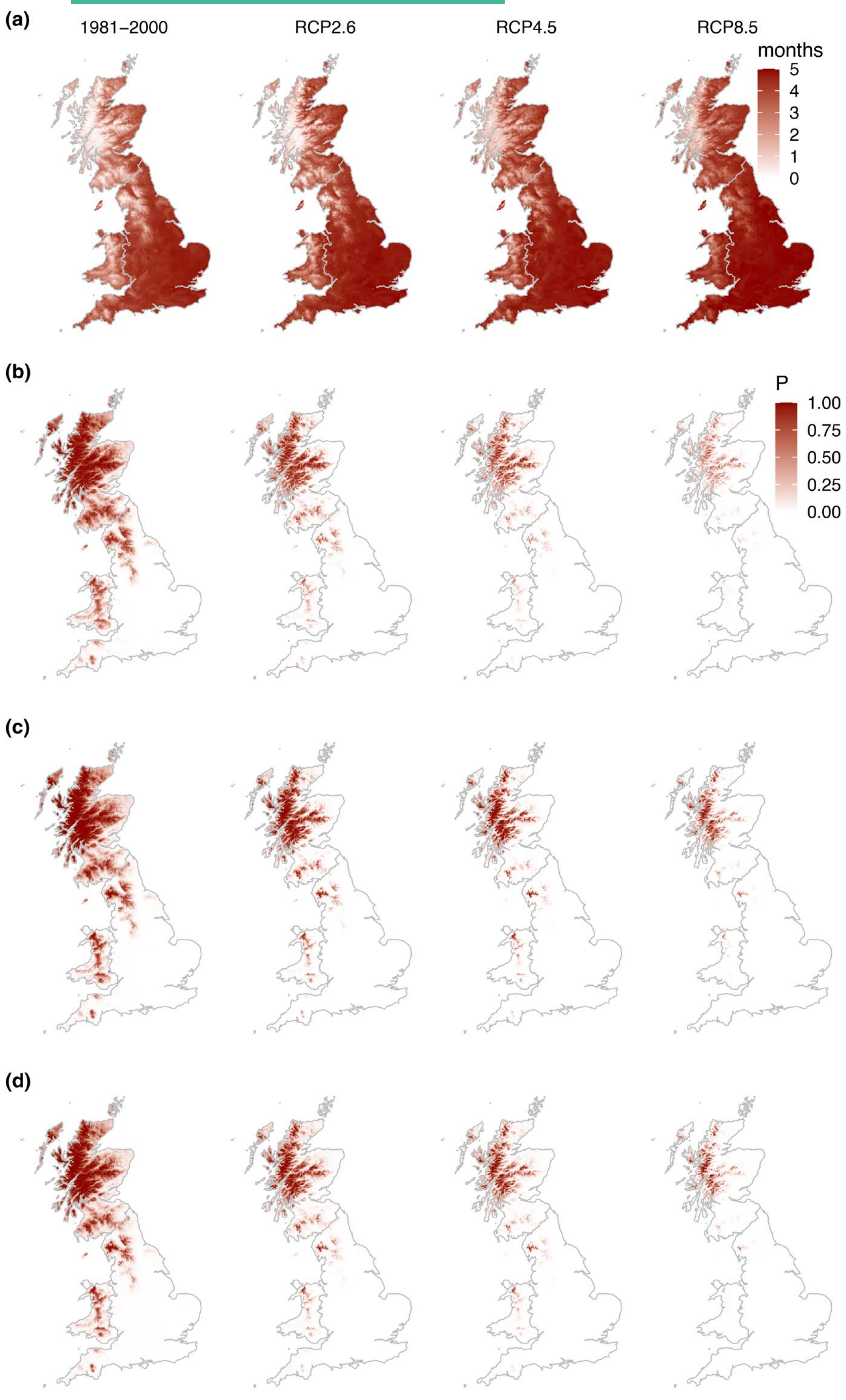

FIGURE 4 Climate change effects on peat bog distributions. Maps show (l-r) 1981–2000 mean under Representative Concentration Pathways (RCP) 2.6, 2061–2080 means under all RCPs. (a) Mean months per year experiencing irreversible desiccation of peat mosses (Bragazza, 2008). (b) Probability of peat presence, BBOG-GLM model. (c) Probability of peat presence, LM-GLM model. (d) Probability of peat presence, LDA-P model using P and T_{max}.

