Expert perspectives on global biodiversity loss and its drivers and impacts on people

Forest Isbell[1*], Patricia Balvanera[2†], Akira S Mori[3†], Jin-Sheng He[4,5†], James M Bullock[6†], Ganga Ram Regmi[7,8], Eric W Seabloom[1], Simon Ferrier[9], Osvaldo E Sala[10], Nathaly R Guerrero-Ramírez[11], Julia Tavella[12], Daniel J Larkin[13], Bernhard Schmid[14,15], Charlotte L Outhwaite[16], Pairot Pramual[17], Elizabeth T Borer[1], Michel Loreau[18], Taiwo Crossby Omotoriogun[19,20,21], David O Obura[22], Maggie Anderson[1], Cristina Portales-Reyes[1], Kevin Kirkman[23], Pablo M Vergara[24], Adam Thomas Clark[25,26,27], Kimberly J Komatsu[28], Owen L Petchey[29], Sarah R Weiskopf[30], Laura J Williams[31], Scott L Collins[32], Nico Eisenhauer[27,33], Christopher H Trisos[34,35,36], Delphine Renard[37], Alexandra J Wright[38], Poonam Tripathi[39], Jane Cowles[1], Jarrett EK Byrnes[40], Peter B Reich[31,41,42], Andy Purvis[43,44], Zati Sharip[45], Mary I O'Connor[46], Clare E Kazanski[47], Nick M Haddad[48], Eulogio H Soto[49], Laura E Dee[50], Sandra Díaz[51,52], Chad R Zirbel[1], Meghan L Avolio[53], Shaopeng Wang[54], Zhiyuan Ma[54], Jingjing Liang[55], Hanan C Farah[1], Justin Andrew Johnson[56], Brian W Miller[57], Yann Hautier[58], Melinda D Smith[59], Johannes MH Knops[60], Bonnie JE Myers[61], Zuzana V Harmáčková[62], Jorge Cortés[63,64,65], Michael BJ Harfoot[66], Andrew Gonzalez[67], Tim Newbold[16], Jacqueline Oehri[29], Marina Mazón[68], Cynnamon Dobbs[69], and Meredith S Palmer[70]

Despite substantial progress in understanding global biodiversity loss, major taxonomic and geographic knowledge gaps remain. Decision makers often rely on expert judgement to fill knowledge gaps, but are rarely able to engage with sufficiently large and diverse groups of specialists. To improve understanding of the perspectives of thousands of biodiversity experts worldwide, we conducted a survey and asked experts to focus on the taxa and freshwater, terrestrial, or marine ecosystem with which they are most familiar. We found several points of overwhelming consensus (for instance, multiple drivers of biodiversity loss interact synergistically) and important demographic and geographic differences in specialists' perspectives and estimates. Experts from groups that are underrepresented in biodiversity science, including women and those from the Global South, recommended different priorities for conservation solutions, with less emphasis on acquiring new protected areas, and provided higher estimates of biodiversity loss and its impacts. This may in part be because they disproportionately study the most highly threatened taxa and habitats.

Front Ecol Environ 2023; 21(2): 94–103, doi:10.1002/fee.2536

Recent global reports (Díaz *et al*. 2019; IPBES Secretariat 2019; CBD 2020) have rigorously synthesized the large scientific literature on biodiversity and have identified major knowledge gaps. These gaps include large uncertainties in how many species are threatened with extinction (Díaz *et al*. 2019; CBD 2020; IUCN 2020), a lack of estimates for the impacts of global biodiversity loss on ecosystems and people (Isbell *et al*. 2017), and geographic and taxonomic biases in the available information (Tydecks *et al*. 2018). It remains difficult to fill these knowledge gaps due in part to the impressive diversity and complex biogeographic patterns of life on Earth. For example, in the past two decades, only about 1% of the estimated number of species have been assessed for risk of extinction by the International Union for Conservation of Nature (IUCN) (Mora *et al*. 2011; CBD 2020). Additional sources of information are urgently needed to inform global biodiversity conservation goals, targets (Díaz *et al*. 2020; Rounsevell *et al*. 2020; CBD 2021), and the policies and other transformative changes that will be needed to achieve them (CBD 2020).

Decision makers often rely on expert judgement to fill knowledge gaps (Cooke 1991; Sutherland and Burgman 2015; Cooke *et al*. 2018). Expert judgement has provided estimates and predictions of key unknowns in fields as diverse as nuclear-power safety (Cooke 1991), volcanic eruptions (Aspinall 2010), climate change (Bamber *et al*. 2019), and biodiversity loss (Schlapfer *et al*. 1999; Sala *et al*. 2000). The most accurate estimates and predictions come from large and diverse groups of experts, in part because expertise declines precipitously outside an individual's area of specialization (Aspinall 2010; Burgman

In a nutshell:

- Biodiversity experts estimated that about 30% (uncertainty range: 16–50%) of species have been globally threatened or driven to extinction since the year 1500
- There was overwhelming consensus that global biodiversity loss will likely decrease ecosystem functioning and nature's contributions to people
- Global biodiversity loss and its impacts may be greater than previously thought, due to higher estimates provided for understudied taxa and by underrepresented experts
- Experts estimated that greatly increasing conservation investments and efforts now could remove the threat of extinction for one in three species that may otherwise be threatened or extinct by the year 2100

[1]*Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, MN* [*](isbell@umn.edu); [2]*Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de*

et al. 2011; Sutherland and Burgman 2015). For example, biodiversity experts often study a small subset of taxa and ecosystems, whereas the drivers of biodiversity loss and sustainable solutions vary from place to place (Balvanera *et al.* 2017). Furthermore, even when small groups of specialists are carefully selected to ensure a diversity of expertise and geographic representation, the typical selection criteria (eg academic credentials, numbers of publications, years of experience) do not necessarily correspond to an expert's ability to provide accurate estimates or predictions (Burgman *et al.* 2011; Sutherland and Burgman 2015). Instead, the best judgements tend to come from experts who are less self-assured and assertive, and who integrate information from diverse sources (Sutherland and Burgman 2015). Input from a large and diverse group of biodiversity experts could therefore add to existing information and help fill remaining gaps in knowledge of global biodiversity loss.

Here, our objective was to gather and synthesize estimates and perspectives from thousands of biodiversity experts worldwide who collectively study all major taxa and habitats in freshwater, terrestrial, and marine ecosystems. We developed a survey to (1) identify points of global consensus, (2) help fill knowledge gaps for understudied taxa and regions, and (3) test for significant differences in estimates and perspectives among groups of experts. We compared survey results to other sources of information, where available (eg for well-studied taxa). Survey questions were developed by an international team of biodiversity experts to ensure that they were widely relevant and understandable to a geographically and linguistically diverse group of experts. Detailed methods are provided in WebPanel 1 and the full survey is provided in WebPanel 2.

