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Biodiversity losses associated with global warming of 1.5 to 4 °C above pre-industrial levels in six countries

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Abstract

We quantify the projected impacts of alternative levels of global warming upon the climatically determined geographic ranges of plants and vertebrates in six countries (China, Brazil, Egypt, Ethiopia, Ghana and India), accounting for uncertainties in regional climate projection. We quantify in a spatially explicit fashion the species richness remaining or lost, allowing the identification of climate refugia which we define as areas where > 75% of the species currently present remain in a world with a particular level of global warming above pre-industrial levels. In all countries and in both taxa, species richness declines with warming, as does the proportion of each country remaining a climate refugium for plants or vertebrates. In percentage terms, refugia loss relative to a 1961–1990 baseline period is greatest in India and Brazil, and least in Ghana and Ethiopia for the same level of warming, and is greater for plants than for vertebrates. Taking account of present land uses (i.e. area still considered natural), and using species richness of plants as a proxy to indicate biodiversity more generally, the proportion of land acting as climate refugia for biodiversity in five of the countries variously declines from 32–75% of a country in the 1961–1990 baseline period to 20–64% for 1.5 °C global warming, 11–53% for 2 °C, 3–33% for 3 °C and 2–24% for 4 °C warming. In Ethiopia, India, Brazil and China, climate refugia decline rapidly with warming while in Ghana and China some refugia persist even with 3–4 °C of warming. Only small percentages of Brazil, India and China are both climate refugia and lie within protected areas; hence, an expansion of the protected area networks in these countries would be required to deliver climate resilient biodiversity conservation. These percentages are larger in Ethiopia and Ghana and, in some areas of Ghana, the only remaining refugia are in protected areas, the remaining landscape converted to other uses.

Keywords Climate change · Biodiversity · Risk · Climate refugia · Species richness

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1 Introduction

Climate change is projected to affect the distribution of most species on Earth. Climatically driven geographic range losses of more than 50% is projected in ~ 49% of insects, 44% of plants and 26% of vertebrates for warming of 3.2 °C above pre-industrial levels (Warren et al. 2018a, IPCC 2018). At 2 °C, these projections of loss fall to 18% of insects, 16% of plants and 8% of vertebrates, and at 1.5 °C, to 6% of insects, 8% of plants and 4% of vertebrates. The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to constrain global temperature rise to 'well below 2 °C' and to 'pursue efforts' to limit this warming to 1.5 °C above pre-industrial levels' (UNFCCC 2016a). However, the total of countries' nationally determined contributions (NDCs) is projected to lead to a warming of 2.9-3.4°C above pre-industrial levels by 2100 (UNFCCC 2016b; Rogelj et al. 2016). We use the 1850-1900 period to represent a pre-industrial baseline relative to which levels of global warming are referred, in line with the Paris Agreement which also does so, itself based on IPCC (2013).

The global analysis reported in Warren et al. (2018a) is based on the Wallace Initiative database (https://wallaceinitiative.org/) and contains projections of potential climate change impacts on the climatically determined geographic ranges of more than 125,000 individual species of plants and vertebrates. This study mines and post-processes this database to quantify the risks posed by climate to biodiversity in six countries at different levels of global warming. We use species richness of plants and vertebrates as a proxy or indicator of biodiversity levels in general, and in particular we quantify the geographic extent and location of the climate change refugia where over 75% of the species currently present are projected to remain despite a particular level of global warming.

To do so, we extract projections of the impacts of climate change upon these two taxa in China, Brazil, Egypt, Ethiopia, Ghana and India. These six countries provide a range of contrasting sizes and different levels of development on three continents spanning tropical and temperate biomes, and forest, grassland and desert habitats. In these countries, many societies are closely dependent upon ecosystem services for their livelihoods. The results presented here also feed into the paper on natural capital risk (Price et al.) elsewhere in the Topical Collection. The study was completed as part of a wider project, looking at a range of climate risks across a range of countries on different continents, in line with the companion papers in this Topical Collection.

2 Methodology

The results presented here come from mining the well-established Wallace Initiative database (Warren et al. 2013, 2018a, 2018b; Smith et al. 2018; Jenkins, Warren and Price 2021; Bednar-Friedl et al. 2022; Costello et al. 2022; Mycoo et al. 2022; Parmesan et al. 2022; Trisos et al. 2022; Saunders et al. 2023). The methodology used in developing the models in this database can be found in Warren et al. (2018a, 2018b) and Warren et al. (2013), where more details on the methods, caveats and limitations can be found (see also Parmesan et al. 2022). Briefly, the global scale Wallace Initiative (WI) database was created using an established species distribution model, MaxENT (Phillips et al. 2006), to estimate potential changes to the ranges of more than 130,000 species associated with levels of global warming between 1.5 and 6 °C (relative to pre-industrial levels of 1850–1900).

