CLIMATE CHANGE

Accelerating extinction risk from climate change

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Current predictions of extinction risks from climate change vary widely depending on the specific assumptions and geographic and taxonomic focus of each study. I synthesized published studies in order to estimate a global mean extinction rate and determine which factors contribute the greatest uncertainty to climate change–induced extinction risks. Results suggest that extinction risks will accelerate with future global temperatures, threatening up to one in six species under current policies. Extinction risks were highest in South America, Australia, and New Zealand, and risks did not vary by taxonomic group. Realistic assumptions about extinction debt and dispersal capacity substantially increased extinction risks. We urgently need to adopt strategies that limit further climate change if we are to avoid an acceleration of global extinctions.

We critically need to know how climate change will influence species extinction rates in order to inform international policy decisions about the biological costs of failing to curb climate change and to implement specific conservation strategies to protect the most threatened species. Current predictions about extinction risks vary widely, suggesting that anywhere from 0 to 54% of species could become extinct from climate change (1–4). Studies differ in particular assumptions, methods, species, and regions and thus do not encompass the full range of our current understanding. As a result, we currently lack consistent, global estimates of species extinctions attributable to future climate change.

To provide a more comprehensive and consistent analysis of predicted extinction risks from climate change, I performed a meta-analysis of 131 published predictions (table S1). I focused on multispecies studies so as to exclude potential biases in single-species studies. I estimated the global proportion of species threatened in a Bayesian Markov chain Monte Carlo (MCMC) random-effects meta-analysis that incorporated variation among and within studies (5) and with each study weighted by sample size (6). I evaluated how extinction risk varied depending on future global temperature increases, taxonomic groups, geographic regions, endemism, modeling techniques, dispersal assumptions, and extinction thresholds. I used credible intervals (CIs) that do not overlap with zero and a deviance information criterion (DIC) greater than four to assess statistical support for factors. The majority of studies estimated correlations between current distributions and climate so as to predict suitable habitat under future climates. A smaller number of studies determined extinction risks by using process-based models of physiology or demography (15%), species-

area relationships (5%), or expert opinion (4%). Species were predicted to become extinct if their range fell below a minimum threshold. An important caveat is that most of these models ignore many factors thought to be important in determining future extinction risks such as species interactions, dispersal differences, and evolution.

Overall, 7.9% of species are predicted to become extinct from climate change; (95% CIs, 6.2 and 9.8) (Fig. 1). Results were robust to model type, weighting scheme, statistical method, potential publication bias, and missing studies (fig. S1 and table S2) (6). This proportion supports an estimate from a 5-year synthesis of studies (7). Its divergence from individual studies (1–4) can be explained by their specific assumptions and taxonomic and geographic foci. These differences provide the opportunity to understand how divergent factors and assumptions influence extinction risk from climate change.

The factor that best explained variation in extinction risk was the level of future climate change. The future global extinction risk from climate change is predicted not only to increase but to accelerate as global temperatures rise (regression coefficient = 0.53; CIs, 0.46 and 0.61) (Fig. 2). Global extinction risks increase from

2.8% at present to 5.2% at the international policy target of a 2°C post-industrial rise, which most experts believe is no longer achievable (8). If the Earth warms to 3°C, the extinction risk rises to 8.5%. If we follow our current, business-as-usual trajectory [representative concentration pathway (RCP) 8.5; 4.3°C rise], climate change threatens one in six species (16%). Results were robust to alternative data transformations and were bracketed by models with liberal and conservative extinction thresholds (figs. S2 and S3 and table S3).

Regions also differed significantly in extinction risk (ΔDIC = 12.6) (Fig. 3 and table S4). North America and Europe were characterized by the lowest risks (5 and 6%, respectively), and South America (23%) and Australia and New Zealand (14%) were characterized by the highest risks. These latter regions face no-analog climates (9) and harbor diverse assemblages of endemic species with small ranges. Extinction risks in Australia and New Zealand are further exacerbated by small land masses that limit shifts to new habitat (10). Poorly studied regions might face higher risks, but insights are limited without more research (for example, only four studies in Asia). Currently, most predictions (60%) center on North America and Europe, suggesting a need to refocus efforts toward less studied and more threatened regions.