We identified biodiversity experts as corresponding authors of papers published in scientific journals over the past decade on the topic of biodiversity (WebPanel 1). Focusing on the taxa and ecosystems they are most familiar with, these experts estimated past and future global biodiversity loss, which was defined in the survey as the percentage of species that are globally threatened or extinct (WebTable 1). Experts also ranked the drivers of global biodiversity loss and estimated its impacts on ecosystems and people. We received 3331 responses from biodiversity experts (WebTable 2) residing in 113 countries and conducting research on biodiversity in nearly all (187) countries (WebFigure 1), including all major habitats in freshwater, terrestrial, and marine ecosystems. Results reveal a few points on which experts overwhelmingly agreed and, notably, substantial differences in estimates and perspectives among geographic and demographic groups of experts. A follow-up survey (WebPanel 3) formally assessed the accuracy of estimates for a subset of experts (WebPanel 1; Cooke 1991; Colson and Cooke 2018; Quigley *et al.* 2018).

Magnitudes of past and future global biodiversity loss

Biodiversity experts estimated that about 30% (uncertainty range: 16–50%) of species have been globally threatened or driven extinct since the year 1500 (Figure 1a). Estimates of past biodiversity loss were highest among experts who study freshwater ecosystems, amphibians, mammals, and freshwater plants (Figure 1a; WebTable 3). Many tropical habitats (eg tropical and subtropical rivers, wetlands, and forests) were estimated to have the greatest percentage of species threatened or driven extinct since 1500 (Figure 2a).

Biodiversity experts studying terrestrial or freshwater invertebrates (which are mostly insects) estimated that about 30% (uncertainty range: 20–50%) of these species have been threatened or driven extinct since 1500 (Figure 1a). For these hyperdiverse and understudied taxa, expert estimates help fill an important knowledge gap and suggest that many more species may be threatened than previously thought. In particular, insects are the most diverse and understudied group of species, given that they make up about 75% of all species of animals and plants (Díaz *et al.* 2019; Purvis *et al.* 2019; IUCN 2020) and the IUCN has assessed threatened status for less than 0.2% of the roughly six million species (Purvis *et al.* 2019; IUCN 2020). A recent estimate that at least one million species of animals and plants are currently threatened with extinction assumed that 10% of insect species are threatened, based on a comprehensive review of the limited available evidence (Díaz *et al.* 2019; Purvis *et al.* 2019). Our survey estimates, which were provided by 629 experts who study terrestrial and freshwater invertebrates, therefore suggest that the percentage of insect species that are threatened may be much higher. Further investigations of the diversity and threatened status of insects and other hyperdiverse and understudied taxa are urgently needed (Clausnitzer *et al.* 2009; Eisenhauer *et al.* 2019; van Klink *et al.* 2020), especially in light of large recent declines in insect abundance in some locations (Eisenhauer *et al.* 2019; van Klink *et al.* 2020).

For well-studied groups of animals and plants, where at least 80% of the species have been assessed by the IUCN (IUCN 2020), expert estimates were not systematically higher or lower than IUCN estimates (Figure 1a, paired *t* test: $t = -0.93$, $P = 0.39$), although expert estimates were somewhat higher than previous estimates for birds and mammals (IUCN 2020) and somewhat lower than previous estimates for plants (Figure 1a; Nic Lughadha *et al.* 2020). Expert estimates would be expected to be slightly higher because they include not only currently threatened species but also extinctions since 1500 (Ceballos *et al.* 2015; Humphreys *et al.* 2019). For the species groups assessed by the IUCN, survey estimates may be partly influenced by IUCN estimates, creating an unavoidable circularity in comparisons. When responding to survey questions, experts were instructed to use their knowledge of the scientific literature, but to provide their current best estimates rather than rely on their recollection of previously published estimates.

If current trends continue, then further loss of biodiversity is expected, and experts estimated that 37% (uncertainty range: 20–50%) of species might be threatened or

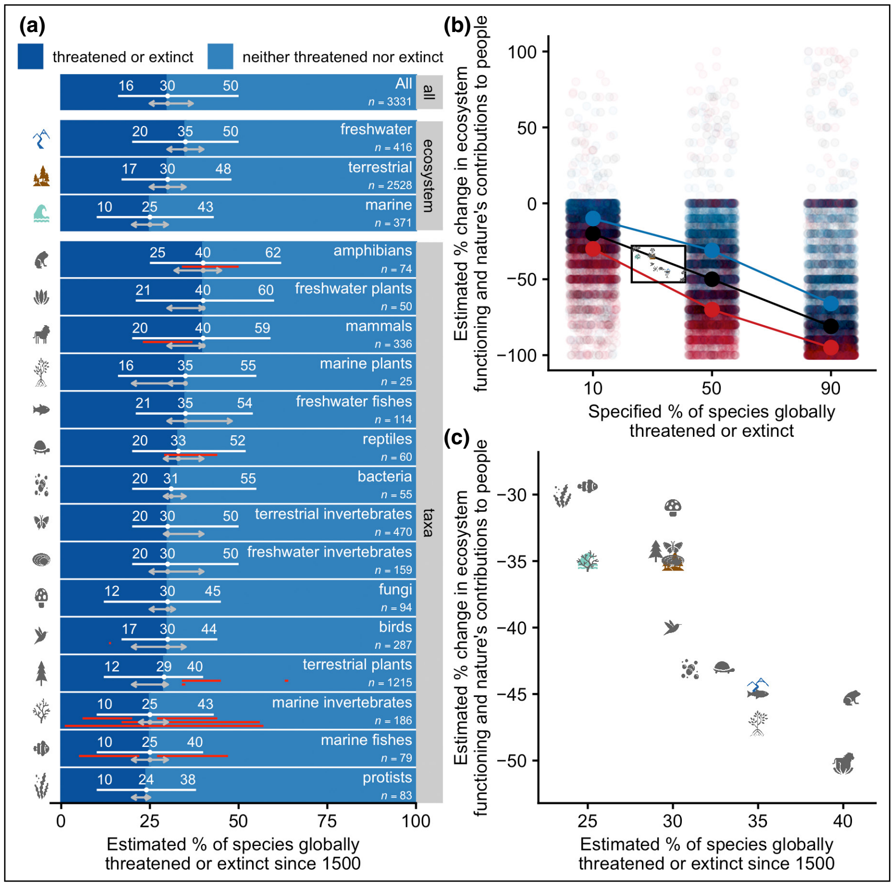

Figure 1. Expert estimates of (a) global biodiversity loss and (b, c) its impacts. (a) Medians of estimates and upper and lower bounds for past biodiversity loss (white circles, lines) and future biodiversity loss by 2100 if current trends continue (rightward gray arrows) or if conservation efforts are increased (leftward gray arrows). Where available, IUCN estimates are shown (red lines). (b) Expert estimates (black) as well as lower (blue) and upper (red) bounds for impacts of three levels of biodiversity loss (jittered on the x-axis). (c) Combining estimates of past biodiversity loss (a) and its impacts (b, linearly interpolated) shows the estimated impacts of past biodiversity loss. Sample sizes show the number of responses, which do not always sum to the total because respondents were not required to answer all questions.