As in Warren et al. (2018a, 2018b), calculations were carried out at a 20 × 20 km scale. The MaxENT analysis relies on developing a statistical relationship between current species distributions (GBIF 2015) and current climate, and assuming this relationship holds into the future, using 21 alternative regional CMIP5 climate change projections for each level of warming to incorporate uncertainty in regional climate projection. These levels of warming span the goal set in the UNFCCC Paris Agreement of limiting warming to well below 2 °C and to pursue efforts to limit it to 1.5 °C, as well as higher levels of warming such as 3 °C which are consistent with the current national policies under the UNFCCC in terms of their NDCs (Rogelj et al. 2016). The lower temperature targets correspond to lower primary energy demand and a higher share of renewable energy supply such as solar, wind and bio-energy.

Once the individual species' models were developed, they were then aggregated into species richness remaining in each grid cell within each of the six countries, based on projected regional climate change patterns resulting from constraining global warming to the lower levels of 1.5 °C and 2 °C, compared to higher global warming levels of 3 °C and 4 °C. We then use this to quantify the geographical extent of areas we term climate refugia, defined as areas retaining at least 75% of the species currently modelled (excluding dispersal) present under the changed climate (Warren et al. 2018b). This proportion of species must be projected to be retained in a grid cell, under at least one-half of the regional climate model projections for a given level of global warming, in order for that grid cell to qualify as a refugium at that level of global warming. Thus, uncertainty in regional climate projection is accounted for in the identification of refugia. Well-functioning ecosystems depend on the retention of the species that they contain, whereas species loss contributes to loss of ecosystem functioning (Gaston and Fuller 2008; Parmesan et al. 2022). Degradation of ecosystem functioning can then impact ecosystem services and natural capital (see Price et al., this issue). Hence, these climate refugia indicate locations where the current ecological community is projected to best be able to be preserved under future climate change. We also consider the extent to which these areas currently are 'protected', as in being within the current Protected Area Network of a country. Note that the analyses presented here do not explore the potential for species to move to new geographical locations (adaptation by movement) under climate change. Many mammals and birds have an ability to disperse (DeVictor et al. 2012), however plants, reptiles and amphibians much less so (Warren et al. 2018a). While dispersal has clear benefits to the survival of individual species, the benefit (or risk) to the ecological community is less clear. Additionally, the degree to which this dispersal results in successful shifting of an individual species' range will be affected by their dependency on plants and insects which may have been unable to track their shifting climate envelope. Therefore, dispersal is excluded from the process of identifying climate refugia that are designed to act as indicators of ecosystem intactness. Dispersal is frequently modeled as an important adaptation for the persistence of individual species. However, at the level of the community, potential changes in competition for limited resources, and/or changes to predator-prey, pollinator and seed dispersal interactions, may counter individual species level benefits (Burkett et al. 2005).

As well as quantifying the theoretical areal extent of refugia for plants and vertebrates in a pristine environment (i.e. climate only), we also quantify the areal extent of refugia in areas whose land cover has been defined as 'natural' in 2015 using data from the European Space Agency Climate Change Initiative Land Cover Database (ESA CCI; 300 m resolution). In this study, 'natural' land was defined as cells with > 50% natural vegetation. In some countries, most notably Egypt, large areas are classified as bare (sand/desert). While these areas may contain unique species, and while some agricultural landscapes and even urban areas may be important for some species, they generally contain lower levels of biodiversity than ‘natural’ areas. Finally, we look at how many of these refugia are located within areas defined as being part of the Protected Areas network (UNEP-WCMC and IUCN 2019). These are provided to give a more realistic estimate of the extent of well-functioning ecosystems that may remain intact under various climate change scenarios, when current land use and biodiversity conservation efforts are taken into account.

We also provide maps showing the locations of climate refugia in each country at different levels of global warming for plants and vertebrates, showing how these are projected to shrink with increasing global warming. In general, areas that are refugia at a higher level of warming are also refugia at lower levels of warming.

2.1 Climate change scenarios

This particular study relies on mining the existing Wallace Initiative database that projects changes in species’ climatic distributions at alternative levels of global warming (specific warming levels (SWLs)) of 1.5, 2, 2.7, 3.2 and 4.5 °C. For consistency with sister publications in this Topical Collection, it was necessary to interpolate linearly between simulations in the database in order to extract projections matching the SWLs of 3 and 4 °C.

The current Wallace Initiative simulations begin with global temperature time series corresponding to the four Representative Concentration Pathways (RCPs (Moss et al. 2010)) that are used to scale 21 alternative patterns of regional climate change derived from the CMIP5 model inter-comparison project (IPCC 2013). Projected climates were produced matching four different levels of warming in the 2080s (i.e. average of the 30-year period 2071–2100), using the RCP global temperature time series, as follows: RCP8.5 in the 2020s as a proxy for a 1.5 °C world; RCP 2.6 in the 2080s for a 2 °C world; RCP 6.0 in the 2080s for the higher end of the Intended Nationally Determined Contributions (INDC) range (here 3.2 °C) and RCP 8.5 in the 2080s for 4.5 °C warming (see SI for further detail). The regional climate change patterns were obtained from the IPCC Data Distribution Centre at www.ipcc-data.org and were scaled according to the amount of warming provided by the time series and combined with observational climate data (WorldClim database for 20 km (10 arc minutes, version 1.4, (Hijmans et al. 2005)) in order to create 21 alternative patterns of regional projected climate futures (one corresponding to each General Circulation Model) at a fine spatial resolution of 10 arc minutes (Osborn et al. 2016), for each SWL.

