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RESEARCH ARTICLE

Assessing the exposure of UK habitats to 20th- and 21st-century climate change, and its representation in ecological monitoring schemes

Oliver J. Wilson[1] | Oliver L. Pescott[2]

[1]Plantlife, Salisbury, UK
[2]UK Centre for Ecology and Hydrology, Wallingford, UK

Correspondence
Oliver L. Pescott
Email: olipes@ceh.ac.uk

Present address
Oliver J. Wilson, Department of Environment and Geography, University of York, Wentworth Way, Heslington, York, North Yorkshire YO10 5NG, UK

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Abstract

1. Climate change is a significant driver of contemporary biodiversity change. Ecological monitoring schemes can be crucial in highlighting its consequences, but connecting and interpreting observed climatic and ecological changes demands an understanding of monitored locations' exposure to climate change. Generalising from trends in monitored sites to habitats also requires an assessment of how closely sampled locations' climate change trajectories mirror those of wider ecosystems. Such assessments are rare but vital for drawing robust ecological conclusions.
2. Focusing on the UK, we generated a metric of climate change exposure by quantifying the change in observed historical (1901–2019) and predicted future (2021–2080, pessimistic emissions scenario) conditions. We then assessed habitat-specific climate change exposure by overlaying the resulting data with maps of contemporary (2019) land cover. Finally, we compared patterns of climate change exposure in locations sampled by ecological monitoring schemes to random samples from wider habitats.
3. The UK's climate changed significantly between the early 20th century and the last decade, and is predicted to undergo even greater changes (including the development of Iberian/Mediterranean climate types in places) into the 21st century. Climate change exposure is unevenly distributed: regionally, it falls more in southern, central and eastern England; locally, it is greater at higher-elevation locations than nearby areas at lower elevations.
4. Areas with contemporary arable and horticulture, urban, calcareous grassland and suburban land cover are predicted to experience the greatest overall climatic change, though other habitats experienced relatively greater change than these in the first half of the 20th century.
5. The extent to which locations sampled by ecological monitoring schemes represent broader habitat-level gradients of climate change exposure varies. Monitored

sites' coverage of wider trends is heterogeneous across habitats, time periods and schemes.

6. *Policy implications*. UK ecological monitoring schemes can effectively, though variably, capture the effects of climate change on habitats. To improve their performance, climate change could be explicitly included in the design of such programmes. Additionally, our findings on how effectively different datasets represent wider patterns of climate change are crucial for informing syntheses of ecological change connected to shifting atmospheric conditions.

KEYWORDS
climate change, climate change exposure, data synthesis, ecological monitoring, risk of bias

1 | INTRODUCTION

Earth's intertwined climate and biodiversity crises are two of the largest and most complex problems facing life on our planet (IPBES, 2019; Pörtner et al., 2022). While much attention is focused on the future impacts of climate change, human drivers have already shifted atmospheric conditions significantly away from those of the pre-industrial period—changes which often play significant roles in shaping present-day biodiversity patterns (Christidis et al., 2020; Kendon, McCarthy, et al., 2021; Martin et al., 2019; Pörtner et al., 2022). Understanding the past and present impacts of anthropogenic climate change on biodiversity—both for their own sake and for the insights they can provide into the future—ideally requires long-term data on both climatic conditions (e.g. from weather stations) and facets of biodiversity (e.g. from ecological monitoring schemes). Although this combination of co-located and robust data streams is unfortunately rare, where both are available, they can shed important light on how biodiversity has been responding to changing conditions (Morecroft et al., 2009; Pearce-Higgins et al., 2017; Pescott, Humphrey, et al., 2019; Thomas et al., 2011).

Two key considerations arise when interpreting changes in ecological monitoring data in terms of climate change impacts. Firstly, how exposed have different habitats been to climate change in the past? Surveys in more (or less) exposed habitats might be expected to record more (or less) ecological change; a violation of this assumption might reveal unanticipated resilience (or sensitivity) of the habitat's ecological communities to changing conditions (Davies et al., 2018; Pörtner et al., 2022; Willis et al., 2010). Secondly, to generalise from surveyed locations it is also important to understand how well the monitored locations reflect the climate change exposure of the wider habitats. Ecological monitoring sites may be chosen to randomly or systematically sample specific habitats or ecological gradients, or their placement may be more targeted or even opportunistic (Metzger et al., 2013; Pescott, Walker, Harris, et al., 2019; Vibrans et al., 2020; Wood et al., 2017). Unless climate change has been explicitly incorporated in the schemes' designs, monitored locations will not necessarily reflect the climate change exposure of the wider habitats they sample. In that case, changes recorded in sentinel sites may under- or overstate the likely effects of climate change for the wider environment, with potentially significant implications for policy, practice and ecological understanding (Boyd et al., 2021, 2022).

The UK is an excellent test bed for research, which integrates the study of past and future climate changes and their biodiversity impacts. Few other countries have comparable datasets on historical climates—which, in the UK, span over a century in detail (Hollis et al., 2019; Kendon, McCarthy, et al., 2021)—or similarly well-established and large-scale ecological monitoring schemes (Burns et al., 2018; Morecroft et al., 2009; Nisbet et al., 2017; Pescott, Walker, Harris, et al., 2019; Sier & Monteith, 2016; Wood et al., 2017). However, an integrated, habitat-level examination of past and future climate change has generally been lacking. Some studies have used various ecological models to assess the risks and opportunities of future climate change to British species and/or habitats (Berry et al., 2002, 2003; Dawson et al., 2003; Pearce-Higgins et al., 2017), whereas ecological monitoring data has generally been used to examine non-climatic drivers of contemporary or historic change in the latter part of the 20th century (Keith et al., 2009; Smart et al., 2005). Notably, Pearce-Higgins et al. (2017) (following Thomas et al., 2011) uses both biological records and model predictions, using the former to validate the latter, to assess the risks and opportunities facing UK species and, consequently, habitats under future climate change. Yet even this wide-ranging study does not consider the impacts of historic climate change. Moreover, the ways in which data from ecological monitoring schemes reflect broader gradients of climatic change—and therefore their past, present or future ecological effects—have not yet been assessed. This present study therefore has two aims: (1) to assess the exposure of UK habitats to anthropogenic climate change from the early 20th century to the late 21st century, and (2) to evaluate the extent to which the UK's existing ecological monitoring schemes capture these gradients of climate change exposure.

