

The background of the slide is a photograph of a dry, cracked lake bed. The ground is parched and broken into irregular, dark brown polygons. In the distance, there are low, hazy mountains under a bright, hazy sky where the sun is setting or rising, creating a lens flare effect. A large, semi-transparent white arch is overlaid on the image, framing the central text. The arch is composed of several concentric, slightly offset lines, creating a sense of depth and movement.

# D2.5

## Biodiversity impacts of overshoot



Grant Agreement: 101003687  
Call identifier: H2020-LC-CLA-2020-2  
Project full title: PROVIDE – Paris Agreement Overshooting – Reversibility, Climate Impacts and Adaptation Needs

## D2.5 Biodiversity impacts of overshoot

Deliverable lead beneficiary: UEA

Authors: Jeff Price, Nicole Forstenhäusler

Internal Technical Auditor	Name (Beneficiary short name)	Date of approval
Task leader	Rachel Warren/Jeff Price (UEA)	23/01/2025
WP leader	Sonia I. Seneviratne (ETH)	23/01/2025
Coordinator	Carl-Friedrich Schleussner (HU)	23/01/2025
Project Office	Sophie Rau (AI)	24/01/2025

**Abstract:** This report looks at the projected impacts of overshoot scenarios on biodiversity. The FaIR-MESMER results indicate that while the temperature may recover, biodiversity does not.

Due date: 31/12/2024  
Actual submission date: 24/01/2025  
Publication date: 24/01/2025  
Project start date: 01.09.2021  
Project duration: 40 months

**This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 101003687.**

Dissemination Level  
PU Public

## Table of Contents

1. Introduction.....	10
1.1. Zombies, orphans, and emigrants - impacts at the community level .....	11
1.2. The implications of local extinction .....	12
2. Methods .....	13
2.1. Biodiversity models.....	13
2.2. Wallace biodiversity reports .....	13
2.3. Climate data .....	13
2.3.1. Overshoot scenarios.....	13
2.3.2. Annual temperature projections .....	14
2.3.3. Monthly temperature projections .....	14
2.4. Species richness remaining.....	14
3. Results.....	15
3.1. Emulated species richness remaining .....	15
3.2. Modelled species richness remaining compared with the emulator.....	16
4. Discussion.....	24
5. Bibliography.....	26
6. Annexes .....	28
6.1. Wallace Reports: Expanded Text for the Tables and Figures .....	28
6.1.1. Climate.....	28
6.1.2. Future Climates.....	28
6.1.3. Warming Levels .....	29
6.1.4. Climate Variables.....	29
6.1.5. Role of elevation and topography.....	31
6.1.6. Population Data .....	31
6.1.7. Land Cover Changes .....	32
6.1.8. Biodiversity .....	32
6.1.9. Local Extinctions (extirpations) .....	32
6.1.10. Species Richness Remaining.....	32
6.1.11. Refugia.....	33
6.1.12. Adaptation Effort .....	33
6.2. Wallace reports: sources of data .....	33
6.3. Wallace reports: technical details and understanding data sources.....	34
6.3.1. Method of projecting regional climate change .....	34
6.3.2. Origin of global temperature time series used .....	34
6.3.3. Pattern Scaling .....	35
6.3.4. Climate Change Scenarios.....	35
6.3.5. Information about Intended Nationally Determined Contributions (INDCs) .....	37

---

6.3.6.	Information about scenarios that limit warming to 2° C or below.....	38
6.3.7.	Background information about the RCPs and the New Scenarios Process.....	38
6.4.	Wallace Reports: Further information pertaining to biodiversity analyses .....	39
6.4.1.	Refugia, adaptation, and scale of analysis .....	39
6.4.2.	Models and the <i>Precautionary Principle</i> .....	40
6.4.3.	The Wallace Initiative .....	42
6.4.4.	Limitations of species distribution modelling.....	43
6.4.5.	Elevational Downscaling .....	45
6.4.6.	Use of climatic buffers (micro or meso-climatic refugia) and limitations.....	45
6.4.7.	Interactions.....	46
6.5.	Literature Cited .....	46
6.6.	Wallace Reports in Zenodo.....	49

## Table of Figures

Figure 1: Visual representation of the method employed for the emulation of species richness remaining. The curve represents the response function of the species richness remaining to a change in temperature and the orange points on the line represent the values obtained from the output generated by the Wallace Initiative. The blue dashed lines indicate how the emulator derives the remaining species richness remaining from a given temperature change relative to pre-industrial.....	15
Figure 2. Emulated biodiversity species richness remaining under ten different policy scenarios. Blue lines correspond to 100 climate realisations of each policy scenarios used to drive the emulator and the solid black line represents the median of all realisations. To aid visual comparison of the scenarios, the solid red line corresponds to lowest value of species richness remaining for the ensemble median while the dashed black line represents the lowest value across the realisations.....	16
Figure 3. Changes in timber species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios. ....	17
Figure 4. Changes in pollinator species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios. ....	18
Figure 5. Changes in mammal species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios. ....	18
Figure 6. Changes in amphibian species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios. ....	19
Figure 7. Spatial pattern of species richness remaining for timber species with $\sim 1.5^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	20
Figure 8. Spatial pattern of species richness remaining for insect pollinator species with $\sim 1.5^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	20
Figure 9. Spatial pattern of species richness remaining for mammal species with $\sim 1.5^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	21
Figure 10. Spatial pattern of species richness remaining for amphibian species with $\sim 1.5^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	21
Figure 11. Spatial pattern of species richness remaining for timber species with $\sim 2.0^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	22
Figure 12. Spatial pattern of species richness remaining for insect pollinator species with $\sim 2.0^{\circ}$ C warming. Note the spatial resolution of the MESMER model runs is $2.5^{\circ}$ of latitude and longitude while the emulator and Wallace Initiative results presented here are both at $\sim 20$ km resolution. White are areas with no data.....	22

---

Figure 13. Spatial pattern of species richness remaining for mammal species with  $\sim 2.0^\circ$  C warming. Note the spatial resolution of the MESMER model runs is  $2.5^\circ$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20$ km resolution. White are areas with no data.....23

Figure 14. Spatial pattern of species richness remaining for amphibian species with  $\sim 2.0^\circ$  C warming. Note the spatial resolution of the MESMER model runs is  $2.5^\circ$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20$ km resolution. White are areas with no data.....23

Figure 15. Radiative forcing time series in the Representative Concentration Pathways (RCPs).  
.....37

Figure 16. CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081-2100 are given. This figure has been reproduced from IPCC, 2015.....37

Figure 17. Shared Socioeconomic Pathways (SSPs; reproduced with permission from O' Neill et al., 2015) .....39

## List of Tables

Table 1. Representative Concentration Pathways: year 2100 parameters.....	36
Table 2. Possible combinations of RCPs and SSPs .....	39

## Glossary

ABBREVIATION / ACRONYM	DESCRIPTION
CDR	Carbon Dioxide Removal
FaIR	Finite amplitude Impulse Response
GCM	General Circulation Model
GMT	Global Mean Temperature
GSAT	Global Surface Air Temperature
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
MESMER	Modular Earth System Model Emulator with spatially Resolved output
RCP	Representative Concentration Pathway
SDM	Species Distribution Model
SSP	Shared Socio-economic Pathway



## Executive Summary

The paper Overconfidence in Climate Overshoot (Schleussner et al 2024) shows that many impacts of climate overshoot are irreversible, at least over century timescales. These findings can now be extended to biodiversity.

In the policy scenarios examined the suitable climate space for species does not fully recover after overshoot. The greater the overshoot, the greater the impact and the lower the recovery.

For many species groups **the maximum temperature reached in the scenario is the overall impact on biodiversity**. Even if the temperature declines, and the climate space once again becomes suitable, the species will potentially become locally extinct once their suitable climates have been exceeded. For many different species groups (most insects, reptiles, amphibians, many plants) the dispersal rate is so low that they would be unable to recover except over very long periods of time. The exceptions to this are some birds, mammals, butterflies, and dragonflies. However, if key habitat (plant) or food (plant, insect) species have become locally extinct then it would be difficult for the birds, mammals, butterflies, or dragonflies to reclaim their climate space.

The impacts of short-lived overshoot on trees are more difficult to assess. Once the climate suitability of a tree species is exceeded a typical response is to no longer reproduce. However, once the climate once again becomes suitable for reproduction then the species may be able to recover. Disease, pests and fires, especially when coupled with increasing drought, make it more likely that disturbance may lead to local extinctions in which case recovery may take much longer (decades - centuries).

The results presented here were for individual species groups. However, these species occur in communities. With climate change there will be changes to communities as some species persist (climate remains suitable), some species undergo local extinction (climate becomes unsuitable), and some new species arrive. In preliminary studies it was found that the potential impact at the community level is greater, and occurs at lower temperatures, than that for the individual species. Recovery from overshoot potentially exacerbates the problem as species may be leaving and then returning and even more novel assemblages of species in the communities occur.

## 1. Introduction

“There has been a discernible impact of regional climate change, particularly increases in temperature, on biological systems in the 20th century.” (IPCC 2001)

The observed impacts of climate change have been noted for more than two decades. This initial finding from the IPCC Third Assessment Report was followed up by a comprehensive meta-analysis (Root et al. 2003) and in subsequent IPCC Working Group II reports. The most recent report finds that these impacts have now been noted on all continents and across many species' groups (Parmesan et al 2022). The initial findings concentrated mostly on changes in timing of events (phenologies) and changes in species ranges that were associated with local climate change. Later work brought in attribution of the changes to climate change (from the IPCC Fourth Assessment report onwards). The latest IPCC report (Parmesan et al. 2022) notes that at least two terrestrial species, and possibly one subspecies, have become extinct owing to climate change (all tied to extreme events). Extinction is an irreversible event. Furthermore, “Local population extinctions caused by climate change have been widespread among plants and animals, detected in 47% of 976 species examined and associated with increases in the hottest yearly temperatures (*very high confidence*)” (Parmesan et al 2022). These are noted to have occurred more in the tropics than in temperate areas. Thus, there is strong evidence of the impacts of observed climate change on biodiversity, suggesting that there may already be an adaptation deficit in biodiversity.

There have been thousands of papers published on the projected impacts of climate change on biodiversity. Most of these are around single species, or groups of species in small areas, and they tend to use different assumptions, baselines, and climate models. One of the largest studies to date, examining more than 130,000 terrestrial species, found that, globally, projected climatically driven geographic range losses of more than 50% (i.e., local extinctions 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 2018); at 2°C, the projected loss is 18% of insects, 16% of plants, and 8% of vertebrates; 1.5°C, 6% of insects, 8% of plants, and 4% of vertebrates. A reanalysis of this data for the IPCC Sixth Assessment Report found that “Among the groups containing the largest numbers of species at a *very high risk* of extinction for mid-levels of warming (3.2°C) are: invertebrates (15%, and specifically pollinators at 12%), amphibians (11% overall, but salamanders are at 24%) and flowering plants (10%). All groups fare substantially better at lower warming of 2°C, with extinction projections reducing to <3% for all groups, except salamanders that reduced to 7% (*medium confidence*) (Figure 2.8a). Even the lowest estimates of species' extinctions (median of 9% at 1.5°C rise GSAT) are 1000 times the natural background rates” (Parmesan et al. 2022).

What about Overshoot scenarios?

Almost all previous work looking at climate change and biodiversity has looked at either continuing increases or stabilization, focussing on the conditions at the end of the 21<sup>st</sup> century. Based on the available biodiversity models and data three approaches were taken to assess the potential impacts of overshoot on biodiversity:

Using the interpolated Wallace Initiative data (in 0.1°C timesteps) an analysis was taken using the global temperature projections from FaIR-MESMER. The assumption here was that the final potential species richness loss would match the highest temperature in the given FaIR-MESMER global temperature time series. There are many reasons for this, outlined below.

Developing an emulator based on the interpolated Wallace Initiative data and applying it to biodiversity, as well as to a selected number of species groups. This allowed an examination of what might happen if the temperature trajectories of the different FaIR-MESMER pathways were followed and look at whether the climate suitability for species richness would be able to recover as the temperature recovered. This approach only used the average temperature

change per cell from MESMER following different FaIR realizations. These are the results currently in the PROVIDE climate dashboard.

At the scheduled end of the project, the MESMER team were able to generate a new set of climates for some of the FaIR-MESMER realizations. The previous data only included average temperature, while the new data contained both minimum and maximum temperature (precipitation was already available) which are required to directly run the biodiversity models from the Wallace Initiative. In the extension period, we were able to directly run individual species models for a few groups of species using these new data. This allowed us to use the original base models (the lambdas from the original models plus the thresholds used in the original models) against this new climate data. This provided the ability to compare the outputs from the base Wallace Initiative models, the emulator, and the new MESMER climate data.

Based on the observed impacts of climate change on biodiversity (as well as paleoecological data) it is apparent that most species attempt to track their suitable climate, if they are able. This can be seen in shifting climatic ranges (either by latitude or longitude) but also changes in the timing of events (like migration and breeding) that allow species to track their preferred climate. There are many caveats to this. The first is that the species must be able to move to track the changing climate (typically called dispersal, though this is not the same as year-on-year dispersal that many species undergo for other reasons). Only some taxa have dispersal rates large enough to track the current velocity of climate change. These generally include birds, mammals, dragonflies, butterflies and some bees (see Warren et al 2013 for dispersal rates). Not all species within these groups can disperse at the general rate but it is used for large-scale analyses. Other species groups – most plants, reptiles, amphibians, fungi, and most insects are unable to track the current velocity of climate change. Even in those species able to disperse, many of them will require corridors to enable them to move to track the suitable climate. These corridors would need to follow a suitable climatic gradient and provide everything else a species needs to persist and reproduce. In many parts of the world, there are substantial barriers to movement (e.g., roads, waterways, seas, cities, agriculture, etc.). Therefore, the ability to move, except perhaps in flying species, may not be an option in tracking the changing climate. In species that are not able to move at a rate to track the changing climate the ultimate impacts will most likely be driven by life-history traits. Short-lived species, facing an inability to move and a loss of climate space will potentially undergo local extinction. This would include reptiles, amphibians, many insects, fungi and annual plants. Long-lived species, especially trees, may be able to persist in an overshoot scenario, depending on the rate of recovery. A typical response of tree species to climate stress is to stop reproducing until climate conditions are suitable again. However, in these same conditions the trees are more susceptible to disease, pests and fire. Thus, the ability to recover and persist will depend on a host of additional factors.

For these reasons it is reasonable to use, as a first approximation, the lack of climate suitability at the maximum temperature reached (under current Nationally Determined Contributions, approximately 3°C) as leading to equivalent local extinctions. Potential recovery, all things being equal, would also be subject to the same caveats around dispersal as species would need to return to the areas with a returning suitable climate space. For short-lived species with low dispersal rates, this means projected local extinctions with little opportunity for recovery in century timescales. Similarly, the ability of long-lived species to recover will depend on what disturbances the species is subjected to in the recovery period.

### **1.1. Zombies, orphans, and emigrants - impacts at the community level**

Most climate change studies on species deal with a) species remaining in an area (species richness remaining), herein called orphans; b) species going locally extinct in a given area (local extinction rate usually calculated as  $1 - \text{species richness remaining}$ ) that may include zombies, and, sometimes, c) emigrants that potentially move into an area as they track their climate space. Zombies are a special case of local extinction risk and refer to long-lived species whose climate had become unsuitable. This term was first used to describe zombie forests in the Sierra

Nevada region of California – forests whose climate was no longer suitable for the species found there but that persisted owing to ecological inertia. The Wallace Initiative data can be used to estimate each of these three categories independently but visualizing this is very difficult (and not part of PROVIDE). Nevertheless, taking the three parts together indicates that new communities will be different to very different (even non-analogue) to what is currently found in an area. No assumption can safely be made that species emigrating into an area will be able to replace the natural ecosystem services provided by the species lost as they either track their new climate or go locally extinct themselves. Preliminary analyses suggest that the combination of these three responses to climate change will potentially be worse than that shown by any one of the three on its own. Thus, ***the impact of overshoot at a community level is greater than what might be projected for any individual species or groups of species, and the ability to recover is less.***

## 1.2. The implications of local extinction

Biodiversity underpins most of the ecosystem services provided to humans (Price et al. 2024b). The IPCC Sixth Assessment Report estimates that once local extinction passes 50% the impacts on the functioning of the ecosystem and its ability to provide services to humans is compromised (Parmesan et al. 2022). That is not to say that there are no ecosystem service impacts at lower levels of local extinction, just that it would be much more apparent once it passes 50%. In some cases, like pollinators, even the local extinction of a few species will potentially have an impact on flower production and yields in some crops depending on the redundancy of available pollinating insects.

Restoring natural ecosystems, which can be part of CDR (see WP1), can assist both in restoring some lost ecosystem services, and aid in helping some species adapt to a changing climate. This restoration has the potential to increase carbon uptake in some habitats.

## 2. Methods

### 2.1. Biodiversity models

The results presented here are all based on the original models prepared as part of the Wallace Initiative. The Wallace Initiative (phase III) modelled ~135,000 terrestrial fungi, plants, invertebrates, and vertebrates, at warming levels ranging from 1.5°C to 6°C, across 21 CMIP5 climate model patterns at a spatial resolution of ~20km x 20km based on occurrence data obtained from the Global Biodiversity Information Facility (GBIF.org, 2015). More information on the overall project, results, modelling methodology, caveats, and uses can be found in a series of papers (Jenkins et al., 2021; Price et al., 2024a,b; Saunders et al., 2023; Smith et al., 2018; Warren et al., 2018a,b, 2013) and also in the Annex (section 6.4). The data were also used for a number of figures and tables in multiple chapters in Working Group II of the IPCC Sixth Assessment Report (AR6). The data used in the Protected Area reports were then subsequently elevationally downscaled to ~1km x 1km (details in Price et al. 2024a; Saunders et al., 2023; Annex 6.4.5) to better understand which areas of each modelled 20km cell or pixel might be lost sooner or persist longer. In short, a given 20km cell is an average of the temperatures for all elevations within that cell (i.e., the average elevation); for the direct MESMER models it would be the average over 2.5° latitude and longitude. In areas with a varied terrain, some areas will be warmer than the average and some will be cooler. Species in areas that are warmer than the average would be expected to potentially be more susceptible (exposed) to warming, while those in cooler areas would be expected to potentially be less susceptible (or be able to shift into these areas if they are currently too cool). Therefore, species within cooler areas within a climate 'cell' or 'pixel' would be expected to potentially be able to persist in that area longer.

Biodiversity refugia are calculated as cells containing 75% or more of the species modelled for each of the 21 GCMs. By using independent calculations for all 21 climate models, an estimate of the uncertainty of the results can be provided based on the numbers of models in agreement that the area is a refugia. For subsequent analyses it is usually standard to then create a binary raster that is split for half of the models in agreement. This facilitates using this new raster in combination with other rasters or as a filter. These are the data provided to WP1 in PROVIDE.