2.2 Species distribution modelling in the Wallace Initiative

The Wallace Initiative is based on the concept of species climatic niches and can therefore be applied systematically across the globe. Firstly, the observed climate data is post-processed to provide eight bioclimatic variables (Warren et al. 2013). Secondly, MaxENT is used to identify a statistical relationship between the present day bioclimatic variables (in 1961–1990) and the distribution of a single species. Thirdly, the projected climates (Sect. 2.1) are applied to these statistical models to derive potential future climate space for each species in each future scenario. Our refugia are defined as locations where $> 75\%$ of the species currently present remain under the changed climate. ‘Current’ refers to their presence in the database of the Global Biodiversity Information Facility (GBIF; Warren et al. 2013) which contains observations of species records collected over the past several decades, which is a reasonable approximation to the 1961–1990 baseline climate.

Full information is available in Warren et al. (2018a) and Warren et al. (2013). However, for the reader's information, some key measures taken to increase rigor and statistical robustness of the findings are re-iterated here: (i) species are assigned to one of fourteen biogeographic realms for the clipping process (to minimise commission errors in applying MaxENT); (ii) at least 10 geographically separated data points per bioclimatic variable used were analysed to provide sufficient data for a robust statistical analysis; (iii) resampling tests were carried out to identify whether general trends were robust to the inclusion or exclusion of individual species; (iv) rigorous statistical tests were carried out to justify the use of the chosen bioclimatic variables.

3 Results

3.1 Areal extent of climate refugia under future climate change

By definition, without climate change, 100% of the areal extent of each country would act as a climate refugium in 1961–1990 if no land use change had taken place and the habitats are entirely natural. Figure 1 shows how the areal extent of refugia declines under future scenarios of 1.5–4 °C of global warming, by quantifying the percentage of each country's land area continuing to potentially act as a climate refugium for plants and vertebrates (areas climatically suitable for at least 75% of the species currently present in our models). Under projected future climates, in the continued absence of land use change, climate refugia would decline in all six countries (Fig. 1a, c) for both plants and vertebrates.

In the six countries studied here, natural land has already been converted to other uses (e.g. agriculture) to varying degrees (Table 1). In Ethiopia, 75% of land remains un-converted, whilst in India, only one third is un-converted. Egypt is a special situation, as a large portion of the country is classified in the ESA CCI database as bare ground leading to lower overall percentages. However, to maintain comparisons with other countries (each of which has a percentage of bare ground) and the biodiversity models, the percentages given are of the country as a whole.

Because of land use change that has already taken place, the actual extent of climate refugia is smaller if only land currently identified as natural is considered (Fig. 1b, d) and still smaller if only natural habitat within protected areas is considered (Fig. 1e, f). For example, the proportion of land acting as climate refugia for plants in five of the countries variously declines from 32 to 77% of a country in the 1961–1990 baseline period (i.e. the amount of natural land remaining) to 20–64% for 1.5 °C global warming, 11–53% for 2 °C, 3–33% for 3 °C and 2–24% for 4 °C warming. The proportion of land acting as climate refugia for vertebrates variously declines from 32 to 77% of a country in the 1961–1990 baseline period (i.e. the amount of natural land remaining) to 18–53% for 1.5 °C global warming, 13–53% for 2 °C, 7–52% for 3 °C and 2–43% for 4 °C warming. In Ethiopia, India, Brazil and China, climate refugia decline rapidly with warming while in Ghana and China some refugia persist even with 3–4 °C of warming. Only small percentages of Brazil, India and China are both climate refugia and lie within protected areas; hence, an expansion of the protected area networks in these countries would be required to deliver climate resilient biodiversity conservation. These percentages are larger in Ethiopia and Ghana and, in some areas of Ghana, the only remaining refugia are in protected areas, the remaining landscape converted to other uses. The values for Egypt are excluded here as the proportion of the country classified as bare

