CLIMATE CHANGE

The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C

R. Warren,[1]* J. Price,[1] E. Graham,[2] N. Forstenhaeusler,[1] J. VanDerWal[2]

In the Paris Agreement on Climate Change, the United Nations is pursuing efforts to limit global warming to 1.5°C, whereas earlier aspirations focused on a 2°C limit. With current pledges, corresponding to ~3.2°C warming, climatically determined geographic range losses of >50% are projected in ~49% of insects, 44% of plants, and 26% of vertebrates. At 2°C, this falls to 18% of insects, 16% of plants, and 8% of vertebrates and at 1.5°C, to 6% of insects, 8% of plants, and 4% of vertebrates. When warming is limited to 1.5°C as compared with 2°C, numbers of species projected to lose >50% of their range are reduced by ~66% in insects and by ~50% in plants and vertebrates.

Climate change poses risks to biodiversity through a number of mechanisms (*1*–*3*). The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to limit global warming to "well below 2°C" above preindustrial levels and to "pursue efforts" to limit it to 1.5°C. Previous policy-relevant research on the risks climate change poses to biodiversity focused on quantifying the benefits of limiting warming to 2°C above preindustrial levels in terms of avoided range loss (*4*). Studies of the potential effects of climate change on insects generally focused on small groups only [e.g., (*5*–*8*)], although some studies covered a family of insects in a single country [e.g., Australian butterflies (*9*)].

Here we quantify the difference that avoiding an additional 0.5°C warming (from 2° to 1.5°C) by 2100 would make for biodiversity in terms of avoided changes in climatically determined range size (loss or gain, hereafter "range size"). We provide a global assessment of the potential impacts of climate change on the range sizes of more than 115,000 terrestrial species, including more than 34,000 insects and other invertebrates not included in previous global-scale studies of climate change and biodiversity [(*4*, *10*)].

This work builds on the earlier study with a number of notable updates and improvements (*4*, *11*): the inclusion of insects, which are particularly important for healthy ecosystem functioning (*12*); a near-tripling of the number of species studied; a nearly five times higher spatial resolution [allowing the inclusion of species with ranges approximately one-fifth the size of those in a previous analysis (*4*)]; and a set of new climate change scenarios and models. We also specifically looked at warming levels specific to current policy efforts, including a scenario in which countries make no further emission reductions after achieving the first Nationally Determined Contributions in 2030, hereafter referred to as "current pledges," corresponding to the upper end of a warming range of 2.6° to 3.2°C (http://www.wri.org/) (*13*); and with a scenario with little or no climate change mitigation and a warming of 4.5°C [all temperatures relative to preindustrial (*11*)].

Two complementary metrics are used to compare climate change scenario outcomes for the taxa studied: metric 1, the proportion of species losing >50% of their current climatically determined range, providing a broad-brush indicator of biodiversity range loss comparable with previous studies; and metric 2, the total integrated range loss, providing a complementary indicator of biodiversity range loss that allows the full range of outcomes within taxa to be examined. It has a maximum value of 1, which corresponds to 100% range loss in all species and gives the magnitude of range loss across all species in a taxon.

Constraining warming to 1.5°C instead of 2°C reduces the number of plant and vertebrate species exposed to >50% projected range loss by ~50% (Fig. 1 and table S2) for all taxa explored (although the benefits are slightly smaller for reptiles). However, for insects (and more broadly, invertebrates), the risks are reduced by ~66%. Overall, the risks at 4.5°C warming are 8 to 10 times larger than those at 1.5°C warming.

With current pledges (~3.2°C), projected geographic range losses of >50% occur in 49% (31 to 65%) of the insects, 44% (29 to 63%) of the plants, and 26% (16 to 40%) of the vertebrates. At 2°C, these are reduced by 60 to 70%, to 18% (6 to 35%) of the insects, 16% (9 to 28%) of the plants, and 8% (4 to 16%) of the vertebrates. At 1.5°C, this is reduced further to 6% (1 to 18%) of the insects, 8% (4 to 15%) of the plants, and 4% (2 to 9%) of the vertebrates (table S2). Overall, insects are exposed to greater potential climatic range loss than any other animal group (Fig. 1) and also benefit the most if warming is constrained to 1.5°C rather than 2°C. Among insect orders, Diptera, Coleoptera, and Hemiptera show the greatest potential range loss and Odonata the lowest (fig. S1).