2 | MATERIALS AND METHODS

The three main steps in this analysis are: (1) the conversion of past, present and predicted future climate data to a measure of climatic change, (2) the cross-referencing of the climate change data with data on UK habitats and (3) comparing general patterns of climate change exposure to those sampled by different ecological monitoring schemes. No ethical approval was required for this research.

Two sources of climate data are used: HadUK-Grid (Hollis et al., 2019) for historical and contemporary climate data, and UKCP18 Local (Kendon, Short, et al., 2021; Lowe et al., 2018; Met Office, 2019) for future predictions. HadUK-Grid is a gridded data product interpolated from observational weather station records (Hollis et al., 2019). The UKCP18 Local (2.2 km) dataset used here consists of 12 simulations of a convection-permitting model; the 12-member ensemble mean was used in this study, since it was found to come consistently closer to observed climate patterns than any individual model run (Supplementary Information).

For historical and contemporary climate periods, we considered the early 20th century (1901–1930), mid-late 20th century (1961–1990), and the last decade (2010–2020). For each period, HadUK-Grid data on monthly precipitation and maximum, minimum and mean temperatures were downloaded at 1 × 1 km resolution. Averages for the 1961–1990 period were available, since this period is widely used as a 'climate normal', and for the other periods annual data were averaged together to create long-term mean datasets. UKCP18 Local data for the coming decades (2021–2040) and later 21st century (2061–2080) were downloaded at 5 × 5 km resolution and resampled to 1 km resolution using bilinear interpolation to match the HadUK-Grid data. (UKCP18 Local data are only available for the worst-case emissions scenario, RCP8.5, though there is relatively little difference between emissions scenarios in their predictions of changes in the coming two decades; Met Office, 2019.) Since the area around Shetland in the UK's far north is found close to the edge of the UKCP18 Local dataset's modelled area, and is therefore unreliable, it was excluded from further analyses. The Köppen-Geiger climate classification system (Table 1) was used to summarise conditions across space and their changes through time (Beck et al., 2018; Peel et al., 2007).

For each time period, an extended set of 37 bioclimatic variables were produced from the monthly climate data using the 'dismo' and 'Envirem' packages in R (Hijmans et al., 2021; R Core Team, 2020; Title & Bemmels, 2018). These variables were scaled and their dimensionality reduced using a Principal Components Analysis using the R package 'vegan' (Oksanen et al., 2019; Supplementary Information). The first two principal components (PCs), generally reflecting gradients from warmer and drier to cooler and wetter conditions (PC1, 58.25% of total variance) and from wetter (especially in winter) to more temperature-stable conditions (PC2, 21.43% of total variance), were used to assess monitoring scheme locations' exposure to climate change through time (Supplementary Information). The Euclidean distance between 1 km pixels' positions in PC1–PC2 space (weighted by the PCs' eigenvalues) in adjacent time points was calculated and used as an index of their climate change exposure through time.

To investigate the climate change exposure of UK habitats, the 25 m-resolution UK Land Cover Map 2019 (LCM2019; Morton et al., 2020a, 2020b) was overlaid onto the bilinearly interpolated map of climate change exposure, and the mean and standard deviation of climate change exposure was calculated for each habitat

TABLE 1 Descriptions of Köppen-Geiger climate types relevant to the UK (see Figure 1), adapted from Beck et al. (2018). Codes for climate types are composed of combinations of letters from the first three columns. All climate types listed have mean annual precipitation (mm/year) ≥20 times the mean annual air temperature (°C). References to temperature correspond to mean monthly air temperature.

Climate group	Rainfall pattern	Summer heat	Description	Criterion
C			Temperate	Hottest month >10°C and coldest month 0–18°C
D			Cold	Hottest month >10°C and coldest month ≤0°C
ET			Polar tundra	Hottest month 0–10°C
	s		Dry summer	Driest summer month has <40 mm of precipitation and <1/3 the rainfall of the wettest winter month
	f		No dry season	Not (s)
		a	Hot summer	Hottest month ≥22°C
		b	Warm summer	Hottest month <22°C and ≥4 months >10°C
		c	Cold summer	Hottest month <22°C and <4 months >10°C