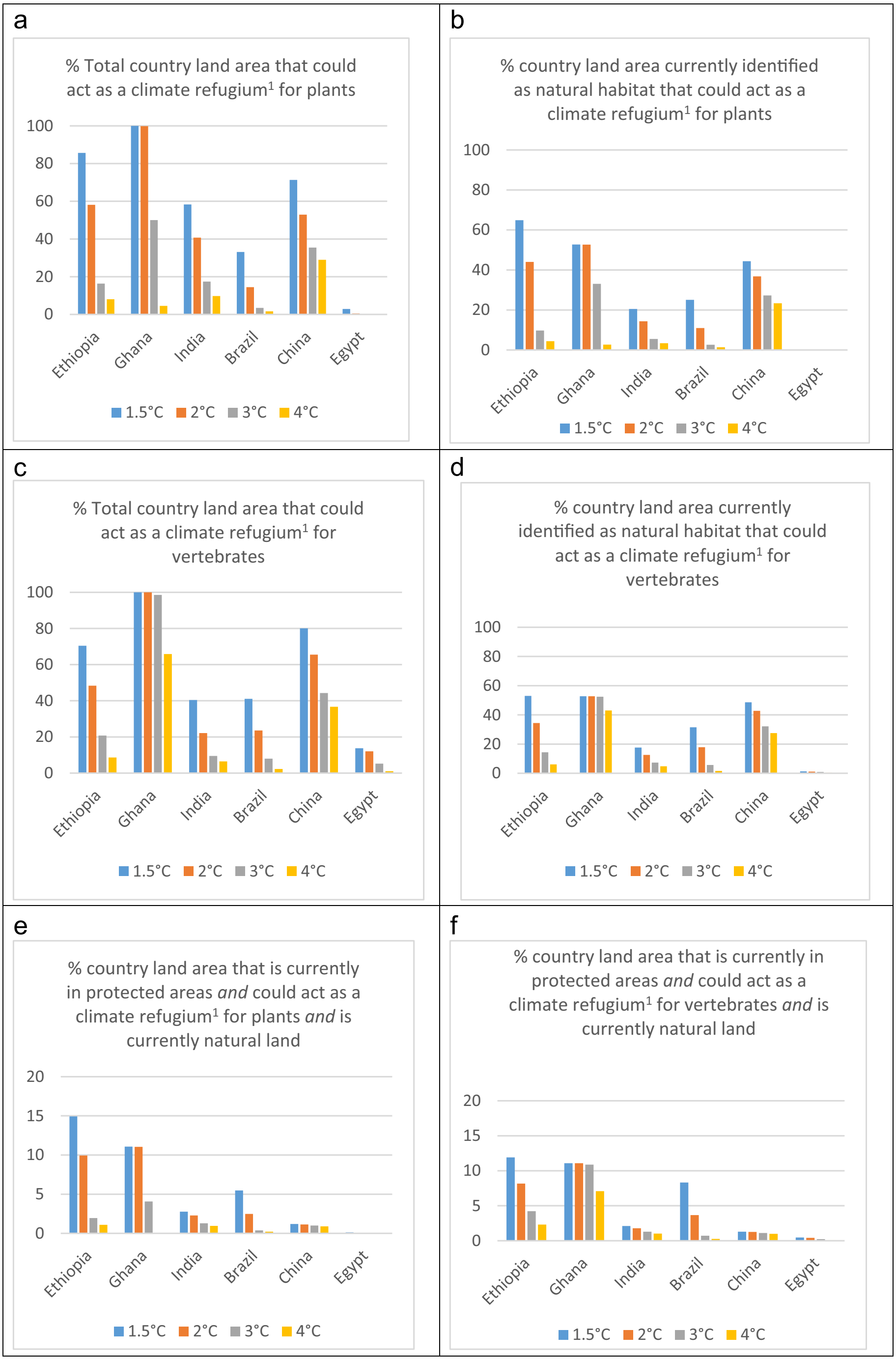


Fig. 1 Areal extent of refugia (remaining climatically suitable for > 75% of the species modelled) for plants and vertebrates under future alternative levels of global warming, excluding (**a**, **c**, **e**) and including (**b**, **d**, **f**) current (2015) land use, and in protected area networks. Temperatures are specific global warming levels above pre-industrial.

Table 1 % Natural land by area presently remaining

Ethiopia	75.2%
Ghana	52.7%
India	32.2%
Brazil	76.5%
China	54.1%
Egypt	2.5%

ground is substantially higher than in any of the other countries, leading to proportionately smaller numbers (e.g. 1% or less of land as refugia even at 1.5 °C).

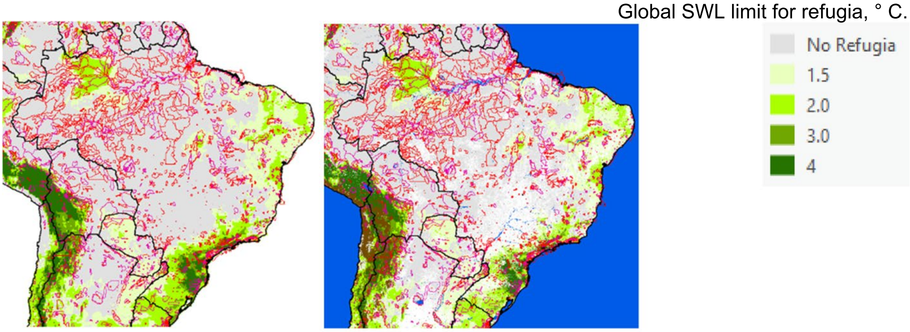
Across the six countries, climate refugia (Fig. 1a, c) for both vertebrates and plants persist to a greater extent for a given level of warming in Ghana. Natural land climate refugia (NLCR; taking into account current land use, Fig. 1b, d) are greatest in Ethiopia, because it has low land conversion, and Ghana, because it appears to be less sensitive to climate change despite significant land conversion in key habitats in the south-western part of the country. NLCR are least in India and Egypt, because there is both high sensitivity of biodiversity to climate change, and a large amount of land conversion has already taken place. In China, whilst there are fewer refugia for the lower levels of warming, they persist longer than in other countries (up to 4 °C warming) due to the large extent of high elevation refugia (see next section).