Endemic species with smaller ranges and certain taxonomic groups such as amphibians and reptiles are predicted to face greater extinction risks (11, 12). I estimated that endemic species face a 6% greater extinction risk relative to models that include both species endemic and non-endemic to the study region (ΔDIC = 8.3). Extinction risks also rose faster with preindustrial temperature rise for models with endemic species (ΔDIC = 8.2) (fig. S4). In contrast to predictions, extinction risks did not vary significantly by taxonomic group (ΔDIC = 0.7) (Fig. 4). One explanation is that trait variation at finer taxonomic scales might play a more important role in modulating extinction risks (13). Also, typical approaches for quantifying extinction risks likely do not capture the full range of differences among taxonomic groups.

Overall extinction risk = 7.9% (95% CI: 6.2, 9.8)
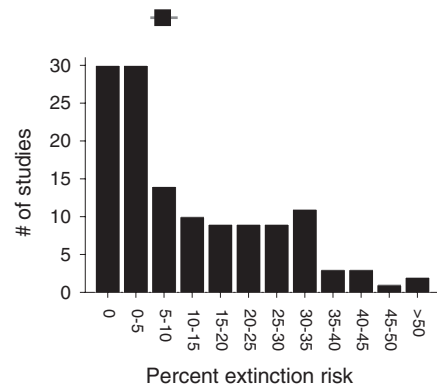
Fig. 1. Histogram of percent extinction risks from climate change for 131 studies. Percent extinction risk refers to the predicted percent of species extinctions in each study, averaged across all model assumptions. The meta-analysis estimated mean with 95% CIs is also shown.

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Key model assumptions altered predictions of future extinction risk. For instance, extinction debts occur when species decline to the point that they are committed to extinction, but not yet extinct (14). Studies differed in how much habitat loss was assumed to commit a species to extinction, commonly applying habitat loss thresholds of 100, 95, and 80%. Extinction thresholds were second only to expected climate change in explaining variable extinction risks. Decreas-ing the extinction threshold from 100% (no extinction debt) to 80% increased risk from 5 to 15% (ΔDIC = 144.1) (Fig. 4), and lower thresholds increased the rise in extinction risk with future temperatures (interaction ΔDIC = 5.9) (fig. S2). The applicability of these thresholds will depend on species-specific characteristics such as generation time and initial population size. We urgently need to understand how range reductions determine future extinction risk bet-ter in order to predict accurately both the num-ber and timing of future extinctions (15).

Species must disperse into newly suitable hab-itats as fast as climates shift across landscapes (16, 17). Modelers variously assume no dispersal, dispersal only into contiguous habitats, dispersal based on each species' ability, or universal dis-persal regardless of distance or ability. Modelers usually assume no dispersal and universal dis-persal and presume that the true value lies be-tween these extremes. I found that assumptions about dispersal significantly affected extinction risks (ΔDIC = 68.5) (Fig. 4). Species-specific dispersal increased extinction risk from 6%, as-suming universal dispersal to 10%. Assuming no dispersal increased risk further to 12%. Ex-tinction risks increase more rapidly with tem-perature rise assuming no- and species-specific dispersal (interaction ΔDIC = 6.1) (fig. S5). Incor-porating more realistic species-specific dispersal