Our findings support earlier literature projecting large increases in range loss and extinction risk potentially associated with warming (*14*, *15*). The shapes of the range loss curves (Fig. 2) provide additional information about numbers of species losing large proportions of their range, showing how these change from concave at 1.5°C to convex by 3.2°C, reflecting increasing risks. For insects (fig. S2), this change in form is particularly strong, which indicates more rapid increases in risk.

Under current pledges (3.2°C), the projected total integrated range loss is 43% (30 to 55%) in the insects, 46% (36 to 57%) in the plants, and 21% (9 to 34%) in the vertebrates. At 2°C, this is reduced by 30 to 60% to 27% (16 to 37%) in the insects, 30% (23 to 38%) in the plants, and 10% (1 to 20%) in the vertebrates; and at 1.5°C, to 20% (11 to 28%) in the insects, 24% (18 to 30%) in the plants, and 6% (–1 to 14%) in the vertebrates (table S3). This metric thus also indicates that insects and plants are the groups with the greatest exposure, closely followed by amphibians, and also that insects benefit the most from constraining warming to 1.5°C rather than 2°C. Our results also show that there is still appreciable climatic range loss at 1.5°C warming, despite the relatively small proportions of species for which range loss of >50% is projected (Fig. 2, figs. S2 and S3, and table S3).

Figure 1, figs. S1 and S3, and tables S4 and S5 include corresponding projections for the alternative assumption of no dispersal. Without dispersal, Lepidoptera and Odonata appears more vulnerable to climate change than otherwise (figs. S2 and S3); as do Aves and Mammalia (fig. S2), indicating how critical dispersal is for potential climate change adaptation for these taxa. Figure 2, fig. S2, and table S6 also indicate the small proportions of species gaining range size via dispersal. Except for Odonata, the proportions gaining more than half their range are vastly greater than the proportions losing over half, except at 1.5°C warming. In this case, when dispersal is included, the proportions of Mammalia and Aves species gaining or losing >50% of their climatic range is similar at 1.5°C (table S6), and the total integrated range loss is also close to zero (Fig. 2 and table S3). Odonata shows a very different climate response to any other taxa, with the number of species gaining range appearing to be balanced by the loss at all levels of warming, and indeed slightly negative values of integrated range loss (table S3).

Figures S4 and S5 show that among Lepidoptera, moths are at greater risk than butterflies, and moths benefit considerably more than butterflies if warming is constrained to 1.5°C rather than 2°C, a finding consistent with a recent attribution study relating 48% of moth population declines in the United Kingdom to climate change (*16*). Projected risks for key insect crop pollinator families (Apidae, Syrphidae, and Calliphoridae; i.e., bees, hoverflies, and blowflies) are also (figs. S4 and S5) greatly reduced.

[1]Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK. [2]College of Science and Engineering, James Cook University, Townsville, Australia.
*Corresponding author. Email: r.warren@uea.ac.uk

Figure 3 indicates the geographical distribution of the benefits of limiting warming to 1.5°C as compared with 2°C, and 2°C compared with 3.2°C in plants, vertebrates, and insects. Areas benefiting the most from constraining warming are Southern Africa, parts of the Amazon, Europe, and Australia. Figure S6 indicates the projected changes in species richness globally at the four levels of warming (1.5°, 2°, 3.2°, 4.5°C above preindustrial levels) and, where appropriate, (for animals) including or excluding realistic dispersal. Areas where potential species richness declines the most due to climate change of 3.2° and 4.5°C are Southern Africa, Australia, and the high Arctic.

We find substantial benefits to limiting warming to 1.5°C above preindustrial levels as compared with 2°C by 2100. The number of insect species projected to lose >50% of their range is reduced by about 66%, whereas the number of plant and animal species projected to lose more than half their range is reduced by ~50%. Hence, successful implementation of the Paris Agreement could lead to substantial benefits for global terrestrial biodiversity. Risks to biodiversity generally increase linearly with increased global temperature rises of between 1.5° and 4.5°C warming irrespective of the metric used (figs. S7 and S8). The projected risks of warming are in general greater for most invertebrates, plants, amphibians, and reptiles than for mammals, birds, and a few of the insect groups studied, owing to their slower dispersal rates. Because range loss may increase extinction risk, it follows that limiting warming to 1.5°C rather than 2°C also reduces extinction risk, and the reduction associated with limiting warming to 1.5°C rather than 3.2°C is greater still.

