Founders Pledge

What is the damage function and associated tipping points for conservation and biosphere preservation?

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Contents

Key takeaways

- The relationship between global temperature rise and species extinction rates is best described by a **quadratic biosphere damage function**, indicating that the rate of biodiversity loss accelerates as temperatures increase (Urban 2015). Our best estimate of the function can be found here.
    - Climate change is expected to have widespread impacts on biodiversity across regions and species groups, with South America, Oceania, and amphibians facing the highest extinction risks due to high endemism, limited suitable future habitat, and other factors.
    - The shape of the biosphere damage function depends on the assumptions underlying the various climate change–extinction models such as extinction thresholds, inclusion of non-endemic species, and species dispersal abilities. More conservative assumptions lead to a steeper damage function, indicating that our best estimate of the damage function might change in the future as further research refines models.

- Among the major drivers of biodiversity loss in the 21st century, climate change is likely the primary cause, followed by land use, nitrogen deposition, biotic exchanges, and atmospheric CO2. However, there is still substantial uncertainty regarding the relative importance of these factors. Our best estimate is that the importance of climate change likely lies between 0.65 and 3 times that of land use.

- The human-centric damage function is steeper than the biodiversity damage function, suggesting that human-centric damages increase more rapidly with rising temperatures compared to biodiversity damages. This difference may be explained in part by humans being more adaptable to small temperature increases, while biodiversity damages start to occur at relatively lower levels of warming.
    - The distribution of expected damages across climate change scenarios is broadly similar for both biodiversity and human-centric losses, with most damage occurring in the most likely climate scenarios. However, a slightly higher share of biodiversity damages occurs at low temperature rise scenarios compared to economic losses.
    - Because of this higher steepness, philanthropists focusing on biodiversity conservation should target their efforts slightly more towards preventing low-warming scenarios compared to those with a purely human-centric focus.

Introduction

Climate change is a major risk to the biosphere. Over the course of the 21st century, rising temperatures will likely cause significant species loss. This report aims to quantify the exact relationship between different levels of warming and the extent of biosphere degradation.

Section 1 reviews the current scientific evidence on the link between global temperature rise and species extinction rates. It focuses on a recent meta-analysis (Urban 2015) that estimates extinction risk at different warming levels — a *biosphere damage function*. The report then evaluates the major related studies to argue that Urban (2015) represents the best current estimate of the damage function even though there are significant uncertainties about key modeling assumptions, including species dispersal abilities, and extinction thresholds.

Section 2 assesses the relative importance of climate change versus other major threats to biodiversity such as habitat loss from increased land use. Climate change is likely the biggest driver of species extinction this century, although land use is also of large importance.

Section 3 compares the biosphere damage function to the usual human-centric damage function from climate change. The comparison reveals that a slightly larger share of the expected damages to biodiversity occurs at lower temperature increases than is the case for economic/human-centric losses. **All else equal, climate philanthropists who want to focus on conservation should concentrate *slightly* more on interventions that affect low global warming scenarios than would be implied by a purely human-centric loss-prioritization. However, a regular climate prioritization is already very close to optimal when it comes to biodiversity conservation.**

The biosphere damage function

Key Points

- The biosphere damage function, which describes the relationship between global temperature rise and species extinction rates, is best approximated by a **quadratic function** according to Urban (2015)'s meta-analysis of 131 studies. This suggests that marginal increases in temperature will lead to increasingly severe biodiversity loss at higher temperature levels.
- **While the predicted extinction rates vary somewhat by region and species taxon, the impact of climate change on biodiversity is expected to be widespread.** South America and Oceania face the highest extinction rates due to the presence of many endemic species and limited suitable habitat on other continents, while amphibians are the most affected taxon.
- **The damage function's curvature is sensitive to assumptions about extinction thresholds, endemism, and species dispersal abilities**; more conservative assumptions (e.g., 100% extinction threshold, inclusion of non-endemic species, and universal dispersal) result in a more linear function, while less conservative assumptions (e.g., 80% extinction threshold, endemic-only species, and no dispersal) lead to a steeper damage function.
- Related studies like Warren et al. (2018) and Newbold (2018) provide additional context on species range loss and extinction rates for specific taxa that can be of interest for philanthropists with specific foci. Overall, Urban (2015) remains our best current estimate of the biosphere damage function.

This section of the report aims to establish the relationship between average global temperature rises and biosphere loss (subsequently called the *biosphere damage function*). This relationship is called the *biosphere damage function*. Damage functions generally describe how different levels of climate change cause various kinds of harmful outcomes. From these functions, it is possible to estimate the particular extent of damages at different temperature rise scenarios (e.g., 2C, or 4C) as well as the curvature of damages. This curvature could in theory take many forms. It could be *linear* such that a marginal 0.1C increase in warming will always lead to the same amount of additional damage regardless of the absolute temperature level. However, it could also be *quadratic* or *exponential* such that a further marginal increase causes more additional damage when it occurs at an already high temperature level. In that case, an increase from 3.5 to 3.6C should be averted much more than an increase from 1.5 to 1.6C. Damage functions are particularly useful because they help us understand on which scenarios we should focus our efforts: The steeper the damage function, the more important it is to prevent the most extreme climate change scenarios. On the other hand, a linear damage function would imply that reducing the chance of low-global warming scenarios is just as valuable as reducing the chance of high-global warming scenarios[1].

Similar to the often-used human-centric damage functions, we can estimate a biosphere damage function. This biosphere damage function shows the relationship between increases in temperature and changes in indicators of biosphere preservation.

There are many ways to quantify the condition of Earth's biosphere. Some of the most common indicators are species richness (biodiversity), species abundance, and ecosystem health. As discussed in our report on the *Most Effective Ways to Protect, Preserve and Rebuild Ecosystems*, there is not enough data for a global assessment of ecosystem health. As such, this report focuses on species richness and, to some extent, abundance. While the academic evidence is strongest with regards to a species richness damage function, we briefly review species abundance in the section Relationship to other studies.

The remainder of this section will review the estimate of a biosphere damage function from a recent meta-analysis (Urban 2015) before evaluating related academic literature to argue that Urban (2015) reflects our best current understanding of the relationship between climate change and species extinction rates. The section concludes with a brief application of the tipping point concept to biodiversity.

Urban (2015)

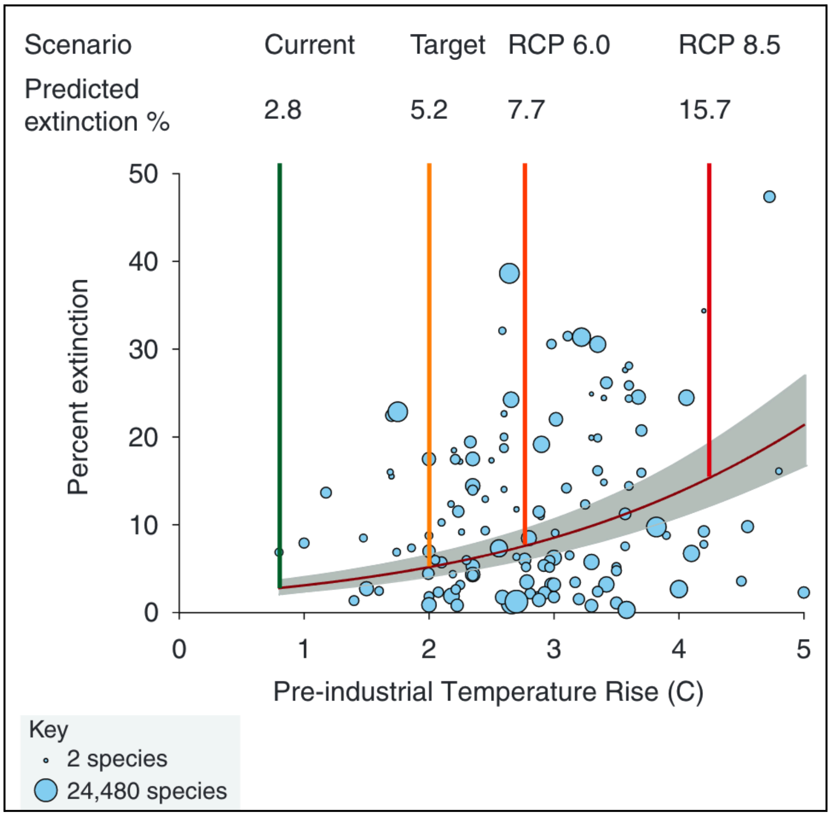
Urban (2015) is the most comprehensive study on the biosphere damage function. The author conducts a meta-analysis of 131 studies that predict the extinction risk posed by climate change to multiple species. Most of these studies estimate suitable habitat under future climate scenarios using the current relationship between species distributions and climates. Of the remaining studies,

- 15% used "process-based models of physiology or demography" (Urban 2015). These studies model the direct effect of climate change on specific extinction mechanisms (e.g., whether critical thermal maxima will be exceeded).
- 5% used species-area relationships. These studies use the relationship between the size of an area and the number of species in it to estimate the loss of species due to reduced habitat.
- 4% were based on expert opinion.