driven to extinction by 2100 (Figures 1a and 2). Furthermore, many currently threatened species were predicted to go extinct before the end of this century. Most experts (84%) expected species to go extinct less than 100 years after becoming threatened, with 75% of experts expecting extinctions to occur within decades (10–100 years) and an additional 9% of experts expecting extinctions to occur within 10 years. Alternatively, if conservation investments and efforts are increased now, immediately implementing all currently known strategies, then experts estimated that 25% (rather than 37%) of species could be threatened or driven to extinction by 2100 (Figures 1a and 2). Thus, greatly increasing conservation investments and efforts now might remove the threat of extinction for about one in three of the species predicted to be threatened or driven to extinction by the end of this century (Figures 1a and 2). Reversing past global biodiversity loss (Mace *et al.* 2018; Leclère *et al.* 2020) will require new and ambitious transformative changes (Díaz *et al.* 2019). As more threatened species become globally extinct, biodiversity loss becomes increasingly irreversible.

Impacts of global biodiversity loss on ecosystems and people

We found overwhelming consensus (96% of experts agreed) that global biodiversity loss is decreasing ecosystem functioning and nature's contributions to people (NCP; Figure 1b). Experts estimated that the global threatening or extinction of species reduces ecosystem functioning and NCP by roughly 10–70%, accounting for large uncertainties in both the estimated magnitude of past global biodiversity loss and its estimated impacts (Figure 1b). That is, experts estimated that a lower bound of global biodiversity loss (10% of species threatened or driven to extinction) could decrease ecosystem functioning and NCP by at least 10%, and an upper bound of global biodiversity loss (50% of species threatened or driven to extinction) could decrease ecosystem functioning and NCP by as much as 70% (Figure 1b). Estimates of the impacts of global biodiversity loss were highest for freshwater ecosystems (Figure 1c; WebTable 3; WebFigure 2b) and for people's experiences in nature, water quality, opportunities for learning and inspiration, and the regulation of detrimental organisms, extreme events, soils, and climate (WebFigure 3). These estimated impacts of the global threatening or

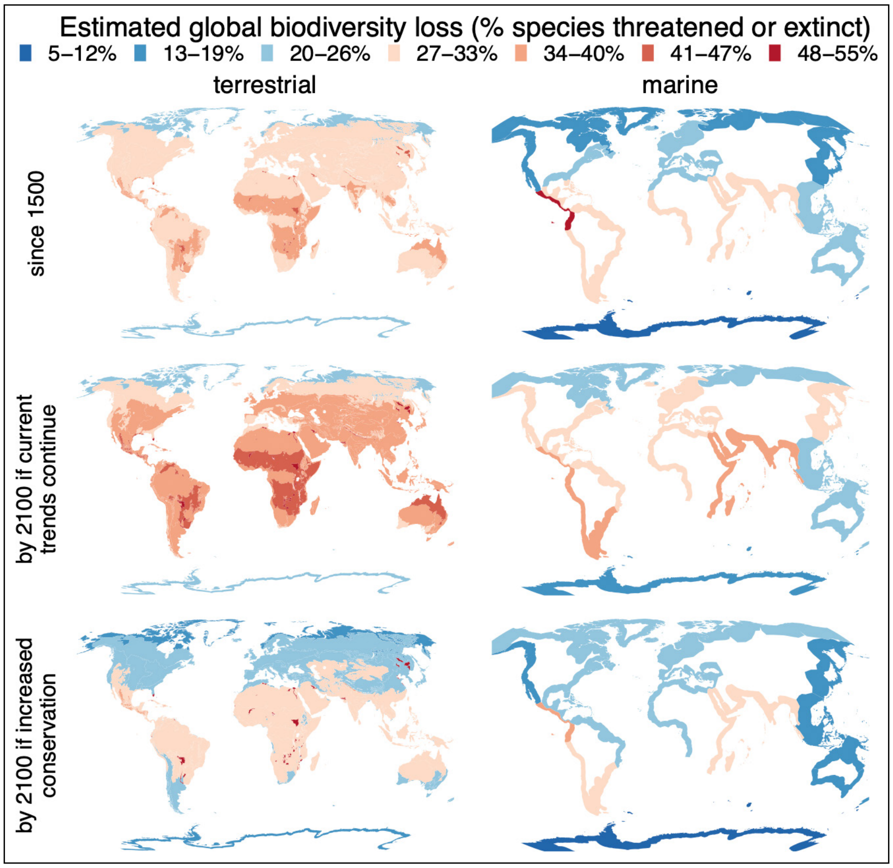

Figure 2. Expert estimates of changes in global biodiversity in terrestrial biomes (left column) and marine realms (right column) since 1500 (top row), by 2100 if current trends continue (middle row), or by 2100 if conservation efforts are intensified (bottom row). Values represent medians across all responses received from experts investigating biodiversity in each terrestrial biome and marine realm and are shown for terrestrial biomes and marine realms with at least ten responses (minimum = 11, median = 35, maximum = 470 responses per biome or realm). See WebFigure 2 for additional marine and freshwater habitats.

extinction of species are larger than the observed impacts of local species loss, which have been thoroughly studied in hundreds of biodiversity experiments and dozens of observational and theoretical studies (Loreau *et al.* 2022; O'Connor *et al.* 2017; van der Plas 2019). However, the impacts of global and local biodiversity loss are not expected to be equivalent (Isbell *et al.* 2017). For example, additional effects of biodiversity on ecosystem functioning can arise at larger spatial and temporal scales (Yachi and Loreau 1999; Isbell *et al.* 2011; Mori *et al.* 2018) and declines in the abundance of threatened species may have impacts before species are locally or globally lost.

Drivers of global biodiversity loss

Expert rankings of direct drivers of biodiversity loss differed substantially and significantly ($P < 0.05$) among taxa and ecosystems (Figure 3, a and c; WebTable 4; WebFigures 4 and 5). Previous studies (Sala *et al.* 2000; Maxwell *et al.* 2016; Purvis *et al.* 2019) identified land-use change and overexploitation as top drivers of global biodiversity loss, but primarily considered terrestrial ecosystems (Sala *et al.* 2000) or the few groups of species that have been thoroughly assessed by the IUCN (Joppa *et al.* 2016; Maxwell *et al.* 2016). Consistent with previous research (Sala *et al.* 2000; Maxwell *et al.* 2016; Purvis *et al.* 2019), we found land- and sea-use change was the top-ranked driver of global biodiversity loss (Figure 3a; WebTable 4), overexploitation was ranked as a major driver for losses of mammals and fishes (Figure 3c; Maxwell *et al.* 2016), and climate change was ranked as a major driver of losses in some of the most rapidly warming terrestrial ecosystems, including the tundra (WebFigures 4 and 5; Sala *et al.* 2000). We also found that climate change and overexploitation were top-ranked drivers of marine biodiversity loss, whereas land- and sea-use change and pollution were top-ranked drivers of freshwater biodiversity loss (Figure 3c; WebTable 4). Land- and sea-use change was identified as the most important driver of biodiversity loss for many well-studied taxa (eg amphibians, mammals, reptiles, birds) and for some hyperdiverse taxa whose threats have not yet been widely assessed by the IUCN (eg terrestrial invertebrates, some plant groups) (Figure 3, a and c). Climate change and pollution were among the major drivers of biodiversity loss for many other understudied taxa, including aquatic invertebrates and microbes (Figure 3c). While demonstrating that land- and sea-use change is essential to address, our results also indicate that comprehensively conserving biodiversity will require tackling many other drivers of biodiversity loss as well.