Fourth, there is a need to overlay management effects on the climate effects modelled here. Grazing, drainage, managed burning, wildfire and rewetting could all influence the continuation of peat formation and *Sphagnum* survival (Lees, Artz, et al., 2021; Lees, Buxton, et al., 2021). This is also relevant in understanding what impact becoming outside the bioclimatic envelope for deep peat will mean for carbon fluxes from the peat itself. For example, losses of carbon due to being outside the bioclimatic envelope would likely be limited by restoration but exacerbated by continued agricultural production. Development of process-based models of carbon cycling within peatlands will be required to understand how future climate and management will interact to determine the fate of carbon stored within these ecosystems (Chadburn et al., 2022).

4.2 | Risk of *Sphagnum* irreversible desiccation

The risk of irreversible desiccation of *Sphagnum* shows an expected N-S gradient driven by temperature and a W-E gradient driven by

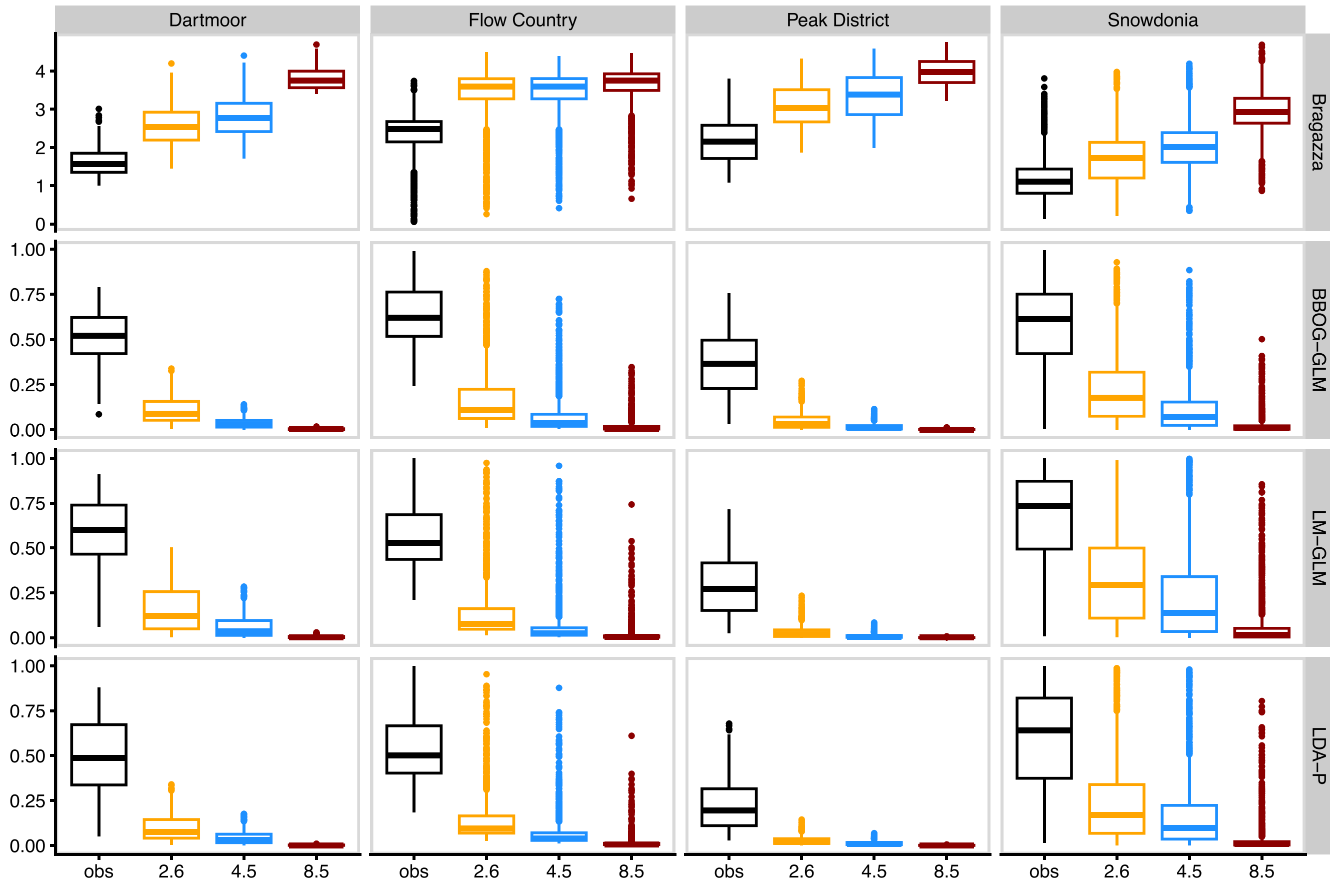

FIGURE 5 Peat suitability under climate change within national parks. Values for the Bragazza *Sphagnum* desiccation model indicate months per year in which desiccation occurs. Values for BBOG-GLM, LM-GLM and the LDA-P model indicate the probability of peat presence. Boxplots show median, interquartile range (IQR) and outliers for mean values in 1 km grid cells currently containing peat soils. Whiskers extend to 1.5 IQR. Box widths indicate relative number of grid cells among parks containing some peat.

rainfall. The parks we analysed in greater detail show differing degrees of risk of die off events with Snowdonia having the least risk (median 2.9 months above threshold per year in RCP 8.5) followed by Dartmoor (3.7 months), the Flow Country (3.8 months) and finally the Peak District (4.0 months). The spatial analysis suggests that the greater risk in the Peak District is, in part, being driven by the eastern areas of the park which are in the rain shadow of the western hills. This knowledge could be used to target *Sphagnum* planting schemes where they are most likely to be successful, however it should be noted that our results indicate greater risk to planting schemes, not that they would be unsuccessful under future conditions. Indeed, Bragazza's threshold was based only on hummocks of *Sphagnum* whereas lawn species, which are closer to the water table and more likely to be shaded, were noted to not have shown any irreversible desiccation under the