Fig. 2. Predicted extinction risks from climate change accelerate with global temperature rise. The gray band indicates 95% CIs. Preindustrial rise was calculated by using standard methods (27). Circles indi-cate posterior means with area proportional to $\log_{10}$ sample size (bottom left, key). Extinction risks for four scenarios are provided: the current postindustrial tem-perature rise of 0.8°C (5), the policy target of 2°C, and RCPs 6.0 and 8.5.
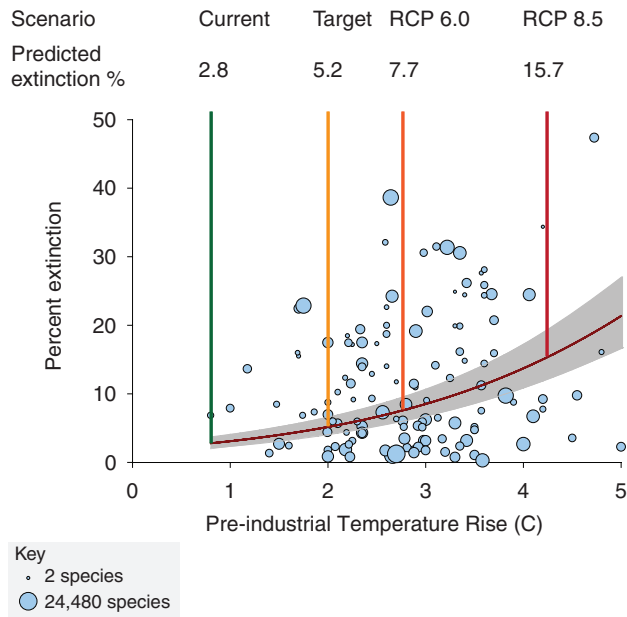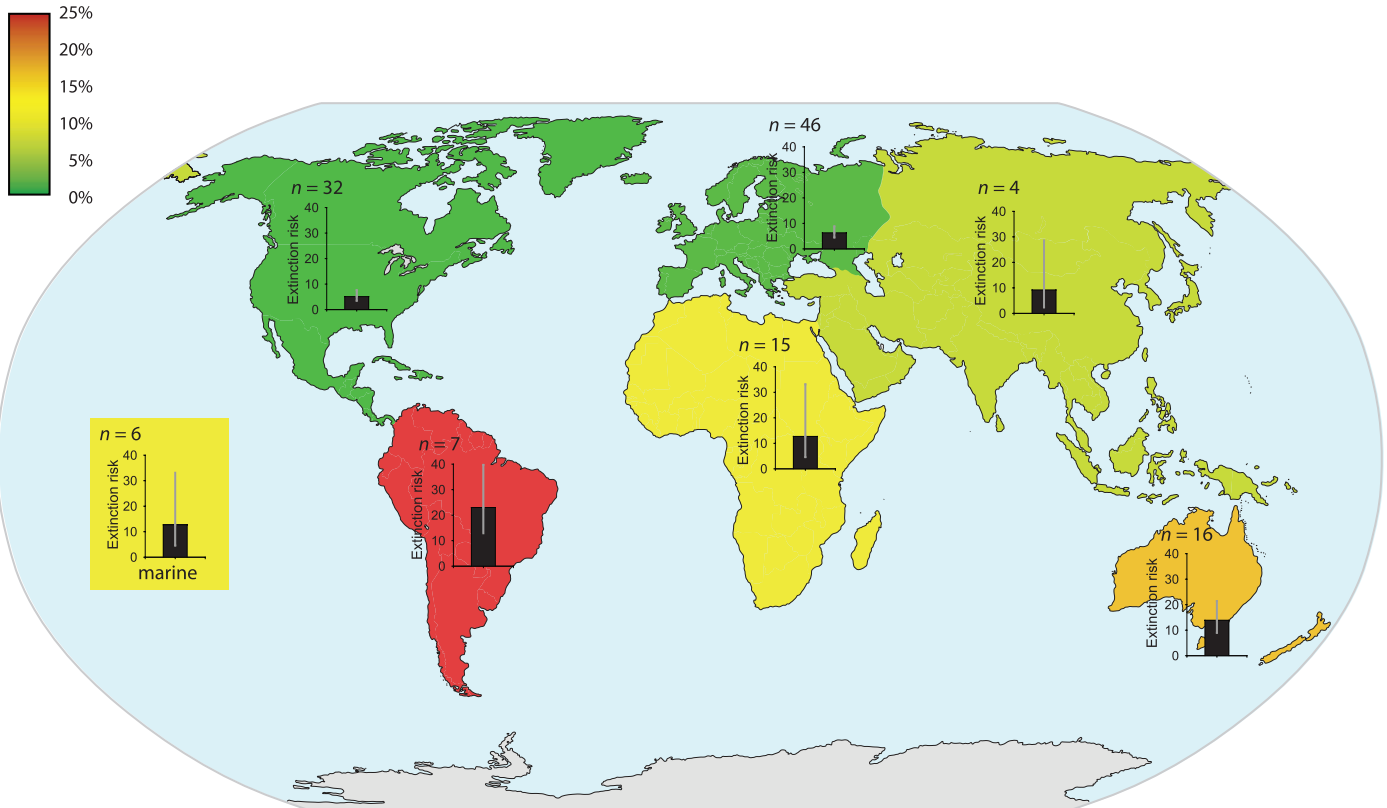
Fig. 3. Predicted extinction risks from climate change differ by region. The highest risks characterized South America, Australia, and New Zealand (14 to 23%), and the lowest risks characterized North America and Europe (5 to 6%). Colors indicate relative risk. Bar graphs with 95% CIs and number of studies (n) are displayed.

abilities resulted in extinction risks midway between the no- and universal-dispersal assumptions as expected.