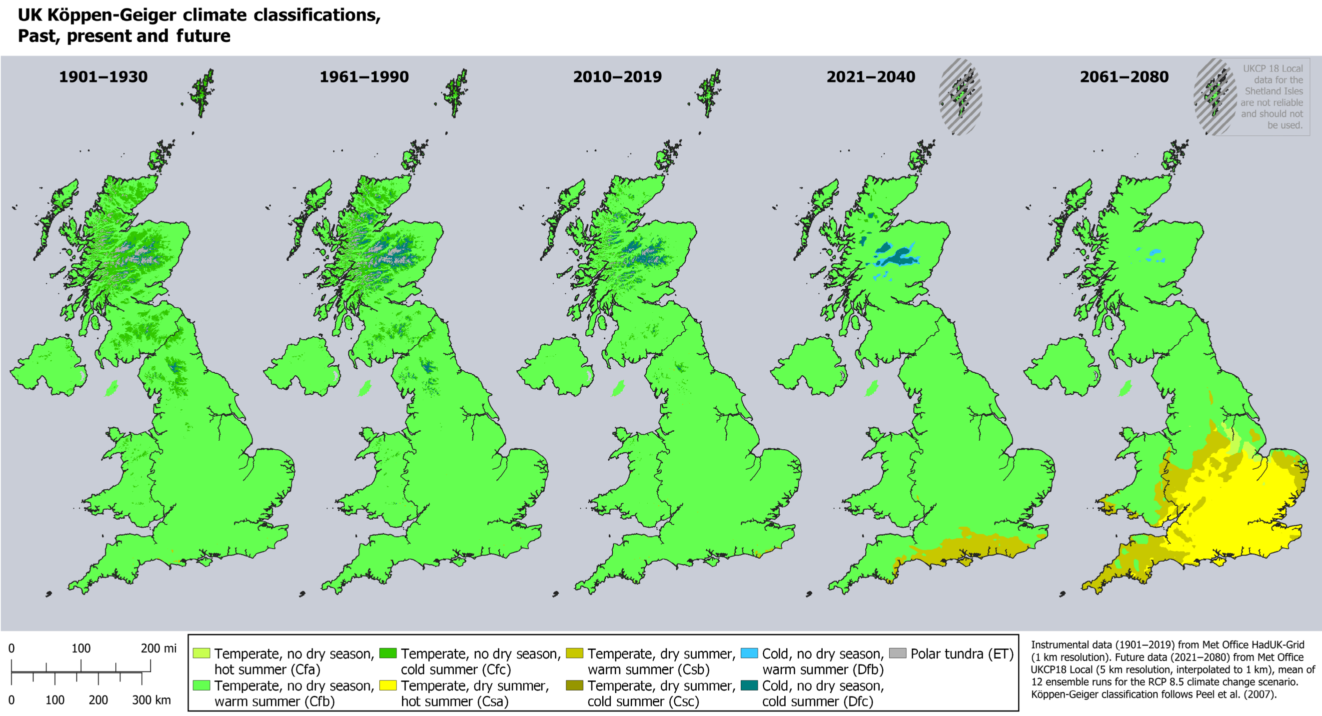


FIGURE 1 Maps showing Köppen-Geiger climate classifications for the UK from the early 20th century to the late 21st century. Data to the last decade (2010–2019) are from HadUK-Grid, and future data come from UKCP18 Local. (For further comparisons of instrumental and modelled data, see Supplementary Information.) Climate classifications follow Peel et al. (2007).

(here represented by the LCM2019 land cover classes). To assess the extent to which the UK's ecological monitoring schemes cover each habitat's gradient of climate change exposure, land cover classes and corresponding climate change exposure values were extracted for each unique surveyed location in four schemes which sample vascular plants within small, fixed plots (see Supplementary Information for further details on each): the Environmental Change Network (ECN, 2537 locations; Sier & Monteith, 2016), Long Term Monitoring Network (LTMN, 3848 locations; Nisbet et al., 2017), rolling Countryside Survey (CS, 1127 locations; Wood et al., 2017) and National Plant Monitoring Scheme (NPMS, 19,324 locations; National Plant Monitoring Scheme, 2021; Pescott, Walker, Harris, et al., 2019). These were compared against values from 1000 points selected at random within each habitat. The degree of overlap in the distributions (kernel density estimates) of climate change exposure between each scheme and the random sample was calculated using the 'Overlapping' package in R (Pastore, 2018; Pastore & Calcagnì, 2019). Saltwater areas were excluded from this part of the analysis since they are not the focus of any of the monitoring schemes included here.

3 | RESULTS

The UK's climate changed significantly between the beginning of the 20th century and the last decade (Figure 1) (Kendon, McCarthy, et al., 2021). Many upland areas have lost the generally cold or cold-summer climates they experienced in 1901–1930 or even 1961–1990, replaced by warmer summers and/or generally more temperate conditions (Figure 1, see Table 1 for definitions). The magnitude of the changes was greater between the mid-late 20th century and the last decade than it had been from 1901–1930 to 1961–1990, and the coming decades are predicted to bring yet greater changes (Figures 1 and 2). The 2021–2040 period is likely to see significant parts of southern England experience dry summers (<40 mm of rain in the driest summer month), and, under a pessimistic emissions scenario, much of southern, central and eastern England will average over 22°C in the hottest summer month (Table 1, Figure 2). The resulting Csa (temperate with dry, hot summers) and Csb (temperate with dry, warm summers) climate types are respectively absent and very rare in the UK across the 20th century; they are currently found in north-westernmost France (Csb), and the Mediterranean coast and Iberian Peninsula (both Csa and Csb) (Supplementary Information; Beck et al., 2018).

