Title: Accelerating extinction risk from climate change

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Abstract: Current predictions of extinction risks from climate change vary widely depending on the specific assumptions and geographic and taxonomic focus of each study. Here, I synthesize published studies 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 1 in 6 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.

Main Text:

We critically need to know how climate change will influence species extinction rates 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 0-54% 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 due 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 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 (see (*6*) for details). 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 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 to predict suitable habitat under future climates. A smaller number of studies determined extinction risks 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 (Fig. 1; 95% credible intervals [CIs]: 6.2, 9.8). Results were robust to model type, weighting scheme, statistical method, potential publication bias, and missing studies (*6*) (Tables S2, Fig. S1). This proportion supports estimates 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. Importantly, these differences provide the opportunity to understand how divergent factors and assumptions influence extinction risk from climate change.

The most important factor explaining 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 (Fig. 2; regression coefficient = 0.53; CIs: 0.46, 0.61). 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 (RCP 8.5; 4.3°C rise), climate change threatens 1 in 6 species (16%). Results were robust to alternative data transformations and were bracketed by models with liberal and conservative extinction thresholds (Figs. S2-3, Table S3).

Regions also differed significantly in extinction risk (Fig. 3; Table S4; ΔDIC = 12.6). 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 (e.g., four Asian studies). Currently, most predictions (60%) center on North America and Europe, suggesting a need to re-focus efforts toward less studied or 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 pre-industrial temperature rise for models with endemic species (Fig. S4; ΔDIC = 8.2). In contrast to predictions, extinction risks did not vary significantly by taxonomic group (Fig. 4A; ΔDIC = 0.7). 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.

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. Decreasing the extinction threshold from 100% (no extinction debt) to 80% increased risk from 5% to 15% (Fig. 4; ΔDIC = 144.1), and lower thresholds increased the rise in extinction risk with future temperatures (Fig. S2; interaction ΔDIC = 5.9). 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 better in order to predict both the number and timing of future extinctions accurately (*15*).

Species must disperse into newly suitable habitats 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 dispersal regardless of distance or ability. Modelers usually assume no dispersal and universal dispersal and presume that the true value lies between these extremes. I found that assumptions about dispersal significantly affected extinction risks (Fig. 4; ΔDIC = 68.5). Species-specific dispersal increased extinction risk from 6% assuming universal dispersal to 10%. Assuming no dispersal increased risk further to 12%. Extinction risks increase more rapidly with temperature rise assuming no- and species-specific dispersal (Fig. S5; interaction ΔDIC = 6.1). Incorporating more realistic species-specific dispersal 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 (ΔDIC = 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 to increase biological realism and therefore the accuracy of future predictions.

In 1981, James 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-induced extinctions will become increasingly apparent if we do not act now to limit future climate change.

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Supplementary Materials

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Materials and Methods

Figures S1-S5

Tables S1 –S4

References (*30-186*)

