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Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss

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Climate change is expected to have significant influences on terrestrial biodiversity at all system levels, including species-level reductions in range size and abundance, especially amongst endemic species[1–6]. However, little is known about how mitigation of greenhouse gas emissions could reduce biodiversity impacts, particularly amongst common and widespread species. Our global analysis of future climatic range change of common and widespread species shows that without mitigation, 57 ± 6% of plants and 34 ± 7%of animals are likely to lose ≥50% of their present climatic range by the 2080s. With mitigation, however, losses are reduced by 60% if emissions peak in 2016 or 40% if emissions peak in 2030. Thus, our analyses indicate that without mitigation, large range contractions can be expected even amongst common and widespread species, amounting to a substantial global reduction in biodiversity and ecosystem services by the end of this century. Prompt and stringent mitigation, on the other hand, could substantially reduce range losses and buy up to four decades for climate change adaptation.

The Intergovernmental Panel on Climate Change[3] (IPCC) estimates that 20–30% of species would be at increasingly high risk of extinction if global temperature rise exceeds 2–3 °C above pre-industrial levels. However, as quantitative assessments of the benefits of mitigation in avoiding biodiversity loss are lacking, we know little about how much of the impacts can be offset by reductions in greenhouse gas emissions. Furthermore, despite the large number of studies addressing extinction risks in particular species groups, we know little about the broader issue of potential range loss in common and widespread species, which is of serious concern as even small declines in such species can significantly disrupt ecosystem structure, function and services[7].

Here we quantify the benefits of mitigation in terms of reduced climatic range losses in common and widespread species, and determine the time early mitigation action can buy for adaptation. In particular, we provide a comprehensive analysis of potential climatic range changes for 48,786 animal and plant species across the globe, using the same set of global climate change scenarios for all species; and a direct comparison of projected levels of potential climate change impacts on the climatic ranges of species in six twenty-first-century mitigation scenarios, including a no-policy baseline scenario in which emissions continue to rise unabated (Fig. 1, Table 1). To calculate the climatic range changes, we employed MaxEnt, one of the most robust bioclimatic modelling approaches especially for cases where only presence data (as opposed to presence–absence) are available[8]. MaxEnt models the probability of a species' presence, conditioned on environment[8] so that in this paper climatic range change specifically refers to the change in the modelled probability of a species' occurrence, conditioned on climatic variables. Eighty per cent of the species studied have climatic ranges in excess of 30,000 km^2, which is the range size used by Bird Life International to delineate restricted-range species, whereas less than 7% have ranges occupying less than 20,000 km^2 (Supplementary Fig. S1). Our study therefore focuses on quantifying the effects on widespread species, which are in general more common and less likely to become extinct than restricted-range species[9], in contrast to previous studies that have only speculated that there may be effects on such species[1–6]. In projecting future distributions, we use three class-specific long-term average dispersal scenarios (zero, realistic and optimistic). These scenarios are based on the available literature and specifically refer to the rates at which species' ranges, through an average of individual dispersal events (colonization and extirpation), shift over time (Supplementary Table S1 and Supplementary Methods).

With no mitigation, the median global annual mean temperature change reaches 4 °C above pre-industrial levels by 2100 (Fig. 1, Table 1, A1B baseline scenario). Even with realistic dispersal rates, 34 ± 7% of the animals, and 57 ± 6% of the plants, lose 50% or more of their climatic range by the 2080s (Table 1, Fig. 2). Here, the standard deviation arises from the use of different general circulation model (GCM) patterns for downscaling (see Methods). With no long-term dispersal (also reflecting the potential for barriers to inhibit realistic dispersal), 42 ± 7% of the animals lose 50% or more of their climatic range, whereas the figures for plants remain unchanged owing to their lower dispersal rates (Table 1). The projected climatic range losses under these realistic long-term dispersal assumptions demonstrate clearly that climate change would have an impact even on more widespread species in addition to the species with restricted ranges that have been the main focus of previous studies[3,10]. These projected losses are not offset by the very small percentage of species projected to gain more than 50% of their climatic range with realistic dispersal rates (4%