Magnitudes of biodiversity loss are expected to increase with further habitat loss (Haddad *et al.* 2015; Isbell *et al.* 2015) and climate change (Urban 2015; Trisos *et al.* 2020). Experts estimated that losing 50% or 90% of habitat threatens or drives to extinction about 41% (range: 30–60%) or 80% (range: 63–95%) of species, respectively (WebFigure 6a). The experts also estimated that global warming by 2°C or 5°C threatens or drives to extinction about 25% (range: 15–40%) or 50% (range: 32–70%) of species, respectively (WebFigure 6b). These estimates are higher than some previous related estimates; for instance, previous studies have projected that loss of 50% or 90% of habitat could lead to loss of 7–36% or 21–78% of species, respectively (Isbell *et al.* 2015), and that warming of 4.3°C could threaten 16% of species (Urban 2015).

Globally, most species are threatened by multiple drivers of biodiversity loss (Maxwell *et al.* 2016). We found overwhelming

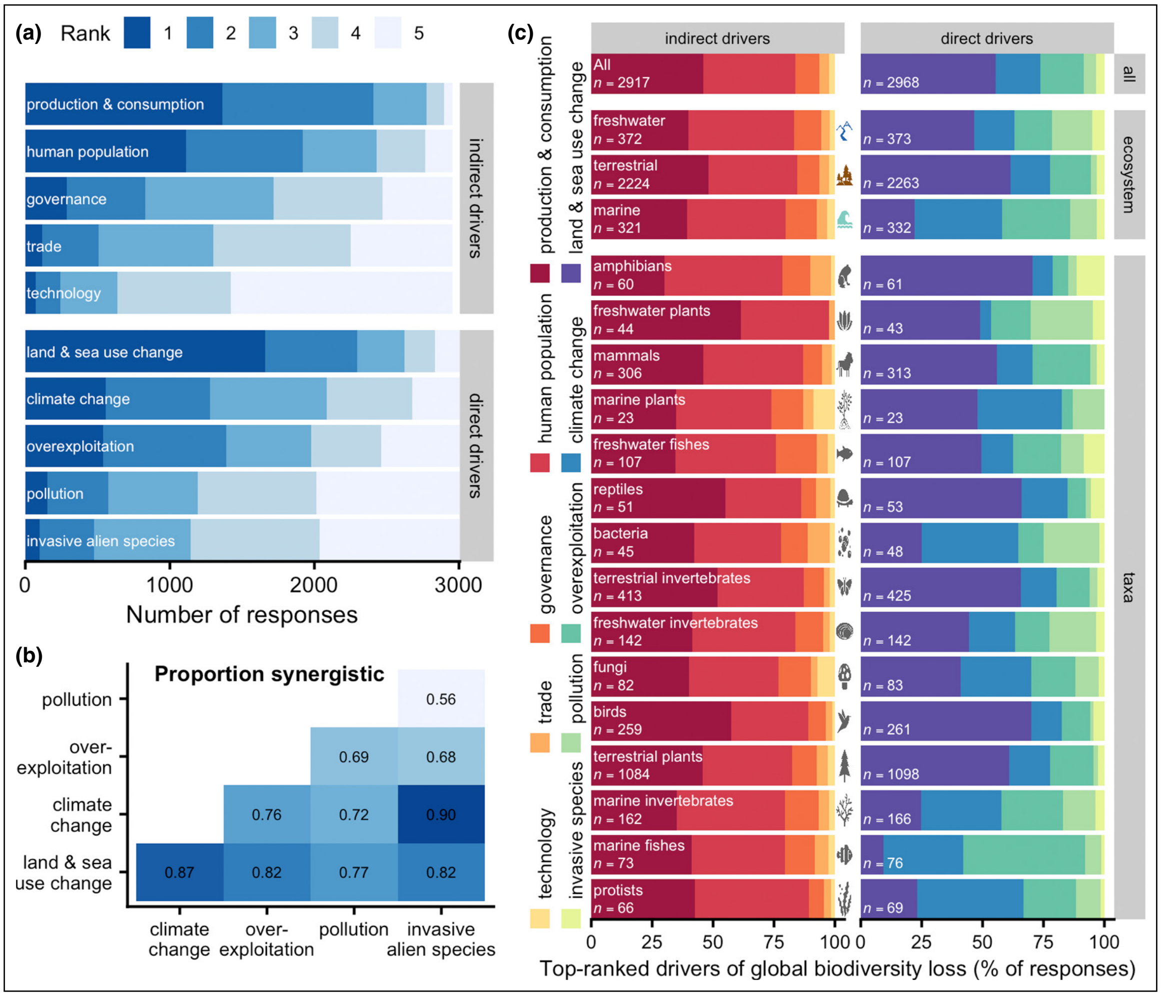

Figure 3. (a) Expert rankings of drivers of biodiversity loss, (b) their synergistic interactions, and (c) top-ranked drivers by ecosystem type and taxa. (a) Low numbers correspond to large impacts on biodiversity. Experts indicated biodiversity loss is driven primarily by changes in land use and sea use resulting from production and consumption patterns and human population growth. (b) Dark colors indicate that many experts expected the pair of drivers to synergistically reduce biodiversity to a greater degree than the sum of their individual effects. See WebTable 4 for tests of significant differences in rankings and WebFigures 5 and 6 for driver rankings by habitat.

consensus (94% of experts agreed) that there are synergistic interactions between pairs of direct drivers of biodiversity loss, such that the combined effects of multiple drivers are greater than the sum of their individual effects. This consensus could help improve the specification and accuracy of projections of future changes in biodiversity (Sala *et al.* 2000). When asked about specific pairs of drivers, 90% of experts reported synergistic interactions between climate change and invasive alien species, whereas just over half (56%) of experts reported synergistic interactions between pollution and invasive alien species (Figure 3b).

Upstream from these direct drivers of biodiversity loss are indirect drivers, which can be considered root causes and leverage points for addressing biodiversity loss (Díaz *et al.* 2019). We asked experts to rank the relative importance of five classes of indirect drivers. Experts reported that biodiversity loss is driven indirectly, in order of decreasing relative importance, by production and consumption, human population dynamics, governance, trade, and technology (Figure 3, a and c; WebTable 4). In contrast to the rankings of direct drivers, these rankings of indirect drivers remained fairly consistent across ecosystems, habitats, and taxa (Figure 3c; WebFigures 4 and 5; WebTable 4).