same conditions (Bragazza, 2008). This would suggest that different *Sphagnum* species distributions may be more likely under climate change with a potential decrease in the characteristic hummock-hollow microtopography of many peatlands. These results bring into question whether restoration to a pre-industrial era flora is possible given future conditions; instead a post-industrial target flora (in the sense of Ritson & Lindsay, 2023) may need to be defined.

Laboratory studies using two species of *Sphagnum* found that both a hummock and a lawn species experienced some bleaching during 12 weeks of low water input (approx. 17 mm per month with an average temperature of 10°C) but no significant change in photosynthesis (Lees et al., 2019). Other samples in the same experiment, however, were subjected to total drought and showed impacts on photosynthesis after 30 days. This impact on photosynthesis was found to be irreversible after rewetting following 3 months of total drought. This work suggests a more extreme drought threshold for *Sphagnum* die-off than Bragazza (2008), although it was conducted under laboratory conditions rather than in the field. Indeed, counter to laboratory experiments, *Sphagnum* was found to be unaffected by a 10-year field experiment in West Wales, which simulated periodic drying and warming episodes, although ericaceous shrubs (e.g. *Calluna vulgaris*) increased in abundance (Andrews et al., 2021). It is unclear what indirect impact this vegetation shift may have on *Sphagnum* through competitive exclusion over longer time-scales, which may increase carbon losses via a reduction in litter quality and greater root exudates (Andrews et al., 2021). Further work is urgently needed on the ability of *Sphagnum* to recover from multiple drought events, particularly as recovery can be slow (Gerdol et al., 1996), and cycling between wet and dry conditions has been

TABLE 1 National park areas most suitable for peat. Values under the park name are the current number of km^2 grid cells containing some peat. Values under the models are the number of grid cells per with predicted peat area >0 for historical and future climates, based on the most accurate classification threshold for each model. Values in parentheses under the historical climate projections are the difference from the current observed values. Values under Representative Concentration Pathway (RCP) projections are differences from the historical projections. The Bragazza and PEATSTASH models are included as classifiers for comparison.