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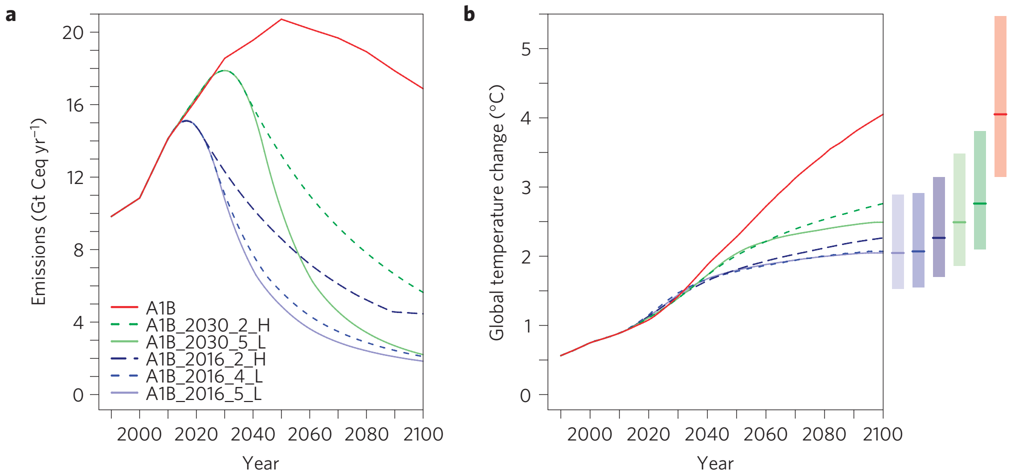

Figure 1 | Global greenhouse gas emissions and temperature rise in the AVOID scenarios. a,**b**, Global greenhouse gas emissions (in gigatonnes of carbon equivalent per year, Gt C eq yr^{-1}; **a**) and projected annual global mean near-surface temperature rise in the AVOID scenarios (**b**), labelled A1B-xxxx-y-z, where xxxx refers to the year during which global greenhouse gas emissions peak, y refers to the rate (% yr^{-1}) at which emissions subsequently decline, and z refers to whether the final emissions floor level is set to high (H) or low (L). The key in **a** also applies to **b**. The shaded bars provide a 10–90% range for temperature rise, and the solid lines indicate the median values. (see Supplementary Information for details).

Table 1 | Proportions of plants and animals losing ≥50% of their present range owing to climate change alone by the 2080s in the various emissions scenarios under no dispersal (ND), realistic dispersal (RD) or optimistic dispersal (OD).

	Baseline A1B	Mitigation 2030-2-H	Mitigation 2030-5-L	Mitigation 2016-2-H	Mitigation 2016-4-L	Mitigation 2016-5-L
Most likely global mean temperature rise by 2100 (°C)	4.0	2.8	2.5	2.2	2.0	2.0
Probability of constraining the temperature rise to 2 °C above pre-industrial levels	<1%	7%	17%	30%	44%	45%
Proportions of plants and animals losing 50% or more of their present range:						
Animals (ND)	42% (35–49%)	25% (20–30%)	23% (18–28%)	13% (10–16%)	12% (9–15%)	12% (9–15%)
Animals (RD)	34% (27–41%)	21% (17–25%)	18% (14–22%)	15% (12–18%)	13% (10–16%)	13% (10–16%)
Animals (OD)	32% (25–39%)	19% (15–23%)	17% (13–21%)	15% (12–18%)	12% (9–15%)	12% (9–15%)
Plants (ND)	57% (51–63%)	36% (31–41%)	36% (31–41%)	33% (28–38%)	24% (20–28%)	23% (19–27%)
Plants (RD)	57% (51–63%)	36% (31–41%)	33% (28–38%)	33% (28–38%)	24% (20–28%)	23% (19–27%)
Plants (OD)	53% (47–59%)	34% (29–29%)	30% (26–34%)	25% (21–29%)	22% (18–26%)	22% (18–26%)

Ranges show variation arising from use of seven different GCM patterns for creating downscaled climate projections.

of the animals and none of the plants; Supplementary Table S3), indicating that on balance the projected impacts of climate change overwhelmingly result in a sizable reduction of climatically suitable ranges for a large number of species.