In each successive interval studied, the UK's climate change exposure has increased drastically (Figure 2): changes from the last decade to 2021–2040 are predicted to be far larger than those within the 20th century, and that entire period's total climate change would be less than that experienced between the periods of 2021–2040 and 2061–2080 under a pessimistic emissions scenario. Regionally, central, southern and eastern England are likely to have the greatest exposure to 21st-century climate change (Figure 2); these are the same areas predicted to develop new (to the UK) Köppen-Geiger climate types in the late 21st century, though they have also had higher than average exposure since the mid- to late 20th century. Climatic changes within the 20th century (between 1901–1930

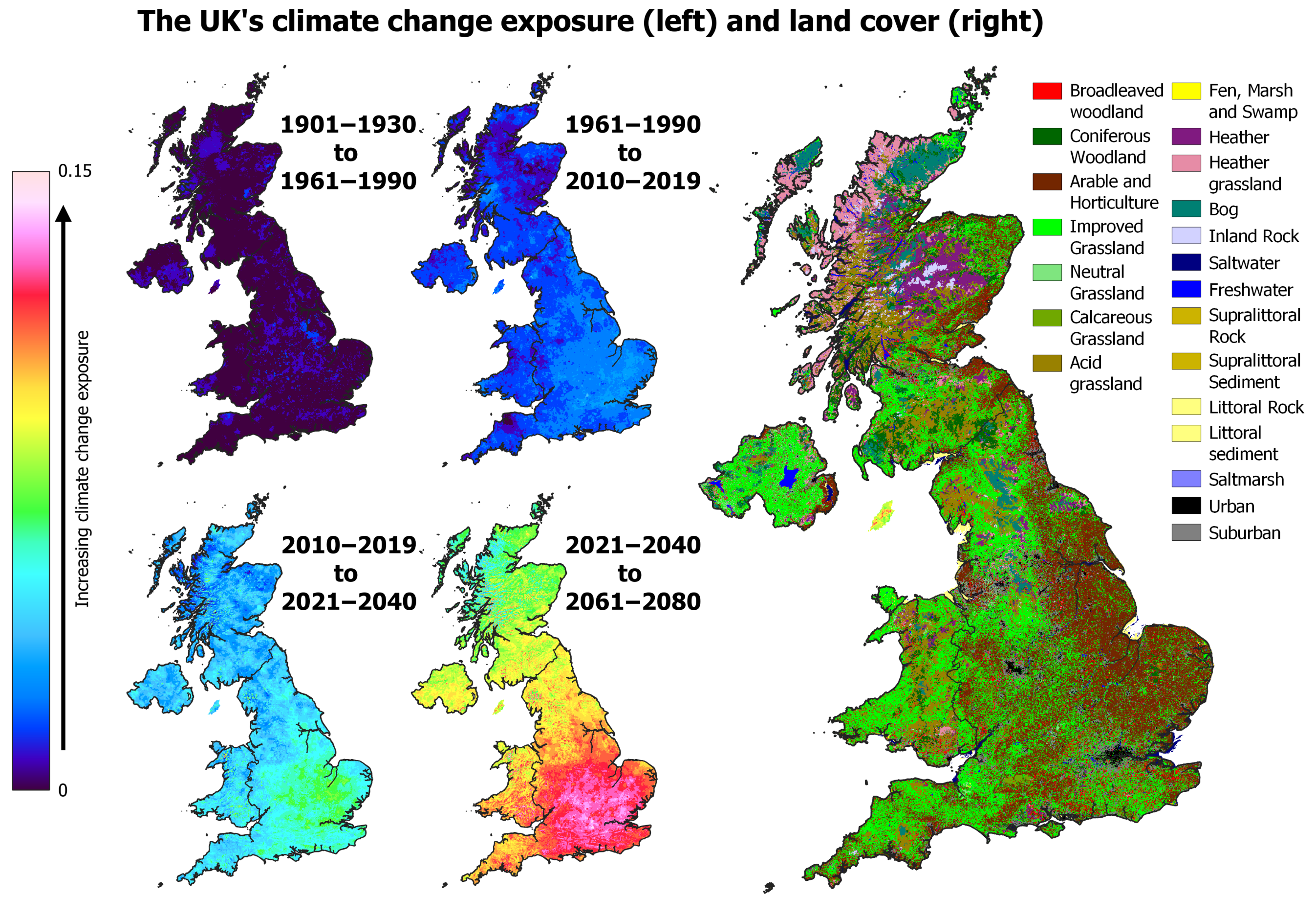


FIGURE 2 Maps showing the spatial distributions of the UK's climate change exposure (unitless) through time (left) and 2019 land cover (right).

and 1961–1990) are less clearly concentrated in this region. Locally, higher-elevation areas are generally more exposed to climate change than nearby lower-elevation locations, though the correlation between relative elevation and relative climate change exposure is much stronger in future predictions (intervals between 2010–2019 and 2061–2080) than in observational data (1901–1930 to 2010–2019) (Supplementary Information).

As well as varying (increasing) through time, exposure to climate change falls unequally on the UK's different habitats (Figure 3). Overall, the 2019 land cover classes with the greatest combined 20th- and 21st-century climate change exposure are arable and horticulture, urban, calcareous grassland, and suburban. Areas which currently have these four land cover classes had the greatest exposure to climate change between the late 20th century and last decade (2010–2019) and are predicted to have the greatest exposure in the 21st century too, but several semi-natural habitats (supra-littoral rock, neutral grassland, freshwater, heather grassland, saltwater, and inland rock) experienced greater climate change than these between 1901–1930 and 1961–1990. Three of the most climate-change-exposed land cover classes (arable and horticulture, urban, and suburban) are highly human-modified, with calcareous grassland the most exposed semi-natural habitat (as well as the most exposed of all between 2021–2040 and 2061–2080). The next highest-ranking habitats are, in order: broadleaved woodland (ranked seventh, sixth and fifth in the intervals from 1961–1990 to 2061–2080; its broad national distribution results in relatively wide ranges of climate change exposure); improved grassland; fen, marsh and swamp (ranked fifth between 1961–1990 and the last decade); saltmarsh (ranked fifth between the last decade and the coming two decades); and neutral grassland (ranked second in the 20th century and sixth between 1961–1990 and the last decade). Although high-elevation areas are generally more exposed to climate change than nearby low-elevation areas, the national patterns of land cover and climate change exposure (Figure 2) mean that upland habitats (such as acid grassland, heather, heather grassland, bog, and inland rock) do not rank among the UK's most exposed (Figure 3).