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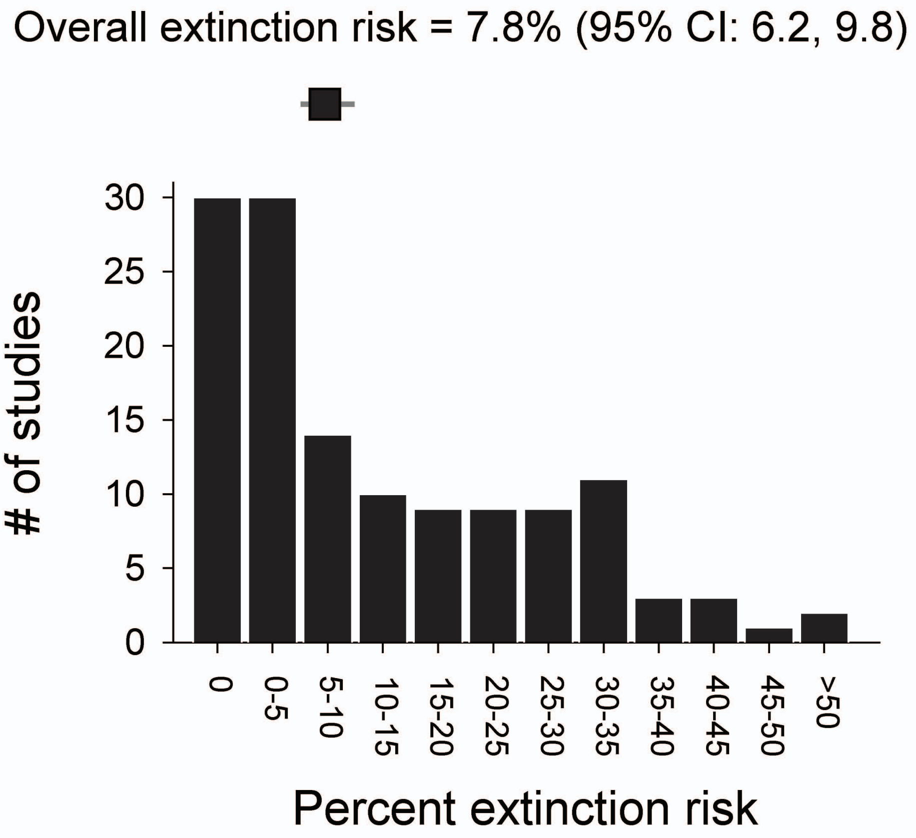
Fig. 1. **Histogram of percent extinction risks from climate change for 131 studies.** Percent extinction risk refers to the predicted percent of species extinctions in each study, averaged across all model assumptions. The meta-analysis estimated mean with 95% credible intervals is also shown.

Fig. 2. Predicted extinction risks from climate change accelerate with global temperature rise. The gray band indicates 95% credible intervals. Pre-industrial rise was calculated using standard methods (*27*). Circles indicate posterior means with area proportional to $\log_{10}$ sample size (see key). Extinction risks for four scenarios are provided: the current post-industrial temperature rise of 0.8°C (*5*), the policy target of 2°C, and representative concentration pathways 6.0 and 8.5.