With mitigation (that is, global emissions peak in 2016–2030 and are subsequently reduced by 2–5% annually; Fig. 1, Table 1), median global annual mean temperature rise is limited to 2.0–2.8 °C with a 7–45% likelihood that it will be constrained to 2 °C above pre-industrial levels. The highest emission reduction rates considered in most integrated modelling studies that attempt to minimize mitigation cost are typically between 3 and 4% (ref. 11), although other studies highlight that for an extra cost slightly higher rates of up to 5% may be achievable[12]. Hence, the most stringent mitigation scenario considered here allows global emissions to peak in 2016 and to be subsequently reduced by 5% annually (Fig. 1, Table 1). In this scenario, with realistic dispersal rates, the proportion of species losing at least half of their climatic range by the 2080s falls from 34 ± 7% to 13 ± 3% in animals, and from 57 ± 6% to 23 ± 4% in plants (Table 1), thus avoiding ∼60% of the potential impacts with smaller benefits accruing by the 2050s (Fig. 2). If mitigation is delayed (that is, global emissions peak in 2030 and are then reduced at 5% annually), cumulative emissions during the twenty-first century rise correspondingly. In this case, substantially fewer climatic range contractions are avoided (Table 1, Fig. 2). With these mitigation delays, the proportion of animals losing at least half of their climatic range rises from 13 ± 3% to 20 ± 6%, and the proportion of plants rises from 23 ± 4% to 35 ± 6% with realistic dispersal (Table 1, Fig. 2), thus reducing climatic range losses by only ∼40% relative to the baseline.

These patterns and trends are also observed in the individual animal taxa (Fig. 2), under all dispersal scenarios (Supplementary Fig. S2a–f), as well as in the proportions of species losing >=70%, >=90% or >=99% of their climatic ranges (Supplementary Table S4a–c). Plants, amphibians and reptiles would be expected to be more at risk from climate change owing to their lower long-term dispersal rates relative to the velocity of climate change[13]. Consistent