The coverage of climate change exposure gradients by the UK's different ecological monitoring schemes varies notably between habitats, time periods (past and future), and schemes (Figure 4, Supplementary Information). Overall, the rolling CS and NPMS sample habitats' climate change exposure more faithfully than the LTMN or ECN: considering exposure to historical climate change (from 1901–1930 to 2010–2019) and only habitats for which two or more survey locations were available, the schemes' mean overlaps

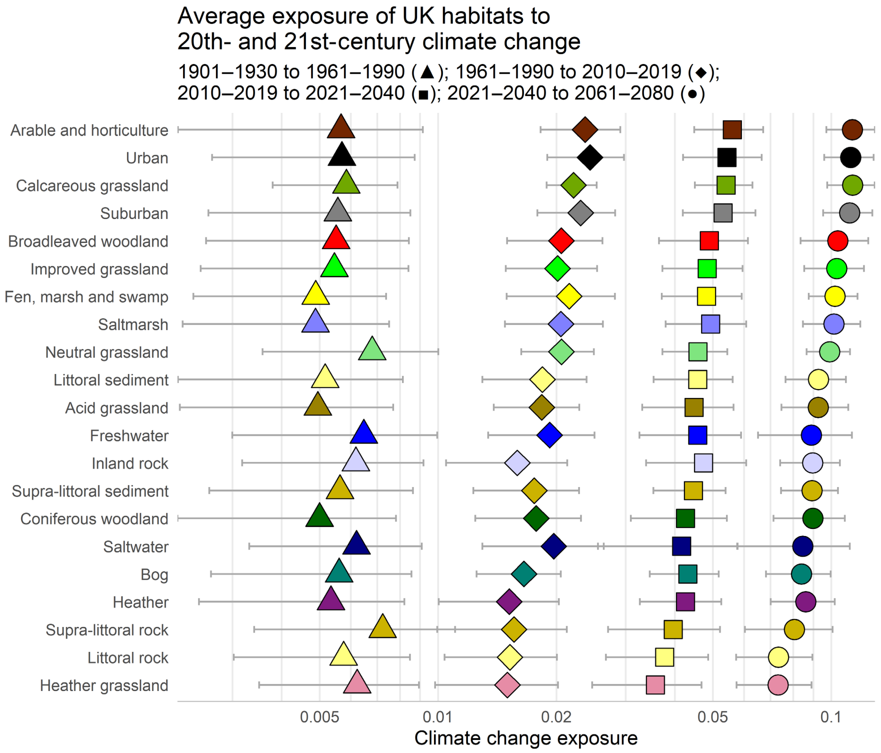
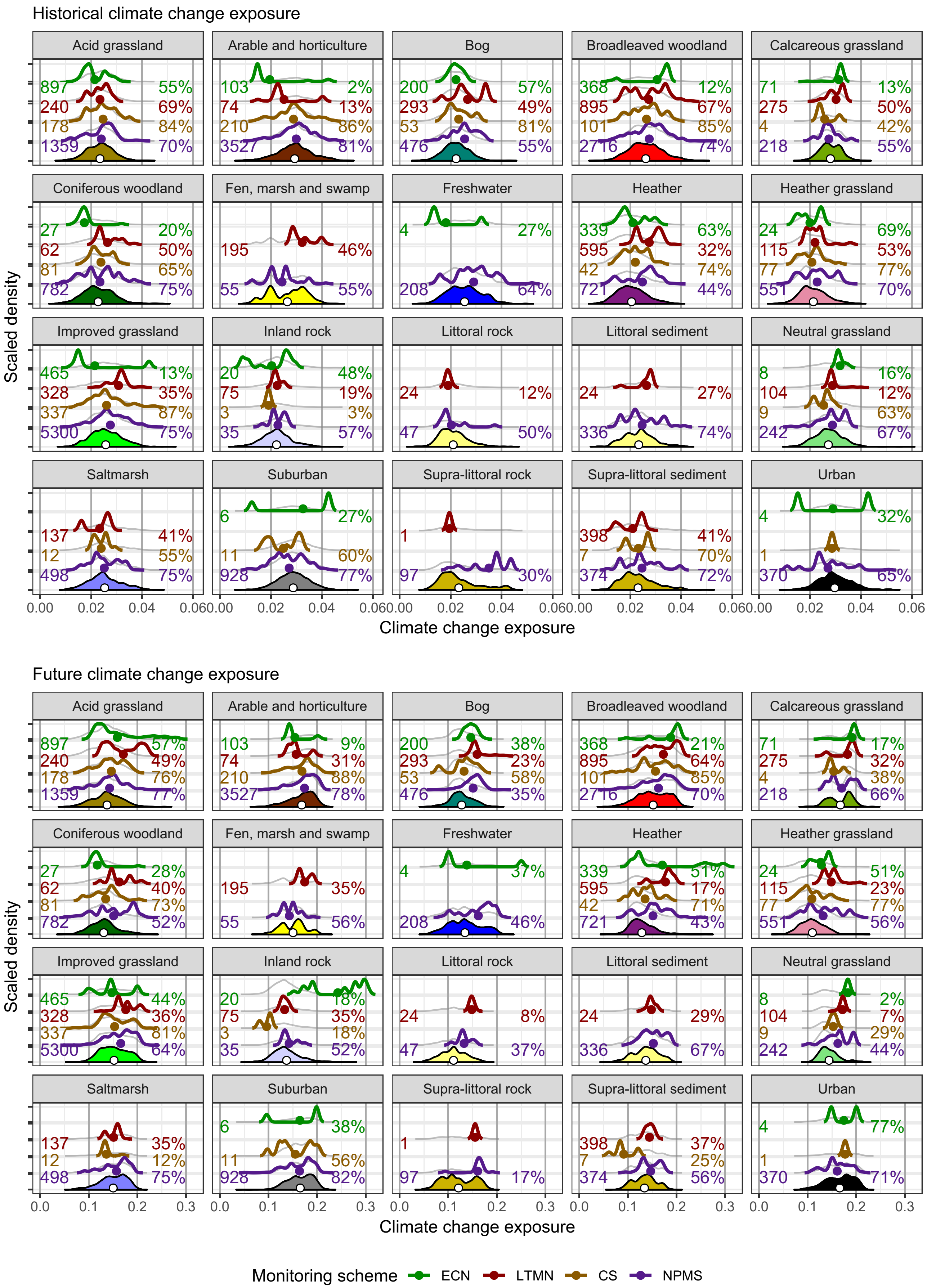