The result of this meta-analysis is an estimate of the increase in extinction risk at various levels of temperature rise compared to pre-industrial levels. The main specification in the study produces the following damage function.

[1] To be precise, lowering the expected temperature by 0.1 is equally effective, whether it targets a low or high global warming scenario.

Figure 1: Extinction rate damage function from Urban (2015)



Note: This figure is Figure 2 in Urban (2015). It shows the predicted mean species extinction risks as a function of climate change, measured as the average rise in global temperatures from pre-industrial levels. The individual light-blue dots indicate the estimates from the different studies included in the meta-analysis (posterior means). The size of the dots reflects the number of species assessed in each study — the smallest dot representing 2, and the largest dot representing 24,480 species. The function plots the relationship between pre-industrial temperature rise and the global species extinction rate predicted from the meta-analysis. The gray band shows 95% credible intervals for this relationship. The four vertical lines indicate the extinction rates at 4 climate change scenarios: "the current post-industrial temperature rise of 0.8°C, the policy target of 2°C, and RCPs 6.0 and 8.5." (Urban 2015)

The paper itself does not provide the underlying damage function. However, our own reproduction[2] of the figure shows that the line is well-approximated by the following **quadratic damage function[3]**:

[2] To be specific, Urban (2015) Figure 2 plots a damage function but does not report the equation for it. Our reproduction takes points from this function and fits a best-fit line through them to approximate the equation that produces the function in the meta-analysis. Appendix Table 1 holds the code for this digitisation and best-fit estimation in R.

[3] Appendix Figure 1 shows that a linear and an exponential fit approximate the Urban (2015) damage function substantially less well.

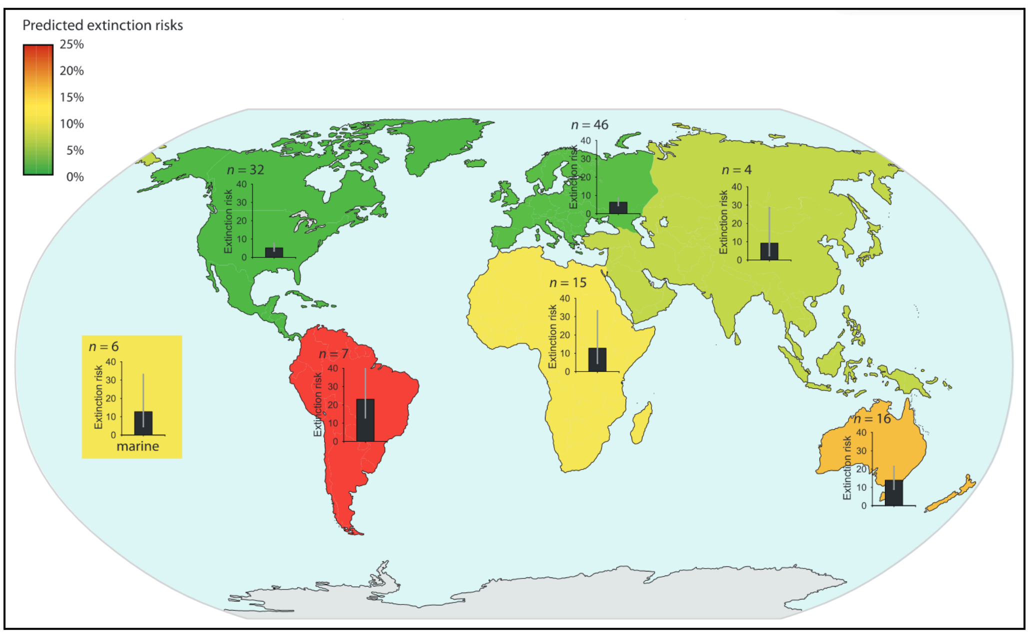
Biosphere damage function

$$Global\ extinction\ rate\ =\ 0.725\ \times\ (pre\ industrial\ temperature\ rise)^{2}\ +\ 2.162$$

In addition to the damage function, the paper breaks down the expected damage by continent and species taxon.

Figure 2 reproduces the regional breakdown. South America and Oceania face the highest extinction rates (mean = 23% and 14% respectively), and North America and Europe the lowest (mean = 5% and 6% respectively). There are two main reasons for the higher extinction rates in the former regions (see Urban 2015). Those areas have fewer comparable climates on other continents and are home to many endemic species with small ranges. In addition, Australia and New Zealand face higher extinction rates because species cannot easily move to new habitats because of the relatively small landmasses.

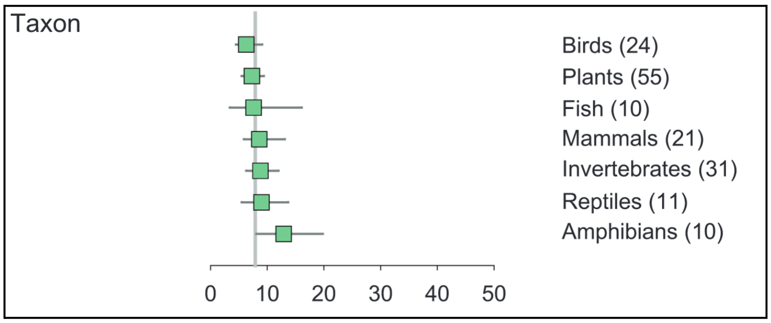
Figure 2: Predicted mean extinction rate by continent



Note: This figure is Figure 3 from Urban (2015). It shows the expected extinction risk by continent with 95% credible intervals and the number of studies on which each estimate is based.

Figure 3 reproduces the breakdown by species category. Birds are least affected by climate change (6–7% extinction rate) while amphibians are on average most affected (~12% extinction rate) — however, the credible intervals on these estimates are quite wide, so we are not very certain of this finding. Despite the variation in extinction rate by taxon and region, those sub-analyses show primarily that the biodiversity damage caused by climate change will be widespread across different species and locations.

Figure 3: Predicted mean extinction rate by taxon



Note: This figure is Figure 4 Panel B in Urban (2015). It shows the predicted mean extinction rate by species taxon together with 95% credible intervals. The gray bar indicates the meta-analysis' overall mean extinction rate of 7.9%[4]. The number of studies of each taxon is listed in parentheses.

The damage function is quite robust to alternative specifications. In the supplementary material to the article, the author checks for and finds no significant publication bias (Figure S1 in Urban (2015) Supplementary Material). He also concludes that a different transformation of the raw data from the various studies (arcsin vs logit) produces a similar damage function (Figure S3 ibid.).

However, three other assumptions affect the curvature of the damage function substantially: extinction thresholds, endemism, and species dispersal.

Extinction thresholds

Different studies included in the meta-analysis use different extinction thresholds, i.e., the share of habitat lost at which a species goes extinct. The most conservative view is that a species only becomes extinct once all of its habitat is lost — an extinction threshold of 100%. However, research has shown that often species become extinct when a large part of their habitat is destroyed such that it can no longer maintain a minimum viable population. As such, extinction thresholds might be somewhat lower. Figure 2A shows how the damage function varies when the meta-analysis includes only studies at specific extinction thresholds. A 95% extinction threshold produces a damage

[4] Note that this mean extinction rate does not equal the expected extinction rate once the probabilities of different climate change scenarios are taken into account. That rate is somewhat lower. It is calculated in the section Within-climate prioritization based on conservation.

function very similar to the default result. A 100% threshold leads to a damage function that is closer to linear, whereas an 80% threshold results in a far steeper damage function: at a temperature rise of 5 degrees celsius, the predicted global extinction rate would be around 40% — twice the ~20% extinction rate predicted by the default damage function. As discussed above, a more linear damage function would imply that philanthropists should focus relatively more on low-warming scenarios, whereas an even steeper damage function should lead us to shift focus to higher-warming scenarios.