Significantly, many climate refugia have already been lost to land use change, particularly in India. For example, approximately two-thirds of the climate refugia at 1.5 °C global warming in India have already been lost through land conversion (compare Fig. 1a, c with 1b, d). Contrast this with Ethiopia where about three-quarters of the refugia at 1.5 °C are still in natural habitat (compare Fig. 1a, c with 1b, d). Many of these remaining refugia are, however, not in a protected area—only very small percentages of Brazil, India and China identified both as being climate refugia and within protected area networks (Fig. 1e, f). These percentages are larger in Ethiopia and Ghana. In parts of Ghana, the only remaining refugia are those in protected areas, the remaining landscape converted to other uses.

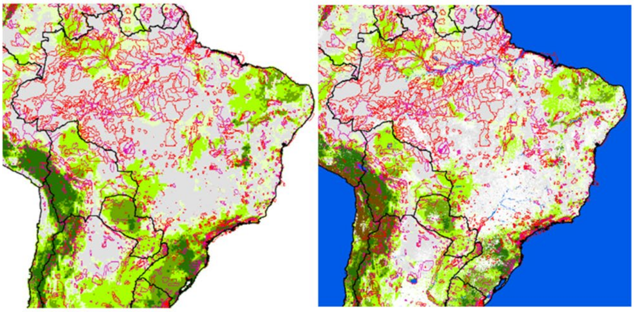
3.2 Location of climate refugia under climate change

Figure 2 a–x show the refugia for plants and animals with and without current (2015) land cover superimposed. In Brazil (Fig. 2a–d), most of the refugia for plants and animals are located in the Caatinga and in the Atlantic Forests. There are refugia for plants and animals in the Pampas, and for animals in the Pantanal. In our models, the climate exposure of the species modelled shows much of the Amazon is not a refuguma even at 1.5 °C global warming. Closer examination of the data (not shown), projects that the transition point for refugia in the Amazon could be as low as 1 °C global warming. This does not mean that the overall ecosystem might collapse at this temperature, only that at 1.5 °C global warming, these areas are not identified as being climatically suitable for more than 75% of the species in more than half of the climate models (the definition of refugia). However, previous work (Warren et al. 2018b) shows that the Amazon, even though it does not act as a refugium, is important for facilitating the

Plant Refugia in Brazil
a climate change only
b climate change with 2015 land cover



Vertebrate Refugia in Brazil
c Climate change only
d climate change with 2015 land cover



Plant Refugia in China
e climate change only
f climate change with 2015 land cover

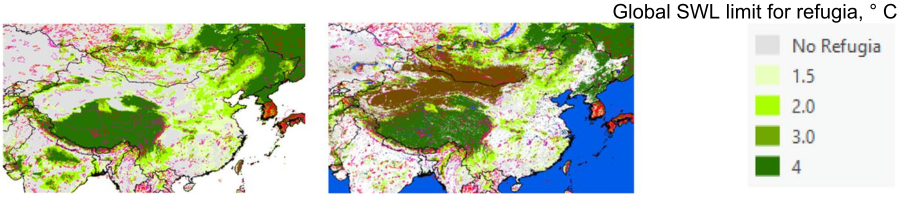


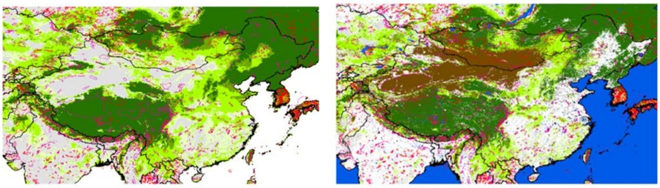
Fig. 2 (a–x) Maps showing location of refugia for the six countries, for plants and vertebrates, without (left hand panels a, c, etc.) and with (right hand panels b, d, etc.) satellite derived land cover (2015) applied as a mask. Each map shows the areas defined as refugia (remaining climatically suitable for > 75% of the species modelled) at warming levels of 1.5 °C, 2 °C, 3 °C and 4 °C above pre-industrial (see legend). Note that areas that are refugia at lower levels of warming may not remain refugia at higher levels of warming, but areas that are refugia at higher levels of warming (e.g. 4° C), also act as refugia at lower levels of warming (i.e. at 1.5°, 2°, and 3°C). Areas in grey lose >25% of the species modelled already at 1.5°C so are not refugia. Additional colors: red/purple line = protected area; black = urban; blue = water; white = agriculture or ice/snow; brown = bare rock/sand

natural adaptation of species in the wider Amazonia region to climate change, by allowing animals to disperse to keep track of geographical shifts in their climate envelopes. This type of analysis is excluded from the study reported here.