However, restricting warming to 1.5°C may be difficult. Of the 166 climate change mitigation scenarios assessed (*17*), 87% of those limiting warming to less than 2°C with >66% probability incorporate "negative emissions technology," typically large-scale bioenergy with carbon capture and storage (BECCS) (*18*). If primary bioenergy is used to supply BECCS, up to 18% of the land surface could be required by the end of the century (*19*); or 24 to 36% of the current arable cropland (*20*). Competition for land between bioenergy and agriculture could intensify, potentially leading to indirect land-use change and ecosystems conversion to cropland (*21*–*23*), unless conservation measures are in place and enforced. It could also lead to agricultural intensification, potentially leading to declines in insect populations (*24*). Hence, to realize the projected benefits to biodiversity quantified here, we introduce the term "Article 2 compliant mitigation." This puts into practice the need to allow "ecosystems to adapt naturally" to climate change; requiring careful design and expansion of existing protected area networks to allow species to persist and disperse with warming in tandem with mitigation activities. New studies are exploring scenarios in which BECCS is produced from secondary biofuels, or in which there are dietary changes in humans, resulting in greatly

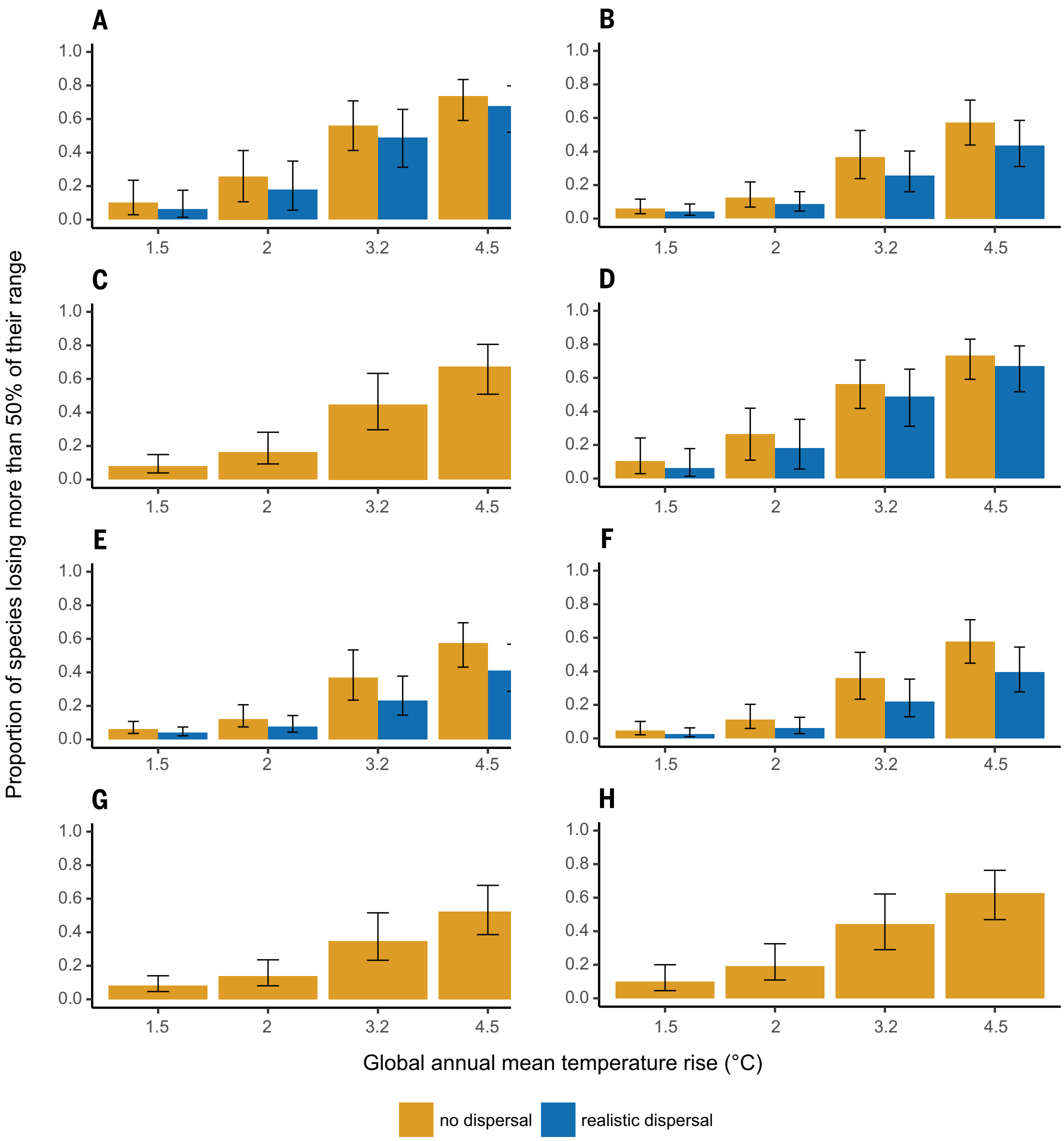

Fig. 1. The proportion of modeled species losing more than half their climatically determined range by 2100 at specific levels of global warming. (**A**) Invertebrates (n = 34,104), (**B**) Chordata (n = 12,640), (**C**) Plantae (n = 73,224), (**D**) Insecta (n = 31,536), (**E**) Mammalia (n = 1769), (**F**) Aves (n = 7966), (**G**) Reptilia (n = 1850), and (**H**) Amphibia (n = 1055). Colors: Including (blue) and excluding (orange) realistic dispersal. Data are presented as the mean projection across 21 alternative climate model patterns with error bars indicating the 10 to 90% range.