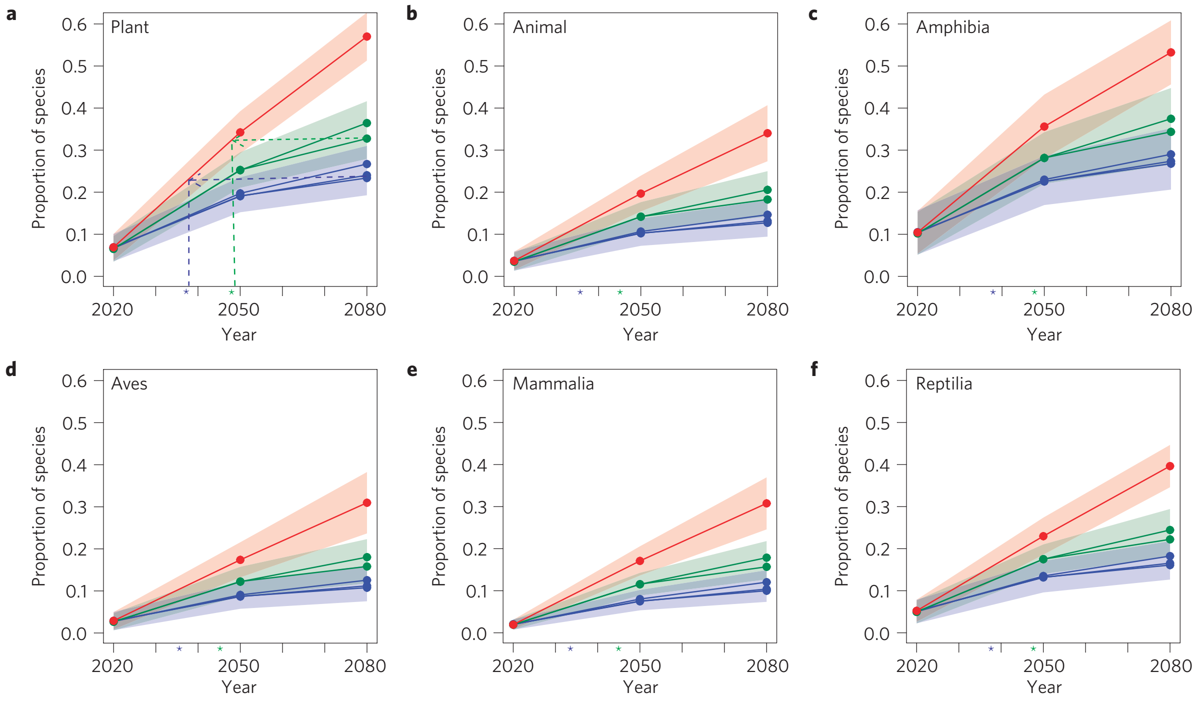

Figure 2 | Proportion of species losing ≥50% of their range by the 2080s under various dispersal and mitigation scenarios. a–f, Proportion of species losing ≥50% of their range by the 2080s with realistic dispersal, under the baseline scenario (red), and in the mitigation scenarios with emissions peaking in 2030 (green) or 2016 (blue), respectively, for plants (**a**), animals (**b**), amphibians (**c**), birds (**d**), mammals (**e**) and reptiles (**f**). The shaded areas show the uncertainties arising from use of a range of GCM patterns for creating downscaled climate projections, as well as over the use of two (green) or three (blue) different mitigation scenarios. Red lines show trends for emission pathway SRES A1B without mitigation; green and blue pathways show those with mitigation in which global greenhouse gas emissions peak in 2030 and in 2016, respectively. The corresponding green and blue dashed arrows in **a** show the adaptation time bought in the AVOID2030 and the AVOID2016 scenarios (2038–2080 and 2048–2080, respectively); the dashed arrows are represented by blue and green stars in **b**–**f**.

with ref. 13, our projections suggest that amphibians are most at risk from climate change, with 50 ± 7% of species losing over 50% of their climatic range under a realistic dispersal scenario, dropping to 28 ± 7% with stringent mitigation. Our analysis revealed that in all taxa, distributions were on average more strongly driven by temperature than by precipitation, although many species are more strongly affected by precipitation (Supplementary Table S2a–c).

Corresponding, but smaller, increases in the proportions of species losing larger percentages of their climatic range were also seen. Our estimates of the proportion of species losing more than 90% of their climatic ranges (for example, 2–6% of animals with realistic dispersal rates; Supplementary Fig. S2 and Table S4b) largely omit more restricted-range species that have previously been shown to be highly vulnerable to climate change. Our focus on widespread species makes our figures much lower, and not comparable to, previous estimates of climate-change-induced commitment to extinction[3,14]. However, all mitigation scenarios examined deliver substantial reductions of (at least) 40–60% in the number of species incurring these large climatic range losses (Supplementary Table S4a–c), for all categories (ranging from ≥50% to ≥99% loss), for all long-term dispersal scenarios and for all taxa.

The impacts of climate change and benefits of stringent mitigation action are not geographically uniform (Fig. 3a,b). With no mitigation, the climate becomes particularly unsuitable for both plants and animals in sub-Saharan Africa, Central America, Amazonia and Australia. Major loss of plant species is also projected for North Africa, Central Asia and Southeastern Europe. We used the number of species from our study with suitable climate predicted in each grid cell as an indicator of species richness. With stringent mitigation, species richness in many of the affected areas shown in Fig. 3a,b is less impacted (that is, more preserved; Fig. 3c,d). Benefits (Fig. 3e,f) are particularly strong in sub-Saharan Africa, Central America, Amazonia, Australia, North Africa, Central Asia and Southeastern Europe. In areas where species richness is projected to increase, gains are generally below 5%. Corresponding maps for the less stringent mitigation scenarios (that is, if global emissions peak in 2030) show smaller, but still positive, benefits (Supplementary Fig. S3a–f). In many of these areas, land-use changes will be acting synergistically[15] with climate-induced autonomous range shifts.

In all cases, stringent early mitigation not only reduces the level of risk to the taxa, it also postpones the changes that would otherwise be incurred by the late 2030s to the 2080s, thus buying approximately four decades of time for autonomous or planned adaptation (Fig. 2a, blue dashed arrow). More generally, levels of adaptation required to adapt to a temperature rise of 2 °C above pre-industrial levels could be required before 2050 if there is no mitigation (Fig. 1b), whereas with stringent mitigation these levels are not required until the end of the century. Adaptation is further facilitated as the rate of climate change is consistently lower in the mitigation scenarios than in the baseline case, so that adaptation to the higher rates of climate change are no longer required. Thus, this type of analysis can help quantify the trade-offs between varying levels of climate change mitigation and adaptation needs.