In China (Fig. 2e–h), the best refugia, for both plants and animals, are located in the montane grasslands and shrublands, and in the temperate broadleaved and mixed forests of

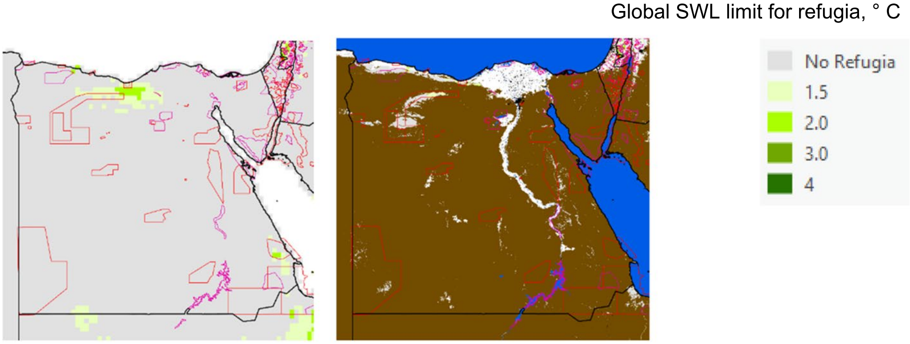
Vertebrate Refugia in China

g Climate change only h climate change with 2015 land cover



Plant Refugia in Egypt

i climate change only j climate change with 2015 current land cover



Vertebrate Refugia in Egypt

k climate change only l climate change with 2015 land cover

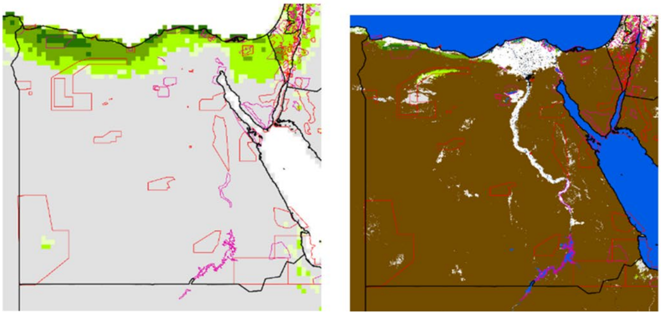
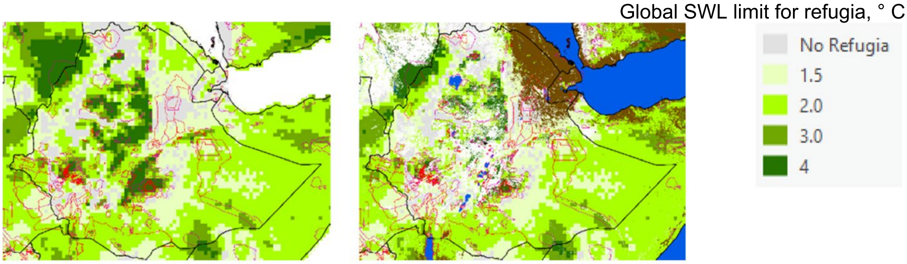
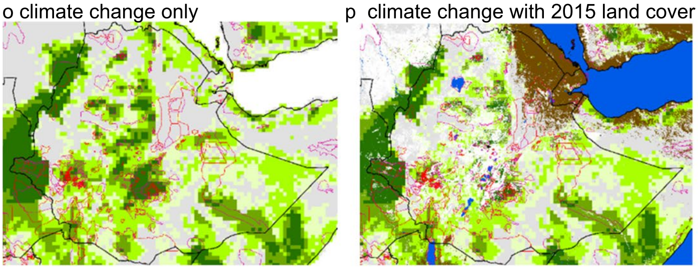


Fig. 2 (continued)

the northeast. While the montane grasslands and shrublands are largely intact, many of the areas in the temperate broadleaved forests have been converted to other uses.