Modelers apply different techniques to predict future extinctions, ranging from correlations between current distributions and climate (species distribution, niche, or climate envelope models) to sophisticated mechanistic models. I found only a marginal effect of modeling technique on extinction risk ($\Delta DIC = 3.4$). The largest extinction risks originated from results based on species-area relationships (22%) and expert opinion (18%). The lowest risks originated from mechanistic (8%) and species distribution models (7%). Species-area models explicitly incorporate an extinction debt and also can overestimate extinction risks because of a sampling artifact (18). The high risk associated with expert opinion could stem from a broader biological understanding, more pessimistic outlook, or greater uncertainty when translating qualitative indicators into quantitative classifications of extinction risk.

Here, I provide a global assessment of climate change–induced extinction risks and the factors that influence them. However, I emphasize that extinction risks are likely much smaller than the total number of species influenced by climate change. Even species not threatened directly by extinction could experience substantial changes in abundances, distributions, and species interactions, which in turn could affect ecosystems and their services to humans (19). Already, changes in species' phenologies, range margins, and abundances are evident (20, 21). Extinctions, although still uncommon, are increasingly attributed to climate change (22).
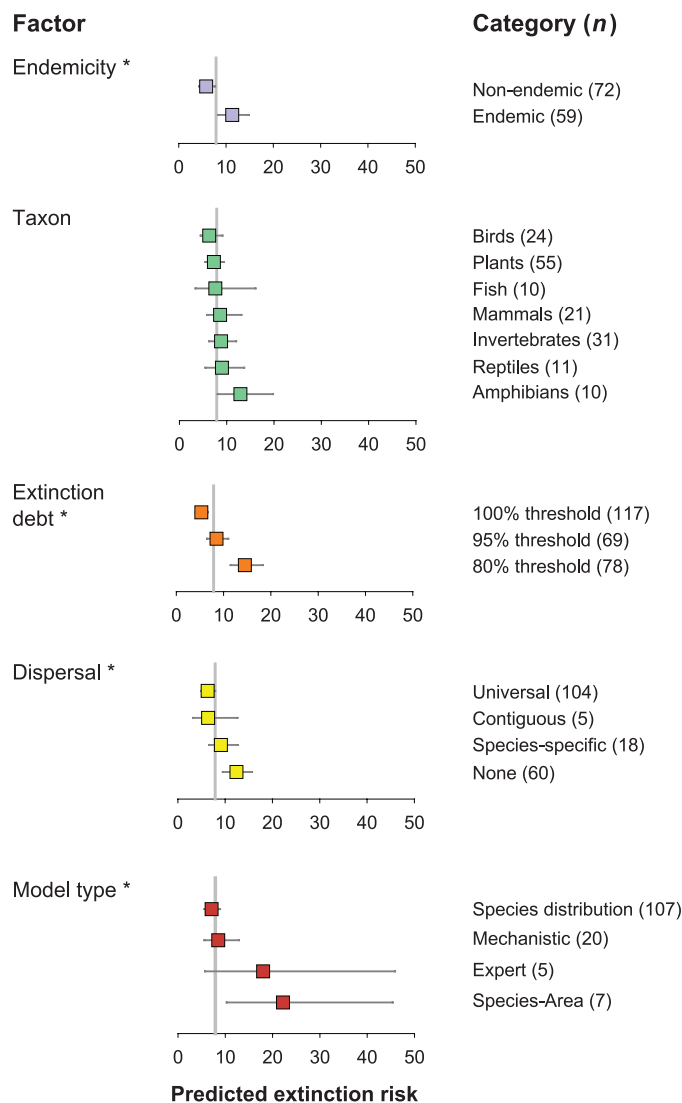
At the same time, we must cautiously interpret the predictions underlying this meta-analysis. The majority of studies extrapolate correlations between current climate and species distributions to novel conditions and omit important biological mechanisms, including species interactions, evolution, landscape dispersal barriers, habitat degradation, and intraspecific trait variation (23). Depending on the mechanism, its consideration can either increase or decrease predicted risks. For instance, evolution can decrease extinction risks by allowing populations to adapt to changing climates (24), whereas anthropogenic landscape barriers can increase risks by limiting dispersal into newly suitable habitats (25). Next-generation models for estimating extinction risks should incorporate these factors in order to increase biological realism and therefore the accuracy of future predictions.