Endemism

Some studies in the meta-analysis focus only on endemic species in a geographical area, i.e., those that can only be found there. Figure 4B shows how the damage function changes when the underlying studies are limited to those studying exclusively endemic species (shown in red) or to those that study both non-endemic and endemic species (shown in black). Endemic-only models steepen the damage function considerably. At a 5 degree celsius increase in temperature, the extinction rate doubles from around 20% in the default model to around 40%. On the other hand, when including both non-endemic and endemic species in a model, the extinction rate halves to about 10% at a 5 degree increase in warming[5].

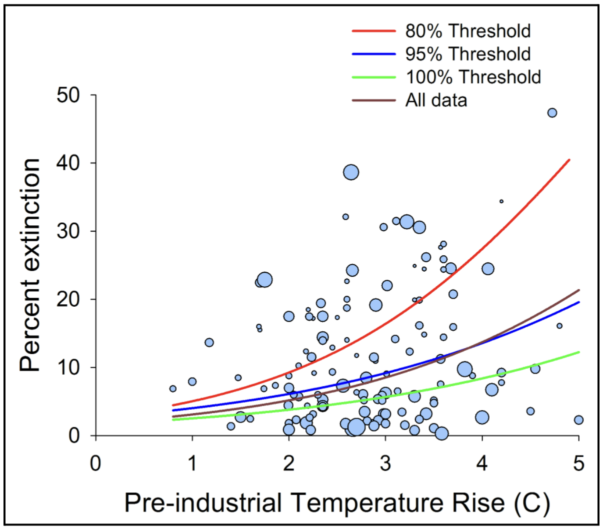
Dispersal

Lastly, assumptions about dispersal also influence the damage function. Models of the impact on temperature rise on extinction assume different dispersal abilities of species, i.e., to what extent they can move to new suitable habitat in other areas. *No dispersal* models assume that species cannot move to new habitat, whereas *universal dispersal* means they can move to suitable habitat regardless of the distance of such habitat or the species' ability to traverse that distance. The more moderate assumptions of contiguous and species-specific dispersal refer respectively to species moving to new habitat if it is adjacent to existing habitat or if their ability to traverse distance allows them to move to the new area. Assuming no dispersal again steepens the damage function such that the extinction rate at a 5 degree celsius temperature rise doubles from 20% to 40% (shown in Figure 2C). On the other hand, allowing for contiguous dispersal lowers it to around 15%.

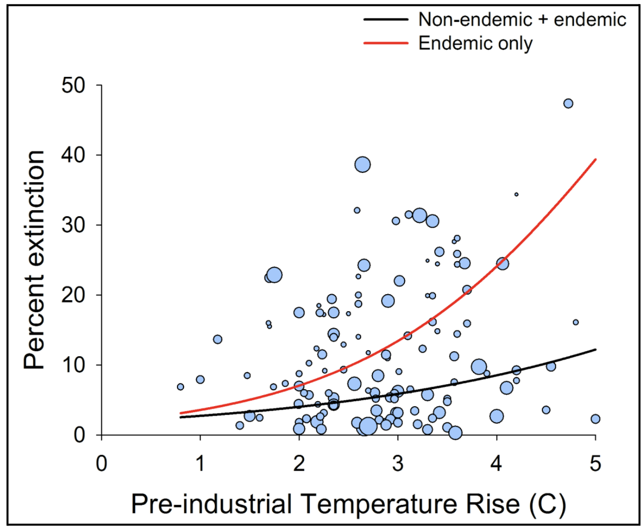
[5] It is not immediately clear whether either of these specifications lead to a more realistic damage function than the default model. Using endemic-only models might overstate the curvature as many species are not endemic. Using non-endemic + endemic models might understate the curvature as non-endemic species will be weighted disproportionately higher as they are counted multiple times in studies of different areas.

Figure 4: Sensitivity of damage function to various assumptions

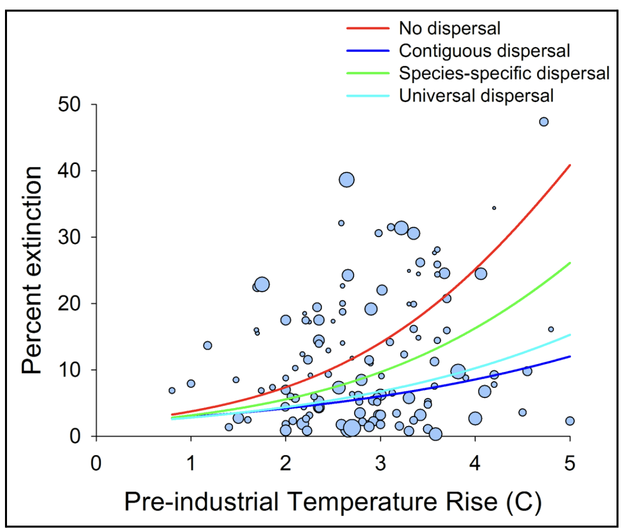
Panel A: Extinction thresholds



Panel B: Endemic vs endemic + non-endemic



Panel C: Dispersal



Note: This figure shows how the damage function estimated in Urban (2015) changes depending on different modeling assumptions. Panel A is Figure S2 from Urban (2015) Supplementary Material. It shows 3 additional damage functions estimated only on the subset of studies that use a specific extinction threshold. Panel B is Figure S4 from Urban (2015) Supplementary Material. It shows two damage functions which are estimated on subsets of studies that either include only endemic species or include both endemic and non-endemic species. Panel C is Figure S5 from Urban (2015)

Supplementary Material. It depicts 4 damage functions which are estimated on subsets of studies with different species dispersal abilities (discussed in the main text). In all three panels, the light-blue dots show the extinction rate vs temperature rise estimates from all individual studies included in the meta-analysis. The size of the dots reflects the number of species that a study includes. The smallest dot represents 2 species, while the largest dot stands for 24,480 species. (As such, the bubbles are not drawn to scale — the largest studies incorporate far more species than the bubble sizes would intuitively indicate.)

How accurate are the models underlying the Urban (2015) analysis? In a follow-up article, Urban et al. (2016) assess the predictive capacity of current models of climate-induced species extinction. They find that models can be made substantially more realistic by incorporating 6 mechanisms through which climate change affects species, including land use, species interaction, species physiology, and dispersal. Zurell et al. (2016) finds that better modeling indeed improves predictions. However, Urban et al. (2016) caveat that even for the most well-studied species, there is often not enough data to apply more realistic models. As such, any model is at the moment limited by data availability. The Urban (2015) damage function is therefore unlikely to be substantially improved upon by different modeling choices or analyses alone.

Relationship to other studies

There are several related studies that focus on other biodiversity variables or specific species. We briefly discuss the most relevant here, and how they relate to the Urban (2015) paper.

The first related study is Warren et al. (2018). They estimate how much of their range various taxa lose under different climate change scenarios (incl. 1.5, 2, 3.2, and 4.5 degrees Celsius). Their headline finding is that limiting temperature rises to 1.5 vs 2 degrees celsius exposes 50% fewer plants and vertebrates to a >50% habitat loss.

How does this study compare to Urban (2015)? We can use the predicted increase in biodiversity losses from a 1.5 to 4.5 degree warming scenario to benchmark the findings of the two articles:

- Share of species losing more than half of their range: 8–10x increase (Warren et al. 2018)
- Global extinction rate: 4.4x increase (Urban 2015)

The first takeaway is that species range is more sensitive to climate change than extinction. Intuitively this makes sense as extinction only occurs at extreme habitat loss (around 80–100% loss). As such, many species will experience range losses over 50% without going extinct. On the other hand, no species will go extinct without a >50% range loss (i.e., range loss is necessary but not sufficient for extinction.).

The second, related takeaway of this comparison is that the Warren et al. (2018) estimate is consistent in magnitude with the Urban (2015) damage function, providing a bit of additional evidence in favor of the Urban (2015) damage function. If a certain number N of species loses 50% or more of their habitat, the number of species that lose more than the extinction threshold of habitat (80/95/100 percent) is somewhat below N. As 4.4 < 8, the two estimates are consistent.

The third takeaway is that the two articles conceptualize biodiversity damages differently. Range loss can approximately be seen as species abundance loss (under the simplifying assumptions of *no dispersal* and uniform distribution of species members across their available habitat). The Warren et al. (2018) study can therefore be seen as measuring species abundance damages at various climate change scenarios. While they do not provide a damage function directly, they provide various related data points from which it is possible to approximate a species abundance damage function. Philanthropists who are particularly interested in species abundance over species richness could use this study as a starting point for estimating such a damage function.