The large expanse of desert in Egypt (Fig. 2i–l) means that most of the land is classified as bare ground (only 2% classified as natural land); hence, only small areas are available to be classified as refugia using Wallace Initiative data (hence the very low extent of refugia shown in Fig. 1), and thus, results for Egypt (e.g. Fig. 1) cannot be fairly compared with the findings for the other five countries. The majority of the refugia identified in Egypt are for animals with only a few refugia for plants; these refugia are mostly located along the coast. However, refugia potentially identified along the Nile Delta have already been converted to other land uses. The major refugia in Ethiopia (Fig. 2m–p), for both plants and animals, are found in the dry afro-montane biome especially at higher elevations in the tropical highland forests. Much of Ethiopia is a climate


Plant Refugia in Ethiopia
m climate change only
n climate change with 2015 current land cover


Vertebrate Refugia in Ethiopia
o climate change only
p climate change with 2015 land cover

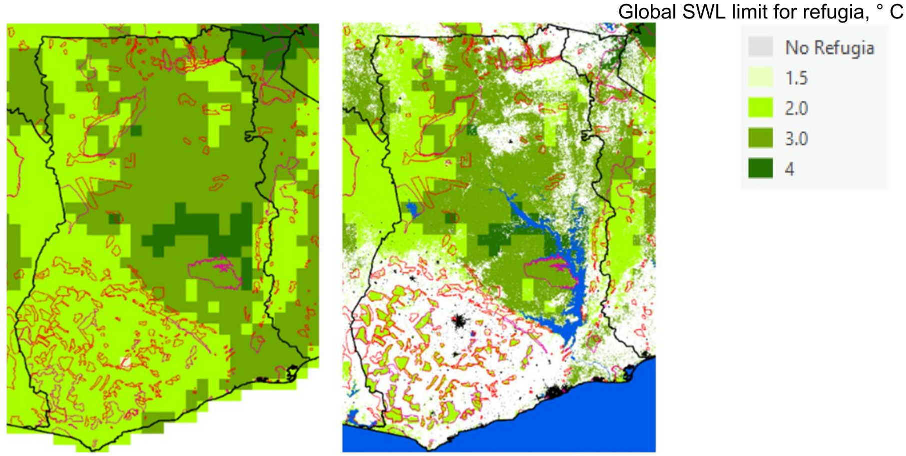
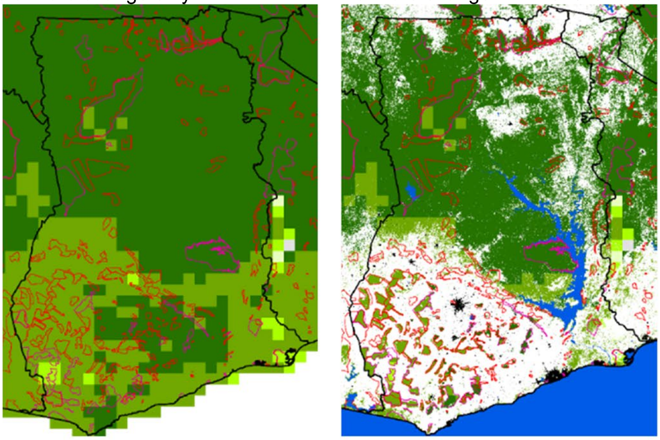
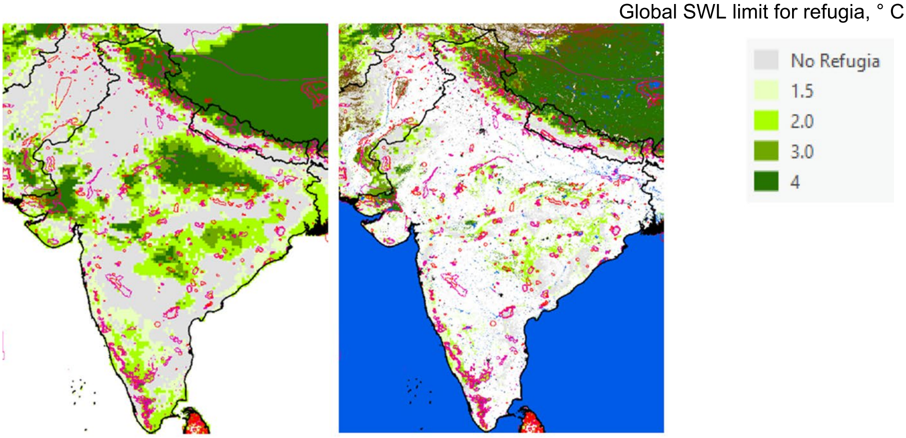

Plant Refugia in Ghana
q climate change only
r climate change with 2015 current land cover

Fig. 2 (continued)