### 2.2. Wallace biodiversity reports

The reports of the Wallace Initiative on the observed climate, projected climate and projected biodiversity changes under differing levels of warming leverage output from close to ten years of collaborative work between the Tyndall Centre of Climate Changes Research at the University of East Anglia (UK), and the eResearch Centre at James Cook University (Australia). Each report overviews experienced and expected climatic changes, particularly temperature, precipitation, drought events and waterlogging. They further assess the state of biodiversity given certain levels of global warming, outlining the expected species richness remaining and identifying climate refugia within a selected area. These reports were generated for every terrestrial Protected Area on Earth >1km<sup>2</sup> in size. Approximately 100,000 reports have been generated and work is underway to make all of them freely and publicly available on a web server. Approximately 30 of them are on the web portal Zenodo and the list of these can be found at the end of the Annex. The Annex also contains information on the origin of all the data used in the reports and some information on interpretation (which is also present in each report). These reports were made available to WP4 of PROVIDE for Norway, Pakistan and Portugal (although not The Bahamas owing to its overall size and being a series of islands making any report potentially problematic for accuracy).

### 2.3. Climate data

#### 2.3.1. Overshoot scenarios

For this project, a total of ten different overshoot scenarios were considered, namely CurPol (Current Policy pathway), ModAct (Moderate Action pathway), GS (Gradual Strengthening Public

pathway), Neg (Negative emissions pathway), Ren (Renewable pathway), LD (Demand-Limiting pathway), SP (Shifting Pathways), SSP1-1.9, SSP5-3.4-OS (SSP5-3.4 overshoot) and Ref1.5C (follows LD until 1.5 °C and then remains at this temperature level). A detailed description of the scenarios can be found in Lamboll et al. (2022).

### **2.3.2. Annual temperature projections**

Spatially explicit annual global mean temperature (GMT) projections for the ten selected overshoot pathways were generated using the climate emulators FaIR (Finite amplitude Impulse Response) and MESMER (Modular Earth System Model Emulator with spatially Resolved output). These steps are described in detail in Schwaab et al. (2024) and only a summary will be given here. First, emissions associated with each of the overshoot pathways were used to drive FaIR and obtain a set of 100 annual GMT trajectories for each pathway. These trajectories were then used to drive MESMER for each of the 25 GCMs it can represent coupled with 1000 of its stochastic realisations. This resulted in a coherent set of  $100 \times 25 \times 1,000 = 2.5$  million spatially explicit annual temperature fields per overshoot pathway. To reduce the overall number of required simulations, only 100 representative temperature fields were selected for each pathway and used for further analysis.

### **2.3.3. Monthly temperature projections**

In addition to the annual temperature fields, monthly fields of precipitation, mean temperature, minimum temperature, and maximum temperature were generated following a similar approach. To achieve this, MESMER was extended by module MESMER-M-TP which allows for generation of monthly precipitation fields coherent with a given set of monthly temperature fields (Schöngart et al., 2024).

## **2.4. Species richness remaining**

To obtain estimates of species richness remaining under different overshoot scenarios, an emulator was built based on the CMIP5 driven results from the Wallace Initiative. Here, the species richness remaining estimates for six levels of global warming from the Wallace Initiative (1.5°C, 2°C, 2.7°C, 3.2°C, 4.5°C, 6°C) were statistically associated with their respective temperature anomalies. Assuming a linear response curve, this allowed for the generation of dedicated functions to determine spatially explicit estimates of species richness given a set of temperature anomalies. Because the response curves between the lowest and highest level of global warming would ignore increasing or decreasing rates of changes between different temperature levels, the response functions were built as piecewise functions, allowing for different rates of change depending on temperature (Figure 1). The emulator was then driven using the 100 spatially explicit temperature anomaly fields derived by coupling FaIR and MESMER for each of the ten overshoot pathways.

In addition to the emulator, a subset of species distribution models (SDMs) from the Wallace Initiative (see section 2.1) was driven by FaIR-MESMER derived monthly climate data for five of the emission pathways. To this end, the monthly temperature and precipitation fields were first converted to the bioclim variables required by the SDMs. Subsequently, the SDMs were run, producing annual projections of suitability for each individual species. To derive a measure of suitability for any 30-year period considered by this project, the mean suitability was determined and, based on thresholds identified during the original Wallace project, converted to absence/presence fields. Finally, a measure of species richness remaining for each species group was calculated in each grid cell as the ratio of the number of species present in the cell in the selected 30-year period and the total number of species present in the period 1961-1990. Due to the large number of species, only a limited subset of species groups were considered here.

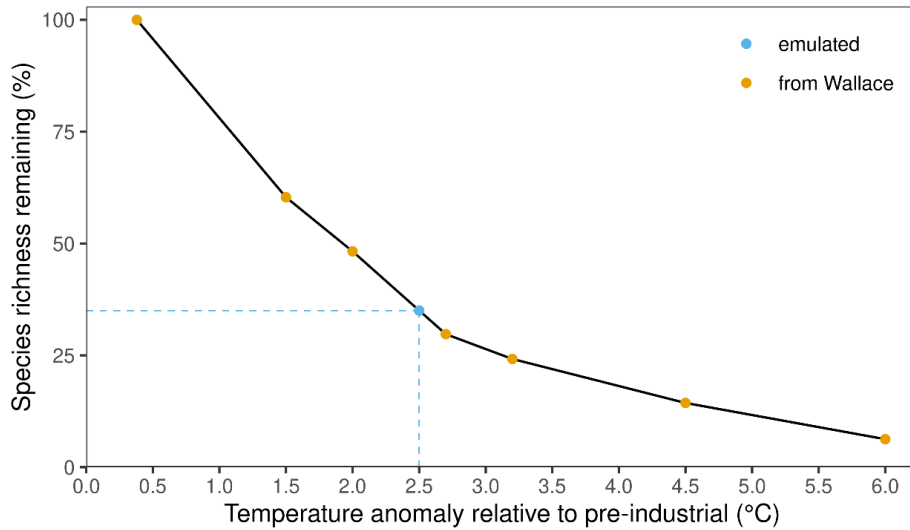


Figure 1: Visual representation of the method employed for the emulation of species richness remaining. The curve represents the response function of the species richness remaining to a change in temperature and the orange points on the line represent the values obtained from the output generated by the Wallace Initiative. The blue dashed lines indicate how the emulator derives the remaining species richness remaining from a given temperature change relative to pre-industrial.

### 3. Results

#### 3.1. Emulated species richness remaining

Figure 2 presents the global mean biodiversity species richness remaining derived by driving the biodiversity emulator with 100 different realisations of ten distinct emission scenarios. For those scenarios in which the global level of warming starts to decrease within the simulation period of 2020 to 2100, the results clearly show that **the rate of recovery of suitable climate space for species richness remaining is substantially lower than the rate of decline expected on route to the highest level of global warming**. As the period of the analysis starts in 2020 the numbers are below 100 representing the local extinction inertia present in the system owing to warming up to 2020. The **maximum local extinction by 2100 ranges from >45% in the CurPol scenario to approximately 30% in many of the emission scenarios with lower levels of warming**. While the curves show some recovery **MAY** be possible (scenarios LD, Neg, SP, SSP 119, SSP534-Over) the recovery does not return to the level seen in 2020 (at least by 2100).

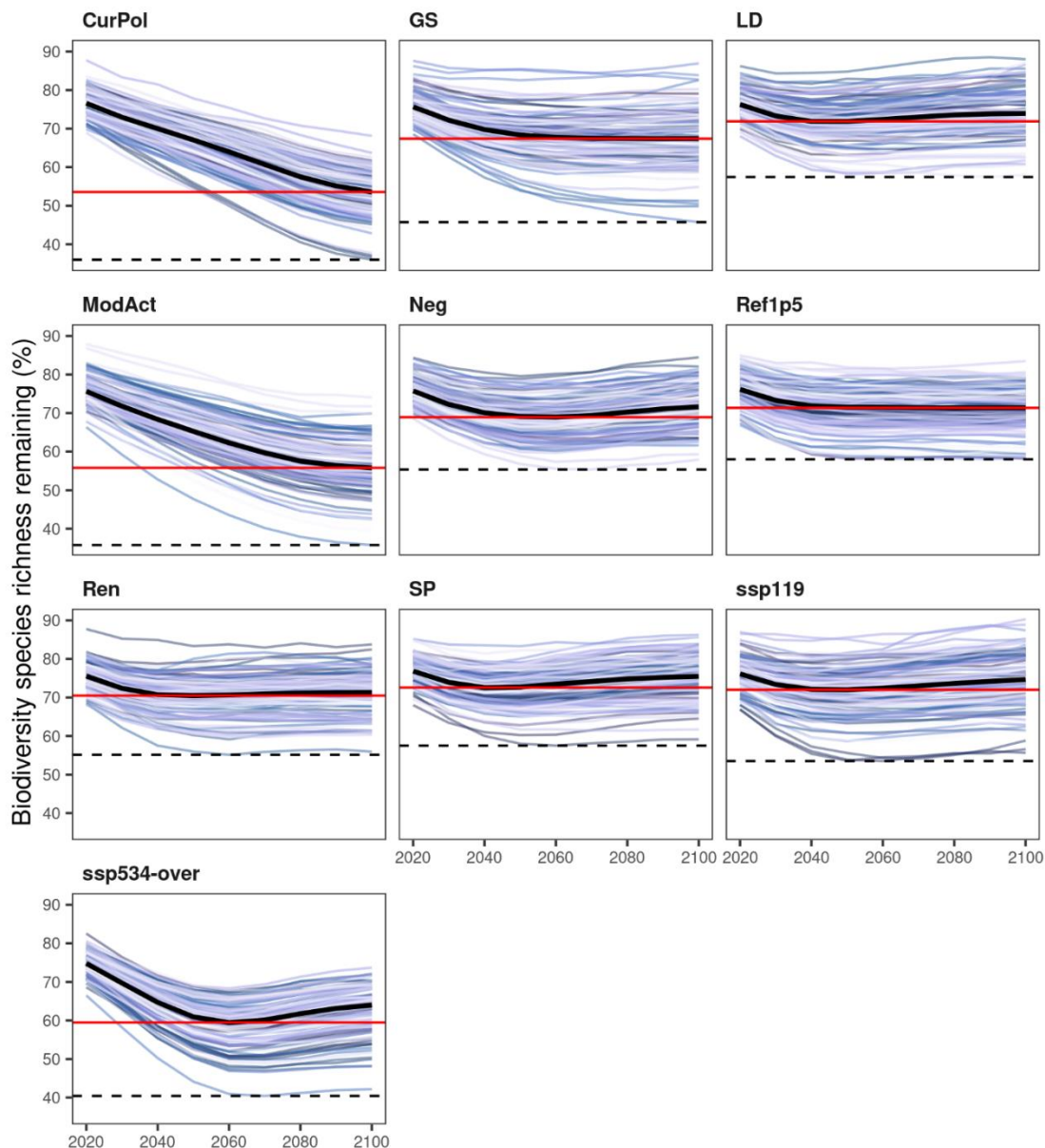


Figure 2. Emulated biodiversity species richness remaining under ten different policy scenarios. Blue lines correspond to 100 climate realisations of each policy scenarios used to drive the emulator and the solid black line represents the median of all realisations. To aid visual comparison of the scenarios, the solid red line corresponds to lowest value of species richness remaining for the ensemble median while the dashed black line represents the lowest value across the realisations.

### 3.2. Modelled species richness remaining compared with the emulator

It was only possible to model biodiversity as a whole with the emulator owing to the number of species involved. For smaller groups of species, it was possible to run both the emulator and new models driven by new MESMER runs.

Figure 3 shows the species richness remaining under 5 policy scenarios for timber species (>1000 individual species) for both the emulator (blue and black lines) and for the new MESMER outputs (gold line). There is a consistent difference between the two approaches in terms of overall decline and recovery potential. This difference, for timber is <5%. However, the patterns of decline and recovery are the same. In all cases, recovery by 2100 does not return to the same point as it was in 2020, although the trajectories indicate it may possibly recover post-2100. This is especially true for the SSP534-Over scenario. Timber species generally fall into the category known as zombies. Most timber species are long-lived and individuals in an area will likely stop reproducing yet still survive in the absence of disturbance (pests, disease, fire). Thus, there may



be individuals within a given cell to allow for slow recovery of populations once temperatures recover to the point where a species' climate suitability is restored.

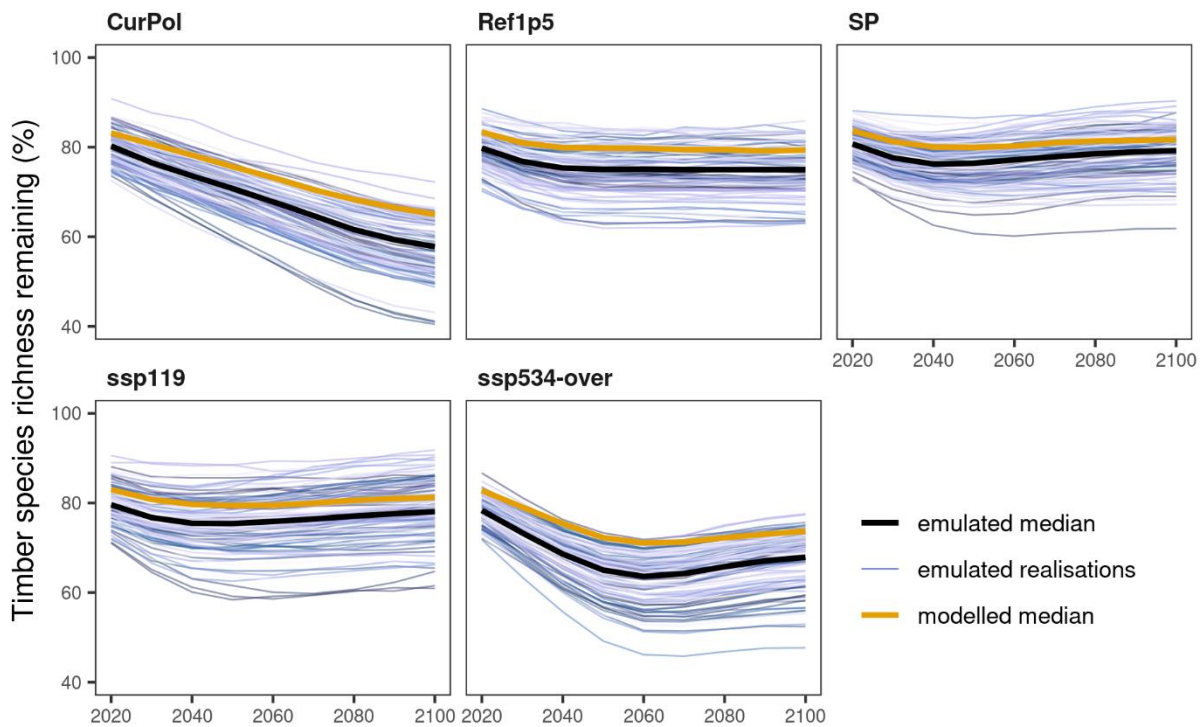


Figure 3. Changes in timber species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios.

Figure 4 shows the species richness remaining under five emission scenarios for insect pollinator species for both the emulator (blue and black lines) and for the new MESMER outputs (gold line). There is a consistent difference between the two approaches in terms of overall decline and recovery potential. This difference, for insect pollinators is ~5-10%. However, the patterns of decline and recovery are the same. In all cases, recovery by 2100 does not return to the same point as it was in 2020, although the trajectories indicate it may possibly recover post-2100. This is especially true for the SSP534-Over scenario. Insect pollinators are made up of some species that may be able to track current climate velocities and those that are unable to. In the case of species with low dispersal potential this would represent local extinctions and species becoming locally extinct would be unlikely to recover within the time frames shown here (or, indeed, well into the next century). Thus, **many areas would become depauperate of insect pollinators and recovery would not be at the rate shown here**. The curves shown here show a recovery in suitable climates of that percentage of species, but in the case of insect pollinators it would be unlikely that they would be able to take advantage of the improved climatic conditions. Thus, the final species richness remaining in insect pollinators would be somewhere between the lowest point reached in the curves and the point of recovery depending on the species makeup of insect pollinators in a given cell. This would then have knock-on effects on some flowering plants and crops depending on which insect pollinating species were involved.

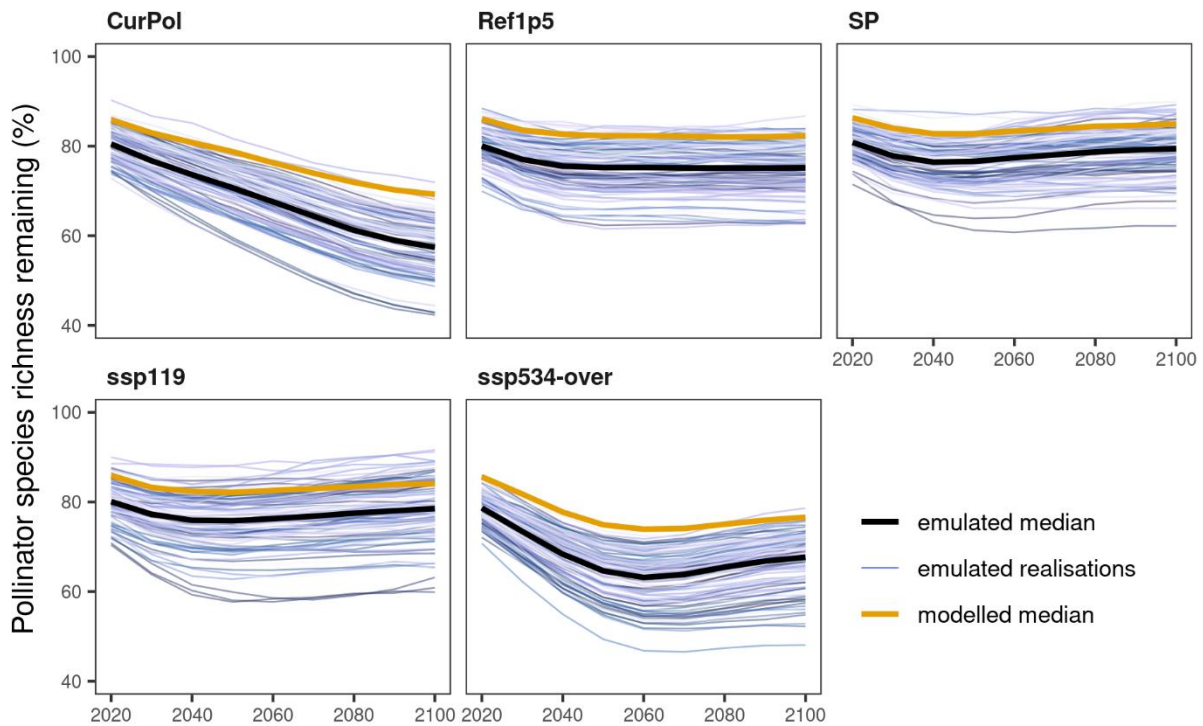


Figure 4. Changes in pollinator species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios.