Thomas et al. (2004) is an earlier study that aimed to estimate the extinction risk from climate change. It simulated extinction rates based on habitat loss due to climate change. It found much higher extinction rates and a steeper curvature. Even under a universal dispersal scenario, extinction rates would be 19% at 2 degrees warming and 33% at 2.6 degrees warming (compared to 5.2% and around 7.5% respectively in Urban 2015). Newbold (2018) is a similar simulation study that applies climate change scenarios to species' ranges and predicts extinction rates globally based on the scenarios. The study focuses only on terrestrial vertebrates. This study generally finds extinction rates between Thomas et al. (2004) and Urban (2015): 10% at 2 degrees warming compared to around 5 degrees in Urban (2015). It also finds a steeper increase in extinction rates as temperatures rise more (around 30% at 4.3 degrees compared to about 15% in Urban 2015)[6]. While both studies provide a systematic global analysis, we put less weight on them compared to the Urban (2015) meta-analysis, which is based on a much more extensive range of evidence (over 130 individual studies).

Pereira et al. (2010) is a widely-cited article that reviews biodiversity scenarios for the 21st century. However, it does not estimate a damage function or the effect of different climate change scenarios on biodiversity. It concurs with Urban (2015) that the modeling assumptions (for example with regards to species dispersal) have a large impact on forecasts.

To sum up, Urban (2015) reflects our best current estimate of the biodiversity damage function. Nonetheless, there is substantial variation in the damage function estimate due to the different modeling assumptions. To improve the accuracy of the biosphere damage function, studies need to incorporate richer mechanistic models. However, as these models are currently limited by a lack of data on the majority of species, new analyses and models alone are unlikely to change the conclusion from Urban (2015).

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[6] Newbold (2018) does not estimate a damage function. These extinction rates by climate change scenarios are shown in Figure 1 Panel A. The implied damage function would be steeper than Urban (2015).

Lastly, we briefly discuss whether there are associated tipping points with the biosphere damage function. In climate change research, tipping points refer to thresholds that, once crossed, push a system into a qualitatively different state. One example of such a tipping point is the Amazon rainfall-dieback theory: once deforestation exceeds a certain threshold, the reduction in captured water leads to more extensive droughts, leading to the death of more trees, which in turn further reduces the amount of captured water (see the *Climate* section in our report on the *Most Effective Ways to Preserve, Protect, and Rebuild Ecosystems* for more details). Eventually, the theory posits, the Amazon is pushed into a savannah-like state. For biodiversity, the same tipping points as for climate apply. Since crossing climate tipping further raises temperatures, those temperatures will then impact biodiversity as specified by the damage function.

In theory, it might be possible that biodiversity tipping points exist, too. Those species extinction rate thresholds, once crossed, might lead to further extinctions. However, there is very little research on such tipping points and we are not aware of any levels that would trigger further extinction and loss beyond the damage function outlined in the section above. While individual species are affected abruptly — a loss in range has very little impact on extinction risk until most of the range is lost — it is not clear at this point that similar discontinuities exist on a global scale.

Importance of climate change in biosphere conservation

Key Points

- While there is substantial uncertainty regarding the relative importance of climate change and land use as drivers of biodiversity loss in the 21st century, our best estimate is that **climate change is likely the primary cause of biosphere degradation, with land use somewhat behind**, followed by nitrogen deposition, biotic exchanges, and atmospheric CO2.
- Sala et al. (2000) estimate that climate change is about 0.65 times as important as land use in driving biodiversity loss, while Newbold (2018) suggests that climate change is more than 5-10 times as important. However, based on Powers and Jetz (2019), which provides an upper bound for extinction rates due to land use change, **the importance of climate change likely lies between 0.65 and 3 times that of land use.**

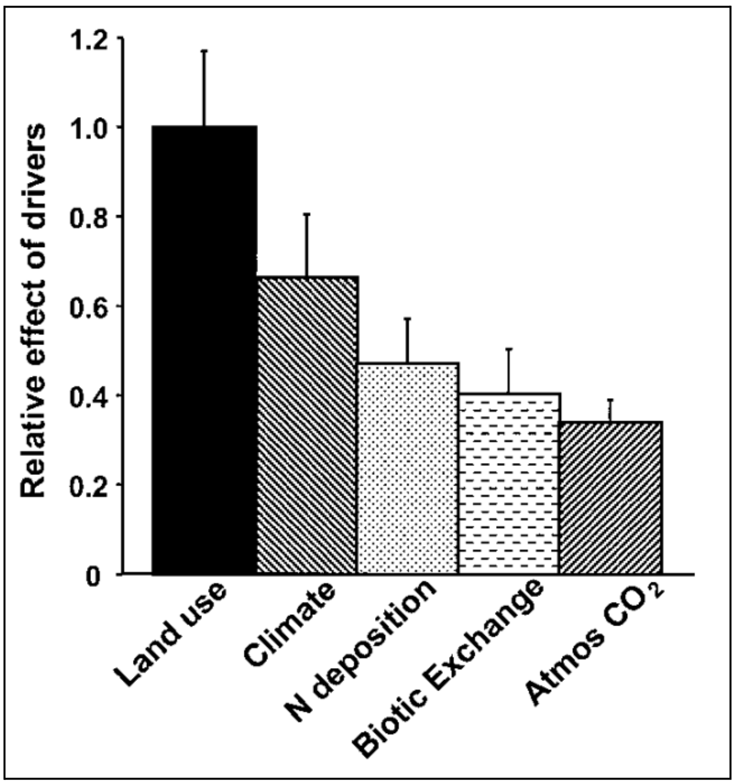
Sala et al. (2000) estimate biodiversity scenarios for the 21st century. They first research the 5 most important determinants of changes in biodiversity globally:

- Land use
- Atmospheric CO2 concentration
- Nitrogen deposition and acid rain

- Climate change
- Biotic exchanges (introduction of plants and animals to an ecosystem)

They then estimate separately the expected change in each driver and the impact of a one-unit change in each driver on biodiversity loss. Lastly, they multiply both sets of results to obtain the expected change in biodiversity due to expected changes in each driver over the course of the 21st century. The result is shown in Figure 5 below. According to this study, land use is the most important factor, followed by climate and nitrogen deposition.

Figure 5: Relative effect of drivers of biodiversity in the 21st century in Sala et al. (2000)



Note: This figure is Figure 1 in Sala et al. (2000). It shows the relative effect of the 5 most important drivers of biodiversity loss. The relative effect is obtained in three steps. First, the authors estimate the sensitivity of biodiversity to a one-unit change in each factor. Second, they calculate the expected change in each driver over the 21st century and multiply it with the sensitivity from step 1. Lastly, they scale the effects with the maximum effect (land use) equalling 1 such that relative effects are measured in shares of the land use effect size.

Newbold (2018) on the other hand estimates the effect of both climate change and land use on extinction rates for terrestrial vertebrates and finds that climate is a far bigger driver. In fact, while land use has led to a roughly 11% extinction of species so far, Newbold (2018) estimates that the future effect of land use change is negligible or even positive. At the same time, he predicts a 10–30% increase in extinction rate due to climate change depending on the specific RCP scenario[7]. The combination of these results would suggest that climate change far outweighs land use as a driver of extinction in the 21st century (by a factor of 5x or more).

In order to reconcile these two studies — Sala et al. (2000) placing climate at ⅔ the importance of land use and Newbold (2018) concluding that climate is multiple times as important as land use — we turn to a third study. Powers and Jetz (2019) estimate the impact of future land use on habitat and biodiversity loss. One of their main outcome variables is uplisting, which describes species moving from a lower to a higher risk category in the IUCN classification scheme (e.g., if a species was previously listed as vulnerable but is now listed at the higher level of endangered, it would be considered uplisted). They find that uplisting rates due to land use change are 16% for amphibians, 5% for birds, and 8% for mammals. These numbers provide an upper bound for extinction rate increases due to land use change. As extinction is a category in the IUCN classification scheme, every extinction would be classified as *uplisting*. On the other hand, a species can become more vulnerable, e.g., moving from endangered to critically endangered, and be classified as *uplisted* without going extinct. As a ballpark estimate, if one quarter of the uplisting occurs from critically endangered to extinct, the implied extinction rate due to land use change would be roughly 2.4%. Since the most likely extinction rate increase due to climate change is around 6–7%, it is likely that land use is less than half as important, though not negligible.