Park	Climate	Bragazza	BBOG-GLM	LM-GLM	LDA-P	PEAT STASH
Dartmoor	Hist, 1981–2000	831 (+41%)	623 (+6%)	642 (+9%)	609 (+4%)	739 (+26%)
588	RCP2.6, 2061–2080	442 (−47%)	101 (−84%)	206 (−68%)	155 (−75%)	0 (−100%)
	RCP4.5, 2061–2080	330 (−60%)	0 (−100%)	78 (−88%)	44 (−93%)	0 (−100%)
	RCP8.5, 2061–2080	0 (−100%)	0 (−100%)	0 (−100%)	0 (−100%)	0 (−100%)
Flow Country	Hist, 1981–2000	2196 (−6%)	2344 (0%)	2344 (0%)	2344 (0%)	2326 (−1%)
2344	RCP2.6, 2061–2080	470 (−79%)	792 (−66%)	739 (−68%)	1109 (−53%)	1050 (−55%)
	RCP4.5, 2061–2080	429 (−80%)	316 (−87%)	291 (−88%)	384 (−84%)	524 (−77%)
	RCP8.5, 2061–2080	319 (−85%)	59 (−97%)	87 (−96%)	65 (−97%)	62 (−97%)
Peak District	Hist, 1981–2000	1120 (+27%)	790 (−10%)	685 (−22%)	624 (−29%)	1070 (+21%)
882	RCP2.6, 2061–2080	372 (−67%)	32 (−96%)	29 (−96%)	14 (−98%)	13 (−99%)
	RCP4.5, 2061–2080	218 (−81%)	0 (−100%)	0 (−100%)	0 (−100%)	0 (−100%)
	RCP8.5, 2061–2080	0 (−100%)	0 (−100%)	0 (−100%)	0 (−100%)	0 (−100%)
Snowdonia	Hist, 1981–2000	2185 (+2%)	1976 (−8%)	1990 (−7%)	1987 (−7%)	2021 (−5%)
2138	RCP2.6, 2061–2080	1973 (−10%)	957 (−52%)	1326 (−33%)	1171 (−41%)	395 (−80%)
	RCP4.5, 2061–2080	1870 (−14%)	432 (−78%)	920 (−54%)	856 (−57%)	133 (−93%)
	RCP8.5, 2061–2080	1260 (−42%)	55 (−97%)	250 (−87%)	130 (−93%)	18 (−99%)

shown to decrease *Sphagnum* spore viability and germination (Fan et al., 2023).

4.3 | Probability of peat presence

Our updated bioclimatic envelope model for peatlands in Great Britain offers increased accuracy over previous model attempts, particularly in the mountainous regions which is where most deep peat is found. Under the RCP8.5 pathway our model suggests that the bioclimatic envelope in which peat is likely to be found will have virtually disappeared by 2061–2080 for all our case study areas except Snowdonia, where the median probability of peat presence is 0.01 for both the BBOG-GLM and LM-GLM models. Under RCP4.5 the projection is still concerning, with Snowdonia having the highest probability with a decrease from a median probability of peat presence of 0.61 to 0.07, whereas the Peak District has the least probability, decreasing from 0.36 to 0.01. Even under RCP 2.6, which would require very rapid decarbonisation or largescale greenhouse gas removals given current emissions, decreases in the probability of peat presence are sever (Table 1).