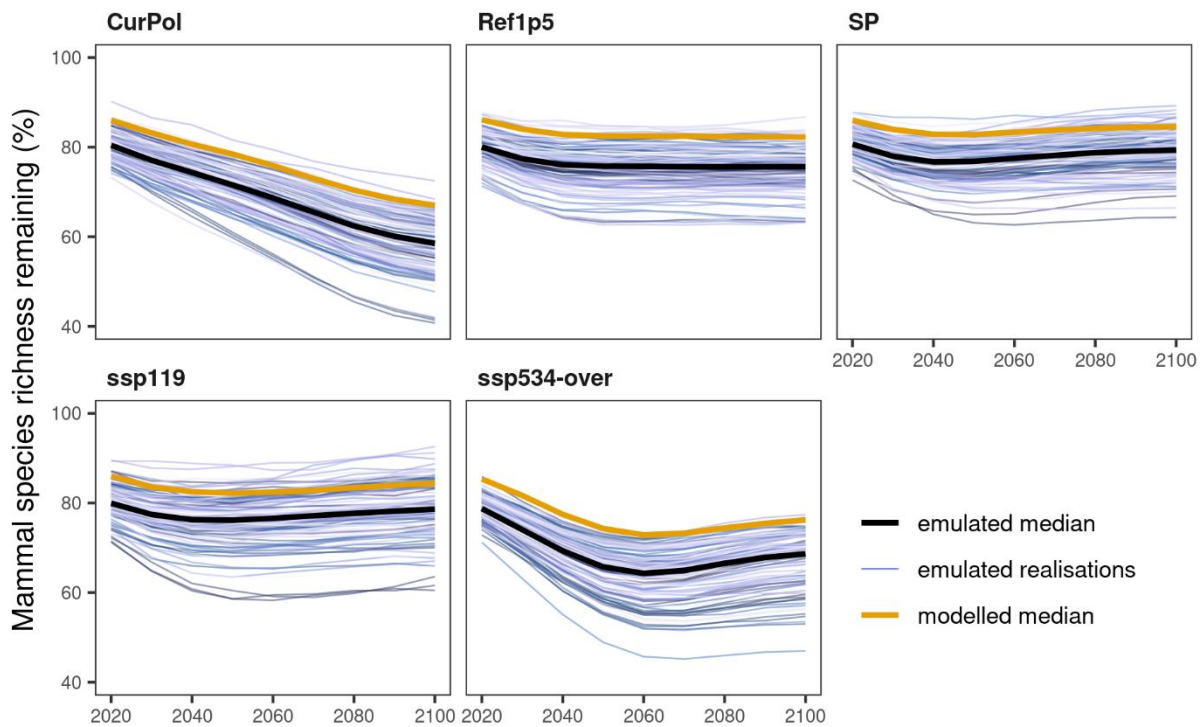


Figure 5. Changes in mammal species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios.

Figure 5 shows the species richness remaining under five emission scenarios for mammal species for both the emulator (blue and black lines) and for the new MESMER outputs (gold line). There is a consistent difference between the two approaches in terms of overall decline and recovery potential. This difference, for mammals is ~5-10%. However, the patterns of decline and recovery are the same, and the MESMER results usually match the emulated realisations with the lowest sensitivities. In all cases, recovery by 2100 does not return to the

same point as it was in 2020, although the trajectories indicate it may possibly recover post-2100. This is especially true for the SSP534-Over scenario. Many mammal species (although not all groups) have dispersal rates that may be able to track current climate velocities if climatically suitable corridors are available and in the absence of barriers. In the case of species with low dispersal potential this would represent local extinctions and species becoming locally extinct would be unlikely to recover within the time frames shown here (or, indeed, well into the next century, especially in the MESMER runs owing to the spatial resolution). Thus, many areas would be depauperate of mammals and recovery would not be at the rate shown here. The curves shown here show a recovery in suitable climates of that percentage of species, but in the case of mammals it would be unlikely that they would be able to take full advantage of the improved climatic conditions. Thus, the final species richness remaining in mammals would be somewhere between the lowest point reached in the curves and the point of recovery depending on the species makeup of mammals in a given cell. This would be further exacerbated by projected losses in species richness of plants (habitat and forage) and insects – both of which show greater exposure to a given level of warming than mammals do.

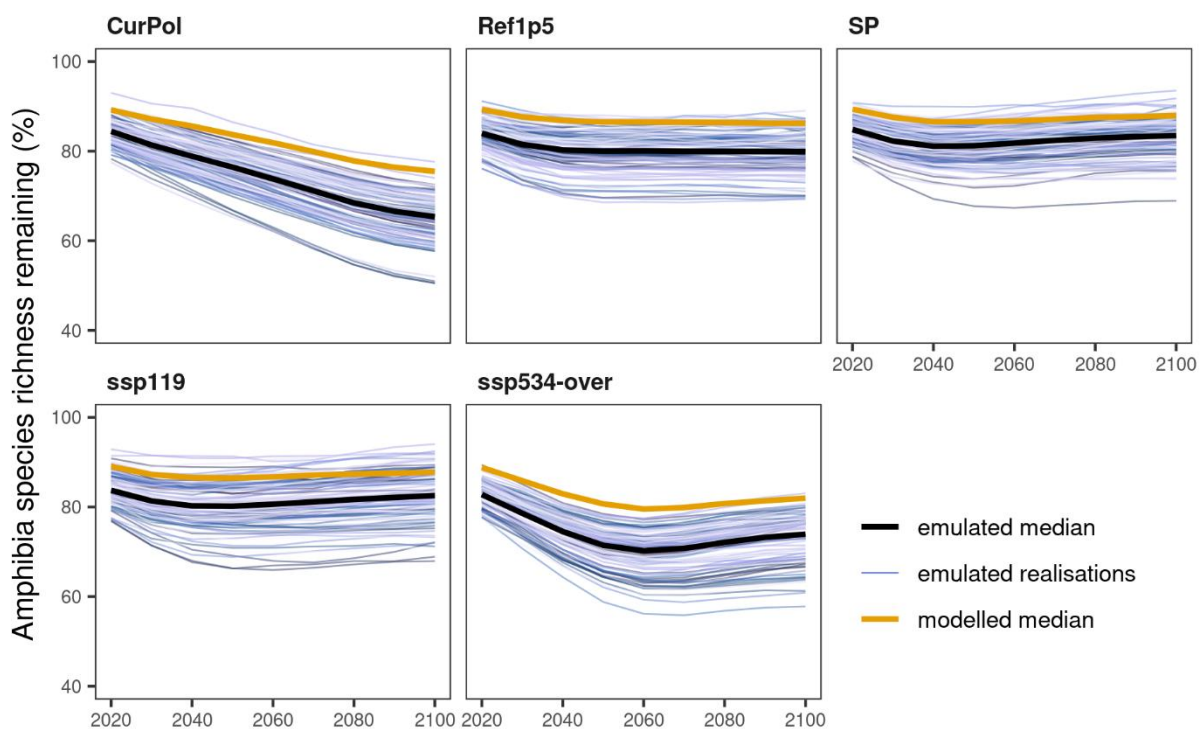


Figure 6. Changes in amphibian species richness for the biodiversity emulator and MESMER modelled pollinator results (based on individual species) for five different emission scenarios.

Figure 6 shows the species richness remaining under five emission scenarios for amphibians for both the emulator (blue and black lines) and for the new MESMER outputs (gold line). There is a consistent difference between the two approaches in terms of overall decline and recovery potential. This difference, for amphibians is ~5%. However, the patterns of decline and recovery are the same with the curves for the MESMER model runs being generally in line with the least sensitive of the emulator runs. In all cases, recovery by 2100 does not return to the same point as it was in 2020, although the trajectories indicate it may possibly recover post-2100. Amphibians are the vertebrate group that previous analyses have found are most exposed to climate change and dispersal rates are such that they are unable to track the velocity of the changing climate. Owing to the low dispersal potential of amphibians this would then represent local extinctions and species becoming locally extinct would be unlikely to recover within the time frames shown here (or, indeed, well into the next century or beyond). Thus, **many areas would remain depauperate of amphibians and recovery would essentially not occur**. The curves shown here show a recovery in suitable climates of that percentage of species, but in

the case of amphibians it would be unlikely that they would be able to take advantage of the improved climatic conditions. Thus, **the final species richness remaining in amphibians should be considered to be the lowest point reached in each of the scenarios, with no recovery.**

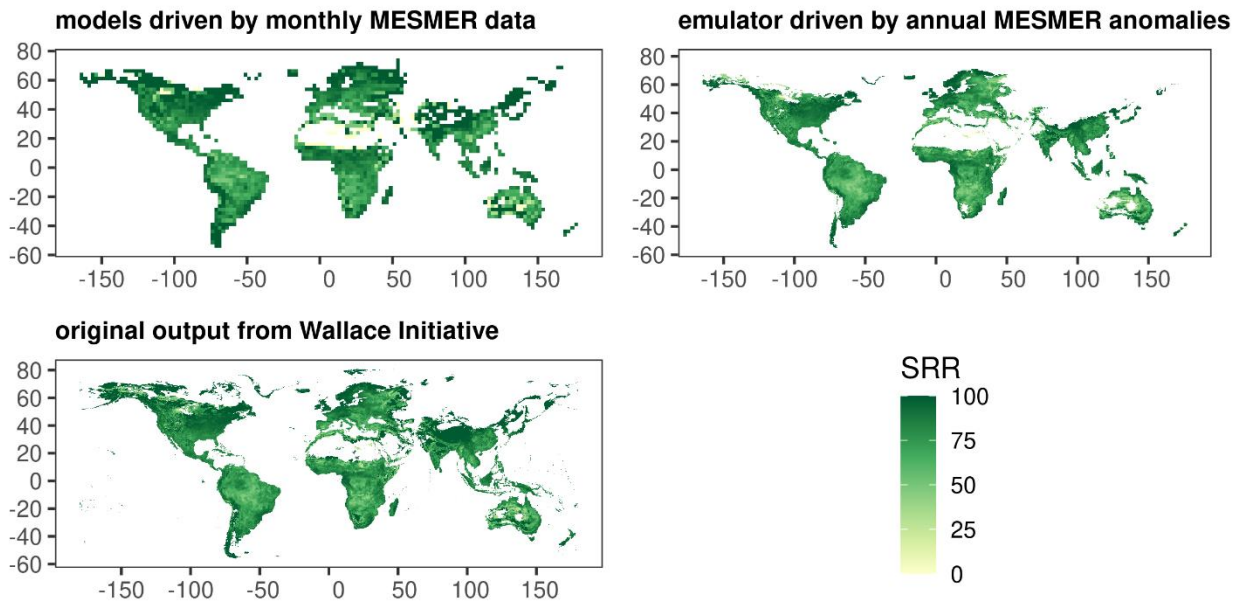


Figure 7. Spatial pattern of species richness remaining for timber species with  $\sim 1.5^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

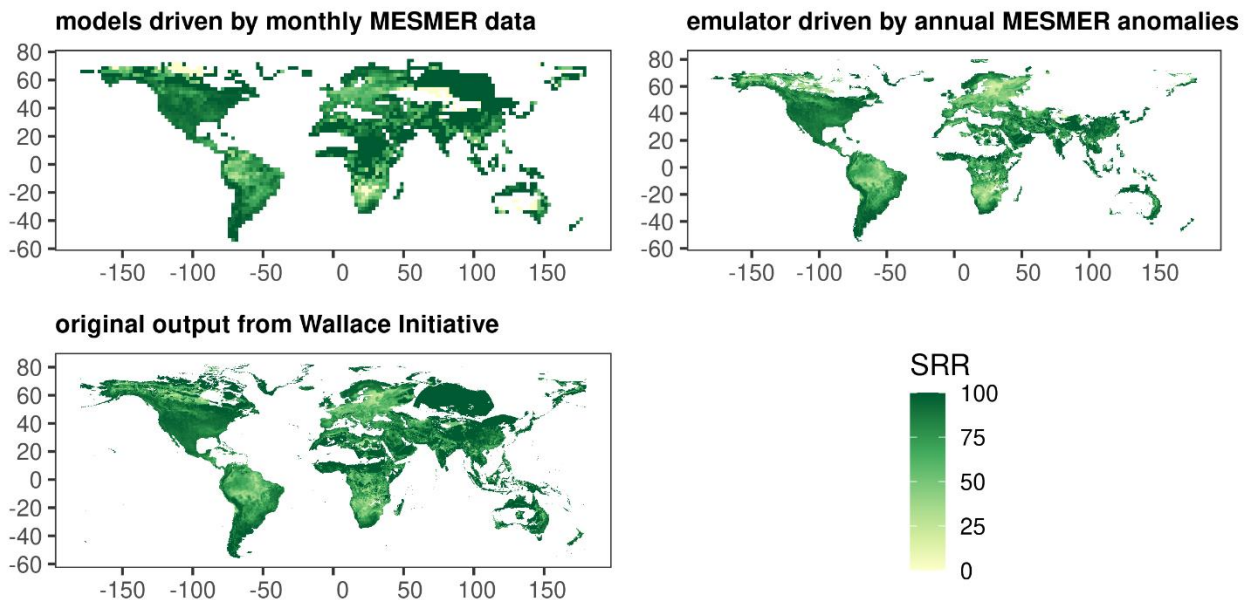


Figure 8. Spatial pattern of species richness remaining for insect pollinator species with  $\sim 1.5^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

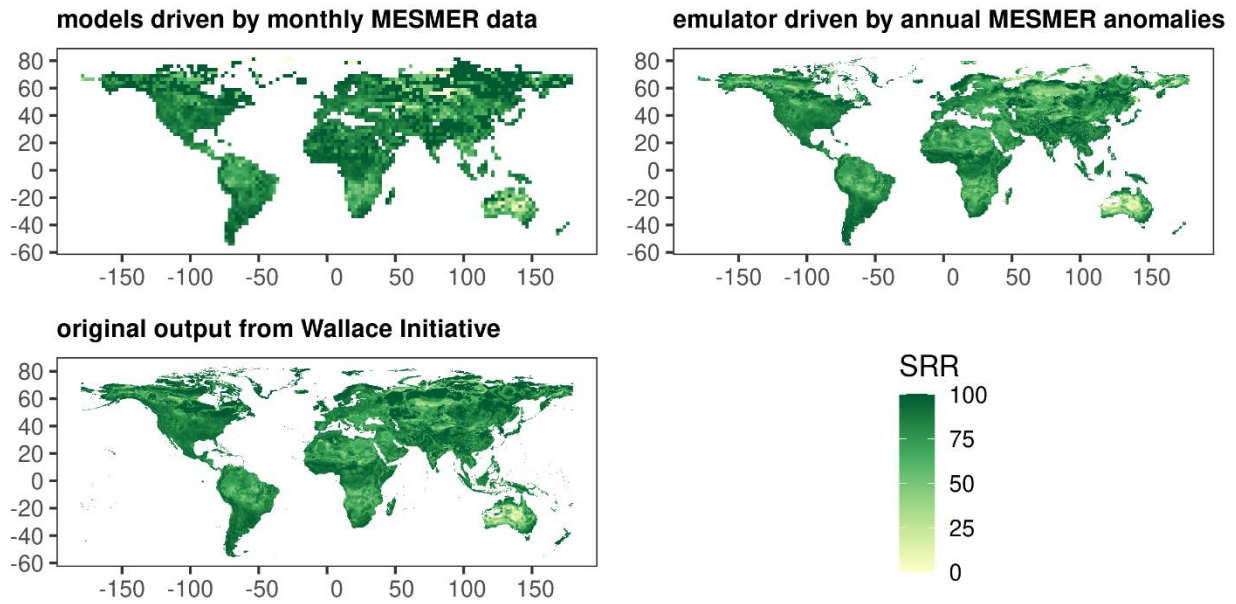


Figure 9. Spatial pattern of species richness remaining for mammal species with  $\sim 1.5^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

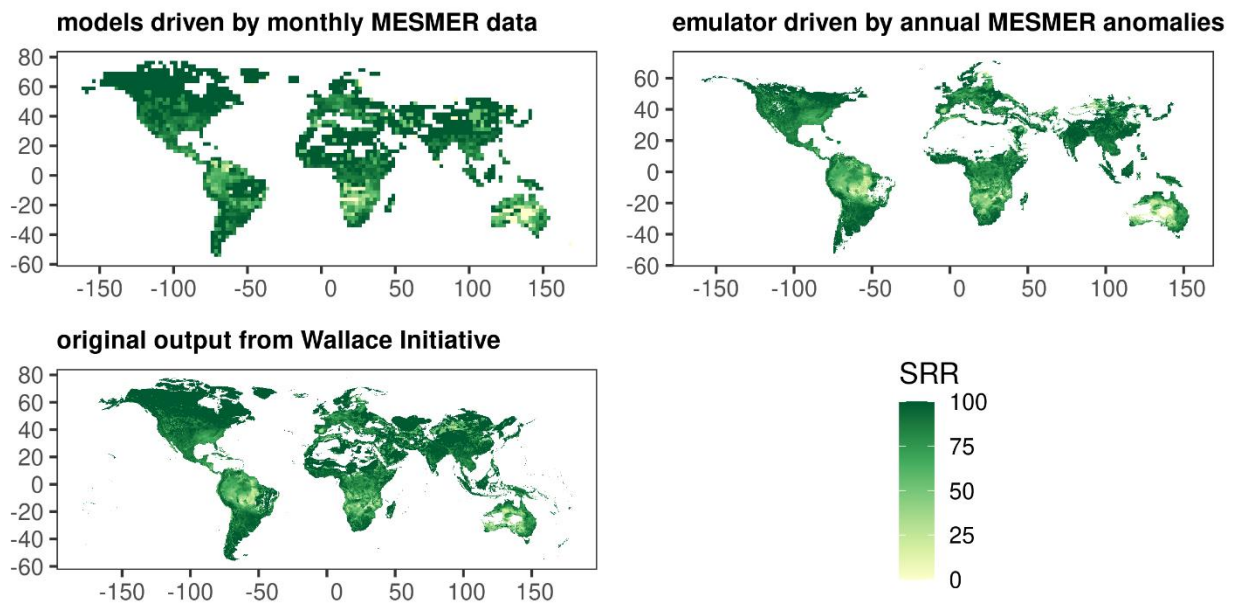


Figure 10. Spatial pattern of species richness remaining for amphibian species with  $\sim 1.5^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