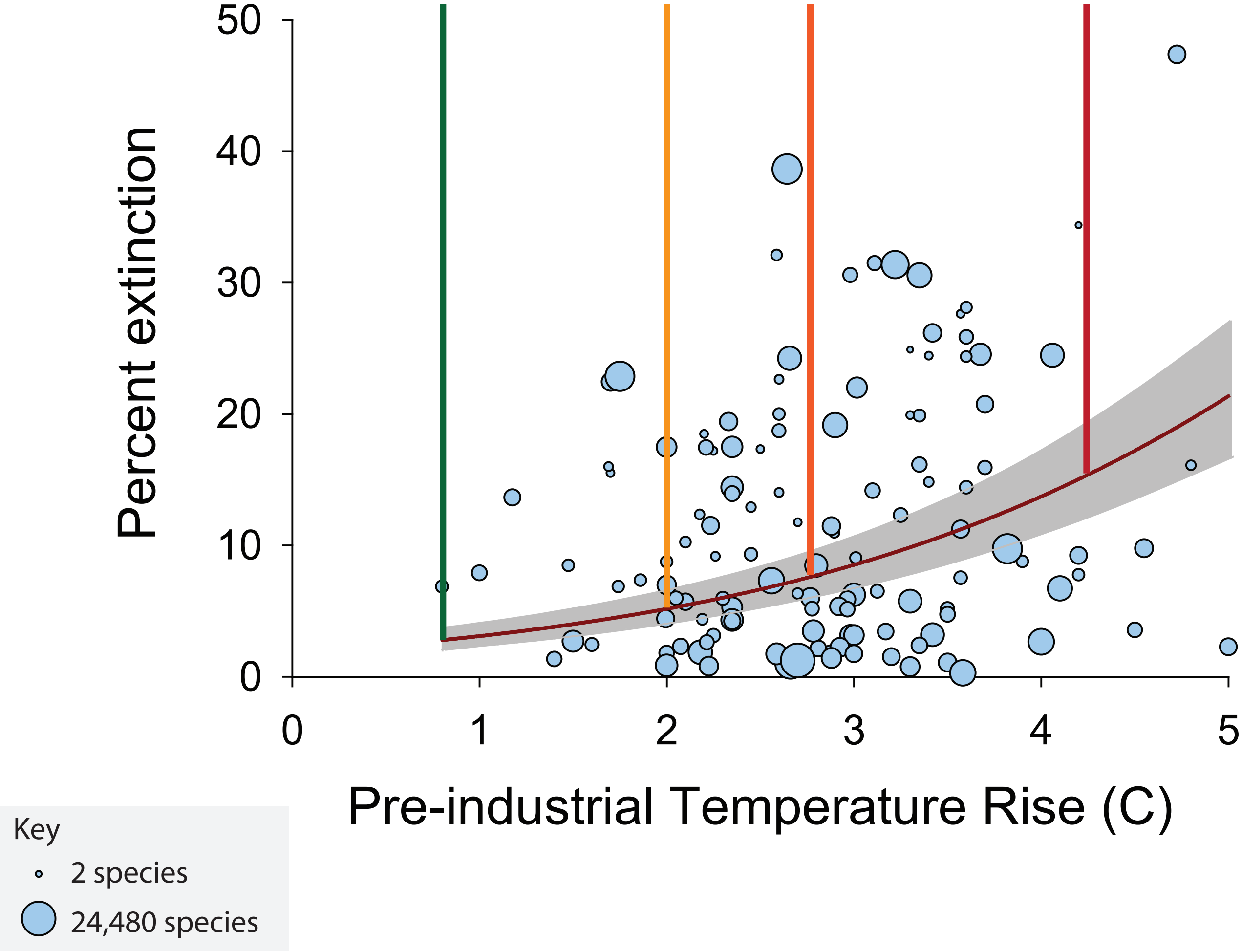
Fig. 3. Predicted extinction risks from climate change differ by region. The highest risks characterized South America, Australia, and New Zealand (14-23%), and the lowest risks characterized North America and Europe (5-6%). Colors indicate relative risk. Bar graphs with 95% credible intervals and number of studies (*n*) are displayed.