Demographic and geographic differences in experts' estimates and recommendations

In addition to helping fill knowledge gaps and identify points of consensus, expert judgement can also reveal important demographic and geographic differences in perspectives and estimates. Demographic and geographic groups of experts provided similar rankings of direct and indirect drivers of biodiversity loss (Figure 4b; WebTable 4), but recommendations for allocating conservation budgets varied (Figure 4c; WebTable 3). Specifically, we asked experts to indicate their recommended allocation of conservation investments to five

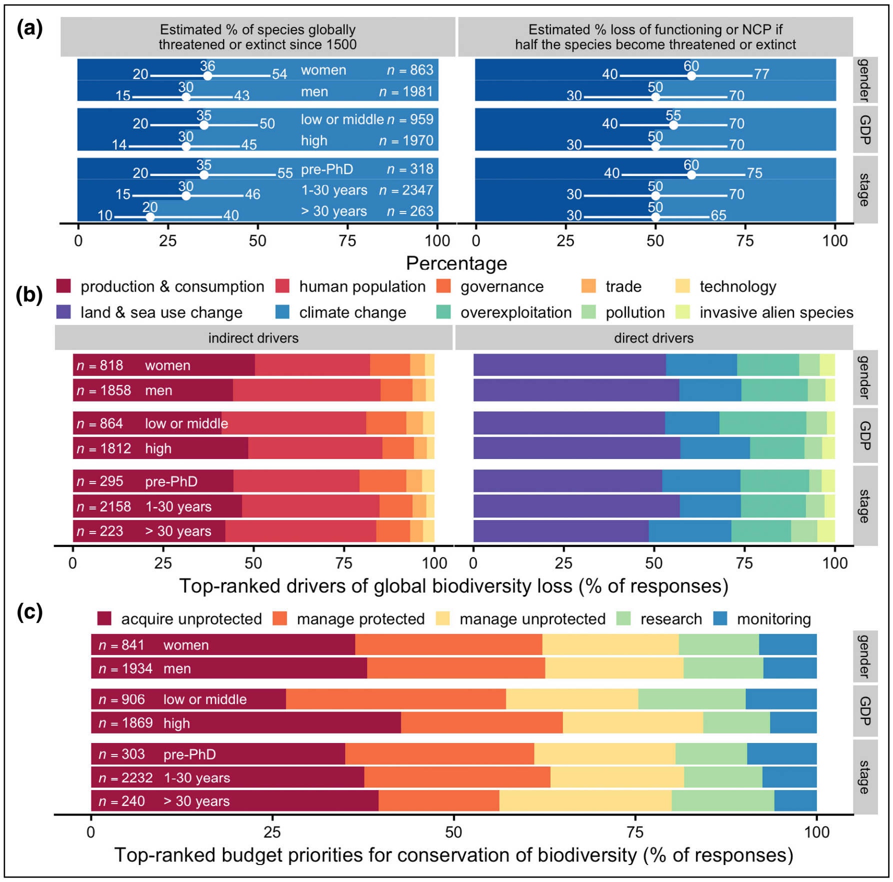

Figure 4. Demographic and geographic groups of experts provided (a) different estimates of biodiversity loss and its impacts, (b) similar rankings of drivers, and (c) different recommended top priorities for conservation budgets. Symbols, lines, and colors in (a) and (b) match those in Figure 1 and Figure 3, respectively. Genders were self-identified. NCP = nature's contributions to people. See WebTable 2 for other genders with small sample sizes. For gross domestic product (GDP) comparisons, countries were grouped into high-income countries or all other income groups, following the World Bank's classification for 2020. For career stage, the number of years of related work post-PhD is provided.

categories: acquire new protected areas, manage protected areas, manage unprotected areas, monitor biodiversity, and research biodiversity. Experts who identified as women recommended investing more in monitoring biodiversity ($P<0.01$) and less in acquiring unprotected areas ($P<0.001$) than experts who identified as men (Figure 4c; WebTable 3). Experts who live in low- or middle-income countries recommended investing more in researching and monitoring biodiversity ($P<0.001$), and less in acquiring and managing unprotected areas ($P<0.001$), than experts who live in high-income countries (Figure 4c; WebTable 3). Experts less than 30 years post-PhD recommended investing more in managing protected areas ($P<0.05$) and monitoring biodiversity ($P<0.01$) than experts at later stages in their careers (Figure 4c; WebTable 3). In addition, a multivariate analysis of variance indicated a significant two-way interaction between gender and income group ($F_{2,2764}$ = 3.82, $P<0.01$), as well as significant main effects of gender ($F_{4,2764}$ = 4.07, $P<0.01$), income group ($F_{4,2764}$ = 32.64, $P<0.001$), and career stage ($F_{4,2764}$ = 8.67, $P<0.001$) on the overall recommended budget allocation strategy. Men from wealthy countries, who tend to be overrepresented in biodiversity science and policy (Tydecks *et al*. 2018; Maas *et al*. 2021; Mori 2022), recommended investing in significantly different priorities than their colleagues, especially women from the Global South. Experts who recommended allocating more funds to research also recommended allocating more funds to monitoring (Pearson's r = 0.27, t = 14.74, $P<0.001$).

Furthermore, demographic and geographic groups of experts provided significantly different estimates for the magnitude of biodiversity loss and its impacts (Figure 4a; WebTables 2 and 3). Notably, certain groups of experts that have been underrepresented in global biodiversity science, including experts who identify as women and who are from the Global South (Tydecks *et al*. 2018; Maas *et al*. 2021; Mori 2022), provided significantly ($P<0.01$) higher estimates for past biodiversity loss and its impacts (Figure 4a; WebTables 2 and 3). There are several potential explanations for this variability in estimates (Figure 4a).

First, groups of experts may provide higher estimates if they disproportionately study the places or taxa that are experiencing the greatest biodiversity loss. For example, low- and middle-income regions are known to harbor a disproportionate share of the world's ecoregions and threatened species (Tydecks *et al*. 2018). Therefore, it is perhaps unsurprising that experts who live in these countries, and who compose the majority (79% of responses) of all experts who study biodiversity in those nations, provided higher estimates of biodiversity loss (Figure 4a). Indeed, we found that even experts who live in high-income countries provided higher estimates of past biodiversity loss if they study biodiversity only in low- or middle-income countries than if they study biodiversity only in high-income countries (Mood's median test, Z = –2.30, P = 0.021). Moreover, we found that experts who identify as women disproportionately study taxa that experts estimated are under greatest threat. That is, estimates of past biodiversity loss were higher for the taxa that are disproportionately studied by women, regardless of whether we considered all experts (Mood's median test, Z = 3.21, P = 0.0014) or, to avoid circularity, only those who identify as men (Mood's median test, Z = 3.09, P = 0.0020). Consequently, at least some of the geographic and demographic variation in estimates is likely due to underlying variation in rates of biodiversity loss and differences in which locations or what taxa various groups of experts tend to study.