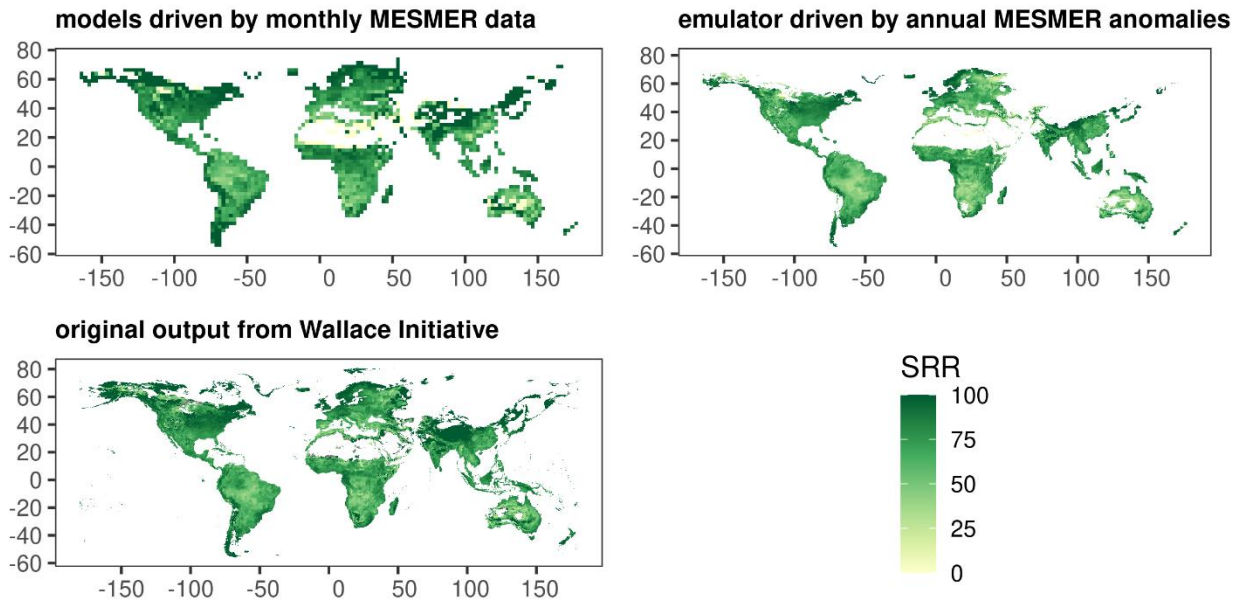


Figure 11. Spatial pattern of species richness remaining for timber species with  $\sim 2.0^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data

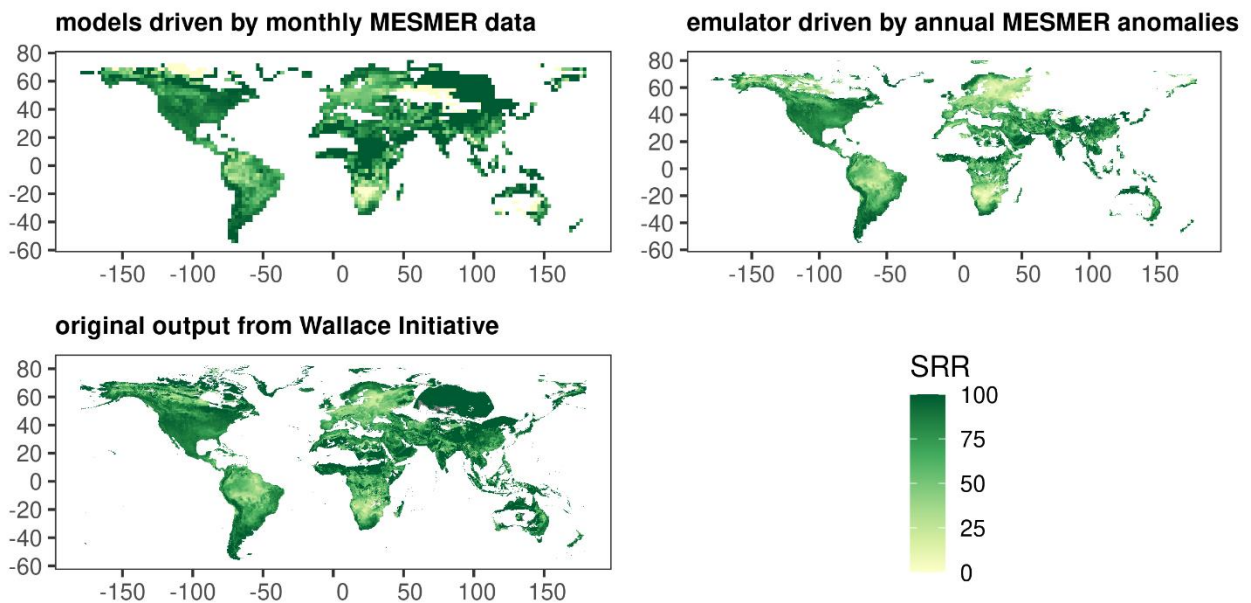


Figure 12. Spatial pattern of species richness remaining for insect pollinator species with  $\sim 2.0^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

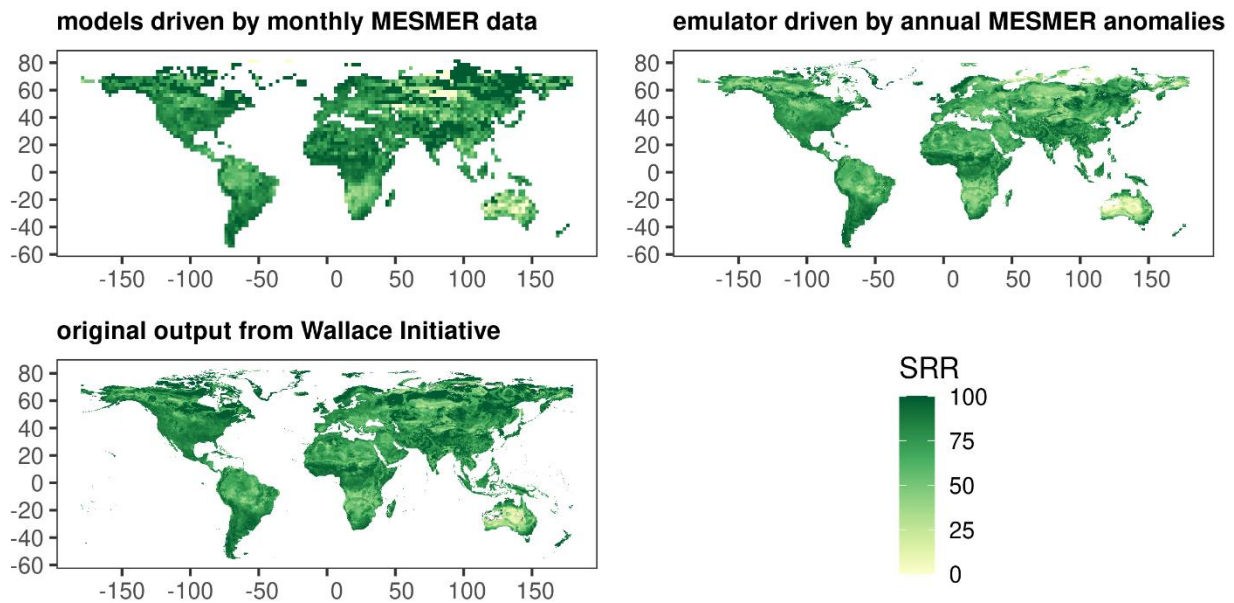


Figure 13. Spatial pattern of species richness remaining for mammal species with  $\sim 2.0^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

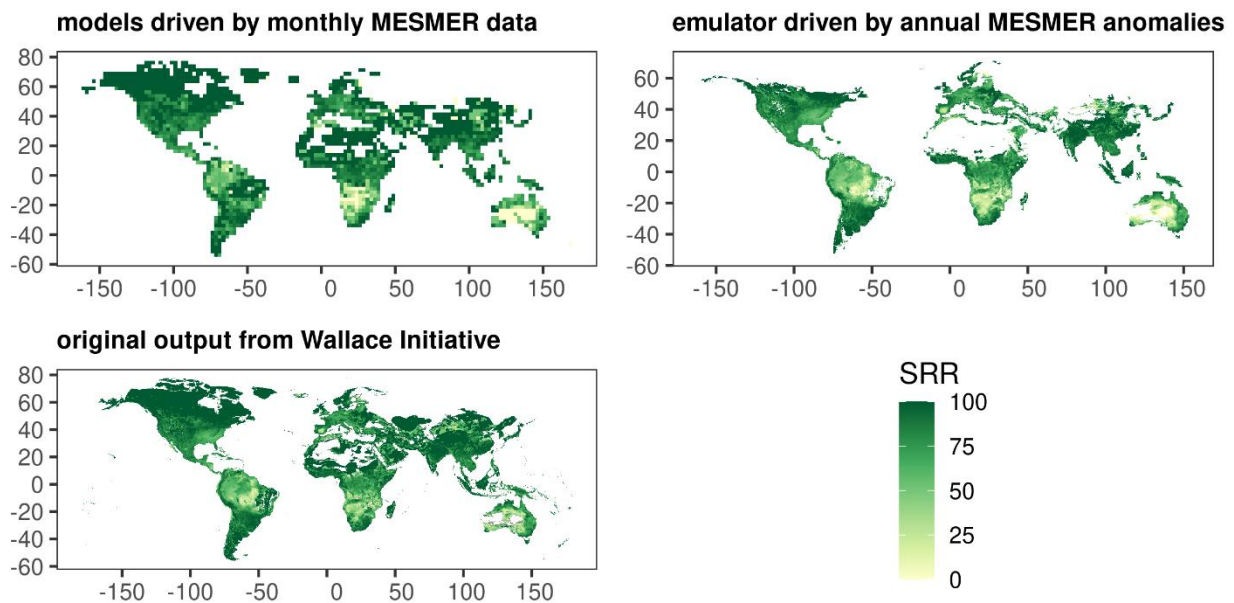


Figure 14. Spatial pattern of species richness remaining for amphibian species with  $\sim 2.0^{\circ}\text{C}$  warming. Note the spatial resolution of the MESMER model runs is  $2.5^{\circ}$  of latitude and longitude while the emulator and Wallace Initiative results presented here are both at  $\sim 20\text{km}$  resolution. White are areas with no data.

Figures Figure 7-Figure 14 show how the spatial pattern of climate suitability for species richness remaining is essentially the same for the original (Wallace Initiative), the emulator, and the MESMER model runs. While there are slight differences, owing primarily to the different spatial resolutions of the different models, the patterns are very similar. In some cases, the emulator shows more areas with no data or slight differences (some higher, some lower) to the original Wallace Initiative data. However, there does not seem to be any systemic differences in the species richness remaining in different parts of the World.

## 4. Discussion

In both cases where overshoot was directly examined (emulator, MESMER model) for different policy scenarios the climate suitability does not completely recover by the end of the century. The trajectories suggest that the climate suitability in some of the scenarios might eventually recover post-2100 but the climate data was not available to allow investigating how suitable climates for existing biodiversity might recover out to 2200 or beyond. Given the current state of biodiversity declines largely independent of climate change then the ability for recovery is even less likely.

However, **recovery of climate space does not mean that many individual species will be able to recolonize areas that had previously become climatically unsuitable.** Realistic dispersal rates for different species groups have previously been estimated to be 1.5 km/year for birds and mammals and 0.1 km/year for reptiles, amphibians and plants (Warren et al 2013). For insects the realistic dispersal rate previously examined was 2.6 km/year for butterflies and 3 km/year for dragonflies (Warren et al. 2018). Thus, if the maximum temperature was reached in 2060 (SSP534-Overshoot) with recovery over the following 40 years, then some butterfly species might be expected to be able to shift 104 km (up to five cells in the emulator but not even one in the MESMER results); some dragonfly species might be able to shift up to 120 km (six cells in the emulator but not even one in MESMER); some bird and mammal species shift by 60 km (three cells in the emulator but not even one in MESMER); and reptile, amphibian, plant, and most insect species by only 4 km (not detectable in either the emulator or MESMER). Dispersal rates (or inability to disperse at rates matching climate velocity) has profound implications for the projected impacts of overshoot on the ability of species to be able to return to their recovering climate spaces. This would be driven primarily by life history traits. While dispersal was not actively investigated as part of this project, it can be considered in any discussion of the recovery potential of biodiversity.

**As the majority of species studied have very low dispersal rates (and thus very low recovery rates) the impacts on biodiversity and smaller groups of species groups is the impact of the highest temperature reached.** This is supported by the observations of range shifts and local extinctions even with <1°C warming above pre-industrial. **While the climate suitability for species may recover, many will already have been driven to climatically induced local extinction (through loss of suitable climate space).** This is especially true for many insects, reptiles, amphibians, annual and other short-lived plants and possibly short-lived mammals (which also tend to have low dispersal rates). Many birds, butterflies, dragonflies would potentially be able to recover with the recovering climate suitability (depending on whether there were any climate driven population bottlenecks). Some mammals, especially larger mammals, would also potentially to return to areas previously climatically unsuitable if climatically suitable corridors with no barriers were available for movement.

The ability of plants to persist or recover is more difficult to fully assess. For example, some plants can recover from seeds in the soil that may have been dormant for many years, allowing them to recover as the climate suitability of that species recovers. This includes many annual flowering plants, that would also require pollinators to be available at the time of flowering – while many pollinators are also expected to lose their climate suitability. This may be a case of an ecological disconnect where one species loses another species, or group of species it is dependent on. These disconnects make local extinctions more likely. In long-lived species (many trees, including those in the timber species plots above) have lifespans of greater than 40 years. These species would be expected to have sporadic reproduction (only in climatically 'good' years) to complete cessation of reproduction while the climate is no longer suitable. As the climate recovers these species might be expected to begin reproducing again, maintaining the species in that area. However, the same loss of suitable climate conditions that halt



reproduction also tends to make many of these species more susceptible to disease, pests, and fire (especially when coupled with increasing drought conditions). Thus, the recovery of these species is subject to multiple outside influences.

Thus, the precautionary principle would suggest that **overshoot should not be seen as any sort of panacea to the maintenance or recovery of biodiversity with increasing warming, this is especially true once global temperatures exceed 3°C warming from pre-industrial**. The safest option for biodiversity is to avoid the higher temperatures completely. The projected impacts of climate change on biodiversity is yet one more reason to not have 'Overconfidence in Overshoot' .

#### Why the differences between the emulator and direct MESMER model run results

There is a consistent ~5-10% difference in changes in species richness between the results obtained by the emulator and those obtained directly from running the species models with the MESMER climate data. The consistency of these differences, which are consistent with the taxa run, and the results showing there are no major spatial differences, plus the similarity between the patterns of decline and recovery suggest that this is likely being driven by two main factors

The emulator was run using individual realisations of the FaIR-MESMER average temperatures. This captured the variability between the different realisations and can be seen in the fainter lines in the figures above. The median of these realisations was then calculated as the ensemble median. This is the preferred way of performing this sort of impact analysis as it is an ensemble relevant to the impact x climate model. It also allows for calculating percentiles of differences, if desired. However, the MESMER climate data for Tmax and Tmin was not available until late in the project, and this did not allow for the full set of realisations to be run in the same way (they were not available, nor would it have been possible to run individual models of thousands of species using the full suite of realisations in a very short period. This meant that an ensemble of the climate data was provided giving just the median Tmax, Tmin, and Precipitation. This is not the preferred way of running impact models as much of the potential variability is lost, especially differences in precipitation.

The emulator was run on long-term average climate using 30-year averages around the center year of each decade (e.g. the value for 2020 was obtained by driving the emulator with the average climatic conditions of the years 2006-2035) while the models were run on annual data and a 30-year average was calculated from the resulting species richness remaining. The emulator generated results hence do not capture the year-to-year variability in species richness in the same way the models do. Ideally, the emulator would have been used to generate annual values as well.

The biggest contributor to the differences is most likely the difference in spatial resolution between the two approaches. The emulator was run at a spatial resolution of ~20km, while the data modelled directly with the new MESMER variables was 2.5° latitude/longitude - a substantial difference (there would be more than 150 cells difference between the two). The emulator would better capture those areas that were lower, and thus warmer, and those that were higher, and thus colder providing a better overall estimate of the potential changes in species richness with warming. The ensemble of the MESMER climate variables would thus be an average over the ~150 cells rather than capture the actual spatial heterogeneity.

## 5. Bibliography

GBIF.org (2015). GBIF Occurrence Download. Version March 2015. The Global Biodiversity Information Facility. DOI: 10.15468/DL.KECDHX. URL: <https://www.gbif.org/occurrence/download/0000129-150523225239109>.

IPCC, 2001: Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 398 pp.

Jenkins, R. L. M., Warren, R. F., and Price, J. T. (2021). Addressing Risks to Biodiversity Arising from a Changing Climate: The Need for Ecosystem Restoration in the Tana River Basin, Kenya. *PLOS ONE* 16(7), e0254879. DOI: 10.1371/journal.pone.0254879.

Lamboll, R., Rogelj, J., & Schleussner, C.-F. (n.d.). *A guide to scenarios for the PROVIDE project*. Retrieved 17 December 2024, from <https://www.authorea.com/doi/full/10.1002/essoar.10511875.2?commit=4d2d973c7a857b8eb4a50d5647a15f6e62b0df84>

Osborn, T. J., Wallace, C. J., Harris, I. C., and Melvin, T. M. (2016). Pattern Scaling Using ClimGen: Monthly-Resolution Future Climate Scenarios Including Changes in the Variability of Precipitation. *Climatic Change* 134(3), pp. 353–369. DOI: 10.1007/s10584-015-1509-9.

Parmesan, C., M.D. Morecroft, Y. Trisurat, R. Adrian, G.Z. Anshari, A. Arneth, Q. Gao, P. Gonzalez, R. Harris, J. Price, N. Stevens, and G.H. Talukdar, 2022: Terrestrial and Freshwater Ecosystems and Their Services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Lösschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 197–377, doi:10.1017/9781009325844.004.

Price, J., Warren, R., and Forstnhäusler, N. (2024a). Biodiversity Losses Associated with Global Warming of 1.5 to 4 °C above Pre-Industrial Levels in Six Countries. *Climatic Change* 177(3), p. 47. DOI: 10.1007/s10584-023-03666-2.

Price, J., Warren, R., Forstnhäusler, N., Jenkins, R., and Graham, E. (2024b). Assessing the Potential Risks of Climate Change on the Natural Capital of Six Countries Resulting from Global Warming of 1.5 to 4 °C above Pre-Industrial Levels. *Climatic Change* 177(3), p. 46. DOI: 10.1007/s10584-023-03650-w.

Price, J., Warren, R., Forstnhäusler, N., Wallace, C., Jenkins, R., Osborn, T. J., and Van Vuuren, D. P. (2022). Quantification of Meteorological Drought Risks between 1.5 °C and 4 °C of Global Warming in Six Countries. *Climatic Change* 174(1), p. 12. DOI: 10.1007/s10584-022-03359-2.

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig and J.A. Pounds. 2003. Fingerprints of global warming on animals and plants. *Nature* 421: 57-60.