FIGURE 3 Means (points) and standard deviations (bars) of climate change exposure for UK habitats (based on 2019 land cover). Habitats are arranged from greatest (top) to least (bottom) total exposure, with a logarithmic *x*-axis.

with randomly-sampled exposure were 32.4% (ECN), 38.7% (LTMN), 62.5% (NPMS), and 66.5% (CS). Future climate change was generally sampled less well, with LTMN, NPMS and CS locations having mean overlaps of 31.4% (LTMN), 55.8% (NPMS), and 56.3% (CS); ECN locations bucked this trend, with a slight improvement in overlap to 34.9%. Comparing schemes' absolute differences from the random sample's mean climate change exposure (Figure 4, Supplementary Information) results in the same ranking—across both broad time periods CS is closest, followed by NPMS, LTMN and ECN.

Across the four schemes, the habitats whose historical exposures to climate change are best sampled are acid grassland (average overlap 69.6%), heather grassland (67.3%), supra-littoral sediment (60.9%), bog (60.3%), broadleaved woodland (59.5%) and saltmarsh (57.3%; Figure 4, Supplementary Information). Urban (74.4%), acid grassland (64.8%), broadleaved woodland (59.9%), suburban (58.7%), and improved grassland (56.3%) fared best for the future period (Figure 4, Supplementary Information). Few habitats' climate change exposure gradients are sampled well by all four schemes—in only two habitat-time period combinations do all schemes have >50% overlap with the exposure distribution of the random sample (acid grassland surveys have overlaps of 55.3%–84.1% for historical climate change exposure vs. 48.6%–76.8% for the future; heather grassland locations have 53.3%–76.7% (historical) and 23.1%–77.4% (future) overlap with the random sample). Of the 40 habitat-time period combinations, NPMS survey locations had the greatest overlap with the random sample 25 times; CS locations ranked first in 14 instances (of 28 for which the scheme's overlaps could be quantified); ECN has the highest overlap with future climate change exposure in urban land cover but has only four sample points. However, ECN and LTMN locations outperform one of CS and NPMS in several habitats, having the second-highest overlap in bog (ECN), calcareous grassland (LTMN, historical), heather (ECN), inland rock (ECN, historical, and LTMN, future), saltmarsh (LTMN, future), and supra-littoral sediment (LTMN, future). ECN and LTMN also provide important coverage of the seven habitats for which no CS survey locations were identified, including fen, marsh and swamp, where there are 3.5 times more LTMN survey locations than NPMS plots. (NPMS, which has locations overlapping with all land cover types, frequently has an order of magnitude more plots than the other schemes.)

FIGURE 4 Comparison of historical (1901–2019, top) and future (2021–2080, bottom) climate change exposure in UK terrestrial habitats (based on 2019 land cover). Filled polygons show the distribution of climate change exposure, as measured by 1000 random sample points within each land cover type. Coloured lines show the distribution of exposure for each monitoring scheme's unique surveyed locations overlaid on the 2019 land cover map (from top to bottom: ECN, LTMN, CS and NPMS). Faint grey lines show the random sample's distribution on the same scale as each scheme's, to aid visual comparisons. Each distribution (i.e. each row within each panel) is scaled between 0 and 1 for visualisation. Note that the *x*-axis limits differ between historical and future plots. Numbers on the left of each pane indicate the number of locations included for each habitat-scheme combination; percentages show the overlap of scheme- and randomly sampled climate change exposure within each habitat.



Historical climate change exposure
Acid grassland
Arable and horticulture
Bog
Broadleaved woodland
Calcareous grassland
Coniferous woodland
Fen, marsh and swamp
Freshwater
Heather
Heather grassland
Improved grassland
Inland rock
Littoral rock
Littoral sediment
Neutral grassland
Saltmarsh
Suburban
Supra-littoral rock
Supra-littoral sediment
Urban
Scaled density
Climate change exposure
Future climate change exposure
Acid grassland
Arable and horticulture
Bog
Broadleaved woodland
Calcareous grassland
Coniferous woodland
Fen, marsh and swamp
Freshwater
Heather
Heather grassland
Improved grassland
Inland rock
Littoral rock
Littoral sediment
Neutral grassland
Saltmarsh
Suburban
Supra-littoral rock
Supra-littoral sediment
Urban
Scaled density
Climate change exposure
Monitoring scheme
ECN
LTMN
CS
NPMS

4 | DISCUSSION

The UK's habitats clearly face a significant challenge from anthropogenic climate change: our results suggest that the coming two decades will see changes in conditions of approximately equivalent magnitude to the entire period between the present and the early 20th century (and, most likely, long before; Kendon, McCarthy, et al., 2021). Notably, we find that habitats typically associated with upland areas (e.g. heather, bog and inland rock) are generally less exposed to climate change than others (Figure 3), although high-elevation areas are more exposed than nearby lowlands (Supplementary Information). There are, however, two important considerations for the interpretation of these results.