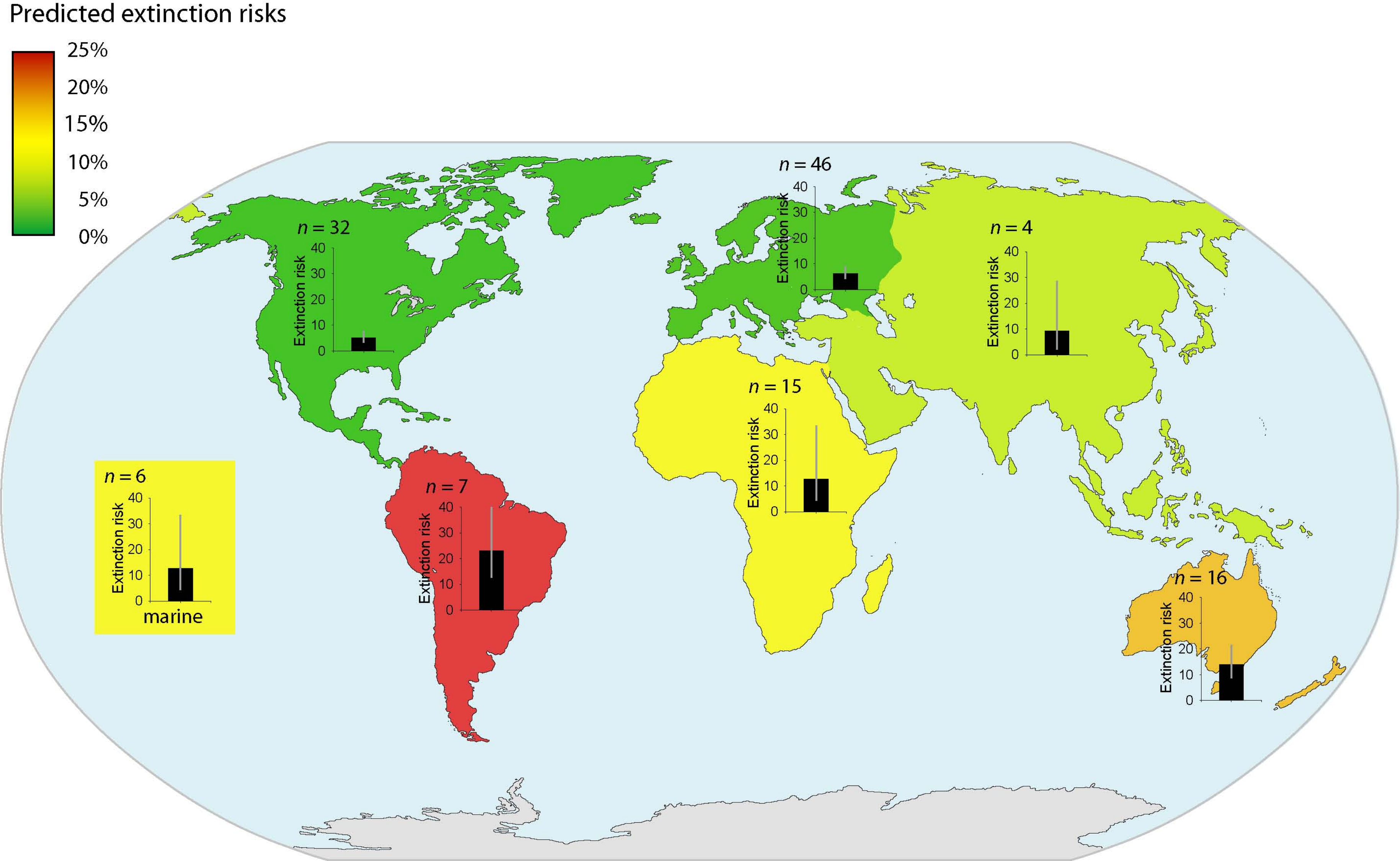
Fig. 4. Predicted extinction risks from climate change depend on model characteristics. The asterisk indicates model support (ΔDIC > 4) for each factor separately, and number of studies is included in parentheses. Categories within each factor are listed in order of increasing extinction

risk. The gray vertical reference line indicates mean overall extinction risk. Bars represent 95% credible intervals.


Overall extinction risk = 7.8% (95% CI: 6.2, 9.8)
# of studies
30
25
20
15
10
5
0
0
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
>50
Percent extinction risk

Scenario	Current	Target	RCP 6.0	RCP 8.5
Predicted extinction %	2.8	5.2	7.7	15.7




Predicted extinction risks
25%
20%
15%
10%
5%
0%
n = 32
n = 46
n = 4
n = 15
n = 7
n = 6
n = 16
Extinction risk
40
30
20
10
0
marine


Factor
Endemicity *
Non-endemic (73)
Endemic (59)
0
10
20
30
40
50
Taxon
Birds (24)
Plants (55)
Fish (10)
Mammals (21)
Invertebrates (31)
Reptiles (11)
Amphibians (10)
0
10
20
30
40
50
Extinction debt *
100% threshold (117)
95% threshold (69)
80% threshold (78)
0
10
20
30
40
50
Dispersal *
Universal (104)
Contiguous (5)
Species-specific (18)
None (60)
0
10
20
30
40
50
Model type
Species distribution model (107)
Mechanistic (20)
Expert (5)
Species-Area (7)
0
10
20
30
40
50
Predicted extinction risk