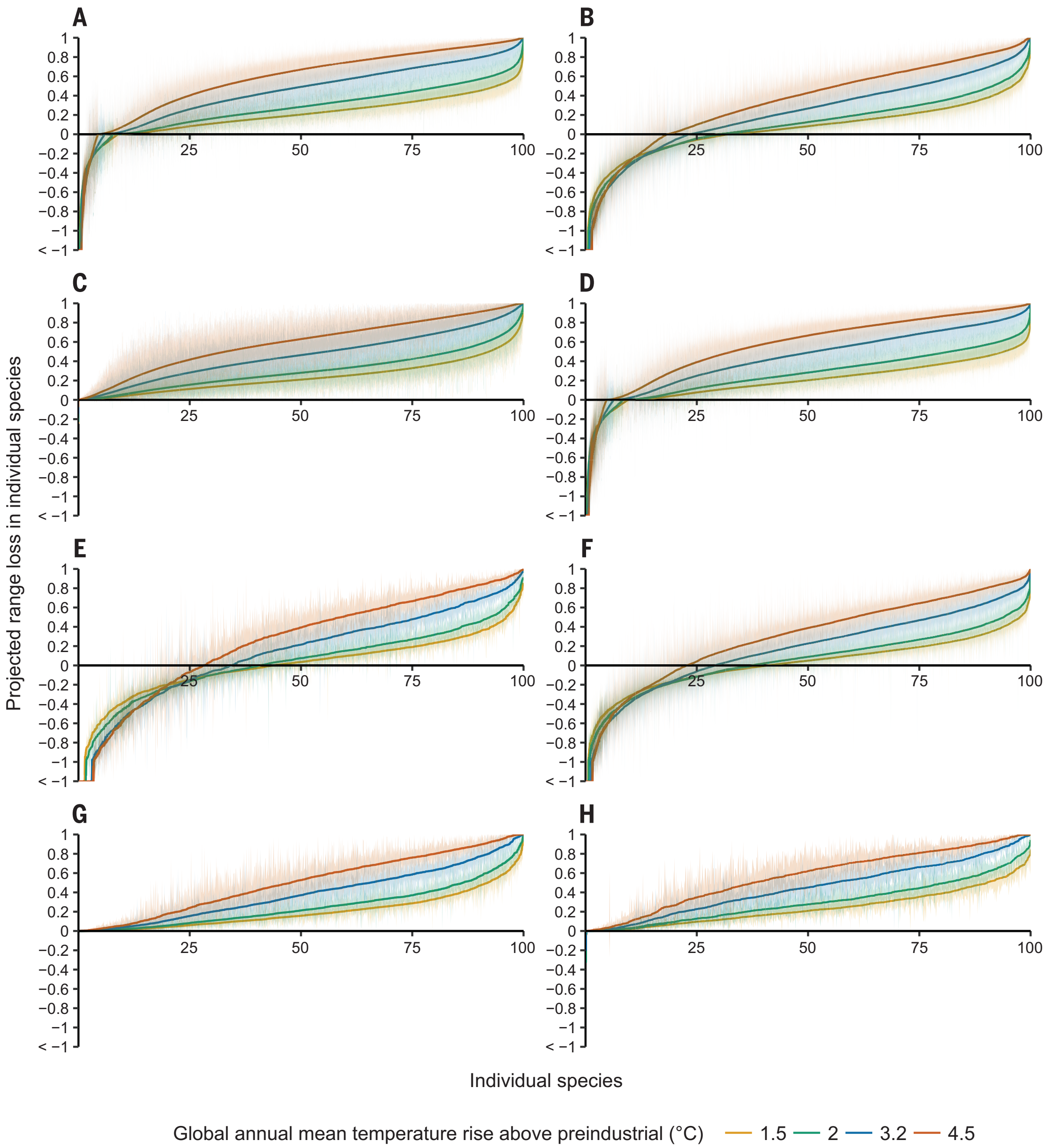

Fig. 2. Projected climatically determined range loss by 2100 for all species at specific levels of global warming. (**A**) Invertebrates (*n* = 34,104), (**B**) Chordata (*n* = 12,640), (**C**) Plantae (*n* = 73,224), (**D**) Insecta (*n* = 31,536), (**E**) Mammalia (*n* = 1769), (**F**) Aves (*n* = 7966), (**G**) Reptilia (*n* = 1850), and (**H**) Amphibia (*n* = 1055). The proportion ranges from +1 (100% loss) to −1 (100% gain); values <−1 indicate more than 100% gain. *X* axes represent the 0th to 100th percentile of species arranged in order of increasing range loss, normalized by the number modeled in the taxon. Losses for each species are shown as mean and 10 to 90% range across regional climate model patterns as in Fig. 1.

reduced effects of indirect land-use change (*25*). The implications of "overshoot" scenarios in which temperatures exceed a particular level and later return to it are provided in the supplementary materials (*11*).

This study has focused on a comparison of benefits of reaching 1.5°C versus 2°C warming by 2100. On other time scales, the risks associated with reaching these alternative levels of warming will depend on the time scale: The earlier a particular level of warming is reached, the greater the risks, because species will have less time to disperse naturally to track their climate envelope, and society will have less time to expand protected area networks or otherwise facilitate movement. Mitigation, therefore, "buys time" for adaptation.

Caveats notwithstanding (*11*), our results are generally considered to likely be conservative, in particular in light of the lack of consideration of the potential disruption of predator-prey, plant-pollinator, mutualistic, or other species-species interactions (*2*, *26*) and the limited evidence that mutualisms may or may not be substituted under climate change (*27*). Such disruptions may lead to losses of ecosystem functioning, particularly important given the finding that projected range losses in insects and plants may, in many places, exceed those for birds and mammals that have a greater ability to disperse naturally to track their geographically shifting climate envelope. Additionally, lack of consideration of potential risks associated with extreme weather events, projected to become more frequent and intense in many regions (*28*, *29*) or fire regimes (*11*), may lead to impacts potentially occurring sooner than models project.

These projected declines in climatically determined ranges of species would be expected to have a concomitant effect on ecosystem functioning and the delivery of important provisioning and regulating ecosystem services and the maintenance of human well-being (*30*). Recently, declines of 76 to 82% in flying insect populations have been reported in Germany over the past 27 years (*24*); and, globally, 67% of the invertebrates studied showed a 45% abundance decline (*31*). If these observations are representative of global trends, any projected declines arising from climate change would add to those observed. Such declines would reduce ecosystem