Saunders, S., Grand, J., Bateman, B., Meek, M., Wilsey, C., Forstnhäusler, N., Graham, E., Warren, R., and Price, J. (2023). Integrating Climate-Change Refugia into 30 by 30 Conservation Planning in North America. *Frontiers in Ecology & the Environment* 21(2). DOI: 10.1002/fee.2592.

Schleussner, C.F., Ganti, G., Lejeune, Q. *et al.* Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024). <https://doi.org/10.1038/s41586-024-08020-9>

Schwaab, J., Hauser, M., Lamboll, R. D., Beusch, L., Gudmundsson, L., Quilcaille, Y., Lejeune, Q., Schöngart, S., Schleussner, C.-F., Nath, S., Rogelj, J., Nicholls, Z., & Seneviratne, S. I. (2024). Spatially resolved emulated annual temperature projections for overshoot pathways. *Scientific Data*, 11(1), 1262. <https://doi.org/10.1038/s41597-024-04122-1>

Schöngart, S., Gudmundsson, L., Hauser, M., Pfleiderer, P., Lejeune, Q., Nath, S., Seneviratne, S. I., & Schleussner, C.-F. (2024). Introducing the MESMER-M-TPv0.1.0 module: Spatially explicit Earth system

model emulation for monthly precipitation and temperature. *Geoscientific Model Development*, 17(22), 8283–8320. <https://doi.org/10.5194/gmd-17-8283-2024>

Smith, P., Price, J., Molotoks, A., Warren, R., and Malhi, Y. (2018). Impacts on Terrestrial Biodiversity of Moving from a 2°C to a 1.5°C Target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376(2119). DOI: 10.1098/rsta.2016.0456.

UNEP-WCMC and IUCN (2024). The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM). Version March 2024. Cambridge, UK: UNEP-WCMC and IUCN. URL: [www.protectedplanet.net](http://www.protectedplanet.net).

Warren, R., Price, J., Graham, E., Forstnerhaeusler, N., and VanDerWal, J. (2018a). The Projected Effect on Insects, Vertebrates, and Plants of Limiting Global Warming to 1.5°C Rather than 2°C. *Science* 360(6390), pp. 791–795. DOI: 10.1126/science.aar3646.

Warren, R., Price, J., VanDerWal, J., Cornelius, S., and Sohl, H. (2018b). The Implications of the United Nations Paris Agreement on Climate Change for Globally Significant Biodiversity Areas. *Climatic Change* 147(3), pp. 395–409. DOI: 10.1007/s10584-018-2158-6.

Warren, R., VanDerWal, J., Price, J., Welbergen, J. A., Atkinson, I., Ramirez-Villegas, J., Osborn, T. J., Jarvis, A., Shoo, L. P., Williams, S. E., and Lowe, J. (2013). Quantifying the Benefit of Early Climate Change Mitigation in Avoiding Biodiversity Loss. *Nature Climate Change* 3(7), pp. 678–682. DOI: 10.1038/nclimate1887.

## 6. Annexes

This annex provides in-depth background information biodiversity modelling as well as understanding and technical underpinnings of the Wallace's pARCs Reports overall.

### 6.1. Wallace Reports: Expanded Text for the Tables and Figures

The text in each of the reports provides a brief overview of what the tables/maps show and how to read them. This was shortened to allow more ready access to understanding the data. However, some users may want more detail on the tables and figures and this information is set out below.

#### 6.1.1. Climate

The text of the reports reviews the observed climate, climate variability, and potential climate changes in the region selected. It contains an analysis of the output of the Community Integrated Assessment System (CIAS; Warren et al. 2008) with downscaled climate change projections from the IPCC CMIP5 climate model patterns from the ClimGEN pattern scaling system (Osborn et al 2016). It also provides analyses of observed climate data from the Climatic Research Unit (CRU) TS 4.07 database.

The reports look at high, low, and average temperatures, precipitation, and meteorological drought/waterlogging (Price et al 2022) for the area listed. These projected changes are explored in the context of the current climate variability to which the area is already exposed (1-2 standard deviations, shaded as yellow or red respectively). This assumes that many human and ecological systems may be largely resilient to changes lying within the bounds of recently experienced natural variability, depending on the return rate of the event. The first set of tables (1-12) summarises observed climate variability and projected climate change. For temperature and precipitation variables comparisons are also provided between two recent periods to show the recent trends in climate in the area. The tables also provide a comparison between the magnitudes of projected climate changes with observed climate variability in terms of standard deviations (yellow - >1 standard deviation, occurring ~1 in 3 years; red is >2 standard deviations, occurring ~1 in 20 years). Thus, if a month is shaded as red it means that the future average climate will exceed that currently occurring only once in every twenty years.

Both observational and projected climate change data presented here have a spatial resolution of 0.5° of latitude by 0.5° of longitude, all calculated monthly. The observed climate data comes from the University of East Anglia Climatic Research Unit (CRU TS 4.07 dataset, which provides monthly gridded climate data through 2022). Versions of these data have previously been used extensively in IPCC reports and many different works on climate change impacts. The data presented here cover two time periods: 1961-1990 and 1991-2020 (except drought which uses 1986-2015). Summary statistics are provided giving the difference between the climates in 1961-1990 and 1991-2020 to provide information on what changes (if any) in temperature and precipitation have been observed between these two time periods. The first period, 1961-1990, is one of the standards used for climate modelling results and is a commonly used baseline for impact models (including the biodiversity results presented here); by this time, the world had warmed by 0.35°C since 1861- 1890 (see HadCRUT4 dataset of Morice et al., 2012). By the second period (1990-2020) warming had increased by ~0.9°C – 1.0°C since 1861-1890. Similarly, the IPCC (2023) states that global land temperatures were 1.59 (1.34 to 1.83) °C warmer between 1850-1900 and 2011-2020.

#### 6.1.2. Future Climates

Projected climate data comes from the Community Integrated Assessment System (CIAS; Warren et al. 2008) and its component module ClimGen (Osborn et al. 2016). In this approach, a simple climate model is first used to project global temperature rises (using a probabilistic approach to encompass the key uncertainties in state-of-the-art global climate change projections) over the 21st century, as a time series. The Climatic Research Unit has a database of stored outputs from 21 general circulation models (GCM) from a model inter-comparison

project known as CMIP5. These outputs provide the pattern of how climate variables are projected to change regionally for specific levels of global temperature rise. ClimGEN scales these patterns to the amount of warming provided by the time series, to create 21 new patterns of projected changes corresponding to the desired future time periods/warming levels for each area. These are the changes provided here.

The projected climate change data are expressed as quantified changes, typically called anomalies (e.g., degrees of temperature rise, millimetres of precipitation), relative to the baseline climate of 1961-1990. For example, an anomaly of 2.3°C means that the temperature is projected to be 2.3°C warmer than the 1961-1990 average. In preparing these reports, these projected changes are generally averaged across 21 climate model patterns, and then compared against the observed baseline, as well as to the standard deviation in the observed (1961-1990) baseline.

### **6.1.3. Warming Levels**

The tables of projected results give the projected monthly average changes in the different climate variables, together with the corresponding projected global temperature rise (also referred to as specific warming level). The warming levels used in this report are 1.5°C (Paris Accord aspirational goal), 2.0°C (upper limit of Paris Accord goals), 2.5°C, 3.0°C, 3.5°C (approximately the range of warming projected if countries meet their Intended Nationally Determined Contributions and make no additional improvements, and 4°C as a Business as Usual (BAU) pathway if temperature trajectories follow their current trajectory. In general, many impacts are tied to the amount of warming and its accompanying climate change and are not strongly dependent on time (as different scenarios reach the same temperature at different times). This approach is used to aid the reader in determining potential projected changes depending on what global policies are agreed upon (and followed) in international negotiations. The projected climate change model data presented here is provided for different warming levels as averages of 30-year periods.

The tables of projected climate change (Tables 2, 4, 6, 8, 11, and 12 in a protected area report) provide monthly values averaged across the 21 climate change model patterns AND the entire area of interest (e.g., Country, Protected Area, Key Biodiversity Area, Ecoregion, etc.). The values are the average relative change (also called the delta or anomaly) compared to the observed data for 1961-1990. Yellow and red shading in the tables shows the warming level when the average climate equals the climate currently occurring at greater than one (yellow) or two (red) standard deviations (SD) of the 1961-1990 average. Some adaptation practitioners use 2 SD as the limit to which systems may have autonomously adapted; greater deviations potentially leading to greater impacts. For example, a change of greater than 2 standard deviations in rainfall is classified as either being extremely dry or extremely wet. For climate change this is considered RELATIVE climate change – the amount of climate change (expressed as an anomaly) RELATIVE to the observed climate variability. For example, the absolute climate change in temperature is projected to be greatest nearer the poles. However, the relative climate change in temperature is projected to be greater in the tropics. This is because the year-to-year variability in temperature, for a given season, is greater near the poles than it is in the tropics.

### **6.1.4. Climate Variables**

#### **6.1.4.1. Temperature**

This report provides information on observed (Tables 1, 3, 5) and projected values (Tables 2, 4, and 6) of three terrestrial seasonal temperature variables – high, average, and low. The data does not give the maximum temperature of each day but the average value of these ~30 daily high temperatures, to give the monthly average high (usually mid- to late-afternoon). This is similar for the monthly average low (usually right before dawn) temperature.

#### 6.1.4.2. Observed

For observed data, differences between the two observed periods, 1961-1990 and 1991-2020, are provided. Two additional metrics are also provided – the average of each of the variables in the warmest year and the coolest year. In other words, for a given thirty-year period the warmest/coolest/average monthly temperature (for low, high, and average) was calculated. As previously mentioned, this is not derived from the extremes of daily data but is rather an indication of how warm the 'warmest' overall month was and how cool the 'coolest' overall month was. This can be viewed as the warmest month and coolest month observed (and thus experienced by the people and biodiversity in the area) in the 30 years of 1961-1990 and 1991-2020. Given the size of the spatial area analysed, the warmest year may not have been the same year in every part of the area.

#### 6.1.4.3. Precipitation

Also provided are observed and projected values for terrestrial precipitation. As for temperature, for a given thirty-year observational period, the wettest monthly average and the driest monthly average are also provided. This is often driven by exceptionally wet or dry years, so the variability is much greater than with temperature and the number of 'extreme' years (i.e.,  $> 2$  SD) are fewer. For future projections of precipitation, when averaging across the 21 GCM patterns used, the median is used rather than the mean as the median is a better measure of central tendency. Finally, summary statistics are provided giving the difference between 1961-1990 and 1991-2020 for average precipitation to show what changes (if any) may have already been observed. Unlike temperature, the average precipitation projections in the future rarely exceed the wettest or driest years of the past ( $>1$  or  $>2$  SD). The extremes in one direction or another may become more common (and true extreme events will also usually become greater and more common) but the median may not shift by that much.

Note on interpreting projected precipitation changes - While looking at climate change projections for temperature is relatively straightforward, it is less so for precipitation. For a given area, patterns of change from some GCM models will project a wetter future whilst others will project a drier one, as illustrated in Figure 12.22 of IPCC's Working Group I report (IPCC, 2013), which presents the degree of concurrence of the sign of projected precipitation change across models. In general, GCMs tend to project that wet areas in mid and high latitudes become wetter and dry, low latitude areas become drier as climate changes, and there is high confidence that "the contrast of seasonal mean precipitation between dry and wet regions will increase in a warmer climate over much of the globe" (IPCC, 2013). However, there is a great deal of variation in the details and there are some parts of the world where model agreement on the sign of precipitation change is poor. This means that the use of an overall mean, or even median, change across models could potentially even lead to maladaptive responses and planning. Care still must be taken in deciding how these climate changes might turn into impacts. One overview of how climate impact drivers can turn into impacts can be found in the IPCC Working Group 1 Fact Sheet on Biodiversity and Ecosystems ([https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC\\_AR6\\_WGI\\_Sectoral\\_Fact\\_Sheet\\_Terrestrial\\_Freshwater\\_Ecosystems.pdf](https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Sectoral_Fact_Sheet_Terrestrial_Freshwater_Ecosystems.pdf))

The following provisions should also be kept in mind:

- 1) Depending on the size of the area/park analysed the changes may not be the same, or even in the same direction in all parts of the park (mostly true in larger areas). Thus, some parts might currently be being observed to be becoming drier, while others are becoming wetter. However, this study only looks at the area as an overall average so some levels of important detail may be lost.
- 2) The monthly differences may be in different directions. So, some months might become wetter while others become drier in the same area of study. IPCC (2013, p. 1079) gives "high

confidence that the contrast between wet and dry seasons will increase over most of the globe as temperatures increase”.

3) One approach to consider in adaptation planning is to look for the trend in precipitation (or the differences between 1961-1990 and 1991-2020) and use that to think about how precipitation (at least in the near term) might change. So, if it is getting drier now, this drying trend may continue (and vice versa).

#### 6.1.4.4. Drought

The drought metric used here is the Standardized Precipitation Evapotranspiration Index (SPEI) as it uses changes in both precipitation and temperature. Specifically, the metric used is SPEI12 - an SPEI value averaged over the SPEI values of the preceding 12 months. This metric is often used when looking at potential drought issues for agricultural and natural lands. For this report, the specific metric was SPEI12 -1.5, severe drought. SPEI12 means that the drought has been developing over the preceding 12 months before the ‘counting’ begins. Thus, an area identified as having a maximum drought duration of 12 months has been in drought for up to 24 months. The values in the table are calculated for the 30-year period that includes the specific warming level given. More data on the drought metric and interpretation can be found in Price *et al.* 2022.

#### 6.1.4.5. Waterlogging

Waterlogging is the reverse of the drought metric and uses an SPEI12 of +1.5 (SPEI > 1.5 SD of the mean precipitation). This is an indication of areas having excess moisture for extended periods, potentially leading to waterlogged soils.

Two different metrics are provided for observed and projected. The first is the number of months and the second is the number of consecutive months, both in a 30-year period. The first could have other months in between not meeting the threshold of -1.5 or +1.5. Consecutive months mean there is no break in the run of month’s meeting the threshold (there could also be other, shorter, consecutive months with severe drought/waterlogging in the given 30-year period).

### 6.1.5. Role of elevation and topography

The climate data used in these reports is at a spatial resolution of ~50km x 50km (0.5° of latitude and longitude) and the original biodiversity models are at ~20km x 20km (subsequently elevationally downscaled to ~1km x ~1km). This means that it is an average across a pixel (cell) of this size. As an average, there may be areas that are hotter and others that are cooler (or wetter and drier) than the average. Thus, areas with varying topography will have more hotter/drier or cooler/wetter areas. Thus, elevation differences might ‘buffer’ the overall climate change in a given cell. For example, the same elevation on two sides of a mountain may not have the same temperature as one side of the mountain may be moister and the other drier (depending on prevailing wind/moisture patterns). This becomes especially notable when comparing results from the emulator model runs and those run directly with the new MESMER data provided for biodiversity modelling (GCM scale).

### 6.1.6. Population Data

Table 13 presents the projected population for the years 2000 through 2100 at a 1 km<sup>2</sup> spatial resolution. These data are provided both in terms of the total (summed across all 1 km<sup>2</sup> cells) population within the boundary, and those within an area that includes a 15 km wide buffer zone around the boundary. The data from 2000 and 2010 are interpolations of observed population sizes, the other periods are projections of future change. There are several caveats around these data: First, in many cases, a protected area may be managed in a way that precludes any population or population growth within the protected area. These are not captured in the modelling underpinning these population data but would still be captured in the second row (area + 15 km buffer). Second, the population change projections are from what is

known as the Shared Socioeconomic Pattern (SSP) 2 scenario. This is one of five scenarios used in the IPCC to look at alternative pathways for climate change. In the SSP2 scenario, the trends into the future follow those existing today and is sometimes referred to as a 'middle of the road scenario'. A good general source on the different SSPs can be found at <https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/> with the underpinning science data discussed in Riahi *et al.* 2017. Different SSPs would therefore provide different projections of future populations. The projections themselves use a weighting where areas currently increasing in population continue to increase, and those that are decreasing continue to decrease. This is a major assumption that may or may not hold up over time. More information on the process used to derive the population projections and subsequent downscaling can be found in Jones and O'Neill, 2016, and Gao, 2017.

#### **6.1.7. Land Cover Changes**

Table 14 shows the percentage of different landcover types in 1992 and 2020 as well as the change between these two time periods within the boundaries of the area in this report. These data come from the European Space Agency Climate Change Initiative (ESA Land Cover CCI project team, 2019) and have a resolution of 300 metres. The main limitation of the ESA data is that it is automatically classified, and not "ground-truthed". This means that areas designated as 'forest' may be plantations of non-native species. These figures are provided to assist in understanding how these land cover classes have changed over time as this may have immediate biodiversity implications in the area studied for this report.

#### **6.1.8. Biodiversity**

The biodiversity information presented here is from the Wallace Initiative. The Wallace Initiative modelled ~135,000 terrestrial fungi, plants, invertebrates, and vertebrates, at warming levels ranging from 1.5°C to 6°C, across 21 CMIP5 climate model patterns at a spatial resolution of ~20km x 20km based on occurrence data obtained from GBIF (GBIF, 2015). More information on the overall project, results, modelling methodology, caveats, and uses can be found in a series of papers (Warren *et al.* 2013; Warren *et al.* 2018 a, b; Smith *et al.* 2018; Jenkins *et al.* 2021, Saunders *et al.* 2023, Price *et al.* 2024a). The data were also used for several figures and tables in Working Group II of the IPCC Sixth Assessment Report (AR6). The data used in these reports were then subsequently elevationally downscaled to ~1km x 1km (Saunders *et al.* 2023, Price 2024b) to better understand which areas of each modelled 20km cell or pixel might be lost sooner or persist longer. In short, a given 50 km or 20 km cell is an average of the temperatures for all elevations within that cell (i.e., the average elevation). In areas with varied terrain, some areas will be warmer than the average and some will be cooler. Species in areas that are warmer than the average would be expected to potentially be more susceptible (exposed) to warming, while those in cooler areas would be expected to potentially be less susceptible (or be able to shift into these areas if they are currently too cool). Therefore, species within cooler areas within a climate 'cell' or 'pixel' would be expected to potentially be able to persist in that area longer.

#### **6.1.9. Local Extinctions (extirpations)**

Table 15 shows the percentage of species in different taxa projected to be at risk of local extinction (extirpation, losses within the area of the report) owing to changes in climate alone. Yellow-shaded areas are projected to become climatically unsuitable for >25% of the species studied (by taxa listed); orange areas are projected to become climatically unsuitable for >50% of the species studied; and red areas are projected to become climatically unsuitable for >75% of the species studied. NA means there is insufficient data in the cell to assess overall likelihood. The climate suitability is the average change (ensemble of biodiversity models) across the 21 climate models examined.

Species Richness Remaining



Figures 1-7 show the species richness *remaining* in each 1 km cell within the boundaries of the area under study (also depicted on the map as a solid black line) for selected taxa. This shows the spatial variability in the potential patterns of loss.