It is also possible that differences in estimates are due to some groups of experts providing more accurate estimates than other groups, although we found no evidence of this. To formally assess the accuracy and informativeness of expert estimates, a follow-up survey, which included test questions with accepted answers, was completed by 59 coauthors of this paper (WebPanel 1). We then used the classical model of expert elicitation (Cooke 1991; Quigley *et al.* 2018) to analyze results. We found considerable variation in the accuracy and informativeness of estimates within all groups of experts (WebTable 5; WebFigure 7), but no significant differences between demographic or geographic groups of experts (WebTable 6). We also found no evidence that experts who provided higher or lower estimates of past biodiversity loss also tended to provide more accurate or informative estimates (WebPanel 1).

Survey limitations

We acknowledge some limitations of our survey and explain how we attempted to address them, even if imperfectly. Our main survey did not include test questions with accepted answers. We did, however, include test questions in our follow-up survey to (1) test for systematic bias in estimates and (2) assess the statistical accuracy of several equal-weighted or performance-weighted approaches for combining expert estimates (WebPanel 1). We found no evidence for systematic bias in estimates (WebPanel 1; WebFigure 7). We also determined that the equal-weighted median approach, which we used throughout our analysis to combine expert estimates, was sufficiently statistically accurate, albeit less so than performance-weighting (WebPanel 1; WebTable 5).

Our survey and its sample of biodiversity experts were biased toward experts who publish and communicate in English. Although the invitation to complete the survey was translated into several languages (see "author contributions" in the Acknowledgements), our main survey was offered only in English. In addition, although we received responses from a large and diverse group of experts, our process of identifying biodiversity experts as corresponding authors of scientific papers published in English failed to include many other experts, such as many Indigenous peoples, conservation practitioners (Sandbrook *et al.* 2019), and other experts who primarily publish or communicate in non-English languages. Failing to include non-English-language studies can bias ecological meta-analyses (Amano *et al.* 2016; Konno *et al.* 2020). In an effort to make the survey questions relevant and accessible to experts worldwide, we iteratively revised the questions with an international team of experts who together study all major taxonomic groups and ecosystem types, and represent multiple career stages, genders, and regions of the world. We encourage future studies that collaboratively develop and translate surveys into multiple languages and that fully include the perspectives and voices of more biodiversity experts worldwide, including those in the Global South and East (Mori 2022).

Other biases in the sample of biodiversity experts were also apparent. We received twice as many responses from experts who identified as men than from experts who identified with other genders, and twice as many responses from experts who live in Europe and Central Asia than from experts who live in any other region of the world (WebTable 2). Often, the overrepresented groups of experts provided relatively low estimates for the magnitude of past biodiversity loss and its impacts on ecosystems and people (WebTable 2). Thus, the overall values we report likely underestimate the projections that would be provided by a demographically or geographically stratified sample.

Conclusions

Our results help fill knowledge gaps, identify points of consensus, and reveal important differences in experts' estimates and recommendations. The expert estimates reported here complement, but do not supersede, other existing empirical evidence. Together, our results suggest that more species may be threatened than previously thought, given relatively high estimates of biodiversity loss for understudied and hyperdiverse taxa and from some historically marginalized groups of experts, including experts who identify as women or are from the Global South (Tydecks *et al.* 2018; Maas *et al.* 2021). Furthermore, our results suggest that a currently emphasized biodiversity conservation solution – the expansion of protected areas (Dinerstein *et al.* 2019; CBD 2021) – is perceived as a higher priority by historically overrepresented groups of experts, including experts who identify as men or who live in the Global North (Tydecks *et al.* 2018; Maas *et al.* 2021). We encourage biodiversity experts to use these results to learn how their own perspectives differ from those of other experts (Sandbrook *et al.* 2019; Mori 2022), and to ensure that a diversity of perspectives is included when conducting global biodiversity assessments, setting global biodiversity goals and targets, and formulating the novel policies and other transformative changes needed to conserve biodiversity.

Acknowledgements

We thank all biodiversity experts who responded to our survey. Funding was provided by the US National Science Foundation (DEB-1545288, DEB-1845334, DBI-2021898). NE gratefully acknowledges the support of the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig funded by the German Research Foundation (FZT 118, 202548816) as well as the Jena Experiment (DFG; FOR 5000). *Author contributions:* FI conceived the project, created the first draft of the survey, analyzed the data, and wrote the paper, with substantial input from all coauthors. An international team with expertise in all major taxonomic groups and ecosystem types, and who represent multiple career stages, genders, and regions of the world, provided feedback on multiple drafts of the survey, including: MA, MLA, PB, JMB, JEKB, ATC, SLC, JCow, JCor, LED, NE, AG, NRG-R, NMH, YH, CEK, KK, KJK, DJL, JL, ML, ASM, TN, MIO, MSP, OLP, PP, CP-R, PBR, DR, OES, BS, EWS, MDS, CHT, LJW, AJW, and CRZ. To encourage survey responses from parts of the world where English is not the primary language, PB, ASM, and J-SH translated the survey invitation into other languages (Spanish, Japanese, Chinese), and PB, ASM, J-SH, and JMB helped disseminate the survey to ecological societies. To promote geographic and gender diversity of coauthors, and to avoid "helicopter science" (https://doi.org/10.1016/j.cell.2020.12.019), multiple experts, including those identifying as women, were invited as coauthors from each habitable continent. To promote equity in author order, coauthors were randomly, rather than alphabetically, ordered into two groups, with PB, ASM, J-SH, and JMB contributing the most. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Data Availability Statement

Data and metadata are available through the Environmental Data Initiative at https://doi.org/10.6073/pasta/127ceb32ee80675b1484e154c3920b45.

References

Amano T, González-Varo JP, and Sutherland WJ. 2016. Languages are still a major barrier to global science. *PLoS Biol* **14**: e2000933.

Aspinall W. 2010. A route to more tractable expert advice. *Nature* **463**: 294–95.

Balvanera P, Calderón-Contreras R, Castro AJ, *et al*. 2017. Interconnected place-based social–ecological research can inform global sustainability. *Curr Opin Environ Sust* **29**: 1–7.

Bamber JL, Oppenheimer M, Kopp RE, *et al*. 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. *P Natl Acad Sci USA* **116**: 11195.

Burgman MA, McBride M, Ashton R, *et al*. 2011. Expert status and performance. *PLoS ONE* **6**: e22998.

CBD (Convention on Biological Diversity). 2020. Global biodiversity outlook 5. Montreal, Canada: CBD.

CBD (Convention on Biological Diversity). 2021. First draft of the post-2020 global biodiversity framework. Montreal, Canada: CBD.