These model results suggest that the majority of peat within Great Britain will be outside its bioclimatic envelope by the 2060s, even if we keep global emissions within the RCP4.5 pathway. These results, based on climate projections with higher accuracy in mountainous regions where blanket bogs occur, suggest much lower likelihood of blanket bogs remaining within their bioclimatic envelope than earlier modelling attempts (Clark, Billett, et al., 2010; Clark, Gallego-Sala, et al., 2010; Gallego-Sala et al., 2010). The fate of peatlands once they are outside the bioclimatic envelope is therefore an urgent research priority and the extent to which carbon losses can be slowed or reversed by different management techniques will need to be considered. Evidence of elevated rate of loss of peat once out of its bioclimatic envelope could facilitate restoration as carbon finance (the selling of carbon credits based on avoided emissions or greenhouse gas removals) funding models are typically based on the avoided emissions from a 'do nothing' scenario, however future conditions could also increase the risk of project failure.

A key consideration in restoration viability is whether rewetting can compensate for the projected decreases in rainfall and soil moisture, and increases in evapotranspiration. Water Table Depth (WTD) can fall dramatically during drought periods. Rewetting through blocking erosion gullies or drainage ditches has, however, been shown to stabilise WTD, particularly by reducing drops in water levels during dry months (Gatis et al., 2023; Wilson et al., 2010). Wilson et al. (2010) found that WTD in rewetted peatland never fell below approx. 7 cm, whereas in other areas WTD fell to approx. 16 cm. Gatis et al. (2023) found that in rewetted areas WTD was 6–7 cm higher during dry periods, but that without rewetting WTD fell to approximately 55–60 cm. Holden et al. (2011) found that rewetting had minimal effect on WTD in dry months whereas Evans et al. (2016) found drawdown to be ~60 mm less in recently rewetted sites with lower rates of drawdown once the site was revegetated. These mixed results can be interpreted that in some areas rewetting may indeed be able to compensate for the falls in WTD caused by drought periods, whereas in other areas it may not. This is likely influenced by local hydrology and the extent of peat degradation through gullying, drainage and/or proportion of bare peat and peat compaction prior to restoration. More research is needed to determine the factors affecting the success of rewetting in terms of this compensation; however we interpret our results to mean that this will become ever more challenging due to climate change. This is particularly worrying as low antecedent water tables have been shown to decrease the resilience of *Sphagnum* mosses to drought events (Kokkonen et al., 2024). Evans et al. (2016) noted that although an immediate improvement in WTD was seen on rewetting, this was still improving across their sites 10 years post-restoration. This means action on restoration is required now if we want to increase the resilience of peatland ecosystems to climate conditions likely to be observed mid-century (Defra, 2021).

4.4 | PEATSTASH

Our use of LDA achieved a greater peatland classification accuracy compared with the rectilinear thresholds employed in the original PEATSTASH bioclimatic envelope model (Gallego-Sala et al., 2010). The greater accuracy may be due to our analysis using GB specific data, whereas the original PEATSTASH analysis used thresholds for blanket bogs derived from global data at much lower spatial resolution. The use of LDA allows that blanket bog presence is possible at higher T_{max} values (>14.5°C) were *P* or MI are also high. However, we recognise that the spatial resolution, climate data, evapotranspiration calculations and peatland distributions differ from the original PEATSTASH analysis and so our results are not directly comparable.

5 | CONCLUSIONS

Our results suggest the probability of peat in Great Britain in 2061–2080 being inside its baseline bioclimatic envelope is virtually zero under the RCP8.5 pathway. Under RCP4.5, some areas in Snowdonia have small chance of remaining inside the bioclimatic envelope. However, Dartmoor, the Peak District and the newly inscribed Flow Country World Heritage Site will become largely unsuitable for peat even under moderate climate change. Whilst RCP2.6 shows less severe impacts and greater likelihood of peat presence in Dartmoor and the Flow Country, this pathway is now challenging to meet given current emissions. Our results are more pessimistic than those previously modelled using earlier climate projections. This suggests there is an urgent need to understand the fate of peatlands under climate change and how this can be mitigated through land management. Our results suggest the frequency of *Sphagnum* desiccation events will increase by between 44% and 82% across our case study areas in Great Britain. This could lead to a decrease in the prevalence of hummock forming species and consequently the hummock-hollow microtopography currently found in many peatlands. Our model did not include *Sphagnum* lawn species which may persist in wetter microsites. More generally, global emissions must be cut to reduce the risk of high temperatures that exceed the peatland bioclimatic envelope (Fewster et al., 2022; Hugelius et al., 2020).