In the more stringent mitigation scenarios in which global emissions peak in 2016, climate change stops increasing by the end of the century (Fig. 1b). In all cases, earlier mitigation results in greater avoidance of range losses (60%), and buys more time for adaptation. Delay in the date at which global emissions peak causes reduced effectiveness even if higher emission reduction rates are implemented subsequent to the peak. Thus, the date of peak

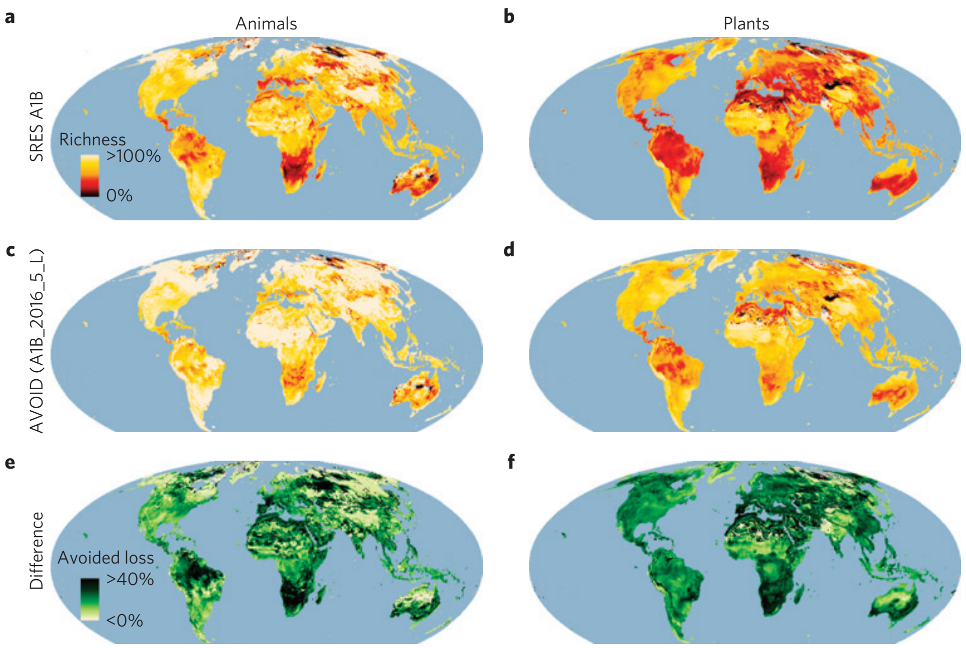

Figure 3 | Species richness in the 2080s. a–d, Species richness of animal (**a**,**c**) and plant (**b**,**d**) species in the 2080s under realistic dispersal for the stringent mitigation case in which global greenhouse gas emissions peak in 2016 and are subsequently reduced at 5% annually (**c**,**d**) compared with the no mitigation case SRES A1B (**a**,**b**). The colour scale in **a** also applies to parts **b**–**d**. **e**,**f**, The species richness change that is avoided by such mitigation. White areas are those where no data exist in the GBIF network. Species richness gains occur only on the edges of these white areas, where they are artefacts of data paucity, and hence are not shown. The colour scale in **e** also applies to **f**.

emissions is key to the efficacy of mitigation in avoiding the risks to biodiversity. Ref. 11 uses the same methodology as in this study to show that constraining median global temperature rise to 2 °C if emissions peak in 2016 requires a subsequent emission reduction rate of 3–4%, but if the emission peak is delayed by 5 years, a reduction rate of 6% is required to constrain median temperature rise to 2 °C. Thus, the date of peak emissions is arguably more important than the overall amount in terms of reduced impacts and the adaptation time that can be bought. Although some studies highlight that mitigation rates of up to 5% (as considered here) may be achievable[16], mitigation at faster rates is widely considered to be infeasible, and thus the possibility that widespread climate change impacts on biodiversity can be avoided if mitigation is delayed seems remote.