Firstly, habitats with higher exposure will not necessarily be affected more by climate change, since the impacts of changing conditions are a function both of habitats' exposure (evaluated here) and their sensitivity (not considered) (Platts et al., 2019; Pörtner et al., 2022; Rinnan & Lawler, 2019). Ecosystems at higher elevations often have less capacity to respond to increased temperatures, so may undergo larger climate-induced changes than might be inferred from their exposure alone (Berry et al., 2002, 2003; Dullinger et al., 2012; Pearce-Higgins et al., 2017). Secondly, and conversely, our findings also demonstrate that the ecosystem effects of climate change may well be significant in areas of the UK traditionally considered less vulnerable. Central, southern and eastern England is predicted to experience the UK's greatest climate change (Figure 2), including the development in the 21st century of climate types that have historically been absent from the UK (Figure 1; Arnell et al., 2021; Christidis et al., 2020). This leaves semi-natural habitats like calcareous grassland—as well as anthropogenic areas such as urban, suburban and arable and horticultural land—which are relatively widespread in these areas, highly exposed to climate change (Figure 3), and at risk of undergoing significant ecological change.

For semi-natural habitats, the consequences of climate change exposure will intersect with those of other drivers of change which are already causing shifts in ecological communities (Platts et al., 2019; Smart et al., 2005). In particular, land use change and habitat loss (and the resultant reduction or absence of landscape connectivity) will limit species' ability to redistribute in response to changing conditions: more climate-change-exposed habitats which are also more fragmented or isolated, such as calcareous grasslands or lowland heaths or bogs, are more likely to experience greater ecological change (Duffield et al., 2021; Pearce-Higgins et al., 2017; Platts et al., 2019). Protected area designations could be important for these highly climate change-exposed habitats, since they often shelter relatively intact landscapes and may be better placed to implement management interventions which mitigate the impacts of changing conditions; however, static park boundaries designed around historical habitat locations may be unsuitable for the distribution shifts that many communities will undergo in response to climate novelty (Asamoah et al., 2021; Duffield et al., 2021; Hoffmann et al., 2019). For arable and horticultural land, significant exposure to 21st-century climate changes is likely to have a range of impacts, from potential yield gains and changes to the crops which can be grown, to increased damage from extreme weather events and the rise of new agricultural weeds (Peters et al., 2014; Rial-Lovera et al., 2017; Wheeler & Lobley, 2021). The combinations and interactions of these changes and shifting conditions will be complex and will require farmers to take adaptation measures that may prove to be challenging (Rial-Lovera et al., 2017; Wheeler & Lobley, 2021).

Our findings demonstrate that all four of the monitoring schemes considered in this study have roles to play in recording the ecological impacts of climate change on UK habitats. The rolling CS provides excellent coverage of climate change exposure gradients in many habitats (and, for many plots, also provides much longer-term time series as well; Wood et al., 2017); the NPMS has by far the most unique survey locations, is the only scheme to cover every land cover class (though it actually samples semi-natural habitats in urban and suburban areas rather than those areas themselves), and frequently provides good coverage of exposure gradients (Figure 4). While the ECN and LTMN have relatively few locations and narrower, more skewed coverage of most habitats, they provide important complements to the rolling CS and NPMS sites in key habitats the latter schemes sample less well (Figure 4). This is most likely a consequence of the schemes' design (see Supplementary Information for more details). 1 × 1 km squares sampled for CS and NPMS are selected using stratified (CS) and weighted (NPMS) random approaches, which should lead to good coverage of environmental gradients (though, compared to the professional, even-effort surveys of CS, NPMS volunteers monitor a more skewed sample of the country) (Metzger et al., 2013; Pescott, Walker, Harris, et al., 2019; Wood et al., 2017). Since ECN and LTMN intensely sample relatively few dedicated long-term monitoring sites, their coverage is necessarily less extensive or representative (Nisbet et al., 2017; Sier & Monteith, 2016).

Two caveats are required in the analysis of monitoring scheme coverage of climate change exposure gradients, however. The first is that not all the unique locations used in this analysis will be repeatedly surveyed as part of the scheme. Although all the schemes prioritise repeat surveys, some locations in each have only been surveyed once, and so would not provide information on ecological change through time without being re-examined. In some cases this is by design, such as with the ECN and LTMN's combination of single- and repeat-survey locations, but it can also have a stochastic element—it can follow year-to-year changes in participation by NPMS volunteer surveyors, for example (Pescott, Walker, Harris, et al., 2019). The second is that the ecosystems surveyed may not exactly match those predicted from the land cover map. The difficulty of distinguishing different types of grassland from remote sensing alone introduces uncertainties into the calculation of habitat-specific exposure gradients (Figures 3 and 4), for example, and minor inaccuracies in plot coordinates may result in them being linked to the wrong habitats, altering the scheme-level distributions in Figure 4 (Pescott, Walker, Smart, et al., 2019). Nonetheless, the four habitat monitoring schemes examined will have a valuable role in capturing ecological change across the UK's gradients of climate change exposure. This is despite climate change being only a minor factor in decisions about plot/site location for the schemes: climatic conditions in the mid- to late 20th century played a role in the underlying environmental classification for CS (Wood et al., 2017), and predicted climate change was considered for LTMN sites (Nisbet et al., 2017), but it was not explicitly addressed in the NPMS sampling strategy or for selecting ECN locations (Pescott, Walker, Harris, et al., 2019; Sier & Monteith, 2016).