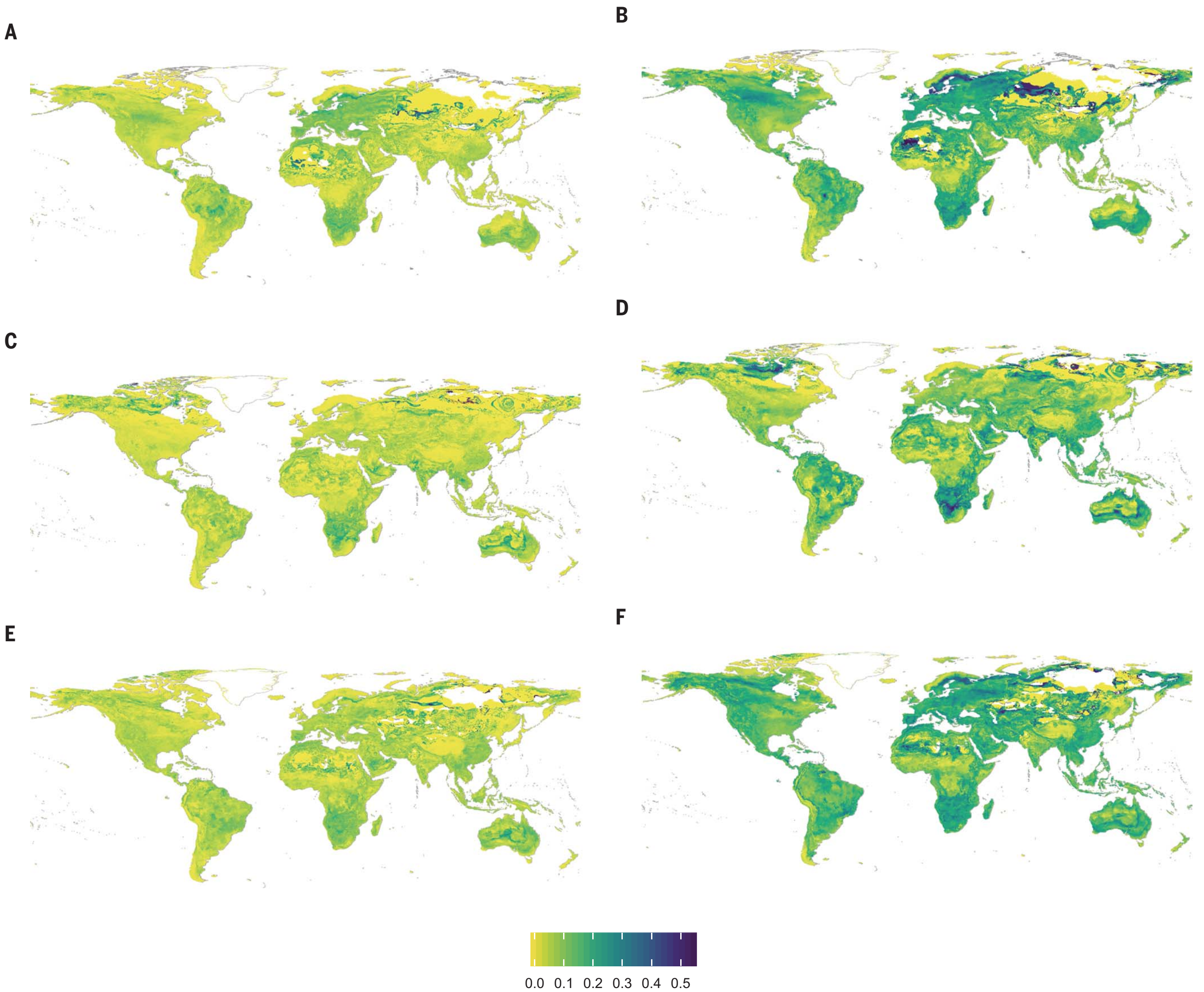

Fig. 3. Benefits of global annual mean temperature rise in terms of avoided species richness loss. (**A** and **B**) Insecta, (**C** and **D**) Chordata, and (**E** and **F**) Plantae without dispersal. (A, C, E) 1.5°C versus 2°C; (D, E, F) 2°C versus 3.2°C.

services with concomitant implications for plant survival (*29*, *30*). Insects are also key to food provisioning for higher trophic levels and perform other key functions in ecosystems such as detritivory, herbivory, and nutrient cycling (*28*, *32*, *33*). Hence, risks to these vital ecosystem functions and services performed by insects are substantially smaller if global warming is constrained to 1.5°C above preindustrial levels as compared with 2°C.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/360/6390/791/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S8
Tables S1 to S6
References (*34*–*55*)

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