### 6.1.10. Refugia

Table 16 shows the percent of the area remaining a climate refugia for the taxa. We define a climate refugia as an area remaining climatically suitable for >75% of the species in those taxa. The two columns, for each level of warming, are >0 (meaning at least one climate change model projects that the area is a refugia) and >10 (meaning that more than 10 models, out of 21, project the area remains a refugia). The shading is – darker green, >75% of the area is a refugium; medium green, 50% - 75% of the area is a refugium; light green, 25% - 50% of the area is a refugium; and white, less than 25% of the area is a refugium.

Figures 8 – 14 show the number of models in agreement that a particular pixel (cell) is a refugium for the taxa indicated. These maps provide a spatial representation of the agreement in the models (or areas with potentially lower uncertainty) to be refugia for the different taxa as well as how this potentially varies within the area under study.

### 6.1.11. Adaptation Effort

Figures 15 – 21 present a spatial representation of the potential 'adaptation effort' that might be needed to maintain at least 75% of the species modelled (i.e., the area remains climatically suitable) in each ~1km pixel. Adaptation effort is a combination of the number of climate models (+ 1 to 21) projecting an area is a refugium (remaining climatically suitable for >75% of the species) as well as the number of climate models (- 1 to -21) projecting the area to be an Area of Concern (becomes climatically unsuitable for >75% of the species) in each pixel. One way of looking at this is to consider areas with high values (+18 to +21) as being less exposed to climate change and thus potentially more resilient. Business-as-usual conservation, especially if coupled with building resilience around extreme climates (e.g., drought, heat waves) might be a reasonable adaptation approach to take. As the score drops, increasingly greater amounts of adaptation might be needed to maintain the existing species in that pixel. While micro-refugia (areas <1km) might be available, the amount of habitat available as micro-refugia would be less than the pixel. Once the adaptation effort drops into the negative zone, adaptation to maintain the existing species is likely to become increasingly difficult. A score of -15 to -21 the best approach might be to consider facilitating change as opposed to putting large efforts into trying to maintain existing species. Scores this low indicate that the area becomes climatically unsuitable for a large percentage of species. While this does not preclude micro-refugia, large areas (and potentially the area of conservation interest) would appear to be transforming. In the case of an area where restoration or afforestation/reforestation is planned, then consideration might be given to planting the species that might be expected to move into the area, given enough time (considering species with similar structure and native, if possible). This type of adaptation begins to make the new 'habitat' that species from surrounding areas will need to autonomously adapt to climate change.

There are many complexities in these analyses. Not least of which is that an area may remain a refugia for vertebrates and yet potentially become unsuitable for many of the species making up the habitat or food resources for these species. If the habitat becomes unsuitable, or food becomes more unavailable, then this is likely to have major implications for those taxa that a cell remains a refugia for. With increasing warming, fewer areas remain refugia, more areas become areas of concern, and adaptation effort increases (i.e., become more negative)

## 6.2. Wallace reports: sources of data

**Biodiversity:** Wallace Initiative (this is data produced in a decade long partnership between Tyndall Centre for Climate Change Research and eResearch at James Cook University, Australia

(see below for more details). Wallaceinitiative.org ; [jeff.price@uea.ac.uk](mailto:jeff.price@uea.ac.uk) for data requests; research partnerships.

**Biodiversity Occurrence Data:** Global Biodiversity Information Facility (GBIF, 2015).

**Observed Climatology:** Climatic Research Unit (CRU) TS 4.07 database.

[https://crudata.uea.ac.uk/cru/data/hrg/cru\\_ts\\_4.07/](https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.07/) (Climatic Research Unit (University of East Anglia) and Met Office, 2024).

**Projected Climate Data:** ClimGEN and CIAS (see below).

<https://crudata.uea.ac.uk/~timo/climgen/> (Osborn et al., 2016).

**Population Data:** (see below) <https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-km-downscaled-pop-base-year-projection-ssp-2000-2100-rev01> (Gao et al. 2017, 2020).

**Landcover Data:** (see below) <https://www.esa-landcover-cci.org/> (ESA Land Cover CCI project team; Defourny, P. 2019)

## 6.3. Wallace reports: technical details and understanding data sources

### 6.3.1. Method of projecting regional climate change

General circulation models (GCMs) are complex tools used to project global climate changes and single runs can take many months on the most powerful computer systems in the world. However, GCMs do not themselves encompass the full range of uncertainty inherent in the climate system, since other variants of these models could be constructed in which certain key variables take different values. Our approach in this project was to take account of as much of the uncertainty in model projection as possible by use of a simple climate model that produces probabilistic global temperature time series that reflect the full range uncertainty in key variables.

GCMs typically produce regional output at a spatial resolution of a few degrees of latitude/longitude, which is too coarse for most applications, including this study. The scientific community has invested much effort in considering how to combine GCM outputs with other information or techniques to project climate change at a finer resolution to facilitate climate change impacts, adaptation and vulnerability studies. This process is called 'downscaling' (see Wilby and Wigley 1997 for an overview). While using regional climate projections from different GCMs is also possible (and are usually at the same scale used in this study), there are fewer of them, they differ in magnitude and are particularly inconsistent in the case of precipitation. Therefore, a comprehensive analysis of climate change impacts that can be useful to inform decision making requires consideration of a wide range of outcomes. This is the reason we chose to use downscaled data.

To encapsulate the variation in regional projections across general circulation models, and to produce projections of change at a resolution useful to drive this study, a technique called pattern scaling is used to produce climate projections at 0.5° spatial resolution (approximately 50km x 50km at the equator). This uses the global temperature time series produced by the simple model as a driver and combines these time series with information about patterns of regional climate change from GCMs, but also with observational climate data.

The next two sections describe the simple climate model used to project the global temperature time series and the methodology of pattern scaling used to create the regional climate change projections.

### 6.3.2. Origin of global temperature time series used

The global temperature time series matching the Representative Concentration Pathways (RCPs) used in this project were kindly provided by the UK Met Office Hadley Centre. They are identical time series to those used in the AVOID2 (Avoiding Dangerous Climate Change) project funded by the UK Department of Energy and Climate Change (Bernie & Lowe, 2014). These time

series encapsulate the uncertainty in GCMs through the process described below. They are probabilistic outcomes of the modelling system used in AVOID2, which samples scientific uncertainties in the climate system by sampling distributions of physical parameters which have a dominant contribution to uncertainty in climate projections. The main advantage of using these scenarios is that they are internally consistent as to when a given global temperature is reached across climate models, making them more useful for adaptation and for comparing different policy options.

The three physical parameters used in developing the scenarios are: the equilibrium climate sensitivity (ECS), which is the long-term warming response to a doubling of atmospheric CO<sub>2</sub>; ocean diffusivity, which affects how quickly heat is removed from the upper ocean, moderating the rates of atmospheric warming; and climate-carbon cycle feedback strength, which accounts for how strongly climate change affects the ability of the carbon cycle to remove CO<sub>2</sub> from the atmosphere. The distribution of carbon cycle feedback uncertainty was based on Friedlingstein et al. (2006); the ECS distribution used is based on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4, Solomon et al. 2007) and is a simple combination of ECS distributions from a number of alternative lines of evidence (Rogelj et al. 2012); and the estimated distribution of ocean diffusivity is based on climate models from the IPCC AR4 (Gohar et al. 2011).

The Met Office calculated 10%, 50% and 90% probability outcomes for each of the four RCP scenarios as time series over the 21<sup>st</sup> century, expressing this as the global temperature rise relative to a 1961-1990 baseline. In this project, we then selected 30-year time periods centred on 2025, 2055 and 2085 (i.e. 2011-2040, 2041-2070, 2071-2100) to represent different levels of temperature rise. Thirty-year time periods are used as this is the standard for providing meteorological data because it tends to span many types of climate variability/oscillations and is therefore not as impacted as heavily by single extreme years (e.g., El Niño) as a ten- or twenty-year average may be.

### **6.3.3. Pattern Scaling**

Downscaled climate data were obtained by running the model ClimGEN (Osborn et al. 2015). ClimGEN uses GCM datasets obtained from the IPCC Data Distribution Centre ([www.ipcc-data.org](http://www.ipcc-data.org)) to produce interpolated patterns of climate change per °C of global warming. The GCM outputs currently incorporated in ClimGEN were used in the IPCC Fifth Assessment Report (AR5, IPCC, 2013). These are the CMIP5 simulations for the four RCPs (van Vuuren et al. 2011). The pattern-scaling approximation is that, for a particular GCM, these patterns should be similar regardless of scenario. ClimGEN combines these change patterns with the observed climatology to yield patterns of mean absolute climate, and then combines them with observed time series of deviations from climatology to yield realisations of climate change with realistic year-to-year variability superimposed. It provides month-by-month climate variations for both observed climate from 1901 to 2015 (CRU TS 3.24) and future climate scenarios over 2001 to 2100, at a resolution of 0.5° latitude by 0.5° longitude, for the entire terrestrial land surface except Antarctica (Mitchell & Jones 2005). Climate fields can be generated for 7 terrestrial climate variables based on GCM outputs, specifically: mean, high and low temperature; precipitation (all presented here); and vapour pressure, cloud cover, and number of wet days (not included here). In the case of precipitation, ClimGEN takes account of projected change in the temporal distribution of precipitation as well as its magnitude; meaning that it captures the way that GCMs project that precipitation variability will change. This means that it can capture projected increases in drought for example (see Osborn et al. 2015 for more information, and Price et al. 2024 for a specific application for drought).

### **6.3.4. Climate Change Scenarios**

This project is based on analyses of alternative potential climate change outcomes associated with the 'Representative Concentration Pathways' (RCPs). RCPs are a set of four new radiative

forcing time-series (Figure 2) developed for the climate modelling community as the basis for long-term and near-term modelling experiments (van Vuuren et al., 2012): these scenarios cover the range from scenarios consistent with the 2°C goal to high emission futures. RCPs are expressed as 21<sup>st</sup> century time series of radiative forcing values and their key parameters are shown in Table A1 and Figure A1.

These scenarios do not span the entire range of potential climate change outcomes, but they do sample a wide range of outcomes that are considered to be plausible and are being widely used by the research community to explore climate change futures. The RCP with the lowest radiative forcing used here is RCP2.6 (Van Vuuren et al 2006, 2007) while the one with the highest forcing refers to a future without mitigation and encompasses rapid large increases in greenhouse gas concentrations (RCP8.5). However, it should be borne in mind that it is still possible that concentrations might exceed these levels, so the range of RCPs should not be taken as encompassing the complete range of future outcomes. This project did not look at what are known as ‘overshoot’ scenarios where global temperatures exceed a threshold for a period of time and then come back down. However, more recent work has shown that while the global temperature may recover, the patterns of change and the impacts on biodiversity are different than if the temperature is not exceeded (work in progress). For biodiversity and overshoot it is best to consider that biodiversity is most likely to be impacted by the highest temperature reached, not the recovery temperature, as dispersal rates for many species is low compared to the rate of change and recovery.

IPCC AR5 reported results from new climate and earth system models provided by CMIP5, the Coupled Model Inter-comparison Project Phase 5. CMIP5 included more than twice as many models as its predecessor (CMIP3), reported in the previous IPCC AR4 (Solomon et al. 2007). CMIP5 models featured a more comprehensive treatment of forcing agents, particularly with respect to aerosols and land use change. CMIP5 projections were driven by the four new RCPs, designed to achieve different targets for radiative forcing by 2100 relative to pre-industrial conditions (2.6, 4.5, 6.0. and 8.5 W/m<sup>2</sup>).

Global surface temperature change by the end of the 21st century is “likely to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5 (Figure 16). Warming will continue beyond 2100 under all RCP scenarios except RCP2.6” (IPCC, 2013, p.20). Across all four RCPs, global mean surface temperature rise relative to 1986-2005 is projected to likely be in the range 0.3 – 4.8°C. The likely range for RCP2.6 is 0.3-1.7°C whilst that for RCP8.5 is 2.6-4.8°C (AR5). Projected temperature rises relative to pre-industrial times (the baseline used in this project) are 0.6°C larger (because temperatures were 0.6°C lower in pre-industrial times than they were in 1986-2005).

*Table 1. Representative Concentration Pathways: year 2100 parameters*

	Radiative forcing (W/m <sup>2</sup> )	CO <sub>2</sub> equivalent concentration (ppm)	Rate of change in radiative forcing
RCP8.5	8.5	1350	Rising
RCP6.0	6.0	850	Stabilizing
RCP4.5	4.5	650	Stabilizing
RCP2.6	2.6	450	Declining

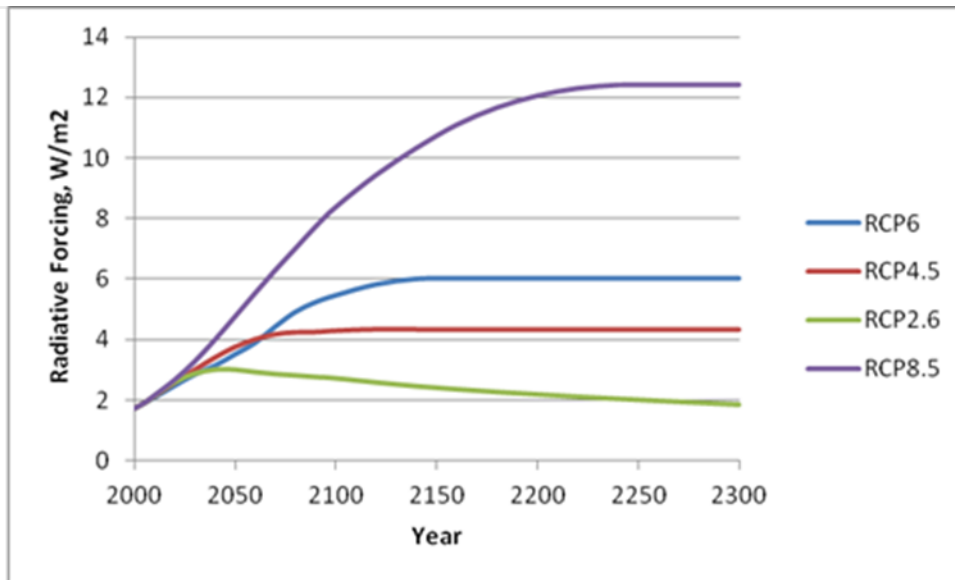


Figure 15. Radiative forcing time series in the Representative Concentration Pathways (RCPs).

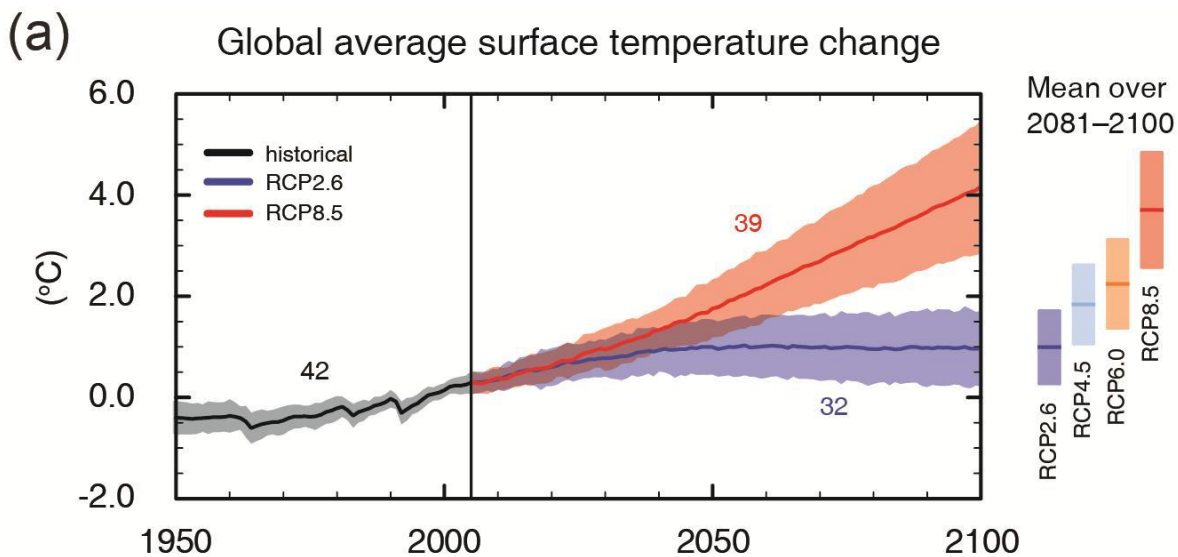


Figure 16. CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081-2100 are given. This figure has been reproduced from IPCC, 2015.

### 6.3.5. Information about Intended Nationally Determined Contributions (INDCs)

The INDCs are countries' post-2020 climate pledges, which largely describe emission mitigation plans to 2025 or 2030. Limiting global temperature rise depends also on emission trajectories after 2030 and so will depend on future NDCs. For example, the global emissions could stay constant after 2030; or they could be further reduced to (for example) meet a 2°C target.

Information about the INDCs was obtained from the AVOID2 project team of which author RW was a member as well as from other meta-analyses from other research groups. AVOID2 analyses explored the temperature outcomes found the warming of approximately 3°C above pre-industrial levels would ensue if INDCs were met but emissions were thereafter held constant (often referred to as a 'no backtracking' scenario). INDC and NDC analyses are expected to be published in 2016 on the AVOID2 website. A useful meta-analysis may be found at <http://buff.ly/1QIZIhe>, and provides a range of estimates from 2.7 to 3.7°C above pre-industrial

levels. In this study we look at 2.5°, 3° and 3.5°C warming levels (above pre-industrial) to capture this range and 4°C as a higher-level business as usual warming level.

### **6.3.6. Information about scenarios that limit warming to 2°C or below**

The AVOID, AVOID2, and subsequent projects concluded that it is “feasible yet challenging” to meet a target of 2°C above pre-industrial levels for warming. However, most scenarios in which global temperature rise remains below 2°C rely on negative-emissions technology, typically bioenergy with carbon capture and storage (BECCS). Here a bioenergy crop takes in carbon dioxide from the atmosphere (via photosynthesis); when the bioenergy crop is then combusted for energy, the resultant carbon emissions are then captured and stored in geological reservoirs and not re-emitted into the atmosphere. A recent study (Wiltshire and Davies-Barnard, 2015) estimated that the median BECCS requirement during the 21<sup>st</sup> century to achieve 2°C would be 166 Gigatonnes of Carbon (GtC) whilst the maximum feasible is 130 GtC (net sequestration accounting for land-use change emissions resulting from planting biofuels). Such extreme BECCS scenarios involve biofuel cropping of 18% of the land surface. This implies enormous associated land-use change and/or competition for land with food production, and potential destruction of ecosystems (Smith et al. 2018). Furthermore, some of these analyses are not life-cycle analyses factoring emissions from cropping and fuel manufacture. Current research is exploring how techniques such as ecosystem restoration, agricultural intensification, changes in dietary preferences, larger scale use of solar energy, or new novel technologies such as cultured meat or insect farms might constrain warming to 2°C above pre-industrial levels or even less.