AUTHOR CONTRIBUTIONS

Daniel P. Bebber, Jonathan P. Ritson, Kirsten J. Lees, James Hill and Angela Gallego-Sala contributed to the design of the study and drafting of the manuscript. Daniel P. Bebber conducted the modelling and statistical analyses, and prepared the figures.

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CONFLICT OF INTEREST STATEMENT

Ritson has received funding from multiple organisations advocating for and implementing peatland restoration programmes.

DATA AVAILABILITY STATEMENT

All datasets used in the analyses are openly available from the following sources (some sites may require registration before data access is granted): Moorland Deep Peat AP Status (Natural England, 2021), https://naturalengland-defra.opendata.arcgis.com/datasets/Defra::moorland-deep-peat-ap-status-england/about. Peatlands of Wales (Welsh Government), https://datamap.gov.wales/layers/geonode:peatlands_of_wales_scg8. Carbon and Peatland 2016 (Scottish Government), https://soils.environment.gov.scot/maps/thematic-maps/carbon-and-peatland-2016-map/. Peat bog distributions from the UK CEH Land Cover Map for 2021 (Marston et al., 2022), 1 km summary rasters, https://catalogue.ceh.ac.uk/documents/a3ff9411-3a7a-47e1-9b3e-79f21648237d. Peat soil parent material distributions (Lawley & Rawlins, 2012), 1 km resolution, https://www.bgs.ac.uk/download/esri-soil-parent-material-model-1km-resolution/. Polygon boundaries of England, Scotland and Wales, https://www.geoboundaries.org/. National Parks of England boundaries, https://naturalengland-defra.opendata.arcgis.com/datasets/d333c7529754444894e2d7f5044d1bbf_0. National Parks of Wales boundaries, https://datamap.gov.wales/layers/inspire-nrw:NRW_NATIONAL_PARK. Flow Country World Heritage Site boundary, https://theflowcountry.org.uk/wp-content/uploads/2024/10/FCWHboundariesFINAL.zip. CHESS-SCAPE 1 km climate projections (Robinson, Huntingford, et al., 2023), https://doi.org/10.5285/8194b416cbee482b89e0dfbe17c5786c. Met Office Hadley Centre monthly HadUK-Grid Gridded Climate Observations v.1.2.0.ceda (Met Office et al., 2022), https://doi.org/10.5285/46f8c1377f8849eeb8570b8ac9b26d86. CHESS-PE daily potential evapotranspiration (Robinson, Blyth, et al., 2023) at 1 km resolution, https://doi.org/10.5285/8651771D-AA6D-4D0F-8BCD-B3BE1F733852. UKSCAPE-G2G monthly soil moisture estimates at 1 km resolution (Kay et al., 2023), https://doi.org/10.5285/f7142ced-f6ff-486b-af33-44fb8f763cde.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Model validation.

Figure S2. Changes in projected T_{max} and P under climate change scenarios in National Parks.

Figure S3. Change in annual minimum monthly soil moisture between 1981 and 2000 mean and 2061–2080 mean, UKSCAPE-G2G estimates, RCP8.5.

Figure S4. Bragazza model predictions.

Figure S5. BBOG-GLM model predictions.

Figure S6. LM-GLM model predictions.

Figure S7. LDA-P model predictions using T_{max} and P.

Table S1. ROC curve metrics for models predicting any peat presence per grid cell.

Table S2. Trends in annual precipitation (P, mm year^{-1}) and temperature of warmest month (°C year^{-1}) between 1981 and 2080 under RCP2.6, 4.5 and 8.5 for peat areas within four focal National Parks.

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