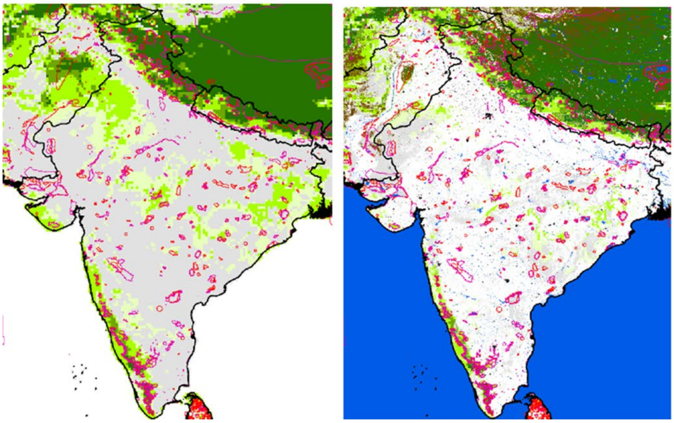
refugium for both plants and animals at 1.5 °C, and a substantial amount at 2 °C, with many areas classified as refugia even up to 4 °C. Many areas that have been converted to other uses would be ideally suited to restoration activities. In Ghana, (Fig. 2q–t) much of the country is refugia for animals at 3–4 °C and for plants at 2–3 °C. However, in the southwestern part of the country, areas that were once rainforest or moist deciduous forest have been converted to other uses. Thus, the only remaining refugia are those within protected areas, and many of these are still undergoing deforestation.



Vertebrate Refugia in Ghana
s climate change only
t climate change with 2015 land cover



Plant Refugia in India
u climate change only
v climate change with 2015 current land cover



Vertebrate Refugia in India
w climate change only
x climate change with 2015 land cover

Fig. 2 (continued)

Finally, in India (Fig. 2u–x), most of the refugia for both plants and animals are located in the Western Ghats as well as in the Himalayas. However, there are many areas that could potentially be plant refugia in the central portion of the country that have been converted to other uses and these would be ideally considered for restoration activities.

4 Discussion and conclusions

The analyses indicate that climate change risk to biodiversity accrues strongly with levels of global warming. Declining biodiversity is indicated in all countries in terms of both the metrics analysed here—that is, species richness and the persistence of climate refugia. This would potentially disrupt the functioning of ecosystems in all countries as the climate warms, with very few refugia remaining under 4 °C warming except in China. There are large declines in refugia between 1.5 and 2 °C, and again between 2 and 3 °C, in all countries except Ghana where refugia are projected to persist under 2 °C and sometimes even 3 °C warming (but not 4 °C). India, in particular, has already lost a large proportion of its climate refugia to land use change. Climate refugia persist to a greater extent in Ghana, China and Ethiopia, however in Ghana only in protected areas. Even in these countries, many of the refugia have been converted to agriculture or other uses. As previously found, plant refugia decline faster than vertebrate refugia (Warren et al. 2018b). The findings for Ghana especially point out the importance of the current protected area system (at least in that country). Protected areas that are still natural habitats will continue to be important even if they are not climate refugia as they continue to provide habitat for many species, just not the minimum threshold for a climate refugia. Furthermore, they potentially provide locations for pioneer species to colonise and potentially hold micro-refugia that cannot be quantified in the spatial resolution of this analysis. However, these findings demonstrate that an expansion of the protected area networks in these six countries, taking into account climate change, will be necessary in order to meet Convention on Biological Diversity targets despite climate change. The information showing areas that should be climate refugia but that have been converted to other uses can help identify areas where restoration efforts might be prioritised. This restoration may not necessarily be trees and guidelines have been published to help assist with the potential conflict between mitigation and adaptation (Parmesan et al. 2022).

Our results are likely to be generally conservative, in particular in light of the lack of consideration of extreme events (e.g. drought, see Price et al. 2022), projected to become more frequent and intense in many regions or fire regimes all may lead to impacts potentially occurring sooner (and hence refugia being smaller at a given level of global warming) than models project. Further, since presently co-located species and their climate envelopes may respond differently to climate change and become separated in space (or indeed temporally through changes in seasonality) there is a potential for disruption of predator-prey, plant-pollinator, mutualistic or other species-species interactions due to climate change. Similarly, other species might become co-located in space when they were previously not, or might become invasive, including the potential for increased prevalence of pests and diseases as climate change. Inclusion of these factors is beyond the scope of our modelling and hence the effects of climate change may be underestimated, as there is limited evidence that mutualisms may or may not be substituted under climate change. Such disruptions may lead to losses of ecosystem functioning, particularly important in the light of the finding that projected range losses in insects and plants may, in many places, exceed those for birds and mammals that have a greater ability to disperse naturally to track their geographically shifting climate envelope. A further discussion of limitations may be found in Warren et al. (2013).

Increasing CO_2 concentrations may reduce protein content changes in plants (Zhu et al. 2018), potentially increasing herbivory. At the same time, CO_2 can act as a fertiliser, enhancing photosynthesis, while also can also cause earlier stomatal closing, with these two effects having opposing effects on water use (Zhang et al. 2022), potentially leading to uncertain hydrological and thus ecological outcomes. It was not practical to include these effects in our modelling of the risks climate change poses to plants, and hence, this could lead to either over- or under-estimation of the effects.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-023-03666-2.

Data and code availability This publication is based on the extraction of data from an existing well established database and hence code availability is not applicable. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author contributions JP and RW wrote the paper. RW coordinated the project. NF processed the data based on pre-existing work by the three authors. Price drew the figures and maps.

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Declarations

Ethics approval and consent to participate N/A

Competing interests The authors declare no competing interests.

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