### **6.3.7. Background information about the RCPs and the New Scenarios Process**

International assessments, such as the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic, N. et al., 2000) previously used self-consistent socio-economic scenarios (characterised by population, GDP, land use and energy use) and emission pathways over time. Four main types of scenarios were produced to which no probability of occurrence was attached. In these scenarios, there were two main ‘axes’ of change that were considered: (a) environmental versus economic and (b) a global versus regional. Hence the four scenarios may be briefly summarised as A1 (Global, economic); A2 (Regional, economic); B1 (Global, environmental); B2 (Regional, environmental). Each socio-economic scenario was thus associated with a particular climate change outcome.

A new process for deriving global scale scenarios, independent of the original SRES scenarios, was developed for use in the IPCC AR5 (and afterwards) (Moss et al. 2008, 2010) recognising that several different socio-economic pathways (Shared Socio-economic Pathways, SSPs) might have the same climate change outcome. The SRES scenarios have now been replaced by the RCPs and were used in the IPCC AR5 and new SSPs (van Vuuren et al., 2012, Kriegler et al. 2012, O’Neill et al 2015). The RCPs and the SSPs offer the potential to mix and match alternative combinations in a framework (a matrix) combining climate forcing on one axis and socio-economic conditions on the other (Table 2; Figure 17). Together, the two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated. The crosses represent combinations that can be explored by analysts. Some combinations of RCP and SSP will not be realistic (for example, conventional development will not be compatible with the RCP scenario with the smallest amount of climate change (RCP2.6).

Like the SRES scenarios, SSPs are narrative descriptions of how the world might evolve and are designed to span the following two dimensions shown in the lower panel of Figure 17: those increasing socio-economic challenges for mitigation (y-axis, such as high business-as-usual emissions and low mitigative capacity), and those increasing socioeconomic challenges for adaptation (x-axis, such as geographic factors (e.g. high coastal population densities), or socio-economic factors (e.g. poorly constructed housing). These dimensions do not have units, as they simply represent a qualitative notion or the ease of mitigation or adaptation, as described

in the narrative. For example, SSP1 describes a more sustainable path of inclusive development, respecting environmental boundaries, and with improved management of resources, effective cooperation at all levels, and low population: this means that the challenges to both mitigation and adaptation are greatly reduced. Five SSPs have now been created (Figure 17, after O’Neill et al. 2015). For example, if society were to become more sustainable (SSP1), challenges to both mitigation and adaptation would be reduced, whereas if it becomes more fragmented (SSP5), the challenges to both increase. The other scenarios reflect trends in society that would create larger or smaller challenges to adaptation or mitigation.

Table 2. Possible combinations of RCPs and SSPs

	Shared Socioeconomic Pathway				
RCP	SSP1	SSP2	SSP3	SSP4	SSP5
RCP2.6	x	x	-	x	-
RCP4.5	x	x	x	x	x
RCP6	x	x	x	x	x
RCP8.5	-	x	x	x	x

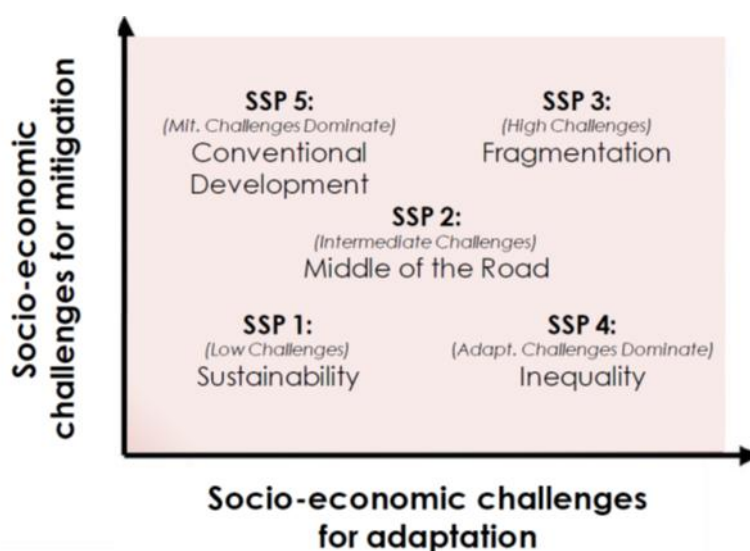


Figure 17. Shared Socioeconomic Pathways (SSPs; reproduced with permission from O’Neill et al., 2015)

## 6.4. Wallace Reports: Further information pertaining to biodiversity analyses

### 6.4.1. Refugia, adaptation, and scale of analysis

Mitigation and adaptation are often thought of as separate, but they are really two sides of the same coin. The easiest and cheapest adaptation is that which does not have to be done. The Wallace Initiative was designed to identify those areas most likely to remain climatically suitable for suites of species under varying levels of climate change. However, the classification of refugia is such that there could still be many species in a given area potentially impacted by climate change, or by interactions with species that are impacted by climate change. Even with mitigation there is some warming already embedded in the Earth system so adaptation, over and above business-as-usual conservation practices, will always be necessary. Furthermore, refugia are defined by changes in average climate conditions. The impacts on species to change in the average climate will play out over long periods of time, while extreme events can have large impacts in a single year. With increasing levels of warming, the exposure to many extreme events is likely to occur more often (see Figure Cross-Chapter Box Extremes.1 in IPCC AR6 Working Group II <https://www.ipcc.ch/report/ar6/wg2/figures/chapter-2/figure-2-cross-chapter-box-extremes-1>) for an illustration. Therefore, adaptation to climatic variability (extreme

events), and impacts tied to extreme events (e.g. fire frequency, flooding) will become increasingly necessary – even in refugia. Analyses of Wallace Initiative results helps to identify those areas where adaptation may just require good management practices PLUS adaptation to climatic variability/extremes, as well as those areas that will require increasing levels of adaptation over time (or where thresholds may very well be exceeded). With increasing levels of warming, in some areas, it may not be possible to adapt to maintain the same species – if the definition of adaptation is to try and maintain ecosystems as they are. However, one adaptation strategy is that it may be necessary to facilitate change – to accept, make possible, and facilitate one system transforming into another. This could include maintaining and developing corridors, restoring an area with species that would be expected to colonise given enough time, preserving environmental gradients, and differentiating between potential colonists (environmental refugees from their current climates) and true invasive species.

#### **6.4.2. Models and the *Precautionary Principle***

The question, then, is how should this be done? This is where the precautionary principle and developing ‘no regrets strategies’ come into play. Recognition of the role of climate in the distribution of species dates to at least 1807 (Essay on the Geography of Plants, Humboldt and Bonpland). There are several techniques used to assess the potential impacts of climate change on species. Many caveats are associated with using bioclimatic models, which are stated in this study. However, not all publications based on these models state the caveats. Separately, bioclimatic models need to be used with care and attention to setting of parameters (such as buffers, see below). Due to these issues, there have been a small number of publications that apply cautionary notes on the use of bioclimatic models, as there are with any statistical model. Some view these publications as being critical of the techniques (even though the authors have published extensively using the same techniques). The Wallace Initiative already took these cautions into account in the development of its models. Hence, the criticisms do not mean that the models are invalid, rather that models (any model) should not be used blindly, and that one must think carefully about the question one is trying to answer when using a modelling approach. Not understanding which criticisms are valid, or how to properly consider uncertainties in model outputs, can lead (and sometimes had led) to poor decisions as to the best practices for understanding how climate change may impact biodiversity. A meta-analysis of many different types of modelling techniques (Urban 2015), including traits-based analyses, showed that the different techniques yielded roughly similar results. IPCC AR6 (Parmesan et al. 2022) also goes into this and the data these reports and underpinning the work for PROVIDE are based on were used in many chapters of the IPCC AR6 Working Group II report. That biodiversity is being impacted by climate change and will increasingly be impacted in the future (Parmesan et al. 2022) should not be surprising given the long history of recognition of the relationships between ecosystems and climates.

There are many different modelling techniques that can be used to look at the potential impacts of climate change on biodiversity (or water, agriculture, etc.). For biodiversity, these include bioclimatic models, mechanistic models, and traits-based analysis. At best, models provide guidance or provide a hypothesis detailing what might happen under a given set of future climate changed conditions. Models, including bioclimatic models, are also scale dependent – both in terms of time and space.

Most bioclimatic models start from observed species distribution data, in our case from the Global Biodiversity Information Facility (GBIF 2015). The finer the resolution of the model, the more accurate the occurrence data needs to be. For example, a study trying to model species to a scale of 100m would need to ensure that all occurrence data had been collected and reported on with that accuracy, that the species home range was also less than 100m, and that the observed climate data had also been collected at that resolution. For global studies, the spatial accuracy of the occurrence data and availability of validated high-resolution observed climate data are key limitations to sub-10 km studies.



To develop these models, before any projection of future change is carried out, the models use one portion of species distribution data together with the corresponding observation climate data, to derive the way that climate constrains species' ranges. These 'draft' relationships are then used to 'predict' whether the model 'thinks' that the species will be present in the other half of its range, given the observations of the climate in that half. It is then possible to measure how well the model works based on this comparison. Ideally this should be repeated, or the model predictions then checked after a period of time has passed to see how well the model performed. By monitoring what happens in a given region, it would be possible to see how well a model has worked and whether the model assumptions are valid. To date, there have been few of these sorts of checks on biodiversity models, mostly owing to the scarcity of data collected consistently over time in many parts of the world. With more models and better monitoring then the models can better be validated over time. No model is perfect and there is no one best technique. Model output, especially when analysed for individual species, should be taken as a potential direction of change, indicating areas or species that may be more vulnerable or sensitive and which should then be monitored.

Even mechanistic models, based on physiology, are limited because the knowledge on the physiology or requirements of a given species varies over its range and different populations (and potentially with epigenetic changes). Even a species' habitat requirement can vary substantially depending on whether the population is in the core or edge of its range.

Most important in thinking about which modelling approach to use is to keep in mind that it is all about the question being asked and then constrained by the data available. Which model, or modelling technique, is best depends on the question. At a large scale, or looking at many species and range changes, many techniques yield similar results. For example, dynamic vegetation models (based largely on plant physiology) project that many of the same regions may be impacted by climate change as do bioclimatic models. Similarly, traits-based models for equivalent taxa (as a group) also show many of the same areas as being vulnerable to future climate change. It is not possible to do a direct one-to-one comparison with any of these techniques as modelling teams often use different baselines, spatial scales, climate models, etc. In contrast, a question about how a single species at a given place may respond to climate change will have an entirely different set of information that needs to be included in the model, and potentially a different set of modelling techniques, that are best.

It is not surprising that different modelling approaches yield similar patterns of impacts – all are based on similar underlying climate change projections. The models are just helping to identify which suite of climates may be more or less likely to impact different suites of species. It does not matter if a species is warm- or cold-blooded, all have physiologies, and are limited in some way by climate. As time goes by, some of the techniques are beginning to be blended – for example, there is ongoing work to merge bioclimatic models (to give exposure) with traits-based models (to give adaptive capacity and sensitivity). However, care need be taken even in these approaches to avoid circular thinking. For example, some authors consider a species found mostly in the canopy to be more exposed to the climate than those on the ground. Thus, terrestrial species are less exposed to the climate and perhaps have better adaptive capacity. The problem with this thinking is that the occurrence data for a species at a given point is based on the species being in its preferred zone. So, if it was a canopy species it was likely detected in the canopy, a terrestrial species on the ground. Thus, these differences are already in the models for the species as there is a relationship between the climate that is measured and the climate in the same area in the canopy and on the ground. As the climate changes, the climates in the canopy and on the ground will also change by equivalent percentages.

Almost all model estimates are likely to be conservative, owing to processes not included in the models that, overall, tend to underestimate projected impacts. A key factor omitted from many models is the effect of extreme events (e.g., floods, seasonal droughts, heatwaves, fire risk), all of which are generally projected to increase in frequency and intensity with climate change.

This is important because species do not experience the mean climate – they experience a series of changing extreme events around the mean. As the climate changes, what was once an unusual climate (e.g., 2 standard deviations from the mean) becomes the new mean (often by 2° - 2.5°C warming) and the extremes become more extreme. This is what would likely cause local extinctions and for the local extinction to happen earlier than the models project. This is particularly important because climate change increases climate variability disproportionately compared to the mean (that is, if for example, the mean summer climate in a place becomes 2°C warmer locally, the heatwaves are likely to be more than 2°C warmer than previously experienced, and they are likely to happen more often). Whether species can recover or not from extreme events depends on how quickly the climate returns to ‘normal’ or how often the event in question occurs. In the few cases where extreme events, or adequate time series, have been included in a bioclimatic modelling study, the projected impacts were modelled to occur much earlier than models based on changes in the mean. While certain traits may make some individual species more resilient to climate change (and research is just beginning to really tease out what these traits are), the lack of inclusion of extreme events suggests that many species may be more sensitive than once thought (McDermott Long et al. 2018). Another key factor omitted is the tendency for changes, often increases, in the ranges of pests and diseases as the climate warms. These pests and diseases then impact on biodiversity and this is not included in the bioclimatic models. Even mechanistic models, based on physiology, that run at daily or yearly time steps often do not include disturbances such as pests and fire.

What this means, in terms of natural resource and conservation planning, is that the **“best” approach needs to combine a no-regrets conservation strategy with the precautionary principle**. No-regrets management means that an action is taken that should benefit biodiversity no matter what happens (only possible up to a point). The precautionary principle would then guide planners and practitioners to consider the information the climate change and bioclimatic models are providing and to use them to guide their activities, whilst also not blindly trusting the projections. This allows a decision maker to take the information from one or more sources (modelling and other sources) and to then use their expert judgement to make the best decision. A key message is that owing to the uncertainty in model projections, it can be helpful to retain flexibility in the decision-making process, so that the decision can be re-visited (adaptive management) as more data or monitoring information comes to light. However, it is important to avoid ‘uncertainty paralysis’ by doing nothing. This allows decisions to be revised as (a) scientific information improves, perhaps allowing more confident regional projections of precipitation to be made and/or (b) monitoring of the effects that climate change is having in an area confirms, or opposes, the effects projected by the models. This concept of adaptive, iterative management is well established in the literature pertaining to adaptation of human systems to climate change. In these situations, it is important to avoid locking into a decision that would not be robust for some of the projected climate change outcomes. So, combining these two activities would suggest that, all things being equal, a given conservation action that would normally be considered as successful, performed in an area projected to be a refugia, would be a better decision than performing the same activity in an area projected to be an area of concern. The biodiversity may be the same in both locations; the models are just helping guide long-term actions when resources are limited.

### 6.4.3. The Wallace Initiative

The Wallace Initiative was designed to bring together experts in bioclimatic modelling and statistics, climate change modelling, and high-performance computing facilities to look at the potential impacts of climate change on biodiversity. The goal of the Wallace Initiative was to look at patterns of change, specifically to identify: (1) where refugia from climate change are projected to be, (2) where areas of concern are projected to be and (3) how the percentage of species projected to lose more than 50% of their range varies over time and across space (Warren et al. 2013, 2018a, 2018b).

Wallace Initiative Phase I looked at ~50,000, and Phase II at ~80,000 terrestrial plant, bird, reptile, mammal, and amphibian species. Phase III added in invertebrates and fungi to bring the total to ~135,000 species. Each species was modelled independently and all discussions of changes in species richness are based on summing the relevant independent models. The spatial scale of Phase I was ~50km x 50 km while it was ~20 km x 20km in phases II and III. Phases II and III used 21 climate model patterns for temperatures ranging from 1.5° to 6°C above pre-industrial. Results have been tested repeatedly using several resampling techniques and the patterns of change have been found to be robust (even across different generations of climate models). Furthermore, we examine the spatial implications of the projected range losses by mapping out areas that tend to retain most of the species currently present (refugia). As in most similar work, issues such as cross-species interactions and effects of extreme weather events are not included and thus the projections are underestimates of the potential impacts.

This report draws from the full suite of Wallace Initiative Phase III data. These outputs include changes in species richness, changes in climatic range sizes for individual species, areas likely to be refugia (i.e. remain climatically suitable for >75% of the species currently present), and areas likely to be areas of concern (i.e. those that become climatically unsuitable for >75% of the species currently present). These are based on assessments of species for which distribution data is available, and the analysis is carried out in each of thousands of 20x20 km cells. The information exists for a range of policy (i.e. emission) scenarios, ranging from no action on climate change, to very stringent action to mitigate it.

Details on the methodology used can be found in Warren et al. 2013 (especially the supplemental material), 2018a and 2018b. The analyses draw on data sourced from the Global Biodiversity Information Facility (GBIF 2015). GBIF facilitates discovery of data from many datasets worldwide, including newer efforts such as eBird (Cornell Laboratory of Ornithology, ebird.org). Many of the gaps and/or outliers in available data in Phase I were eliminated in Phase II and the overall coverage in many areas is improved. Furthermore, the parameters used in the models are such that the outliers have no impact on the models in the area where a species is naturally found. While there are still some gaps in the available data, GBIF provides a source allowing researchers to identify potential patterns of change across the widest range of species and areas possible. The data were then checked for locational consistency and outliers (Warren et al. 2013).

#### **6.4.4. Limitations of species distribution modelling**

Species distribution modelling is a common tool for gaining ecological and evolutionary insight into how species are distributed across a landscape, and how this may change in space and time. The models build statistical relationships between species occurrences and environmental data, assuming that where a species occurs provides useful information on the species' physiological and ecological requirements. The assumptions and limitations of species distribution modelling have been largely reviewed in the literature (e.g. Elith and Leathwick 2009 and references therein). Common to species distribution modelling exercises are several assumptions, including that the observations for each species represent the full environmental range of the species; that there is little-to-no bias in observations; and that background selection excludes areas that have not been searched. We sought to minimize potential violation of these assumptions by: i) using the most robust global data for species observations (GBIF 2015) to represent the full range of species at the time; ii) reducing biases associated with spatial aggregation of observations by using only a single observation record per ~10 km pixel for model training (removing potential for high bias in prevalence); and iii) selecting background points from biogeographic realms appropriate to observed species records.

#### **Other factors of potential importance in our analysis**

Our findings result from the most comprehensive global analysis to date of projected losses in the climatic ranges of plants and animals; nevertheless, we were unable to consider all factors

of potential importance in our analysis. Many factors could lead to either under- or overestimation of potential climatic range shifts (Dormann 2007). For example, it is unclear how and to what extent species might utilise novel climates (especially through epigenetic changes), as they need to be able to disperse to them and, furthermore, it is highly likely that some species' reshuffling will occur resulting in undesirable non-analogue communities (Williams and Jackson 2007). New analyses are underway to look at a new combination that considers species arriving, species leaving, and species remaining in a given cell to measure the extent a given area may become a non-analogue community (ZOE index discussed in the introduction). Changes in the severity of extremes of atmospheric weather and climate variables, such as temperature and precipitation extremes, might exceed the survivability thresholds of some species before the mean climate becomes unsuitable (Welbergen et al. 2008; McDermott Long et al 2018). Changes in fire regimes, while not considered directly, are included indirectly as fire frequency is also strongly related to bioclimatic variables (Krawchuk et al. 2009) and can potentially lead to major changes in biodiversity. There is an expectation that, overall, there will be more increases than decreases in extreme events (Meehl et al. 2007) with concomitant negative impacts on biodiversity.