With these three studies, we now have three different rough estimates of the importance of land use vs climate change:

- Climate = 0.65 x Land use (Sala et al. 2000)
- Climate > 5–10x Land use (Newbold 2018)
- Climate = 3x Land Use (based on Powers and Jetz 2019)

While a full analysis of the differences between these studies is beyond the scope of this report, it is likely that the importance of land use is understated in Newbold (2018). Land use is generally considered a significant risk factor when it comes to biodiversity loss. A reduction in habitat strongly predicts an increase in extinction risk, and — as described in our report *Reducing Land Use and Returning Agricultural Land to Nature* — land use is increasing sharply in many parts of the world over the next 50 years. As a result, Newbold (2018)'s large reported difference in importance between climate change and land use as biodiversity loss drivers is likely overstated, too. It is therefore likely that the importance of climate change lies somewhere between 0.65x and 3x land use. While we have substantial uncertainty about the exact number, **our best estimate is that climate change is likely the primary cause of species extinction risk over the next 100 years, with land use somewhat behind, followed by nitrogen deposition, biotic exchanges, and atmospheric CO2.**

[7] This extinction rate range does not have uniform probability. An RCP 8.5 scenario (around 4–4.5C warming) that would imply a 30% extinction rate is about 1% likely whereas an RCP 2.6 scenario (around 1.5–2C warming) implies a 10% extinction rate and is 26% (i.e., about 26x more) likely.

Within-climate prioritization based on conservation

Key Points

- The human-centric damage function is somewhat steeper than the biodiversity damage function, indicating that human-centric damages increase more rapidly with rising temperatures compared to biodiversity damages (Figure 8).
    - The relative steepness of human-centric damages might be explained by humans being more adaptable to small increases in temperature, resulting in biodiversity damages starting to occur at relatively lower levels of warming.
- The distribution of expected damages across climate change scenarios is **broadly similar** for both biodiversity and human-centric losses, with most damage occurring in the most likely climate scenarios (Figure 10).
- However, due to the steeper human-centric damage function, a slightly higher share of biodiversity damages occurs at low temperature rise scenarios compared to human-centric damages**.** This suggests that **philanthropists focusing on biodiversity damage prevention should target their efforts slightly more towards low-warming scenarios compared to a purely human-centric prioritization.**

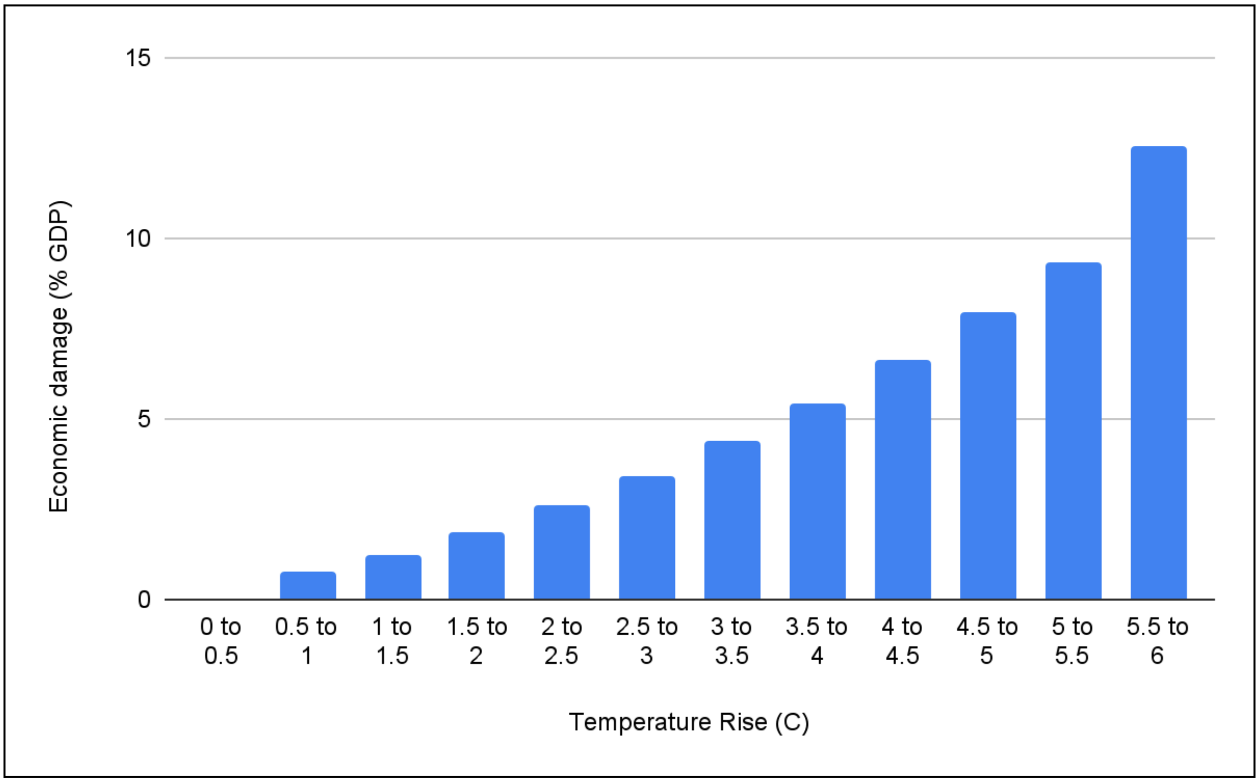
This section analyzes how optimizing for biodiversity conservation alters the distribution of expected damages across climate change scenarios. We proceed as follows:

1. Collect the human-centric and biodiversity damage functions (Figs. 6–7)
2. Compare the relative curvature of the two damage functions (Fig. 8)
3. Collect the probability distribution of temperature rise scenarios (Fig. 9)
4. Multiply the probability distribution of temperature rise scenarios with the damage functions to obtain the expected damages in each scenario (Fig. 10)

Our final goal is to compare the distribution of expected biodiversity vs human-centric damages in Figure 10. From this comparison, we draw out which scenarios philanthropists should focus on relatively more or less than if they were focussed on human-centric losses alone.

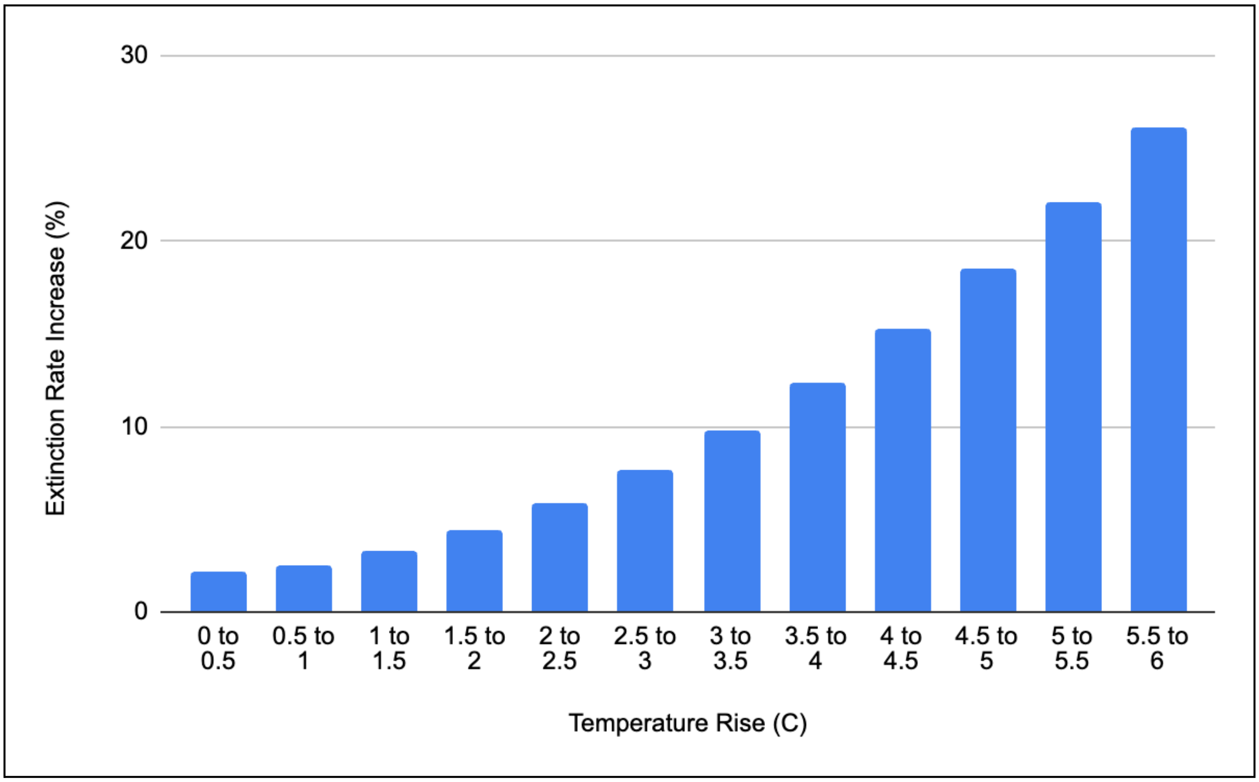
Figure 6 below shows the human-centric damage function of climate change used in Founders Pledge's climate work. It is an aggregation of canonical damage functions from the literature. Figure 7 shows the biosphere damage function estimated in Urban (2015).