On a global scale, ecological monitoring is extremely variable in its coverage and intensity, with schemes set up and run in a range of different ways (Lengyel et al., 2008; Sabatini et al., 2021). Although our scheme- and habitat-specific results are unique to the UK, our finding that scheme size, spatial coverage and sampling design are closely related to how effectively gradients of climate change exposure are captured is likely to be more widely applicable. Since climate change is likely to be an increasingly important driver of ecological change in the 21st century (IPBES, 2019), any further expansions or development of environmental monitoring schemes could build on these findings, or even explicitly aim to improve their coverage of likely climate change gradients (Metzger et al., 2013). The methods in this study provide a straightforward potential pathway for such work, although other approaches are also available (e.g. Anderegg et al., 2022). In addition, assessing the coverage of climate change exposure could also be valuable for national-/global-level syntheses of ecological data. The increasing availability of widespread data on species occurrence/abundance lends itself to the production of ecological time series which, although potentially informative, come with significant challenges, since aggregating spatially and/or temporally heterogeneous datasets can introduce a substantial risk of bias that must be acknowledged, accounted for and/or mitigated (Boyd et al., 2021, 2022; Pescott, Humphrey, et al., 2019). For illustration, a study examining historical climate-driven trends in broadleaved woodland habitats might feasibly use data from ECN sites, but these appear to have had much more exposure to historical climate change than the habitat at large (Figure 4), potentially giving an exaggerated view of the ecosystem's change. The inverse is true of ECN sites in coniferous woodland (Figure 4), so a synthesis relying on data from these locations might underestimate the actual scale of climate-driven changes in this habitat. Accounting for monitoring sites' known or likely coverage of climate space, as in this study, would present a valuable way of assessing—and then, crucially, mitigating and/or communicating—the risk of bias in such time series studies (Boyd et al., 2022). A global-scale risk-of-bias assessment of ecological monitoring locations with respect to climate change exposure would, therefore, be valuable, but to our knowledge such an effort has not yet been implemented.

5 | CONCLUSIONS

The UK's current climate is already markedly different to that of the early 20th century, and the coming decades of the 21st century will bring continually greater deviation from long-term normals (Figures 1 and 2; Kendon, McCarthy, et al., 2021). None of the UK's habitats will escape the consequences of these changes, though some have greater exposure to changing conditions than others (Figure 3). Our study shows that these varying gradients of past and future climate change exposure are effectively, though differently, captured by the UK's ecological monitoring schemes (Figure 4). By integrating data on sample locations, land cover, and past, present and future climatic conditions, the results provide a guide for more accurately synthesising ecological monitoring data to understand how elements of biodiversity have responded to 20th-century climate change, and for interpreting ongoing changes into the 21st century.

AUTHOR CONTRIBUTIONS

Oliver J. Wilson and Oliver L. Pescott conceived the idea for this paper; Oliver J. Wilson led the methodology design; Oliver J. Wilson and Oliver L. Pescott collected the data; Oliver J. Wilson analysed the data and led the writing of the manuscript; Oliver J. Wilson and Oliver L. Pescott contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no relevant conflicts of interest.

DATA AVAILABILITY STATEMENT

Raster files of climate change exposure and the UK Köppen-Geiger climate classification have been submitted to the Environmental Information Data Centre (10.5285/d370cda8-7d3d-4b62-8d09-23711aa18ac2) (Wilson & Pescott, 2023).

ORCID

Oliver J. Wilson https://orcid.org/0000-0002-1834-7542
Oliver L. Pescott https://orcid.org/0000-0002-0685-8046

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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. Comparisons—mean absolute error (MAE, left) and root mean square error (RMSE, right)—between UKCP18 local projections and HadUK-Grid observations for 1981–2000. The 12 UKCP18 local ensemble members (emXX) and their mean (emmn) are assessed for mean, min. and max. monthly temperature (tas) and rainfall.

Table S1. Area (km^2) covered by each climate type (see main text Table 1 for descriptions) at different time points in HadUK-Grid (HUKG, purple, upper half of each row) and UKCP18 Local (UKCP, blue, lower half of each row), including the shared 1981–2000 time period.

Figure S2. The changing distribution of Köppen-Geiger climate types in the UK from the early 20th century to the late 21st century. Top row: HadUK-Grid observations; bottom row, UKCP18 Local projections.

Figure S3. Wider spatial context for the UK's past, present and future Köppen-Geiger climate classes (Figure S2, main text Figure 1). Classes not found in the UK are omitted. For definitions of climate types, see main text Table 1. Data from Beck et al. (2018).

Figure S4. The relationship between local elevation (from the GMTED30 dataset) and local climate change exposure. Values of both variables were normalised to the mean of 11-cell neighbourhoods on 1 km-resolution rasters. Red lines depict linear correlations. Note that the limits of each panel's *y*-axis differ.

Table S2. Data underpinning main text Figure 4 (number of sample points for each habitat-monitoring scheme combination, and their percentage overlap with the distribution of randomly sampled historical/future climate change exposure).

Table S3. Data underpinning main text Figure 4 (mean values of climate change exposure from distributions of climate change exposure as sampled randomly and by different monitoring schemes).

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