In 1981, Hansen and colleagues predicted that the signal of global climate change would soon emerge from the stochastic noise of weather (26). Thirty years later, we are reaching a similar threshold for the effects of climate change on biodiversity. Extinction risks from climate change are expected not only to increase but to accelerate for every degree rise in global temperatures. The signal of climate change–induced extinctions will become increasingly apparent if we do not act now to limit future climate change.

REFERENCES AND NOTES

1. J. R. Malcolm, C. Liu, R. P. Neilson, L. Hansen, L. Hannah, *Conserv. Biol.* **20**, 538–548 (2006).
2. C. D. Thomas *et al.*, *Nature* **427**, 145–148 (2004).
3. R. Warren *et al.*, *Nature Clim. Change* **3**, 678–682 (2013).
4. W. B. Foden *et al.*, *PLOS ONE* **8**, e65427 (2013).
5. S. Nakagawa, E. S. Santos, *Evol. Ecol.* **26**, 1253–1274 (2012).
6. Materials and methods are available as supplementary materials on *Science* Online.
7. I. M. Maclean, R. J. Wilson, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 12337–12342 (2011).
8. S. Fuss *et al.*, *Nature Clim. Change* **4**, 850–853 (2014).
9. J. W. Williams, S. T. Jackson, J. E. Kutzbach, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 5738–5742 (2007).
10. S. E. Williams, E. E. Bolitho, S. Fox, *Proc. Biol. Sci.* **270**, 1887–1892 (2003).
11. B. Sinervo *et al.*, *Science* **328**, 894–899 (2010).
12. J. W. Gibbon *et al.*, *Bioscience* **50**, 653–666 (2000).
13. A. L. Angert *et al.*, *Ecol. Lett.* **14**, 677–689 (2011).
14. S. T. Jackson, D. F. Sax, *Trends Ecol. Evol.* **25**, 153–160 (2010).
15. J. C. Stanton, K. T. Shoemaker, R. G. Pearson, H. R. Akcakaya, *Glob. Change Biol.* **21**, 1066–1077 (2015).
16. C. A. Schloss, T. A. Nuñez, J. J. Lawler, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 8606–8611 (2012).
17. S. R. Loarie *et al.*, *Nature* **462**, 1052–1055 (2009).
18. F. He, S. P. Hubbell, *Nature* **473**, 368–371 (2011).
19. J. J. Lawler *et al.*, *Ecology* **90**, 588–597 (2009).
20. C. Parmesan, G. Yohe, *Nature* **421**, 37–42 (2003).
21. G. R. Walther *et al.*, *Nature* **416**, 389–395 (2002).
22. A. E. Cahill *et al.*, *Proc. Biol. Sci.* **280**, 20121890 (2013).
23. L. B. Buckley *et al.*, *Ecol. Lett.* **13**, 1041–1054 (2010).
24. A. A. Hoffmann, C. M. Sgrò, *Nature* **470**, 479–485 (2011).
25. P. Opdam, D. Wascher, *Biodivers. Conserv.* **117**, 285–297 (2004).
26. J. Hansen *et al.*, *Science* **213**, 957–966 (1981).
27. R. Warren, J. Price, A. Fischlin, S. de la Nava Santos, G. Midgley, *Clim. Change* **106**, 141–177 (2011).

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/348/6234/571/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S5
Tables S1 to S4
References (28–174)

Fig. 4. Predicted extinction risks from climate change depend on model characteristics. The asterisk indicates model support ($\Delta DIC > 4$) for each factor separately, and number of studies is included in parentheses. Categories within each factor are listed in order of increasing extinction risk. The gray vertical reference line indicates mean overall extinction risk. Bars represent 95% CIs.

Factor

Endemicity *
- Non-endemic (72)
- Endemic (59)

Taxon
- Birds (24)
- Plants (55)
- Fish (10)
- Mammals (21)
- Invertebrates (31)
- Reptiles (11)
- Amphibians (10)

Extinction debt *
- 100% threshold (117)
- 95% threshold (69)
- 80% threshold (78)

Dispersal *
- Universal (104)
- Contiguous (5)
- Species-specific (18)
- None (60)

Model type *
- Species distribution (107)
- Mechanistic (20)
- Expert (5)
- Species-Area (7)

Category (n)

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