Figure 6: Damage function of economic (human-centric) loss from climate change



Note: This figure shows the human-centric damage function from climate change that is used in Founders Pledge's climate work. It is an aggregation of various canonical damage functions. Economic losses are measured as % of GDP. We have very little credence in the absolute levels of economic damages — many damage functions are strongly criticized for being too simplistic and omitting certain damages. However, we are more certain in their relative curvature, which is sufficient for prioritization across climate change scenarios.

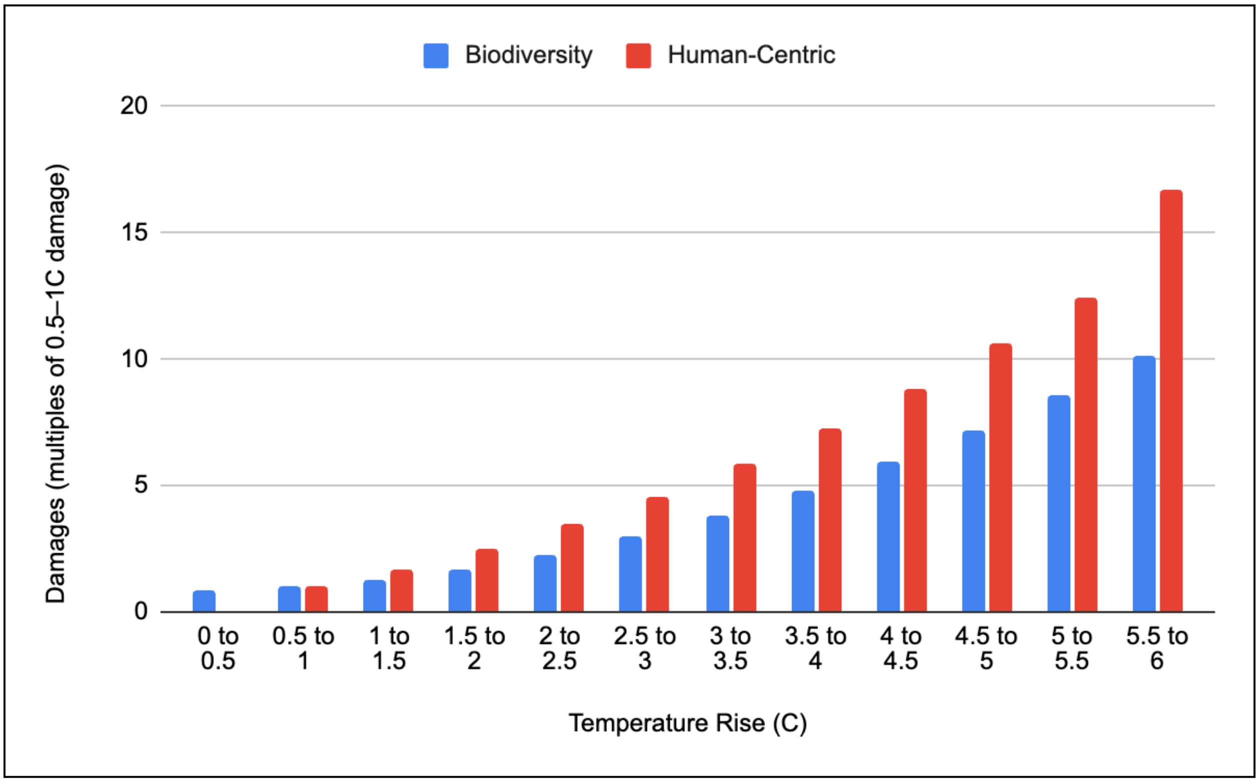
Figure 7: Damage function of extinction rate increase from climate change



Note: This figure shows the biodiversity damage function from climate change that is estimated in Urban (2015). Biodiversity damages are measured as percentage point increases in global species extinction rates.

Figure 8 puts the two damage functions on the same relative scale for ease of comparison. Both biodiversity and human-centric damages are shown in multiples of the respective damages at 0.5–1C warming. The human-centric damage function is somewhat steeper. For example, biodiversity damages rise by a factor of 7 from 0.5–1C warming to 4.5–5C warming, whereas human-centric damages increase by a factor of around 11. As such, philanthropists who plan to focus on biodiversity damage prevention should spread their efforts more evenly across potential climate changes compared to a purely human-centric prioritization. It is important to note, however, that this comparison does not say anything about the absolute levels of damages or how to prioritize between them. To give an example, one might think that the overall human-centric damages are more severe as they rise faster and exceed the relative biodiversity damages in each scenario in Figure 8. However, this reasoning would be misleading as damages are scaled to their low-warming scenario base levels. In fact, one plausible explanation for the steeper damage function is that humans are more robust/adaptable to lower levels of warming, and that for that reason biodiversity damages occur relatively earlier than economic losses.

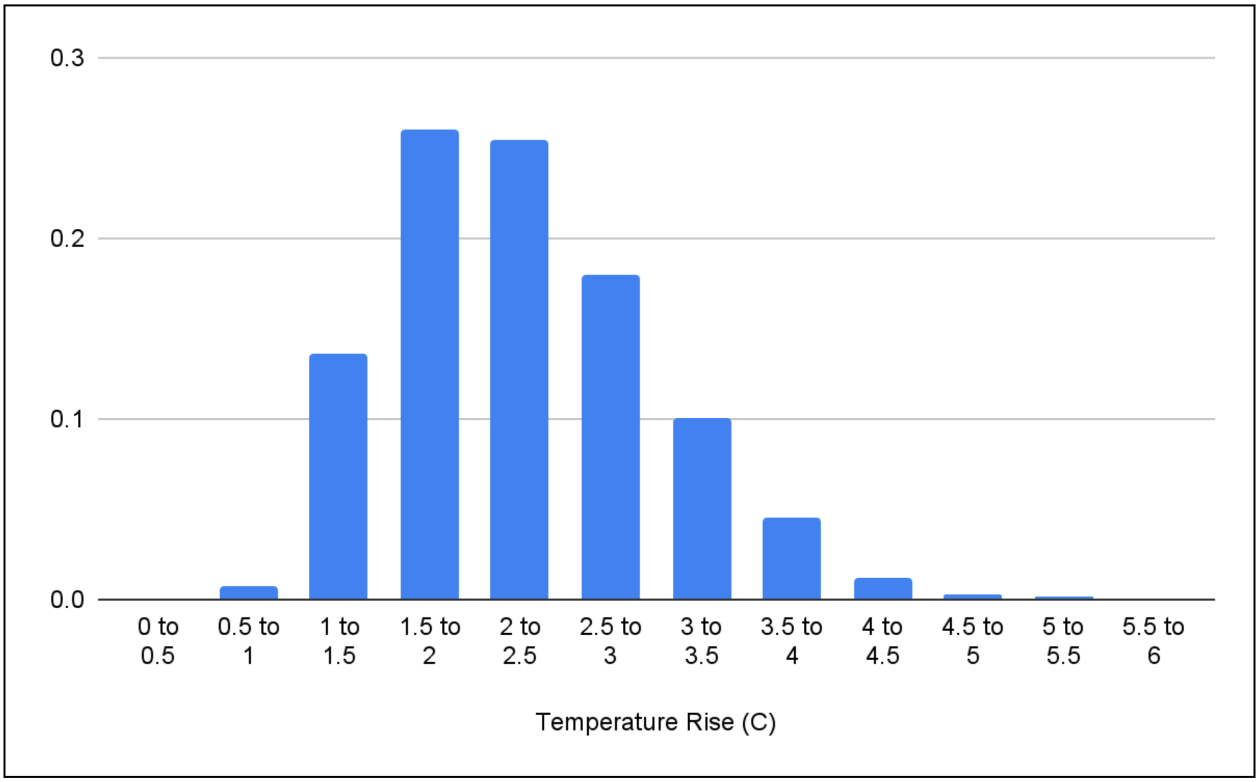
Figure 8: Relative curvature of biodiversity and human-centric damage functions



Note: This figure shows the biodiversity and human-centric damage functions from climate change. For more details on the biodiversity damage function, see the notes to Figure 7. More information about the human-centric damage function is provided in the notes to Figure 6. Both damage functions are scaled relative to their 0.5–1C temperature rise damages. As a result, the damage units are multiples of 0.5–1C warming damage.