The direct biotic effects of increases in CO<sub>2</sub> concentrations (e.g. earlier stomatal closing, protein or phytochemical changes leading to increases/decreases in herbivory, water use) were not included as it would not be practical in a large-scale study such as this. Similarly, the potential effects of biotic interactions, such as climate-change-mediated decoupling of trophic levels or of mutualistic relationships (e.g. Memmot et al. 2007; Visser et al. 1998) or the potential spread of various disease vectors, pathogens and invasive species might also impact species but were also not included here. To some extent, the overall Wallace Initiative database can be used for specific studies on such effects, something that has hitherto been difficult to accomplish.

While species might persist in suitable microclimates (e.g. at higher elevations, protected microhabitats) within areas otherwise apparently climatically unsuitable at a large scale, their overall range would still be smaller than current. Similarly, species might be absent from apparently climatically suitable areas due to unsuitable microclimates. Thus, over the entire range of the species we would expect these two opposing effects to potentially cancel out, especially for more broadly distributed species. While a 1km buffer surface was provided for the climate, no attempt was made to do the same for INDIVIDUAL species. There are several reasons for this:

- 1) Computational - it took 1 million hours of CPU time and 1 Petabyte of hard disk storage to perform the analyses at 20km. Going to 10 km increases this 4x; 5km, by 16x and 1km, by 200x.
- 2) Spatially - as mentioned above the higher the resolution the more accurate the occurrence data must be for each of the 135,000 species. Also, the match between daily movements in the home range of the species and the scale at which the relationship has been modelled. Generally, the higher the resolution of the spatial data the finer the resolution of temporal data is needed.
- 3) Climatologically - there are limits to interpolation based on the number of weather stations, and this is true even for reanalysis datasets. The developer of thin-plate spline smoothing, one of the commonly used interpolation techniques, recommends that it be applied at levels no finer than 10km unless there are many weather stations (pers. comm.). There are newer climate grids based on remote sensing data that eliminate some of the issues of interpolation but these usually span a more recent period of time meaning that a greater amount of climate change will have already occurred, making it more difficult to use them as a baseline. The two main issues are around proper classification and measurement of precipitation in areas of high topography (e.g., separating clouds and virga from actual rainfall) and proper measurement of dew point to adequately calculate the adiabatic lapse rate for the temperature estimation.
- 4) Climate change anomaly application – GCMs run at scales more on the order of >100 km (2° latitude and longitude) rather than <20 km. Even regional climate models tend to be more on the scale of 50 km. Downscaling to the underlying resolution of the observed climate is an

approach but there remain the issues specified in #3 above plus issues around potential changes in wind speed and direction (impacting precipitation in high topography regions, especially near coasts) as well as changes in dew point.

5) Psychological – a map is often seen as reality, so the higher the resolution the more ‘real’ people think it is. There are ways of trying to improve estimates of change at higher resolution that get around many of the issues above, and that is simply to say that x% of an area, without specifying WHERE in a protected area it is, is a refugia at the higher resolution. Guidance can even be given as to the types of areas this might be. However, maps at this fine of scale, unless the issues addressed above have been dealt with, can be misleading to the point of maladaptation strategies (e.g., if an area is identified as being cooler than it actually is owing to a misapplication of lapse rate or improper calculations of precipitation changes).

#### **6.4.5. Elevational Downscaling**

As a compromise to the issues outlined above, we used the average adiabatic lapse rate to provide elevational downscaling to help determine where changes in species richness might be more resilient (smaller changes) or more exposed (larger changes). Elevational downscaling takes into account the physical parameter of adiabatic lapse rate. The modelled data, be they 50km or 20km (or even 1 km) are an average of all the temperatures (and underlying elevations) within that ‘cell’ or ‘pixel’. In other words, if you have a weather station measuring data at 1000m then local areas higher than this will be cooler and areas lower than this will be warmer. This relationship is modified by local vapour pressure (how much water the atmosphere can hold) but the overall relationship would remain approximately the same with warming. This would especially be expected to hold in reference to the average and the surrounding points (as changes in vapour pressure would likely apply over the ‘cell’).

To elevationally downscale the summary biodiversity data (species richness remaining, refugia, adaptation effort; but not the individual species models) a curve was fit through each species group and each cell to determine how much change there was per increment of temperature (warming or cooling). These curves were then applied to the difference between the 20km climate (annual average temperature) and the equivalent 1km climate. In warmer areas the impacts would increase, and the impacts would decrease in cooler (higher) areas. The best way of thinking about this is the difference is a difference in the ability of a species to persist at a scale of 1km owing to differences in temperature.

#### **6.4.6. Use of climatic buffers (micro or meso-climatic refugia) and limitations**

As stated earlier, the climate data used might be considered coarse (~50km x 50km), but it is a commonly accepted resolution for climate change data. There are some scientists who think that even this level of downscaling may be too high for GCM data but many others who accept it. The Helix project tested downscaled climate change model data versus ‘high-resolution’ regional climate model data (both at the same ~50 km scale) and found they produced similar results in impact models. While higher resolution data are theoretically available, that does not mean it is accurate. There are limitations tied to the underlying

observed climate data, the ability of GCMs to adequately portray areas of high topography, etc.

The data sets used here use a form of interpolation to calculate a grid of climate values based on actual observations. There are limitations with all interpolative techniques, but the key underlying point is one of how much data it is based on. In parts of the world with many weather stations the grid will be better than in areas with few. Nevertheless, there is a relationship between elevation and temperature that can be approximated to provide additional information as to how elevation might ‘buffer’ the overall climate in a cell (and this is used in both techniques). This is not a simple relationship, and it varies depending on the amount of water vapour in the air (adiabatic lapse rate). For example, the same elevation on the two sides of a mountain will usually not have the same temperature as one side of the mountain will be

moister and one drier. The smaller (finer) the spatial scale, the more information is required to accurately calculate something like micro-refugia (Suggitt et al. 2017). So, while elevation data is available at very fine scales (e.g., 5m – 30m) at that scale the relationship with elevation, as well as the slope and aspect of the surface, can all make a substantial difference. The finer the resolution of the elevation data, the more accurate the data on species occurrences needs to be, yet some species' home ranges may be large (i.e., hundreds – thousands of meters) so would then potentially span many different cells during a day. This means that there needs to be a temporal match of the occurrence data to the climate data to capture how these differences accrue over space AND time. Thus, while it may be possible to model how a single individual of a species, or possibly even a single population relates to climate, it is not possible to apply the same level of detail to a very large number of species across the globe.

For these reasons, at this time, we are limiting the buffering surface to ~1km x 1km and annual temperature. Precipitation generally follows temperature (or elevation) in these cases, so we have not provided a different buffering surface for precipitation.

Analyses of paleoecological data (and current observations) showed that the response of many species to past climatic changes has been range shifts. Based on this, recent work has projected major disruptions to ecosystems in the future (yet a different technique than mentioned above; Nolan et al 2018). Nevertheless, there may be the potential for genetic variability (especially epigenetic) that might provide adaptive potential for some species, especially less mobile ones that have been exposed to large climate changes in the past. Although the magnitude of this potential is unknown, it is likely to be limited given the rate with which anthropogenic climate change is expected to proceed.

#### **6.4.7. Interactions**

While there have now been several attempts to include species traits in assessments of sensitivity and vulnerability of biodiversity to climate change the same cannot be said of interactions. In large part this is owing to incomplete data on dependencies of species on each other (for example predator-prey, pollinator, seed disperser, etc.) over the entire range of a species. It is true that some individual species are dependent on some specific individual other species (e.g., mutualistic species), but others may be able to shift their diets. Even habitat specificity can vary in the same species in different parts of its range. At the level of entire taxa, such analyses are not only currently not possible, but may never be possible, at least for entire food webs. Some assumptions can possibly be safely made that large impacts on plants will have some additional impacts on birds, mammals, reptiles and amphibians; and the number of nectar producing plants (e.g., largely in the class Magnoliophyta) has been used a proxy for pollinators, but exact quantification of this impact is currently not possible.

### **6.5. Literature Cited**

Bernie, D., and Lowe J. 2014. Future temperature responses based on IPCC and other existing emissions scenarios. AVOID2 WPA.1 Report 1.

Climatic Research Unit (University of East Anglia) and Met Office. CRU TS 4.07.

Dormann, C. F. 2007. Promising the future? Global change projections of species distributions. *Basic and Applied Ecology* 8, 387-397.

Elith, J. & Leathwick, J. R. 2009. Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* 40, 677-697.

ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land\_Cover\_cci): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis, date of citation. <https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c>

Friedlingstein, P. et al. 2006. Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate* 19, 3337-3353.

Gao, J., 2017. Downscaling Global Spatial Population Projections from 1/8-degree to 1-km Grid Cells. NCAR Technical Note NCAR/TN-537+STR, DOI: 10.5065/D60Z721H.

Gao, J. 2020. Global 1-km Downscaled Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways, Revision 01. Palisades, New York: NASA Socioeconomic Data and Applications Center (SEDAC). <https://doi.org/10.7927/q7z9-9r69>. Originally accessed from NCAR in 2017.

GBIF.org (May 2015). GBIF Occurrence Download. <https://doi.org/10.15468/dl.kecdhx>

Gohar, L., S. Raper and J. Lowe. Reducing the uncertainty in simple model projections. AVOID Report 25.

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, G.-K., Plattner, M., Tignor, S.K., Allen, J., Boschung, J., Nauelis, A., Xia, Y., Bex V., and Midgley P.M. (eds.)] Cambridge University Press, Cambridge, UK and New York, NY, USA, 1535 pp

Jenkins RLM, Warren RF, Price JT (2021) Addressing risks to biodiversity arising from a changing climate: The need for ecosystem restoration in the Tana River Basin, Kenya. PLoS ONE 16(7): e0254879. <https://doi.org/10.1371/journal.pone.0254879>

Jones B, O'Neill BC (2016) Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environ Res Lett 11:084003

Jones, B., and B.C. O'Neill. 2016. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environmental Research Letters 11, 084003.

Krawchuk, M. A., Moritz, M. A., Parisien, M. A., Van Dorn, J. & Hayhoe, K. 2009. Global pyrogeography: the current and future distribution of wildfire. Plos One 4, e5102.

Kriegler, E., O'Neill, B.C., Hallegate, S., Kram, T., Lempert, R., Moss, R., Wilbanks, T. 2012. The need for and use of socioeconomic scenarios for climate change analysis: A new approach based on shared socioeconomic pathways. Global Environmental Change 22, 807-822.

McDermott Long, O., R. Warren, J. Price, T.M. Brereton, M.S. Botham, and A.A. Franco. 2017. Sensitivity of UK butterflies to local climate extremes: which life stages are most at risk? J Animal Ecology 86(1): 108-116.

Meehl, G. A. et al. 2007. Global climate projections. In: Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Mitchell, T. D. & Jones, P. D. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25, 693-712.

Moss, R.H. et al. 2008. Towards New Scenarios for the Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Intergovernmental Panel on Climate Change, Geneva, 132 pp.

Moss, R.H., et al. 2010. The next generation of scenarios for climate change research and assessment. Nature 463: 747-756 doi:10.1038/nature08823

Nakicenovich et al. 2000. IPCC Special Report on Emissions Scenarios (SRES) Cambridge University Press, UK

Nolan, C. et al. 2018. Past and future global transformation of terrestrial ecosystems under climate change. Science 361, 920-923.

O'Neill, B., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., and Solecki, W. 2015. The roads ahead: Narratives for shared

socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* 42, 169-180.

Osborn TJ, Wallace CJ, Harris IC, Melvin TM (2016) Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. *Clim Chang* 134:353–369. 10/f795rk

Price, J., Warren, R., Forstnhäusler, N. et al. 2022. Quantification of meteorological drought risks between 1.5 °C and 4 °C of global warming in six countries. *Climatic Change* 174, 12. <https://doi.org/10.1007/s10584-022-03359-2>

Price, J., R. Warren, and N. Forstnhäusler. 2024a. Biodiversity losses associated with global warming of 1.5 to 4 °C above pre-industrial levels in six countries. *Climatic Change* 177(47). <https://doi.org/10.1007/s10584-023-03666-2>

Price, J., R. Warren, N. Forstnhäusler, R. Jenkins, and E. Graham. 2024b. Assessing the potential risks of climate change on the natural capital of six countries resulting from global warming of 1.5 to 4 °C above pre-industrial levels. *Climatic Change* 177, 46. <https://doi.org/10.1007/s10584-023-03650-w>

Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. Crespo Cuaresma, Samir KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42: 153-168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>.

Rogel, J., M. Meinshausen, R. Knutti. 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change* 2, 248–253.

Saunders, SP, J Grand, BL Bateman, M Meek, CB Wilsey, N Forstnhäusler, E Graham, R Warren, and J Price. 2023. Integrating climate-change refugia into 30 by 30 conservation planning in North America. *Frontiers in Ecology and the Environment* 21(2). <https://doi.org/10.1002/fee.2592>

Smith P., J. Price, A. Molotoks, R. Warren, and Y Malhi. 2018. Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Phil. Trans. R. Soc. A*.3762016045620160456. <http://doi.org/10.1098/rsta.2016.0456>

Solomon S et al (eds). 2007. *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Suggitt, A.J., et al. Conducting robust ecological analyses with climate data. *Oikos*. DOI: 10.1111/oik.04203.

UNEP-WCMC and IUCN (2024), *Protected Planet: The World Database on Protected Areas (WDPA)* [Online], March 2024, Cambridge, UK: UNEP-WCMC and IUCN. Available at: [www.protectedplanet.net](http://www.protectedplanet.net).

Urban, M.C. 2015. Accelerating extinction risk from climate change. *Science*, 348(6234), 571-573.

Van Vuuren, D.P.; Kok, M.T.J.; Girod, B.; Lucas, P.L.; Vries, B.J.M. de. 2012. Scenarios in global environmental assessments: key characteristics and lessons for future use. *Global Environmental Change*, 22, 884 – 895

Van Vuuren, D. P., Eickhout, B., Lucas, P. L. & den Elzen, M. G. J. 2006. Long-term multi-gas scenarios to stabilise radiative forcing — Exploring costs and benefits within an integrated assessment framework. *Multigas mitigation and climate policy. The Energy Journal* 3 (Special Issue), 201–234

Van Vuuren, D., M. den Elzen, P. Lucas, B. Eickhout, B. Strengers, B. van Ruijven, S. Wonink, R. van Houdt. 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change* 81, 119-159



Visser, M. E., van Noordwijk, A. J., Tinbergen, J. M. & Lessells, C. M. 1998. Warmer springs lead to mistimed reproduction in great tits (*Parus major*). *P Roy Soc B-Biol Sci* 265, 1867-1870.

Warren, R, S de la Nava Santos, NW Arnell, M Bane, T Barker, C Barton, R Ford, H-M Füßel, R Hankin, R Klein, C Linstead, J Kohler, TD Mitchell, TJ Osborn, H Pan, SCB Raper, G Riley, HJ Schellnhüber, S Winne, D Anderson. 2008. Development and illustrative outputs of the Community Integrated Assessment System (CIAS), a multi-institutional modular integrated assessment approach for modelling climate change. *Environmental Modelling & Software*

23(5): 592-610. <https://doi.org/10.1016/j.envsoft.2007.09.002>

Warren, R., VanDerWal, J., Price, J. *et al.* 2013. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Clim Change* 3, 678–682 (2013). <https://doi.org/10.1038/nclimate1887>

Warren, R., Price, J., VanDerWal, J. *et al.* 2018a. The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change* 147, 395–409. <https://doi.org/10.1007/s10584-018-2158-6>

Warren, R., *et al.* 2018b. The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science* 360, 791-795. DOI:10.1126/science.aar3646

Welbergen, J. A., Klose, S. M., Markus, N. & Eby, P. 2008. Climate change and the effects of temperature extremes on Australian flying-foxes. *P Roy Soc B-Biol Sci* 275, 419-425.

Wilby, R., & Wigley, T.M.L. 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21, 530-548

Williams, J. W. & Jackson, S. T. 2007. Novel climates, no-analog communities, and ecological surprises. *Front Ecol Environ* 5, 475-482.

Wiltshire, A., and Davies-Barnard, T. 2015. Planetary Limits to BECCS Negative Emissions. 1104872 / AVOID 2 WPD.2a Report 1.

## 6.6. Wallace Reports in Zenodo

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Etosha National Park, Namibia under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12760817>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for uMngeni Plateau Nature Reserve, South Africa under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11233738>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Ngorongoro Conservation Area, Tanzania under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11384439>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Serengeti National Park, Tanzania under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11450468>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Monte Verde Cloud Forest Reserve, Costa Rica under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11477291>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Yosemite National Park, California, U.S. under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11576809>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Shenandoah National Park, Virginia, U.S. under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11622544>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Acadia National Park, Maine, U.S. under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11638872>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Banff National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11640934>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Wood Buffalo National Park, Alberta/Northwest Territories, Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.11658151>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Necedah National Wildlife Refuge, Wisconsin under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12087617>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Aransas National Wildlife Refuge, Texas, U.S. under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12100229>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Kruger National Park, South Africa under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12162531>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Yellowstone National Park, U.S. under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12207406>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Bwindi Impenetrable National Park, Uganda under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12665165>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Virunga National Park, DRC under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12666217>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Volcanoes National Park, Rwanda under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12666571>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Mgahinga Gorilla National park, Uganda under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12666771>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Cairngorms National Park, Scotland under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12666955>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Big Bend National Park, Texas under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12667438>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Okapi Wildlife Reserve, Democratic Republic of Congo under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12706114>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Jau National Park, Brazil under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12706755>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Waterton Lakes National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12707111>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Gros Morne National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12745402>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Yoho National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12745618>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Gaspésie National Park (Québec) under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12750257>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Grasslands National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12750608>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Cape Breton Highlands National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12750764>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Bruce Peninsula National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12750918>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Hwange National Park, Zimbabwe under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12760624>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Chobe National Park, Botswana under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12760312>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Mont-Tremblant National Park, Québec under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12759281>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Riding Mountain National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12752216>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Jasper National Park of Canada under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12752130>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for Tarangire National Park, Tanzania under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12752080>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for the Okavango Delta, Botswana under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12751957>

Price, J., Forstehäusler, N., Graham, E., Osborn, T. J., & Warren, R. (2024). Report on the observed climate, projected climate, and projected biodiversity changes for The Broads National Park, UK under differing levels of warming. Zenodo. <https://doi.org/10.5281/zenodo.12751789>