Ceballos G, Ehrlich PR, Barnosky AD, *et al*. 2015. Accelerated modern human-induced species losses: entering the sixth mass extinction. *Science Advances* **1**: e1400253.

Clausnitzer V, Kalkman VJ, Ram M, *et al*. 2009. Odonata enter the biodiversity crisis debate: the first global assessment of an insect group. *Biol Conserv* **142**: 1864–69.

Colson AR and Cooke RM. 2018. Expert elicitation: using the classical model to validate experts' judgments. *Rev Env Econ Policy* **12**: 113–32.

Cooke RM. 1991. Experts in uncertainty: opinion and subjective probability in science. New York, NY: Oxford University Press.

Cooke RM, Dias LC, Morton A, and Quigley J (Eds). 2018. Validation in the classical model. In: Dias LC, Morton A, and Quigley J (Eds). Elicitation: the science and art of structuring judgement. Cham, Switzerland: Springer.

Díaz S, Settele J, Brondízio ES, *et al*. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**: eaax3100.

Díaz S, Zafra-Calvo N, Purvis A, *et al*. 2020. Set ambitious goals for biodiversity and sustainability. *Science* **370**: 411–13.

Dinerstein E, Vynne C, Sala E, *et al*. 2019. A global deal for nature: guiding principles, milestones, and targets. *Science Advances* **5**: eaaw2869.

Eisenhauer N, Bonn A, and Guerra CA. 2019. Recognizing the quiet extinction of invertebrates. *Nat Commun* **10**: 50.

Haddad NM, Brudvig LA, Clobert J, *et al*. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* **1**: e1500052.

Humphreys AM, Govaerts R, Ficinski SZ, *et al*. 2019. Global dataset shows geography and life form predict modern plant extinction and rediscovery. *Nat Ecol Evol* **3**: 1043–47.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) Secretariat. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES.

Isbell F, Calcagno V, Hector A, *et al*. 2011. High plant diversity is needed to maintain ecosystem services. *Nature* **477**: 199–202.

Isbell F, Gonzales A, Loreau M, *et al*. 2017. Linking the influence and dependence of people on biodiversity across scales. *Nature* **546**: 65–72.

Isbell F, Tilman D, Polasky S, *et al*. 2015. The biodiversity-dependent ecosystem service debt. *Ecol Lett* **18**: 119–34.

IUCN (International Union for Conservation of Nature). 2020. The IUCN Red List of Threatened Species (v2020-3). Gland, Switzerland: IUCN.

Joppa LN, O'Connor B, Visconti P, *et al*. 2016. Filling in biodiversity threat gaps. *Science* **352**: 416–18.

Konno K, Akasaka M, Koshida C, *et al*. 2020. Ignoring non-English-language studies may bias ecological meta-analyses. *Ecol Evol* **10**: 6373–84.

Leclère D, Obersteiner M, Barrett M, *et al*. 2020. Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**: 551–56.

Loreau M, Hector A, and Isbell F. 2022. The ecological and societal consequences of biodiversity loss. London, UK: ISTE and Hoboken, NJ: John Wiley & Sons.

Maas B, Pakeman RJ, Godet L, *et al*. 2021. Women and Global South strikingly underrepresented among top-publishing ecologists. *Conserv Lett* **14**: e12797.

Mace GM, Barrett M, Burgess ND, *et al*. 2018. Aiming higher to bend the curve of biodiversity loss. *Nature Sustainability* **1**: 448–51.

Maxwell SL, Fuller RA, Brooks TM, *et al*. 2016. Biodiversity: the ravages of guns, nets and bulldozers. *Nature* **536**: 143–45.

Mora C, Tittensor DP, Adl S, *et al*. 2011. How many species are there on Earth and in the ocean? *PLoS Biol* **9**: e1001127.

Mori AS. 2022. Diversity, equity, and inclusion in academia to guide society. *Trends Ecol Evol* **37**: 1–4.

Mori AS, Isbell F, and Seidl R. 2018. Beta-diversity, community assembly, and ecosystem functioning. *Trends Ecol Evol* **33**: 549–64.

Nic Lughadha E, Bachman SP, Leão TCC, *et al*. 2020. Extinction risk and threats to plants and fungi. *Plants People Planet* **2**: 389–408.

O'Connor MI, Gonzalez A, Byrnes JEK, *et al*. 2017. A general biodiversity–function relationship is mediated by trophic level. *Oikos* **126**: 18–31.

Purvis A, Molnar Z, Obura D, *et al*. 2019. Status and trends – nature. In: Brondiízio ES, Settele J, Díaz S, *et al*. (Eds). Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES.

Quigley J, Colson AR, Aspinall WP, *et al*. 2018. Elicitation in the classical model. In: Dias LC, Morton A, and Quigley J (Eds). Elicitation: the science and art of structuring judgement. Cham, Switzerland: Springer.

Rounsevell MDA, Harfoot M, Harrison PA, *et al*. 2020. A biodiversity target based on species extinctions. *Science* **368**: 1193.

Sala OE, Chapin III FS, Armesto JJ, *et al*. 2000. Biodiversity: global biodiversity scenarios for the year 2100. *Science* **287**: 1770–74.

Sandbrook C, Fisher JA, Holmes G, *et al*. 2019. The global conservation movement is diverse but not divided. *Nature Sustainability* **2**: 316–23.

Schlapfer F, Schmid B, and Seidl I. 1999. Expert estimates about effects of biodiversity on ecosystem processes and services. *Oikos* **84**: 346–52.

Sutherland WJ and Burgman MA. 2015. Use experts wisely. *Nature* **526**: 317–18.

Trisos CH, Merow C, and Pigot AL. 2020. The projected timing of abrupt ecological disruption from climate change. *Nature* **580**: 496–501.

Tydecks L, Jeschke JM, Wolf M, *et al*. 2018. Spatial and topical imbalances in biodiversity research. *PLoS ONE* **13**: e0199327.

Urban MC. 2015. Accelerating extinction risk from climate change. *Science* **348**: 571.

van der Plas F. 2019. Biodiversity and ecosystem functioning in naturally assembled communities. *Biol Rev* **94**: 1220–45.

van Klink R, Bowler DE, Gongalsky KB, *et al*. 2020. Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science* **368**: 417.

Yachi S and Loreau M. 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. *P Natl Acad Sci USA* **96**: 1463–68.

Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.2536/suppinfo

México, Morelia, México; [3]Research Center for Advanced Science and Technology, The University of Tokyo, Tokyo, Japan; [4]Department of Ecology, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China; [5]State Key Laboratory of Grassland Agroecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, China; [6]UK Centre for Ecology and Hydrology, Wallingford, UK; [7]Third Pole Conservancy, Bhaktapur, Nepal; [8]Clouded Leopard Working Group, c/o Small Wild Cat Conservation Foundation, Corrales, NM; [9]CSIRO Land and Water, Canberra, Australia; [10]Global Drylands Center, School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ; [11]Biodiversity, Macroecology and Biogeography, Faculty of Forest Sciences and Forest Ecology, University of Göttingen, Göttingen, Germany; [12]Universidad de Buenos Aires, Facultad de Agronomía, Cátedra de Botánica General, Buenos Aires, Argentina; [13]Department of Fisheries, Wildlife, and Conservation Biology and Minnesota Aquatic Invasive Species Research Center, University of Minnesota, St Paul, MN; [14]Department of Geography, University of Zurich, Zurich, Switzerland; [15]Institute of Ecology, College of Urban and Environmental Sciences, Peking University, Beijing, China; [16]Centre for Biodiversity and Environment Research, Department of Genetics, Evolution and Environment, University College London, London, UK; [17]Department of Biology, Faculty of Science, Mahasarakham University, Maha Sarakham, Thailand; [18]Theoretical and Experimental Ecology Station, CNRS, Moulis, France; [19]AP Leventis Ornithological Research Institute, University of Jos, Jos, Nigeria; [20]Biotechnology Unit, Department of Biological Sciences, Elizade University, Ilara-Mokin, Nigeria; [21]Natural History Museum, University of Oslo, Oslo, Norway; [22]Coastal Oceans Research and Development – Indian Ocean (CORDIO) East Africa, Mombasa, Kenya; [23]School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa; [24]Universidad de Santiago de Chile, Facultad Tecnologica, Departamento de Gestión Agraria, Santiago, Chile; [25]Institute of Biology, University of Graz, Graz, Austria; [26]Department of Physiological Diversity, Helmholtz Centre for Environmental Research, Leipzig, Germany; [27]German Centre for Integrative Biodiversity Research Halle-Jena-Leipzig, Leipzig, Germany; [28]Smithsonian Environmental Research Center, Edgewater, MD; [29]Department of Evolutionary Biology and Environmental Studies, University of Zurich, Zurich, Switzerland; [30]US Geological Survey, National Climate Adaptation Science Center, Reston, VA; [31]Department of Forest Resources, University of Minnesota, St Paul, MN; [32]Department of Biology, University of New Mexico, Albuquerque, NM; [33]Institute of Biology, University of Leipzig, Leipzig, Germany; [34]African Climate and Development Initiative, University of Cape Town, Cape Town, South Africa; [35]Centre for Statistics in Ecology, the Environment and Conservation, University of Cape Town, Cape Town, South Africa; [36]National Socio-Environmental Synthesis Center, University of Maryland, Annapolis, MD; [37]CEFE, University of Montpellier, CNRS, EPHE, IRD, Montpellier, France; [38]California State University, Los Angeles, Los Angeles, CA; [39]International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal; [40]Department of Biology, University of Massachusetts Boston, Boston, MA; [41]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, Australia; [42]Institute for Global Change Biology, and School for Environment and Sustainability, University of Michigan, Ann Arbor, MI; [43]Department of Life Sciences, Natural History Museum, London, UK; [44]Department of Life Sciences, Imperial College London, Silwood Park campus, Ascot, UK; [45]Water Quality and Environment Research Centre, National Water Research Institute of Malaysia, Seri Kembangan, Malaysia; [46]Department of Zoology, Biodiversity Research Centre, University of British Columbia, Vancouver, Canada; [47]The Nature Conservancy, Minneapolis, MN; [48]WK Kellogg Biological Station, Department of Integrative Biology, Michigan State University, Hickory Corners, MI; [49]Centro de Observación Marino para Estudios de Riesgos del Ambiente Costero, Facultad de Ciencias del Mar y de Recursos Naturales, Universidad de Valparaíso, Viña del Mar, Chile; [50]Department of Ecology and Evolutionary Biology, University of Colorado Boulder, Boulder, CO; [51]Consejo Nacional de Investigaciones Científicas y Técnicas, Instituto Multidisciplinario de Biología Vegetal, CONICET, Córdoba, Argentina; [52]Universidad Nacional de Córdoba, Facultad de Ciencias Exactas, Físicas y Naturales, Departamento de Diversidad Biológica y Ecología, Córdoba, Argentina; [53]Morton K Blaustein Department of Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD; [54]Institute of Ecology, College of Urban and Environmental Sciences and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China; [55]Forest Advanced Computing and Artificial Intelligence Laboratory, Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN; [56]Department of Applied Economics, University of Minnesota, St Paul, MN; [57]US Geological Survey, North Central Climate Adaptation Science Center, Fort Collins, CO; [58]Ecology and Biodiversity Group, Department of Biology, Utrecht University, Utrecht, the Netherlands; [59]Department of Biology, Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO; [60]Health and Environmental Sciences Department, Xian Jiaotong-Liverpool University, Suzhou, China; [61]US Geological Survey, National Climate Adaptation Science Center/North Carolina Cooperative Fish and Wildlife Research Unit, Department of Applied Ecology, North Carolina State University, Raleigh, NC; [62]Global Change Research Institute of the Czech Academy of Sciences, Brno, Czech Republic; [63]Centro de Investigación en Ciencias del Mar y Limnología, Universidad de Costa Rica, San Pedro, Costa Rica; [64]Escuela de Biología, Universidad de Costa Rica, San Pedro, Costa Rica; [65]CIBET-Museo de Zoología, Universidad de Costa Rica, San Pedro, Costa Rica; [66]UN Environment Programme–World Conservation Monitoring Centre, Cambridge, UK; [67]Department of Biology, McGill University, Montreal, Canada; [68]Centro de Investigaciones Tropicales del Ambiente y la Biodiversidad (CITIAB), Universidad Nacional de Loja, Loja, Ecuador; [69]Center for Modelling and Monitoring Ecosystems, School of Forest Engineering, Universidad Mayor, Santiago, Chile; [70]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ; [†]coauthors are randomly ordered within two groups, with this group contributing the most

FrontiersEcoPics

Host manipulation by a parasitic plant?

Naturalists recognize that parasites can enhance their reproductive success by manipulating the behaviors of their hosts. While host manipulation has primarily been observed in the animal kingdom, it can also occur between parasites and plants. Approximately 4000 species of parasitic angiosperms rely on other plants for water and nutrients, thus providing many opportunities for host manipulation. On the southern Japanese island of Yakushima, we observed that the roots of an evergreen broadleaf tree *Castanopsis sieboldii* (Fagaceae) parasitized by the non-photosynthetic plant *Mitrastemon yamamotoi* did not burrow underground as they typically do. Instead, the roots spread near or on the soil surface. This change in the distribution of the tree's roots enables the parasitic *M yamamotoi* to flower above ground. This phenomenon arguably illustrates host manipulation by a parasitic plant, suggesting that the manipulation of host plants by parasitic plants may be more widespread than previously thought.

Kenji Suetsugu[1] and Hiroaki Yamashita[2]
[1]Kobe University, Hyogo, Japan; [2]Kagoshima, Japan
doi:10.1002/fee.2607