The relative prioritization across climate change scenarios for a human-centric vs biodiversity focus becomes even more visible in the distribution of expected damages by climate change scenario below. In order to obtain that distribution, we multiply the human-centric damages with the probability mass function of climate change scenarios based on Venmans and Carr (2022). This function is shown in Figure 9 below.

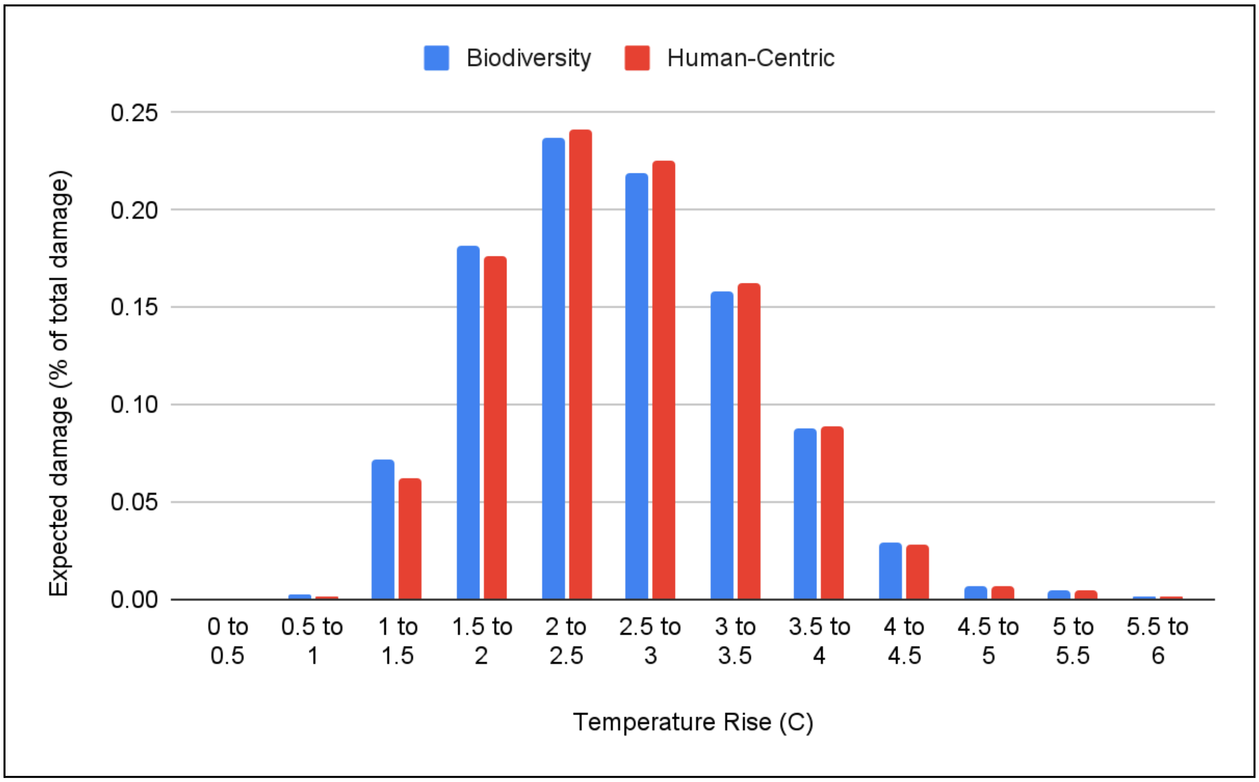
Figure 9: Probability mass function of temperature rise scenarios



Note: This figure shows the unconditional probability mass function of future temperature rises due to climate change. It is used in Founders Pledge's climate research and based on Venmans and Carr (2022).

Finally, Figure 10 plots the expected biodiversity/human-centric damage in each climate change scenario as a share of the total biodiversity/human-centric damage across scenarios.

Figure 10: Distribution of expected damages across climate change scenarios



Note: This figure shows the distribution of expected damages from climate change by temperature rise interval, measured as the share of total expected damages across all climate change scenarios. The series in blue shows biodiversity damages while the series in red shows human-centric damages. The distributions are the product of the probabilities of a given climate change scenario (Figure 8) and the expected damages under that scenario (Figures 6 and 7).

While the two damage distributions are broadly similar and most damage occurs in the most likely climate scenarios, a **slightly** higher share of biodiversity damages occurs at low temperature rise scenarios than is the case for human-centric damages. This is of course due to the steeper human-centric damage function. As a result, philanthropists who choose between interventions that target different climate change scenarios might, all else being equal, place a slightly higher focus on reducing the chance of even low-climate change scenarios than they would if they were focussed on human-centric damages alone. However, given the substantial uncertainty around the damage function curvature, it is possible that this conclusion will change based on further research. Overall, the distribution of expected damages is very similar between biodiversity and human-centric losses.

Conclusion

This report reviewed the evidence on the damage function linking climate change to global species extinction risk. The biosphere damage function estimated in Urban (2015) represents our current best understanding of that relationship. It predicts an expected extinction rate of 6.3% of species (weighted by the likelihood of different climate change scenarios). **The extinction risk increases quadratically as temperatures rise.** While Urban (2015) reflects our best estimate of the damage function, the function varies significantly based on different assumptions about species dispersal abilities, extinction thresholds, and how non-endemic species should be treated. Varying these assumptions can lead to extinction rates of 10%–40% at a temperature increase of 5 degrees Celsius. The default damage function predicts an extinction rate of 20% at that level of warming.

Climate change is likely the most significant driver of species extinction risk in the 21st century, followed by land use change. As a rough ballpark estimate, they may jointly cause around 10% of species to go extinct in expectation by 2100.

Compared to the human-centric damages, expected biodiversity damages from climate change occur slightly more at the lower end of climate change scenarios. This suggests that biodiversity-focused climate philanthropists should — all else being equal — consider focussing slightly more on interventions that have an impact at low levels of warming than they would under an human-centric prioritization framework. However, overall the expected damages distribution is very similar for biodiversity and human-centric damages. As such, a regular climate prioritization is close to optimal also for biosphere preservation goals.

References

Newbold, Tim. 2018. "Future Effects of Climate and Land-Use Change on Terrestrial Vertebrate Community Diversity under Different Scenarios." *Proceedings of the Royal Society B: Biological Sciences* 285 (1881): 20180792. https://doi.org/10.1098/rspb.2018.0792.

Pereira, Henrique M., Paul W. Leadley, Vânia Proença, Rob Alkemade, Jörn P. W. Scharlemann, Juan F. Fernandez-Manjarrés, Miguel B. Araújo, et al. 2010. "Scenarios for Global Biodiversity in the 21st Century." *Science* 330 (6010): 1496–1501. https://doi.org/10.1126/science.1196624.

Powers, Ryan P., and Walter Jetz. 2019. "Global Habitat Loss and Extinction Risk of Terrestrial Vertebrates under Future Land-Use-Change Scenarios." *Nature Climate Change* 9 (4): 323–29. https://doi.org/10.1038/s41558-019-0406-z.

Sala, Osvaldo E., F. Stuart Chapin, Iii, Juan J. Armesto, Eric Berlow, Janine Bloomfield, Rodolfo Dirzo, et al. 2000. "Global Biodiversity Scenarios for the Year 2100." *Science* 287 (5459): 1770–74. https://doi.org/10.1126/science.287.5459.1770.

Thomas, Chris D., Alison Cameron, Rhys E. Green, Michel Bakkenes, Linda J. Beaumont, Yvonne C. Collingham, Barend F. N. Erasmus, et al. 2004. "Extinction Risk from Climate Change." *Nature* 427 (6970): 145–48. https://doi.org/10.1038/nature02121.

Urban, M. C., G. Bocedi, A. P. Hendry, J.-B. Mihoub, G. Pe'er, A. Singer, J. R. Bridle, et al. 2016. "Improving the Forecast for Biodiversity under Climate Change." *Science* 353 (6304): aad8466. https://doi.org/10.1126/science.aad8466.

Urban, Mark C. 2015. "Accelerating Extinction Risk from Climate Change." *Science* 348 (6234): 571–73. https://doi.org/10.1126/science.aaa4984.

Venmans, Frank, and Ben Carr. 2022. "The Unconditional Probability Distribution of Future Emission and Temperatures." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4228706.