In our analyses, all of the patterns were found to be robust, for all animals combined, in separate analyses of mammals, birds, reptiles, amphibians and plants, and in analyses of individual families. Our method encompassed uncertainties in both climate change projections and in the potential ability of species to disperse to areas that become newly climatically suitable. Although some authors caution that these types of study might overestimate potential impacts for example[17], our overall estimates of biodiversity diminution at this scale are probably conservative owing to the expected compounding effects of increases in extreme weather events, pests, diseases and barriers to dispersal, as well as to changes in trophic or mutualistic interactions (see Supplementary Information for discussion). In particular, our estimates for animals will be underestimated owing to their dependence on plants. Actual levels of risk in all classes would also be expected to be higher owing to the concomitant impacts of other environmental stresses, such as land-use change, water and soil contamination, and because extremes associated with increased inter-annual variability[3] could constrain rates of dispersal that might otherwise be considered realistic[18]. Moreover, the rate at which emissions are now increasing exceeds that in our baseline scenario for the present decade[19].

Our projections indicate that without climate change mitigation, large climatic range contractions can be expected, amounting to a substantial global reduction in biodiversity and ecosystem services by the end of this century. However, prompt, stringent mitigation of greenhouse gas emissions has the potential to avoid the risk of systemic biodiversity diminution of common and widespread species, with concomitant declines in ecosystem services, particularly in sub-Saharan Africa, the Amazon, Australia, North Africa, Central Asia and Southeastern Europe. With prompt, stringent mitigation, levels of adaptation that would be required by the late 2030s are not required until the 2080s, whereas if mitigation is delayed such that global emissions do not peak until 2030 then substantially fewer risks to biodiversity can be avoided.

Methods

We used greenhouse gas emissions time series, specifically the SRES A1B baseline scenario[20] and mitigation scenarios[21], to drive a global climate change model MAGICC4.1 (refs 22,23) capable of reproducing global mean warming from complex GCMs that have yet to be run and analysed for stringent mitigation scenarios. In the mitigation scenarios, emissions follow the baseline before transitioning over seven years so that they peak globally in either 2016 or 2030, and are reduced subsequently at rates of between 2 and 5% annually until reaching a lower limit, representing emissions that might be difficult to eliminate. The resultant projections of global temperature change drove a pattern-scaling module ClimGen[24,25] in which scaled climate change patterns diagnosed from seven alternative GCM simulations are combined with a baseline climate. Thus, we produced 42 spatially explicit time-series projections of monthly mean, minimum and maximum temperatures, and total precipitation, downscaled to 0.5° × 0.5° and consistent with the IPCC (ref. 26). This was post-processed to produce 8 bioclimatic indices for our subsequent modelling of species' present and future climate space[27,28]. Biodiversity records were sourced from the Global Biodiversity Information Facility[29] (GBIF) and vetted for locational reliability (see Supplementary Information). We used MaxEnt[27,28] to create statistical relationships between the vetted species occurrence records and present (1961–1990) climate, and to calculate the present geographic distribution of each species[27,30]. To eliminate potential omission and commission biases, distributions were then clipped to the bio-geographic zone(s)[31] from which the species information was derived and to a conservative 2000 km buffer around the species' outermost occurrence records. Next, we used the projected climates and trained models to derive potential future distribution for each species in our future climate scenarios for 30 year periods centred on 2025, 2055 and 2085, applying three class-specific long-term dispersal rate scenarios (zero, realistic and optimistic) that were restricted to contiguous land areas. This enabled us to estimate the proportions of species losing ≥50, ≥70, ≥90 or ≥99% of their climatically suitable range under the various future climate and dispersal rate scenarios.

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Author contributions

J.P. assembled the team, coordinated and advised. R.W. generated and provided the climate projections in collaboration with T.J.O. and J.L. J.R-V. cleaned and processed the GBIF data. R.W., J.V., J.P., L.P.S., A.J. and S.E.W. designed the model experiments. J.V. performed the model experiments and analysis. R.W., J.V., J.A.W., J.R-V. and J.P. wrote the paper. I.A. facilitated and advised on computational issues surrounding modelling and data storage.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.W.

Competing financial interests

The authors declare no competing financial interests.