Warren, R., J. Price, E. Graham, N. Forstenhaeusler, and J. VanDerWal. 2018. "The Projected Effect on Insects, Vertebrates, and Plants of Limiting Global Warming to 1.5°C Rather than 2°C." *Science* 360 (6390): 791–95. https://doi.org/10.1126/science.aar3646.

Zurell, Damaris, Wilfried Thuiller, Jörn Pagel, Juliano S. Cabral, Tamara Münkemüller, Dominique Gravel, Stefan Dullinger, et al. 2016. "Benchmarking Novel Approaches for Modelling Species Range Dynamics." *Global Change Biology* 22 (8): 2651–64. https://doi.org/10.1111/gcb.13251.

Appendix

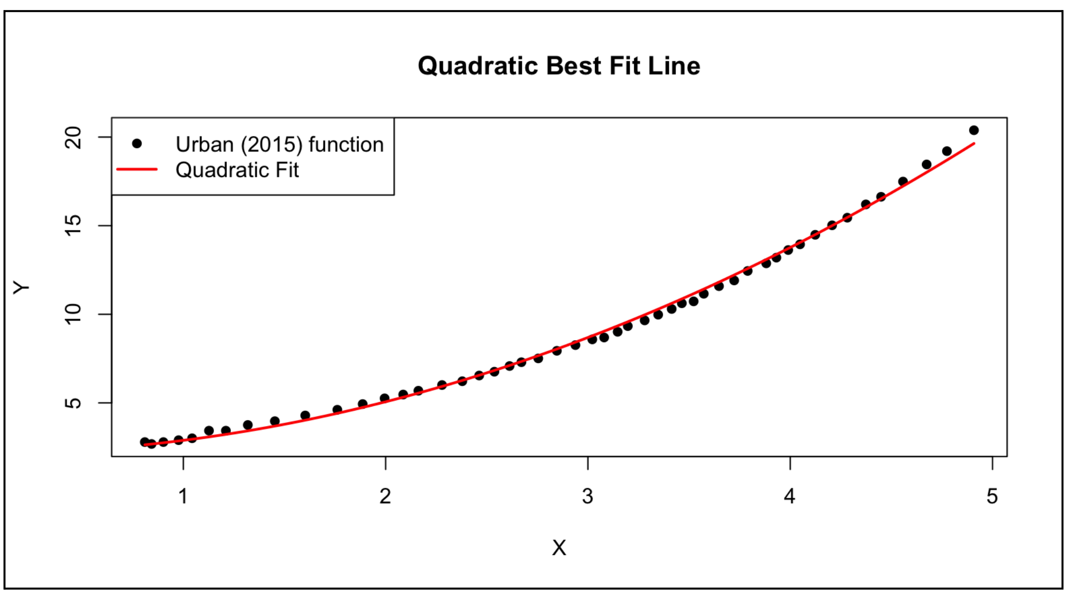
Appendix Table 1: R code to extract damage function from Urban (2015)

Unset

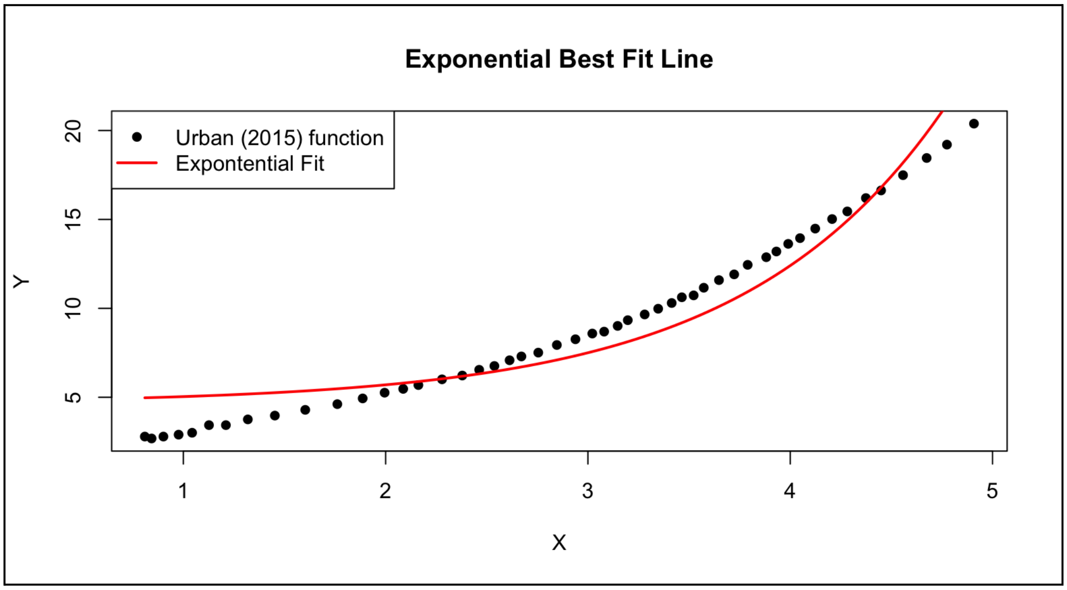
```
library(digitize)
coordinates = digitize("screenshot_of_figure_2", n = 50)
model <- lm(y ~ I(x^2), data = coordinates)
summary(model)
a <- coefficients(model)[2]
b <- coefficients(model)[1]
paste("y =", a, "* x^2 +", b)
plot(coordinates$x, coordinates$y, main = "Quadratic Best Fit Line",
xlab = "X", ylab = "Y", pch = 16)
curve(a * x^2 + b, add = TRUE, col = "red", lwd = 2)
legend("topleft", legend = c("Original Data", "Quadratic Fit"), col =
c("black", "red"), pch = c(16, NA), lty = c(NA, 1), lwd = c(NA, 2))
```

Appendix Figure 1: Approximation of damage function in Urban (2015) using a quadratic, exponential, and linear best-fit line

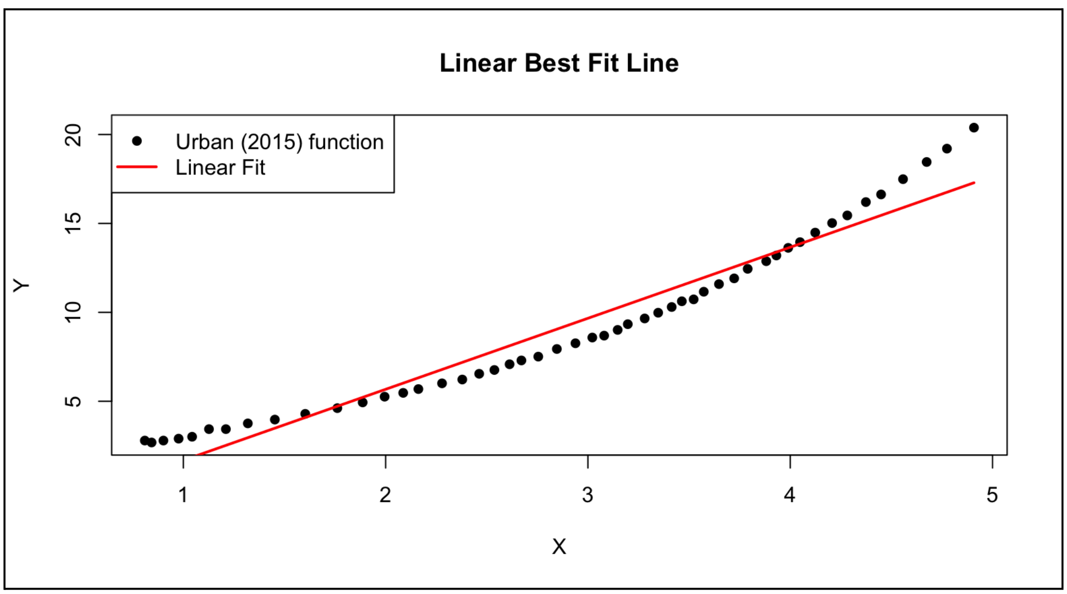
Panel A: Quadratic Best Fit Line



Panel B: Exponential Best Fit Line



Panel C: Linear Best Fit Line



Note: This figure shows individual data points from the damage function shown in Urban (2015) Figure 2. Panel A shows a quadratic best fit line. Panel B overlays an exponential best fit line. Panel C depicts a linear best fit line. The R^2 values are 0.997, 0.92, and 0.94 respectively. Both the R^2 values and the visual fit show that the damage function from Urban (2015) is best approximated by a quadratic function.